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BrM Quantity-Based Bridge Element Deterioration/Improvement Modeling and Software Tools

Prepared By
Gongkang Fu, PE, PhD
Gabriel Bryk, MAS

Illinois Institute of Technology

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16. Abstract

This study reviewed the state of the art and practice in bridge element deterioration / improvement modeling. It also developed a new and practical method for such modeling using element quantities in BrM inspection records along with bridge age. For reliable forecasting, this method uses these quantities directly to determine transition probability matrices (TPMs). The example TPMs were found age-dependent for the do-nothing case. Results show that this approach is effective in forecasting the bridge element life. Condition improvement TPMs were also similarly derived from the quantity evolution for consistency. Examples of renewal construction work are deck overlay of micro-silica concrete, steel beam repainting, bridge cleaning, etc. Two computer software programs in Microsoft Excel were developed to obtain TPMs for do-nothing deterioration and condition improvement. Bridge owners may use the tools to generate TPMs for any element whose inspection records are provided. As a result, TPMs can be continuously updated whenever more inspections are performed and their records are included as input to the software programs. In addition, the software tools are transparent for the user to perform expert elicitation, especially when the inspection records are questionable or unavailable. Such activity can be informatively guided by the results from the software, as illustrated by two application examples in the delivered programs. This new concept and associated tools may be applied by other bridge owners using the BrM system. Two application examples for elements 12 and 107 in the programs can be readily transplanted to other states as a starting point for application of the research products herein. They show that the age-dependent TPM is able to realistically replicate deterioration for the do-nothing case, particularly the behavior of faster deterioration while aging. They also demonstrate that TPMs for different renewal construction work are able to contrast their effectiveness, such as micro-silica overlays vs. sealing for a concrete deck.

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EXECUTIVE SUMMARY

This research effort reviewed the state of the art and practice in the field of bridge element deterioration / improvement modeling. It is noted as a result of the literature review that age-dependent do-nothing deterioration has been widely observed in the field. However, its practical and effective modeling has not been reported or practiced. In addition, modeling for condition improvement due to renewal construction work, preservation, or prevention has been challenging. These issues were the focus of the present research effort.

This study thus developed a new and practical method for deterioration / improvement modeling using bridge element quantities in the BrM inspection records along with bridge age from the National Bridge Inventory (NBI). For reliable forecasting, the new method uses these quantities directly to determine the transition probability matrices (TPMs) for modeling condition deterioration or improvement. BrM quantities evolve as a result of deterioration subject to the environment or condition improvement by renewal construction work. The TPMs were derived exactly from bridge element quantity transitions among the condition states. The example TPMs were found age-dependent for the case of do-nothing, quantifying faster bridge element deterioration when aging. Results show that this approach is effective in forecasting the life of a bridge element. For consistent concept and application, the condition improvement TPMs were also similarly derived from the quantity evolution documented in element inspection records. Examples of renewal construction work are deck overlay of micro-silica concrete, steel beam repainting, bridge cleaning, etc., and they are recorded in agency records of activities.

Two efficient computer software programs were developed in Microsoft Excel for bridge owners to obtain TPMs for the cases of do-nothing deterioration and condition improvement, respectively, using available inspection records. The Excel format provides a convenient visual interface as well as possible transfer of results to other platforms for further analysis or presentation. Bridge owners will be able to use the tools to generate TPMs for any element whose inspection records are provided. As a result, TPMs can be continuously updated whenever more inspections are performed and their records are included as input to the software programs. In addition, the software tools are transparent for the user to readily perform expert elicitation, especially when the inspection records are erroneous or not available. Such activity can be informatively guided by the intermediate and final results of trial calculations from the software tools, as illustrated by two application examples in the software programs.

This new concept and associated software tools may be applied by other bridge owners using the BrM bridge management system. The two application examples for Elements 12 (reinforced concrete deck) and 107 (steel girder beam) in the software programs can be readily transplanted to other states as a starting point for application of the research products herein. The examples show that the age-dependent TPM is able to realistically replicate element deterioration for the do-nothing case, particularly faster deterioration while aging. They also demonstrate that TPMs for different types of renewal construction work are able to contrast their various effectiveness, such as replacement, concrete overlay, bituminous overlay, patching, and sealing to a reinforced concrete deck.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

BACKGROUND

Over the past several decades, virtually all US state transportation agencies have gradually adopted AASHTOWare Bridge Management (BrM). Meaningful bridge element inspection data have been gathered by a large number of bridge owners so far. It is important to ensure that the collected data are effectively employed for forecasting and related decision-making on maintenance, repair, rehabilitation, or replacement.

The overall objective of this research project was to develop deterioration curves based on element-level inspection data from Illinois' bridge inventory. The deterioration curves will provide the basis for the bridge management system of the Illinois Department of Transportation (IDOT): AASHTOWare BrM.

IDOT started to collect condition state data of bridge elements in the BrM framework around 1994. The present study analyzed this dataset along with other available IDOT databases. It accordingly developed a new approach to the transition probability matrix (TPM) directly based on IDOT BrM data. The study implemented this approach into two computer software programs, Mansus and Elevatio, using Excel. Mansus and Elevatio are for typical cases of do-nothing deterioration and condition improvement via renewal construction work, respectively. Illustrations were also developed and documented in this report as to how the resulting TPMs and other intermediate results could be used for forecasting bridge-element condition for a single bridge or a number of bridges in a network. The network can be a route, a region, or the entire state.

ORGANIZATION OF REPORT

This report consists of six chapters, including this introductory chapter.

Chapter 2 documents a literature review of state of the art and the practice in the relevant field. It focuses on bridge element deterioration/improvement modeling using the BrM element inspection records. First, the BrM and NBI systems of inspection and rating are reviewed and contrasted to ensure the present project's effort on the former. Next, it highlights challenges in this focused field.

Chapter 3 presents proposed new approaches to extracting TPMs for both do-nothing deterioration and condition improvement. These approaches reflect intentions to respond to the challenges identified in Chapter 2 observed in previous research efforts. The main and critical advancement of the proposed approaches is to maintain the relation between the previous and future condition statuses through the obtained TPM for each individual bridge element. Then, the resulting TPMs for the bridge element are averaged and evaluated for their variations among all bridges in the scope. This idea also allows the factor of age to be explicitly included in TPMs, because each bridge-associated element has an age recorded in the NBI. In contrast, previous methods ignored the fundamental relation between the previous and future condition statuses through TPM for each basic unit (bridge element).

Chapter 4 introduces two computer software programs, Mansus and Elevatio, in the MS Excel platform for TPM calculation using BrM element inspection records. Their algorithms are based on the proposed new approaches presented in Chapter 3.

Chapter 5 includes two application examples, EN12 and EN107, carried out in the Mansus and Elevatio programs. The presentations also include applications of the TPMs for potential forecasting and relevant decision-making. The researchers expect these applications to inspire further applications in this direction.

Chapter 6 contains a summary of the conclusions and recommendations of the present study.

CHAPTER 2: STATE OF THE ART AND THE PRACTICE

There are two bridge condition rating systems practiced in the United States for bridge management, the NBI and the BrM systems.

The NBI system records aggregated bridge condition ratings for the deck, superstructure, substructure, culvert, and possibly a few other bridge components and/or systems, depending on the bridge owner. Without further detailing to bridge elements such as concrete girder beam, steel bearing, expansion joint, etc., the NBI system uses a rating scale from 0 to 9 in general for these bridge components, subsystems, or systems. There are a few exceptions. For example, the state of New York uses a scale of 0 to 7 for the same bridge components or systems. To enhance or quantify the rating, however, some bridge owners also use agency-specific forms or other tools to gather more detailed condition information contributing to the final rating of the integrated components, subsystems, or systems (i.e., deck, superstructure, substructure, culvert, etc.).

The BrM system is explicitly bridge-element oriented. Each bridge is divided into elements, such as a reinforced concrete (RC) deck, steel girder beam, and elastomeric bearing. Each element's total quantity of the bridge is counted (such as how many RC columns) or quantified (such as how many square feet of an RC deck). Upon an inspection, the total quantity of each element of the bridge is divided according to the condition state (CS). The quantities at each CS are then recorded as the inspection result in the BrM. Currently, four CSs are used for each bridge element: CS1, CS2, CS3, and CS4, from best to worst. This approach is based on the so-called Markov Chain framework (e.g., Fu & Moses, 1986; Fu, 1987; Jiang et al., 1988), which is intended to be able to forecast future conditions of the element based on its past history or evolution of the recorded condition states.

Note that the quantities at CSs are also used to describe the element's condition in a probabilistic context. For example, if there are 5,000, 2,000, 1,000, and 0 square feet (sqft) at CS1, CS2, CS3, and CS4, respectively, for an RC deck of 8,000 sqft, the deck is said to be 62.5% (= 5,000 / 8,000), 25% (= 2,000 / 8,000), 12.5% (= 1,000 / 8,000), and 0% (= 0 / 8,000) at these CSs, respectively. This concept is also extended to RC decks of all bridges on a route, in a region, or in the entire state for network-level bridge management. These probabilities are also organized as the condition probability distribution $\mathbf{q} = \{0.625, 0.250, 0.125, 0\}^t$, a column vector with the superscript *t* indicating matrix transpose. "Condition" here refers to the physical condition of a bridge element, which is different from "conditional" probability referred to in Chapter 3 and thereafter. That condition refers to a hypothesis under which a probability is defined or estimated.

Note that NBI ratings can also be treated in the Markov Chain framework (e.g., Jiang et al., 1988; Agrawal et al., 2009), while the NBI rating system was initiated without the Markov Chain model in the field of vision. To stress the major differences between the NBI and BrM systems, the basic or the smallest unit carrying the condition rating in the NBI is a major bridge component or the entire structure system itself, such as a bridge deck, a bridge superstructure, and a culvert. In contrast, the basic unit associated with the CS rating in BrM is a quantity of a bridge element, such as a square foot of an RC deck or a linear foot of a prestressed concrete girder beam of a bridge. Apparently, BrM offers a much higher fidelity for the condition state of a bridge element down to a fraction of the element, while NBI stops at a major bridge structure component. The two rating systems need different corresponding analysis approaches to meet their respective requirements for application.

Theoretically, the Markov Chain is a special case of a more general set of mathematical models referred to as Markov Random Processes (e.g., Fu, 1987; Ross, 1996). These models have found wide applications in various fields, such biosciences and human population evolution. These random processes can have continuous or discrete states modeled as random variables. The former is generally defined on the entire real number axis $(-\infty,\infty)$ or part of the real number axis (e.g., all positive real numbers). The latter, or the discrete states, for example, can be all positive integers with spaces between every two integers excluded. Markov processes with discrete states are referred to as Markov Chains. As mentioned above, the current BrM system uses a Markov Chain model of four discretized states, CS1 to CS4, which is a very small subset of all integers. More information regarding state definitions can be found in Fu (1987), which introduced both continuous and discrete Markov Random Process frameworks for modeling bridge element condition and load-carrying capacity states.

Markov Random Processes can also be defined on both continuous and discrete temporal or spatial scales. When the former is used, theoretically, the time scale is continuous in $(0,\infty)$. Practically, on the other hand, continuous recording of the condition state can be excessively costly. As a result, this option is used seldomly in engineering applications.

Pontis, the predecessor of BrM using the Markov Chain model, started development in the 1990s, and state bridge owners later accepted and implemented it. Its adoption and implementation gradually extended throughout the United States, and it has become the most popular bridge management system in the country. This Markov Chain–based concept has also gained widespread acceptance internationally. As a result, element inspection records have been growing among state bridge owners—especially in the United States, although the data durations vary depending on when the system was implemented in the jurisdiction.

As stated earlier, NBI ratings are different from BrM ratings. As such, their processing for forecasting will need to be designed accordingly. NBI ratings are aggregated to the bridge so that the history of rating evolution is indexed with the structure number (SN) or bridge ID. For example, a bridge deck, whether concrete or steel, is referenced by the bridge ID. The deck carries the condition rating as the smallest bridge component in the record. BrM ratings, rather, refer to a quantity of a bridge element identified by element number (EN). For example, the smallest quantity for an RC deck is a square foot of the deck indexed to a CS as rating. The history of rating evolution over time for the quantity is of interest here for modeling deterioration / improvement. However, each particular quantity is not tracked or indexed in the BrM inspection records. Namely, part of a quantity (say 500 sqft) may stay in the same CS observed in the earlier inspection (say 200 sqft), another part of that quantity (say the remaining 300 sqft) may have evolved to a different CS in a future inspection. These two parts of the quantity can respectively split again in a further future inspection, becoming two new quantities without being tracked where these quantities physically are or were in the particular bridge. As a result, the BrM element CS ratings are more challenging to track and analyze for processing and deterioration/improvement model extracting. This is the very focus of the present study.

A brief review is presented next in chronological order regarding approaches to analyze Pontis/BrM system inspection records to model bridge element deterioration/improvement. These discussions will lead to a presentation of the proposed approaches developed in the present study, targeting implementable products for IDOT.

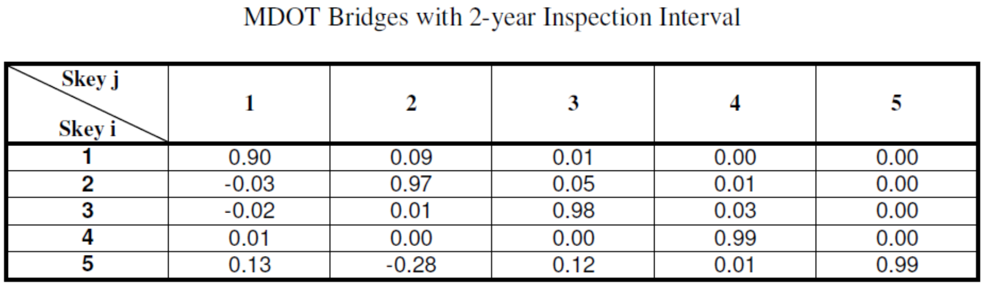
Fu and Devaraj (2008) completed a study for the Michigan Department of Transportation, focusing on the development of the transition probability matrix (TPM) in the Markov Chain model. The study was triggered by issues observed in computing TPM in Pontis and applying the results in practice. The study included detailed analyses for the TPM computation method of Pontis.

The Pontis method assumes that the TPM is constant over time or age of the element—namely, the Markov Chain is homogeneous. With the observed issues analyzed, the research team introduced a new concept of non-homogeneous Markov Chain or age-dependent TPM. A regression-based approach was introduced for the calculation of age-dependent TPMs, using relatively limited inspection records available at the time.

The observed issues with the Pontis method were identified in the report as follows.

(1) Negative probabilities were seen in the computed TPM result. This is due to the regression procedure used without appropriate constraints on the involved quantities, as probabilities are never supposed to be negative. When used in forecasting, the resulting negative probabilities can lead to negative quantities for a bridge element, which makes no practical sense. Table 1 presents an example TPM for a two-year inspection interval, taken from Fu and Devaraj (2008), using the Pontis method applied to Michigan EN=107 (steel girder beam). *Skey i* in Table 1 is the CS from which the element is transitioning, and *Skey j* is the CS to which the element is transitioning. At the time, five CSs were used for EN107. As seen, three transition probabilities were calculated as negative values. However, these negative values were not shown in the Pontis output because they were set to 0 by Pontis. Apparently, this forceful setting may lead to significant errors in forecasting using the artificially set values, especially when the calculated results are as significant as −0.28 (for Skey i=5 and j=2 in Table 1), contrasted by the [0,1] domain for all probabilities.

Table 1. Example TPM from Pontis (Table 6.5 of Fu & Devaraj, 2008)



MDOT Bridges with 2-year Inspection Interval

Skey j Skey i	1	2	3	4	5
1	0.90	0.09	0.01	0.00	0.00
2	-0.03	0.97	0.05	0.01	0.00
3	-0.02	0.01	0.98	0.03	0.00
4	0.01	0.00	0.00	0.99	0.00
5	0.13	-0.28	0.12	0.01	0.99

(2) The probabilities for all transitions from one CS do not add to 1. They should add to 1 because any quantity at one CS may only transition to one of the CSs including itself. Thus, those probabilities not adding to 1 violate this fundamental law of probability. Such results were

also due to the regression numerical algorithm used in Pontis without appropriate constraints. Practically and physically, these results lead to changes in the total quantity from one inspection to another, while the total is supposed to remain unchanged throughout the inspection history. An example in Table 1 is the bottom row for Skey i=5, where 0.13 − 0.28 + 0.12 + 0.01 + 0.99 = 0.97, which is not the required 1 being the total probability.

(3) For the case of do-nothing deterioration, probabilities of transitioning from a poor CS to a better CS existed in the calculated results. For example, Table 1 shows P_{ji} = 13% for i = 5 and j = 1 and P_ji = 12% for i = 5 and j = 3. These were significant probabilities in [0,1] representing a substantially high likelihood for these respective transitions from CS5 to CS1 and from CS5 to CS3, contradicting the condition of do-nothing deterioration. Ignoring these numerical results and setting them to 0, as done in Pontis, can cause a great deal of error in forecasting.

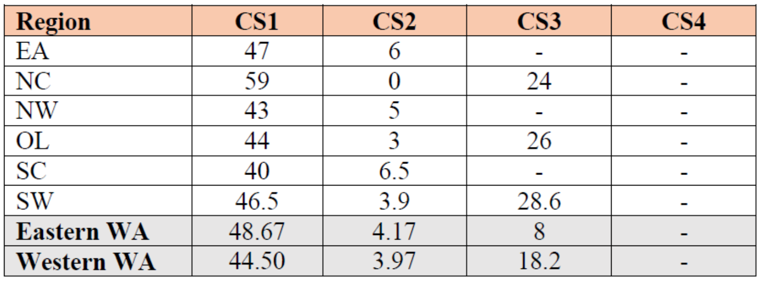
(4) Other issues were also present, but it was not clear how they are treated in Pontis, given the limited documentation. One example is associated with the approach to the regression equation solver. The regression solution is a process of mathematical minimization of the sum of squared residuals between the observed values (i.e., recorded quantities at CSs) and the predicted values using the thereby determined TPM, as formulated in Equations 10 and 11 below. In Pontis, this solution was found using an inverse matrix approach. However, matrix-inversing was not always feasible. When this occurred, no solution could be found. How such a situation was treated in Pontis is not well documented (Fu & Devaraj, 2008).

O'Leary and Walsh (2018) conducted a study for the Washington State Department of Transportation to model deterioration of RC columns/piles (EN = 205 and 227) using BrM element inspection records. The duration of the utilized inspection records was not explicitly given in the report, except for one example bridge of 44 columns/piles with inspection records from 1996 to 2008. These columns/piles were either dry or submerged. Their inspections recorded the numbers of columns/piles at each CS. It was implicitly assumed that the TPM for the case of do-nothing deterioration was constant, not a function of time. Hence, one TPM was pursued and obtained, as discussed next. In addition, it was explicitly assumed that transitions from one CS to another do not cross another CS in between. Namely, condition transitions were assumed to take place only from CS1 to CS2, from CS2 to CS3, or from CS3 to CS4, never CS1 to CS3, CS1 to CS4, or CS2 to CS4.

As a major result, Table 2, taken from O'Leary and Walsh (2018), presents the found average number of years that the RC columns/piles spent between a CS and the next poorer CS. They were identified for six regions in the state. These regions are identified in the first column of Table 2. Eastern WA in the eighth row includes regions EA, SC, and NC. Western WA in the ninth row refers to the collection of the other three regions in the table.

Some empty cells in Table 2 are marked with "-", apparently due to a lack of inspection records for CS4 and sometimes CS3, representing the worst CS of the four. It is also interesting to note that Region NC had an average number of years at CS2 equal to 0. Because this cell is not empty (like those marked with "-"), the 0 value appears to indicate that transitions from CS1 to CS3 have occurred in a very short period, likely within two years as the typical inspection interval. This contradicts the assumption that transitions only occur between two adjacent CSs.

Table 2. Average Years in Each CS for Washington Element 205 (Table 3 of O'Leary & Walsh, 2018)



Region	CS1	CS2	CS3	CS4
EA	47	6	-	-
NC	59	0	24	-
NW	43	5	-	-
OL	44	3	26	-
SC	40	6.5	-	-
SW	46.5	3.9	28.6	-
Eastern WA	48.67	4.17	8	-
Western WA	44.50	3.97	18.2	-

According to O'Leary and Walsh (2018), the number of transitions in Table 2 were counted for the entire state of Washington's population of RC columns/piles from CS1 to CS2, from CS2 to CS3, and from CS3 to CS4. Using their sum as the denominator and the number of transitions from CS1 to CS2 as the numerator, a ratio was arrived at as the probability of transition from CS1 to CS2, namely P_{21} in the TPM. Then, its complement probability was obtained as $P_{11} = 1 - P_{21}$ being the probability that those quantities in CS1 remain in CS1. This assumes no transition from CS1 to CS3 or to CS4. Similarly, P_{32} was the ratio between the number of transitions from CS2 to CS3 and the total number of transitions. Then, $P_{22} = 1 - P_{32}$ was arrived at, assuming no transition from CS2 to CS4. P_{43} was also similarly computed as the number of transitions from CS3 to CS4 divided by the total number of transitions, and then $P_{33} = 1 - P_{43}$. These calculations were shown in Tables 5 to 8 and reorganized in the form of TPM in Figure 3–6 of O'Leary and Walsh (2018).

However, it is not clear how the obtained TPM would be used for forecasting because the time interval for the resulting TPM was not explicitly stated in the report. The time period during which these observed and counted transitions took place is apparently the duration of the entire data history. This duration was not explicitly identified in the report but was at least between 1996 and 2008, as shown in the only example record in Table 1 of O'Leary and Walsh (2018) for a bridge of 44 columns. While each transition summarized in Table 2 above took many years to complete, the resulting TPM appears to be for the corresponding time periods. However, these time periods are not indicated in the report, either. They also must be much longer than the two-year period used in other studies reported in the literature.

Boadi et al. (2022) recently completed a Federal Highway Administration pooled fund study for 12 Midwestern states on bridge element deterioration using BrM records. The work is directly relevant to the present research effort. The study gathered, organized, and scrubbed element inspection records from the 12 states. A total of 219,383 bridges and 1.8 million inspections from these states were included in the study.

Three tiers of bridge elements were covered. Tier 1: RC deck, RC slab, National Bridge Inventory items; Tier 2: wearing surface, deck joints, defect development and progression, paint system effectiveness, steel girder corrosion, and substructure elements in harsh environments; and Tier 3: agency-defined elements and determining nondestructive evaluation translation. In addition to studying do-nothing deterioration for these tiers, an RC deck was studied for the case of condition improvement, namely after major preservation.

The results of this study in terms of deterioration curves were mostly given in terms of transition times. For the do-nothing case, they were based on (constant) transition probability P_{ii} for all i=1,2,3. P_{44} was set at 1 by default. For computation details, Appendix IV of Boadi et al. (2022) gives the transition time T_i from CS_i to CS_{i+1}:

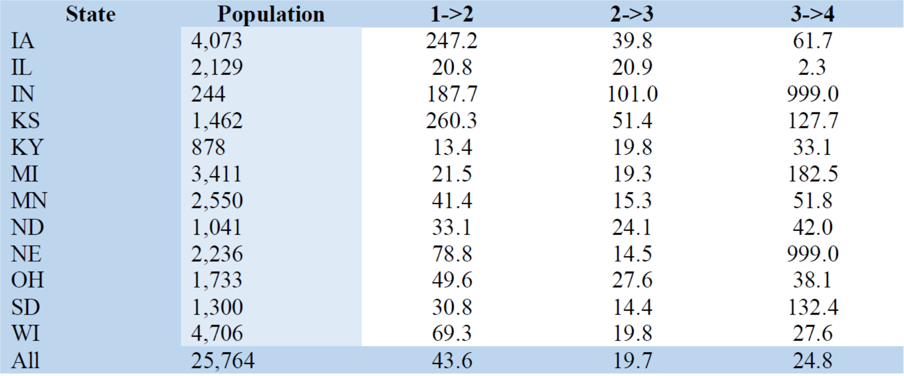
$$T_i = \text{Log}(0.5)/\text{Log}(P_{ii}) \tag{1}$$

Table 3 presents the resulting transition times T_i for RC deck as the most detailed example. Note that the value 999.0 years "indicates a result greater than or equal to 999 years, which is unlikely to be valid, and/or a population size too small to perform the algebraic computations" (Boadi et al., 2022, p. 23).

It should be stressed that Equation 1 includes a significant assumption that the transition from one CS to the next worse CS is defined as when the element quantity reduces to half (from 1.0 to 0.5). The value 0.5 or 50% in Equation 1 defines the end of transition. Nevertheless, Boadi et al. (2022) did not mention whether any state bridge owners use this criterion or definition for CS transition. The present study did not find information in this regard in the literature, either.

For Table 3, it is interesting to note that neighboring states exhibit sometimes very different transition times or lives between two CSs. For example, Illinois and Indiana—neighboring states—are in very similar latitude ranges, meaning that they have very similar climates and temperature ranges. They use similar construction materials and technologies as well. These factors are considered generally to be influential for RC structural components. However, in Table 3, RC decks of Indiana show more than five times (500%) longer transition times or lives than Illinois (i.e., 187.7 vs 20.8 years for transitions from CS1 to CS2 and 101.0 vs 20.9 years for CS2 to CS3). One may argue that the definitions for CSs may vary between the two states. A comparison of the total time or life of these RC decks does not support this argument though. The sum of all three transition times, 1->2, 2->3, and 3->4, for Indiana is 1,287+ years, but only 44 years for Illinois. This contrast is apparently not evidenced.

Table 3. Transition Times for RC Deck (Table 9 of Boadi et al., 2022).



State	Population	1->2	2->3	3->4
IA	4,073	247.2	39.8	61.7
IL	2,129	20.8	20.9	2.3
IN	244	187.7	101.0	999.0
KS	1,462	260.3	51.4	127.7
KY	878	13.4	19.8	33.1
MI	3,411	21.5	19.3	182.5
MN	2,550	41.4	15.3	51.8
ND	1,041	33.1	24.1	42.0
NE	2,236	78.8	14.5	999.0
OH	1,733	49.6	27.6	38.1
SD	1,300	30.8	14.4	132.4
WI	4,706	69.3	19.8	27.6
All	25,764	43.6	19.7	24.8

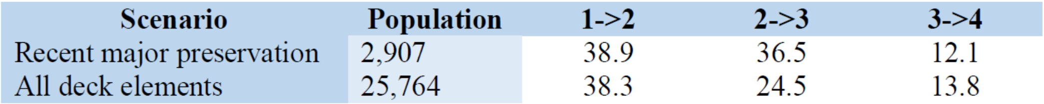
While constant TPM was assumed in the study leading to the results in Table 3 as part of the study recommendations, the report acknowledges the time-dependent or age-dependent nature of TPM:

"Bridge engineers have long believed that transition probabilities are time-dependent—that the probability of transition is low for a new element and increases with age" (Boadi et al., 2022, p. 134).

Table 4, from Boadi et al. (2022), presents the results for the case of condition improvement for RC deck, also in terms of transition times as a result of major preservation work. Such work includes overlay with removal of a certain depth of old concrete. The results in Table 4 were meant to demonstrate the effect of major preservation by comparison. The first row includes the transition times resulting from recent major preservation. It is compared with the second row of the same transition times but for the entire population, mixing decks with and without major preservation.

However, this contrast in Table 4 does not seem to indicate much improvement due to major preservation, if any. The case of improvement showed 0.6 years of increase for the transition from CS1 to CS2 out of 38.3 years, or a 1.6% increase. The transition from CS2 to CS3 experienced a much more meaningful improvement: from 24.5 years to 36.5 years, or a 49% increase. However, the transition from CS3 to CS4 showed that major preservation instead decreased the transition time or life from 13.8 years to 12.1 years, a 12.3% decrease.

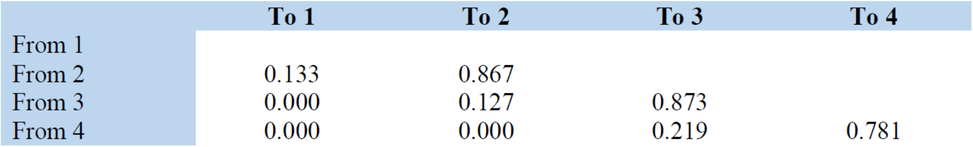
Table 4. Effect of Major Preservation for RC Deck (Table 13 of Boadi et al., 2022) via Transition Time in Years



Scenario	Population	1->2	2->3	3->4
Recent major preservation	2,907	38.9	36.5	12.1
All deck elements	25,764	38.3	24.5	13.8

This condition improvement due to major preservation was also expressed in terms of TPM, as seen in Table 5. Accordingly, Boadi et al. (2022, p. 36) conclude: "These results did not show as much improvement as expected. It is likely that this was caused by difficulties the agencies encountered in gathering activity data and classifying projects as major preservation." Nevertheless, this work on TPM for improvement or preservation was the first reported in the literature. Note that this subject of TPM for condition improvement is part of the present study reported herein.

Table 5. Improvement TPM for RC Deck (Table 14 of Boadi et al., 2022)



	To 1	To 2	To 3	To 4
From 1				
From 2	0.133	0.867		
From 3	0.000	0.127	0.873	
From 4	0.000	0.000	0.219	0.781

The observed issues in processing BrM inspection records for modeling condition deterioration or improvement in the above review can be summarized as follows.

1) Non-homogeneous nature of bridge element deterioration. The traditional Markov Chain model in BrM assumes homogenous behavior. Namely, the TPM for bridge element deterioration is assumed to be a constant matrix for every typical inspection interval (1 or 2 years depending on element and/or need), without variation over the entire life span of the bridge element. This has been observed to be unrealistic. It may also be the cause for

no solution for some cases, because one single TPM is sought to fit different deterioration behaviors at various ages in the regression.

2) Effect of renewal construction work on condition state improvement and TPM, such as maintenance, deck overlay, and rehab. These activities represent important factors in optimizing preservation strategies, as opposed to the do-nothing option. The corresponding TPMs for these activities in BrM are largely, if not all, based on expert judgement, not inspection observations. It is also true that much less research, if at all, on these activities has been reported in the literature developing corresponding TMPs for them. These variables deserve intensive attention in the present study.

3) The transition time (or sojourn time) between two rating levels. This transition time could be a piece of useful information for bridge owners when forecasting and planning. Related to the TPMs, the transition time seems intuitive to understand and use in decision-making. Interest in it has been growing for different elements in various environments. A significant majority of research efforts for bridge element deterioration modeling reported in the literature has been spent on modeling and determining transition time. Equation 1 has been overwhelmingly used for this purpose.

On the other hand, the transition from one CS to another CS has not been well defined quantitively. Unlike the NBI rating, where the transition time is clearly defined referring to a bridge component (Fu, 2021), or 100% of its quantity, the transition time of a quantity (i.e., a fraction) of an element in the BrM system is recorded but not indexed, let alone 100% of this element's deterioration. As a result, finding the transition time from a CS to another CS for the bridge element appears to be baseless, simply because the inspection records do not refer to that element as a unit.

As noted earlier, Equation 1 includes an important assumption that has not been validated. The assumption is that the transition from one CS to the next worse CS is considered completed when the entire quantity reduces to half, with the other half having transitioned to the worse CS and likely further worse CSs if they are still within the definition of CSs. Yet, there has not been documentation that bridge owners do use this half reduction as the criterion to define life exhaustion at a CS. In other words, if the bridge owner does not use this criterion, then the computed transition time according to Equation 1 may have little value to the bridge owner for forecasting or related decision-making.

In addition, if this criterion would be used consistently for transitions from CS1 to CS2, CS2 to CS3, and CS3 to CS4, then the sum of these three transition times would reach an estimate of the total life of the element. Table 3, from Boadi et al. (2022), shows that such sums can vary significantly among states that they do not seem to be valid estimates for practical application.

CHAPTER 3: ILLINOIS BRM INSPECTION RECORDS AND ANALYSIS APPROACH

BRM BRIDGE ELEMENT INSPECTION RECORDS

IDOT provided BrM bridge element inspection records to the research team for the present project. The dataset included inspection results spanning from 1994 to 2021 for state bridges. As seen in Table 6, the records include the following items: structure number (SN), inspection date, element number (EN), total quantity (TOTALQTY), and quantities at condition states 1 (CS1), 2 (CS2), 3 (CS3) and 4 (CS4).

Table 6. Typical Items of IDOT BrM Inspection Records

SN	InspectionDate	EN	TOTALQTY	CS1	CS2	CS3	CS4
10002	7/19/1996	38	836	819	17	0	0
10002	7/19/1996	215	69	55	1	13	0
10002	7/19/1996	234	66	63	2	1	0
10002	7/19/1996	330	52	0	52	0	0
10002	7/19/1996	510	836	819	17	0	0
10002	1/1/1997	38	836	811	25	0	0
10002	1/1/1997	215	69	59	7	3	0
10002	1/1/1997	234	66	63	2	1	0
10002	1/1/1997	330	52	0	52	0	0
10002	1/1/1997	510	836	811	25	0	0
10002	2/6/1998	38	836	811	25	0	0
10002	2/6/1998	215	69	59	7	3	0
10002	2/6/1998	234	66	63	2	1	0
10002	2/6/1998	330	52	0	52	0	0
10002	2/6/1998	510	836	811	25	0	0
10002	8/25/1998	38	836	585	251	0	0

Condition state evolution was divided into two cases here for analysis: do-nothing deterioration and condition improvement. Do-nothing deterioration refers to maintenance without major renewal work, such as concrete bridge deck overlay, steel beam re-painting, and superstructure rehabilitation. Condition improvement refers to occasional and more significant renewal work that noticeably enhances the condition of the bridge element, often immediately, upon completion of the work.

To develop models for these two different cases, the inspection records need to be separated accordingly. Then, corresponding algorithms can be applied respectively to develop reasonable models. The separating approach is presented in the following section along with the algorithms for their respective modeling.

QUANTITY ANALYSIS APPROACH FOR THE CASE OF DO-NOTHING DETERIORATION

Transition Probability Matrix

After the inspection record data were separated, the following concept is applied to develop the do-nothing deterioration model for each bridge element. The target here is the transition probability matrix (TPM), defined as follows.

$$\begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \\ p_{41} & p_{42} & p_{43} & p_{44} \end{bmatrix} = \mathbf{P} \qquad (2)$$

where P_{ij} (i,j = 1, 2, 3, 4) is the transition probability from CS_j to CS_i. For do-nothing deterioration, $P_{ij} = 0$, for j > i. This means that the quantity of a bridge element (say, 5,000 sqft of a bridge's RC deck or 620 ft of a bridge's steel girder beams) in a poorer CS can never transition to a better CS, because no meaningful renewal construction work has ever been done to that particular quantity of bridge element. Hereafter, bolded capital letters are used to designate matrices, such as TPM **P** in Equation 2. A matrix can be a square one, with the same number of rows and columns, as seen in TPM **P** above. A matrix can also be a row vector, with one row and a number of columns (four columns here for the current BrM), or a column vector, with one column and a number of rows (four rows here for the current BrM). Their operations such as addition, subtraction, multiplication, or division follow the rules of matrix operation (e.g., Kreyszig, 2011).

Note also that some publications, particularly those related to bridge management application, have the row index and column index of TPM in Equation 2 switched. This switch is not significant, because a transpose of the matrix can be added to return to what is meant in Equation 2. The option in Equation 2 is used here to be concise, avoiding too many transpose superscripts in Equation 2 and the following mathematical expressions.

TPM for Forecasting

P_{ij} is also the conditional probability that the quantity previously at CS_j (as the stipulation or condition) becomes at CS_i (as the result or consequence). Further note that "condition" here means hypothesis, not physical condition as used in this report until this point. In the remaining portion of this report, these two concepts may be mixed in the text, but the context will be clear as to which one is being referred to.

Based on the total probability theorem, the future quantity distribution column vector

$$\mathbf{Q}_{future} = \{Q_1, Q_2, Q_3, Q_4\}^t_{future} \qquad (3)$$

with superscript *t* for transpose is related to the previous quantity distribution column vector

$$\mathbf{Q}_{\text{previous}} = \{Q_1, Q_2, Q_3, Q_4\}^t_{\text{previous}} \tag{4}$$

as follows:

$$\mathbf{Q}_{\text{future}} = \mathbf{P}\,\mathbf{Q}_{\text{previous}} \tag{5}$$

Since the quantity column vector can be expressed as a product of the total quantity (a scalar) times the element's physical condition probability distribution

$$\mathbf{q} = \{q_1, q_2, q_3, q_4\}^t \tag{6a}$$

Equation 5 can be rewritten as

$$(\text{Total Quantity})\,(\mathbf{q}_{\text{future}}) = \mathbf{P}\,(\text{Total Quantity})\,(\mathbf{q}_{\text{previous}}) \tag{6b}$$

or after cancelling Total Quantity at both sides of Equation 6,

$$\mathbf{q}_{\text{future}} = \mathbf{P}\,\mathbf{q}_{\text{previous}} \tag{7}$$

Note that all terms in TPM **P** and condition probability distribution vector **q** are positive and less than or equal to 1 in the domain [0,1], according to the definition for probability. In addition, the components of each column vector **q** should add to 1 to qualify as a probability distribution vector

$$q_1 + q_2 + q_3 + q_4 = 1 \tag{8}$$

where

$$q_k = Q_k / \text{Total Quantity} \qquad (k=1,2,3,4) \tag{9a}$$

or in the vector form:

$$\mathbf{q} = \mathbf{Q} / \text{Total Quantity} \tag{9b}$$

When the requirement for probability in [0,1] is violated as discussed in Chapter 2 for Pontis, the total quantity in Equation 6 will change between the two inspections and over time. Then, forecasting will be erroneous.

Further note that the time interval in Equations 2 to 9 between the future and previous inspections is not explicitly identified yet. It needs to be specified for practical forecasting. In the literature, this interval is overwhelmingly chosen as two years, because of the two-year minimum time interval used in US bridge-inspection practice. However, the IDOT BrM inspection records show that the real time interval varies quite widely from less than a year to at least 17.1 years. Extreme cases may be even longer. To maximize the use of available inspection records, it is proposed here to use a standard one year by normalizing the **P** matrix to the standard one year, as presented below.

As discussed earlier, TPM **P** is actually age dependent. It, thus, makes sense to identify **P** with its age explicitly indicated, such as $\mathbf{P}^m$ for the age of *m* years of the focused bridge element. Therefore, forecasting a bridge element's condition status in the future at an age of *M* years described by $\mathbf{Q}^{M}$ can be performed based on available current $\mathbf{Q}^{M'}$ as follows, where $\mathbf{Q}^{M'}$ is the element's current quantity vector at the age of *M'* years.

$$\mathbf{Q}^{M} = \mathbf{P}^{M}\ \mathbf{P}^{M-1} \ldots \mathbf{P}^{M'+2}\ \ \mathbf{P}^{M'+1}\ \mathbf{Q}^{M'} \tag{10}$$

The TPMs in Equation 10, $\mathbf{P}^{M}$, $\mathbf{P}^{M-1}$, … $\mathbf{P}^{M'+2}$, $\mathbf{P}^{M'+1}$, are all age-dependent transition probability matrices. The superscripts indicate the corresponding ages, not an exponent. They will be found using BrM inspection records, as presented below. This section will focus on formulating these **P** matrices with age. Accordingly, Chapter 4 will present how to calculate them in the deliverable software program. Chapter 5 will provide illustrative examples of applying Equation 10 and its equivalence in Equation 11 for forecasting using Excel.

Equation 10 can also be equivalently expressed using $\boldsymbol{q}$, the condition probability distribution column vector defined in Equations 6 and 7:

$$\mathbf{q}^{M} = \mathbf{P}^{M}\ \mathbf{P}^{M-1} \ldots \mathbf{P}^{M'+2}\ \ \mathbf{P}^{M'+1}\ \mathbf{q}^{M'} \tag{11}$$

where $\mathbf{q}^{M}$ is the condition probability distribution representing the quantity distribution among CS1 to CS4 at an age of *M* years of the bridge element in the future, and $\mathbf{q}^{M'}$ is the same probability distribution but at an age of *M'* years. $\mathbf{q}^{M'}$ is known and used here to forecast $\mathbf{q}^{M}$ in the future.

Equation 11 can also be used to find when the focused bridge's element is expected to reach its end of expected life or for a network of bridges, such as a district, region, or the entire state. To that end, $\mathbf{q}^{M'}$ will be the element's condition probability distribution (or equivalently the quantity distribution $\mathbf{Q}^{M'}$) at the starting point for that district, region, or the entire state.

As a special case, *M'* can be at 0 years—namely, a fresh start state of the element. *M* can go as long as needed (if $\mathbf{P}^{M}$ is available for all *M* values) in order to reach a condition status meeting the definition for end of expected life. For example, IDOT has been using 15% at CS4 as the end of expected life for an RC deck. Namely, one term $q_4^{M} = 0.15$ in $\mathbf{q}^{M}$ is used here to signal the end of an RC deck's life. This will be used below in Chapters 4 and 5 for the more comprehensive application example of RC deck, starting from

$$\mathbf{q}^{M'} = \mathbf{q}^{0} = \{1,0,0,0\}^{t,0} \tag{12}$$

meaning 100% of the quantity is at CS1. Again, the superscripts *M'*, *0*, and *t* are not exponents but indices for the element age (*M'* and *0*) and matrix transpose operation (*t*). In this report, superscripts are never used as exponents to avoid confusion except for normalization to a one-year interval. Such exceptions will be noted when used.

The TPM calculation for do-nothing deterioration assumes that a quantity of an element at a CS will transition to another CS through the shortest path—namely, from CS1 to CS2, from CS2 to CS3, and from CS3 to CS4. However, more than one transition in an inspection interval is not eliminated or ignored, such as from CS1 to CS2 and then to CS3 over one inspection interval. This is illustrated by examples below.

Illustrative Numerical Examples

For an example of EN=12 (RC Deck) and SN=60149 of IDOT, at an age of 21 years, the following inspection records are available in the dataset along with the respective inspection dates:

$$12/29/2011 \quad \mathbf{Q}_{\text{previous}} = \{10464, 30, 0, 0\}^{t,21} \tag{13}$$

$$1/9/2013 \quad \mathbf{Q}_{\text{future}} = \{10440, 40, 14, 0\}^{t,22} \tag{14}$$

For the given interval of 1.033 years between the two inspection dates, the following diagonal terms of the TPM for one year and for the do-nothing case at 21 years of age is obtained as follows:

$$P_{11} = (10{,}440/10{,}464)^{(1/1.033\text{years})} = 0.9977^{0.96681} = 0.9978 \tag{15}$$

$$P_{21} = 1 - P_{11} = 1 - 0.9978 = 0.0022 \tag{16}$$

$$P_{22} = ((30\text{-}14)/30)^{(1/1.033\text{years})} = 0.5333^{0.96681} = 0.5442 \tag{17}$$

$$P_{32} = 1 - P_{22} = 1 - 0.5442 = 0.4558 \tag{18}$$

$$P_{33} = \text{Not available because no transition of a quantity is observed (NA)} \tag{19}$$

$$P_{43} = \text{Not available because no transition of a quantity is observed (NA)} \tag{20}$$

$$P_{44} = 1 \tag{21}$$

and

$$P_{31} = P_{41} = P_{42} = 0 \text{ and } P_{12} = P_{13} = P_{14} = P_{23} = P_{24} = P_{34} = 0 \tag{22}$$

The value 1/1.033 years = 0.96681 in Equations 15 and 17 is an exponent to convert the diagonal term of **P** for 1.033 years to 1 year. This normalization is used to make the averaging consistent over all inspection pairs of all bridges with various inspection intervals.

To be complete, the above terms in Equation 15 to 22 are given in the form of a TPM:

$$\begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \\ p_{41} & p_{42} & p_{43} & p_{44} \end{bmatrix} = \begin{bmatrix} 0.9978 & 0 & 0 & 0 \\ 0.0022 & 0.5442 & 0 & 0 \\ 0 & 0.4558 & \text{NA} & 0 \\ 0 & 0 & \text{NA} & 1 \end{bmatrix} = \mathbf{P}^{21} \tag{23}$$

As seen, the quantity of 14 at CS3 in the 2013 inspection came from CS2 in 2011, not from CS1, according to the shortest path assumption.

To obtain the TPM for EN=12 at 21 years of age for the entire population of Illinois, all individual TPMs obtained as the example above are averaged over all inspection pairs of all bridges included in

Illinois' inspection record dataset, if the age is 21 years. When a term in the matrix is not available like P_{33} and P_{43} in Equation 3, that term's value is not used in the averaging process.

It is also of interest to highlight that the calculations in Equations 13 to 22 produce results in Equation 23 that all satisfy probabilities within [0,1] and the sequential relations in Equations 10 to 11 between the previous and future probability distributions: $\mathbf{q}^{22} = \mathbf{P}^{21}\,\mathbf{q}^{21}$. This will prevent the issues with Pontis identified by Fu and Devaraj (2008) and Fu (2010) for enhanced forecasting and related decision-making.

For another example, EN=107 (steel girder beam) and SN=530160 of IDOT at an age of 30 years, the following record is found for a pair of inspections:

$$\text{3/19/2019:} \quad \mathbf{Q}_{\text{previous}} = \{412, 26, 29, 14\}^{t,30} \tag{24}$$

$$\text{3/17/2021:} \quad \mathbf{Q}_{\text{future}} = \{412, 26, 27, 16\}^{t,31} \tag{25}$$

Accordingly, for the observed inspection interval of 1.997 years,

$$P_{11} = (412/412)^{(1/1.997\text{years})} = 1^{0.501} = 1 \tag{26}$$

$$P_{21} = 1 - P_{11} = 1\text{-}1 = 0 \tag{27}$$

$$P_{22} = (26/26)^{(1/1.997\text{years})} = 1^{0.501} = 1 \tag{28}$$

$$P_{32} = 1 - P_{22} = 1\text{-}1 = 0 \tag{29}$$

$$P_{33} = (27/29)^{(1/1.997\text{years})} = 0.9310^{0.501} = 0.9648 \tag{30}$$

$$P_{43} = 1 - P_{33} = 1 - 0.9648 = 0.0352 \tag{31}$$

$$P_{44} = 1 \tag{32}$$

and

$$P_{31} = P_{41} = P_{42} = 0, \text{ and} \tag{33}$$

$$P_{12} = P_{13} = P_{14} = P_{23} = P_{24} = P_{34} = 0 \tag{34}$$

Again, the value 1/1.997 years = 0.501 in Equations 26, 28, and 30 is an exponent to convert the diagonal term of **P** for 1.997 years to 1 year. This normalization will make the TPMs addable over all inspection pairs of all bridges with various inspection intervals to find their average TPM.

The terms from Equations 26 to 34 are arranged in a TPM:

$$\begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \\ p_{41} & p_{42} & p_{43} & p_{44} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0.9648 & 0 \\ 0 & 0 & 0.0352 & 1 \end{bmatrix} = \mathbf{P}^{30} \tag{35}$$

TPM with Age

As illustrated, the concept herein is to identify the TPM for every pair of two inspections and index TPM with the bridge's age *m* at the first inspection of the pair. Then, average the obtained TPMs at the same age *m* for all inspection pairs of all bridges with the same element as the TPM for that age *m*, $\mathbf{P}^m$.

QUANTITY ANALYSIS APPROACH FOR THE CASE OF CONDITION IMPROVEMENT

Upper and Lower Bounds for TPM

For easier understanding, an example EN=12 for SN=580084 of IDOT is used here. The element's conditions before and after micro-silica overlay are used. The inspection records are as follows along with the inspection dates:

$$2/15/2011: \quad \mathbf{Q}_{\text{previous}} = \{1215, 4393, 6940, 2860\}^t \tag{36}$$

$$1/15/2013: \quad \mathbf{Q}_{\text{future}} = \{8938, 6450, 20, 0\}^t \tag{37}$$

The values in the quantity distribution vectors $\mathbf{Q}_{\text{previous}}$ and $\mathbf{Q}_{\text{future}}$ all have the unit of sqft for RC deck. In this case, 2,860 sqft in CS4 in 2011 can transition to CS3, CS2, and/or CS1 as possible results of the overlay. In other words, there can be more than one result for the TPM because different transitions are possible. Physically, how these quantities transition depend on how effective the improvement work was, which may vary significantly. For example, for an RC deck, sealing, overlay, and replacement can have very different results in condition improvement, let alone overlay with different materials. Accordingly, a two-bound approach is developed here to treat this situation of possible multiple feasible answers/solutions. These bounds are defined as follows:

> MostEffectiveBound: Maximized transitions from poorest CSs (CS4 and/or CS3) to CS1 is assumed.
>
> LeastEffectiveBound: Minimized transitions from poorest CSs (CS4 and/or CS3) to CS1 is assumed.

The real situation of quantity transition can be within these two bounds. Namely, some quantities take the MostEffectiveBound and others the LeastEffectiveBound, or in between. The MostEffectiveBound can also be referred to as the longest-path bound, because the quantities at the worst CSs go through the longest possible paths to the best CS1. As an example, out of 2,860 sqft in CS4, 2,860 transition to CS1. Out of 6,940 sqft in CS3, 4,863 transition to CS1, 2,057 transition to CS2, and 20 transition to CS3. The corresponding calculations for TPM are given next.

Illustrative Numerical Examples

Note that in the following illustrations, the denominator for calculating P_{ij} is the quantity transitioned from, whose CS is identified by the second subscript *j* of P_{ij}. The numerator for computing P_{ij} is the quantity transitioning to, whose CS is designated by the first subscript *i* of P_{ij}. For example, P_{14}'s subscript 4 is to index the quantity previously at CS4. P_{14}'s subscript 1 designates the quantity received at CS1 as the result of the transition found at the later inspection.

$$P_{14} = 2{,}860/2{,}860 = 1 \quad (38)$$
$$P_{24} = 0/2{,}860 = 0 \quad (39)$$
$$P_{34} = 0/2{,}860 = 0 \quad (40)$$
$$P_{44} = 0/2{,}860 = 0 \quad (41)$$

$$P_{13} = 4{,}863/6{,}940 = 0.7007 \quad (42)$$
$$P_{23} = 2{,}057/6{,}940 = 0.2964 \quad (43)$$
$$P_{33} = 20/6{,}940 = 0.0029 \quad (44)$$
$$P_{43} = 0/6{,}940 = 0 \quad (45)$$

$$P_{12} = 0/4{,}393 = 0 \quad (46)$$
$$P_{22} = 4{,}393/4{,}393 = 1 \quad (47)$$
$$P_{32} = 0/4{,}393 = 0 \quad (48)$$
$$P_{42} = 0/4{,}393 = 0 \quad (49)$$

$$P_{11} = 1{,}215/1{,}215 = 1 \quad (50)$$
$$P_{21} = 0/1{,}215 = 0 \quad (51)$$
$$P_{31} = 0/1{,}215 = 0 \quad (52)$$
$$P_{41} = 0/1{,}215 = 0 \quad (53)$$

These values in Equations 38 to 53 can be organized in the form of a TPM:

$$\begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \\ p_{41} & p_{42} & p_{43} & p_{44} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0.7007 & 1 \\ 0 & 1 & 0.2964 & 0 \\ 0 & 0 & 0.0029 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} = \mathbf{P}_{\text{improvement\_MostEffectiveBound}} \quad (54)$$

Note that this TPM is not indicated as associated with age for the following reasons.

- Practically, improvement work is not frequent enough to provide adequate raw inspection pair data to generate a TPM for every age possible. For example, no data is available to calculate a TPM for replacement or concrete overlay of EN12 for early ages (say younger than 10 years), since such constructions never happen at those ages.

- In practice, as recorded in a construction work log, age is often not the only factor considered for renewal construction work. While the other factors are not recorded, using age only to index the improvement TPM can become misleading. For example, the other factors can be the following: (a) another nearby bridge on the same route urgently needs the same type of work, (b) this bridge carries more truck traffic and is considered to be deteriorating faster, (c) this bridge is in a harsher environment so it needs more frequent renewal work, etc.
- Bridge engineers involved in decision-making for typical improvement work are reasonably knowledgeable as to what particular work may need to be done within which age window and along with what considerations to other factors. They likely would not need the age indexed TPM associated with the improvement work. Instead, how effective the work is in condition improvement is of interest here, as provided by the focused TPM.

The final TPM for the particular improvement work is obtained by averaging the individual TPMs from the above typical computation over all inspection pairs of all bridges that have experienced the same work to the focused element. The resulting TPM **P** can be applied as formulated in Equations 10 and 11 for forecasting. For the reader's convenience, they are explicitly rewritten as follows:

$$\mathbf{Q}^{M} = \mathbf{P}^{M}\,\mathbf{P}^{M-1} \ldots \mathbf{P}^{M'+2}\;\mathbf{P}^{M'+1}\,\mathbf{P}_{\text{improvement}}\,\mathbf{Q}^{M'} \qquad (55)$$

$$\mathbf{q}^{M} = \mathbf{P}^{M}\,\mathbf{P}^{M-1} \ldots \mathbf{P}^{M'+2}\;\mathbf{P}^{M'+1}\,\mathbf{P}_{\text{improvement}}\,\mathbf{q}^{M'} \qquad (56)$$

where $\mathbf{P}_{\text{improvement}}$ is the TPM obtained for the particular improvement work, such as overlay or rehabilitation. One of the two bounds above may be used as $\mathbf{P}_{\text{improvement}}$ here, depending on the purpose of analysis. Note that in some cases the two bounds are identical or very close to each other, as seen in the example applications in Chapter 5.

The other TPMs in Equations 55 and 56—namely $\mathbf{P}^{M}$, $\mathbf{P}^{M-1}$, … $\mathbf{P}^{M'+2}$, and $\mathbf{P}^{M'+1}$—remain unchanged from the do-nothing case. This formulation means that after the construction work for improvement to the condition status at age *M'*, the focused bridge element will resume the mode of do-nothing deterioration. The expected life span of the element is therefore extended by the improvement work.

The LeastEffectiveBound TPM, representing the shortest transition path scenario, is illustrated next. Out of the 2,860 quantities in CS4, 20 go to CS3, 2,057 go to CS2, and 783 go to CS1. Then, 6,940 in CS3 all go to CS1. The computations for TPM are as follows:

$$P_{44} = 0/2{,}860 = 0 \qquad (57)$$

$$P_{34} = 20/2{,}860 = 0.0070 \qquad (58)$$

$$P_{24} = 2{,}057/2{,}860 = 0.7192 \qquad (59)$$

$$P_{14} = 783/2{,}860 = 0.2738 \qquad (60)$$

$$P_{43} = 0/6{,}940 = 0 \quad (61)$$

$$P_{33} = 0/6{,}940 = 0 \quad (62)$$

$$P_{23} = 0/6{,}940 = 0 \quad (63)$$

$$P_{13} = 6{,}940/6{,}940 = 1 \quad (64)$$

$$P_{42} = 0/4{,}393 = 0 \quad (65)$$

$$P_{32} = 0/4{,}393 = 0 \quad (66)$$

$$P_{22} = 4{,}393/4{,}393 = 1 \quad (67)$$

$$P_{12} = 0/4{,}393 = 0 \quad (68)$$

$$P_{41} = 0/1{,}215 = 0 \quad (69)$$

$$P_{31} = 0/1{,}215 = 0 \quad (70)$$

$$P_{21} = 0/1{,}215 = 0 \quad (71)$$

$$P_{11} = 1{,}215/1{,}215 = 1 \quad (72)$$

They are organized as follows in the form of a TPM:

$$\begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \\ p_{41} & p_{42} & p_{43} & p_{44} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 & 0.2738 \\ 0 & 1 & 0 & 0.7192 \\ 0 & 0 & 0 & 0.0070 \\ 0 & 0 & 0 & 0 \end{bmatrix} = \mathbf{P}_{\text{improvement\_LeastEffectiveBound}} \quad (73)$$

A comparison of the two bounds in Equations 54 and 73 indicates more quantities being expected to transition to CS1 from CS4, described by the MostEffectiveBound TPM in Equation 54, than the LeastEffectiveBound TPM in Equation 73. The differences are not alarming for this particular example.

When comparing two different types of construction work for effectiveness, the TPM with larger values closer to 1 in the first row (P_{11}, P_{12}, P_{13}, and P_{14}) is considered more effective because it highlights a higher likelihood for quantities at a poor CS to transition to the best CS (CS1). Note also that P_{11} should be equal to 1 as default, although calculations using the inspection records may not always give that logical value. In case not, adequate attention is recommended to further examine the inspection records and set P_{11} to 1 by expert elicitation.

Similarly, as discussed earlier for the MostEffectiveBound, the individual LeastEffectiveBound TPMs for all inspection pairs of all bridges are then averaged as the final result of analysis as the recommended LeastEffectiveBound TPM for the focused element and the construction work. These bridges can be in a route, district, region, or the entire state. This can be readily performed nationally, as long as inspection records are made available.

HEALTH INDEX AND DAMAGE INDEX

The health index reported in the literature (Shepard, 1999; Boadi et al., 2022) appears to be a convenient indicator for the condition of BrM bridge elements. It converts the quantities or the corresponding probabilities at various CSs of four values in a column vector into a single index. One single index is often more intuitive and easier to visualize and forecast than four values. This single index is defined as follows for the case of four CSs, while there is a more general version for more or less CSs that were used in the past and reported in the literature.

$$\text{Health Index} = \left[(1)q_1 + (\frac{2}{3})q_2 + (\frac{1}{3})q_3 + (0)q_4 \right] x100 \tag{74}$$

where q_1, q_2, q_3, and q_4 are the four components of the condition probability distribution vector **q** as defined in Equation 9. As seen in Equation 74, the four probabilities are summed with different weights. The weights are higher for better CSs, with a 0 weight for the worst CS4.

These weights appear to be reasonable when the focus is on how healthy the bridge element is, but it may not be that straightforward when one would like to highlight how poor the element's condition has become. For example, IDOT uses 15% at CS4 as the end of expected service life for EN=12 (RC deck). It would be challenging to express this criterion using the health index as defined in Equation 74. Therefore, another index is developed herein as follows to cover the other poor end of the spectrum for element condition in the BrM system, referred to as the damage index

$$\text{Damage Index} = \left[(0)q_1 + (\frac{1}{3})q_2 + (\frac{2}{3})q_3 + (1)q_4 \right] x100 \tag{75}$$

The damage index is still consistent with the health index as a weighted sum of the condition probability distribution vector **q**. The weights are reversed, with higher weights for poorer CSs. It can be proven that this new index is actually related to the health index as follows

$$\text{Damage Index} = 100 - \text{Health Index} \tag{76}$$

The two indices are complementary to each other in describing the condition of an element, whether for a single bridge for project-level planning or for bridges on a route or in a region's network for a program-level decision. With the two indices, the element condition can be fully depicted for intuitive treatment and decision-making. Application examples are presented later in Chapter 5.

CHAPTER 4: COMPUTER SOFTWARE TOOLS ON MS EXCEL

COMPUTER SOFTWARE PROGRAMS FOR BRIDGE ELEMENT DETERIORATION/ IMPROVEMENT MODELING

As part of the deliverables for this research project, two computer software programs were developed using Microsoft Excel. One program is for the case of do-nothing deterioration and the other for condition improvement. They were completed to achieve the following goals.

i. The software tools should not be a black box to the user. Rather, it should be transparent and allow user interaction or expert elicitation.

ii. The software tools need to be user-friendly, requiring almost no special training besides general knowledge about BrM, NBI, and agency construction history as well as bridge element inspection.

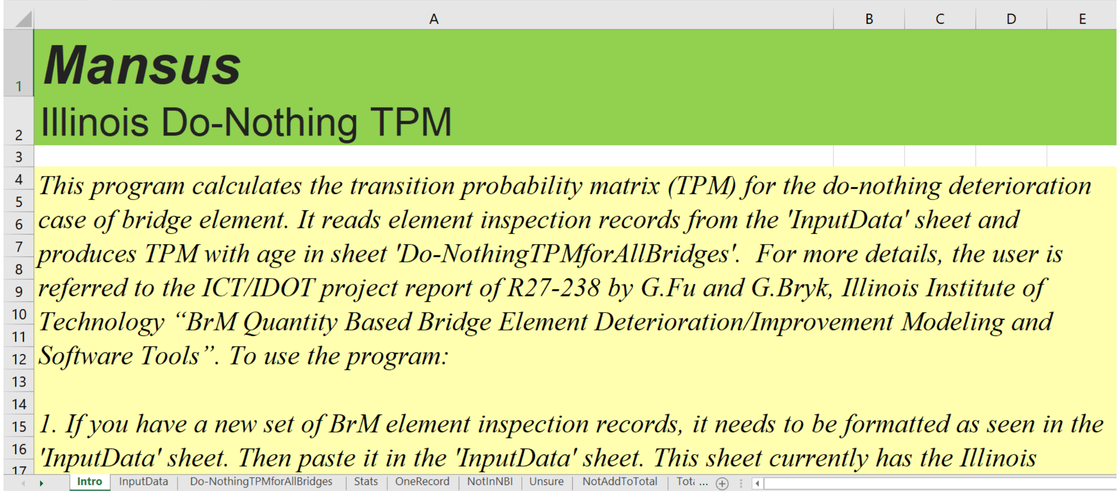
iii. The required input datasets should be currently available with IDOT and/or state bridge owners.

iv. The output needs to be simple to understand and can be readily moved to other platforms for further analysis or presentation if desired.

These goals contributed to the decision to use Excel as the platform, which was approved by the project's Technical Review Panel. The two modules are detailed below, followed by two application examples in Chapter 5. One is for EN=12 (RC deck) and the other EN=107 (steel girder beam).

MANSUS FOR DO-NOTHING DETERIORATION

Figure 1 displays the front sheet of this module for the case of do-nothing deterioration. The program's name is Mansus, a Latin synonym for do nothing.



Mansus

Illinois Do-Nothing TPM

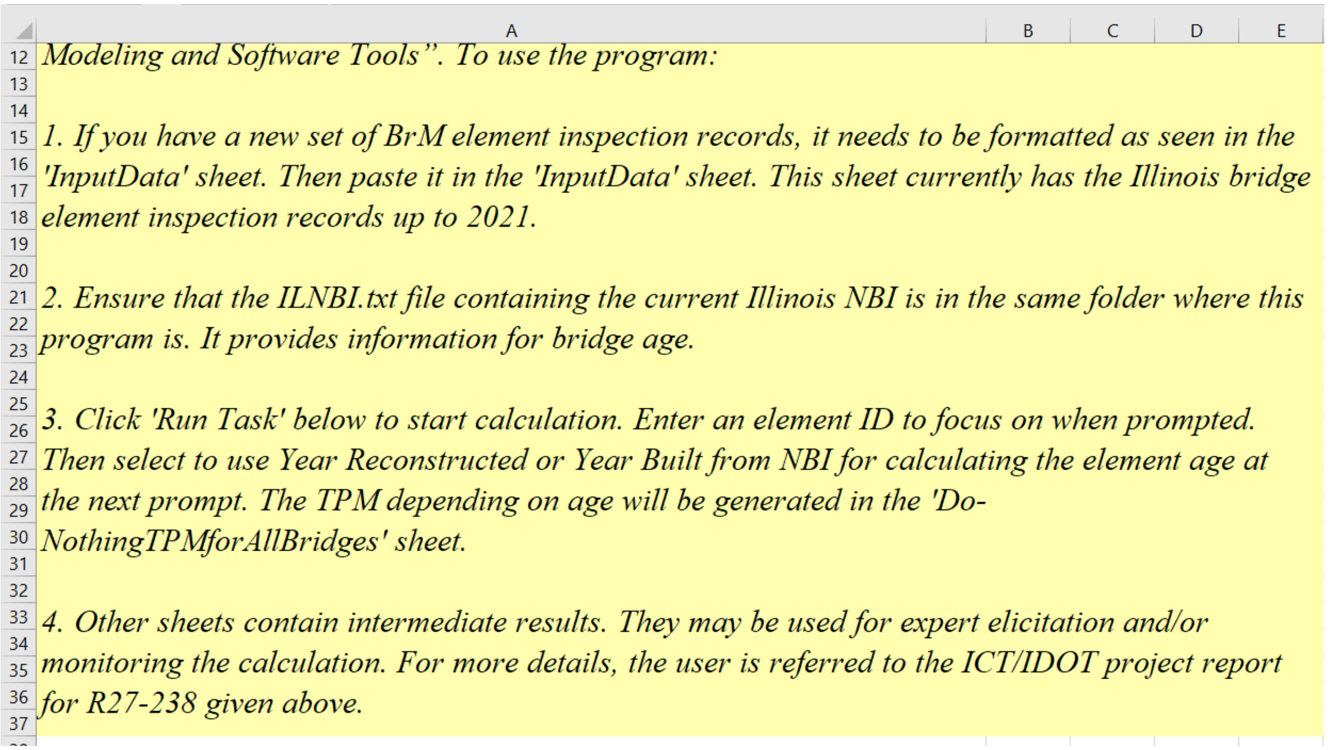
This program calculates the transition probability matrix (TPM) for the do-nothing deterioration case of bridge element. It reads element inspection records from the 'InputData' sheet and produces TPM with age in sheet 'Do-NothingTPMforAllBridges'. For more details, the user is referred to the ICT/IDOT project report of R27-238 by G.Fu and G.Bryk, Illinois Institute of Technology "BrM Quantity Based Bridge Element Deterioration/Improvement Modeling and Software Tools". To use the program:

1. If you have a new set of BrM element inspection records, it needs to be formatted as seen in the 'InputData' sheet. Then paste it in the 'InputData' sheet. This sheet currently has the Illinois

Figure 1. Screenshot. Front "Intro" sheet of Mansus for the case of do-nothing deterioration.

Figure 2 shows simple instructions for running this program. The first two steps involve setting up the input data files: the BrM element inspection records and the state's NBI bridge inventory named ILNBI.txt, in the coding format of the Federal Highway Administration (1995). ILNBI.txt needs to be in the same folder as Mansus for it to run. The Illinois BrM element inspection records are already in the "InputData" sheet of Mansus next to "Intro." Therefore, if no update is to be used, these two steps will be skipped. The third step is to run the program by clicking the "Run Task" button in the front "Intro" sheet. The only input needed from the user is the element number (EN) when prompted and a Yes or No answer as to whether Year Reconstructed or Year Built in the NBI should be used for age calculation, which is prompted after the EN input is accepted. The last instruction in Step 4 is about the other sheets produced by Mansus, which also refers to this report as an additional source of information. If the user is only interested in the TPM, Step 4 can be skipped. As a result of this setup, the program can be run without any training, because the introduction/instruction has been included in the program. If the Mansus user is familiar with the BrM element inspection records (Table 6) and the NBI data setting, s/he may not need to read this report to run the program and understand the TPM results.

When Step 3 is completed, the program starts to run using the provided input information. Right next to the second sheet containing the BrM inspection records, the third sheet provides the final calculation results of TPM with age. This sheet is named "Do-NothingTPMforAllBridges," as seen in Figure 3.



Modeling and Software Tools". To use the program:

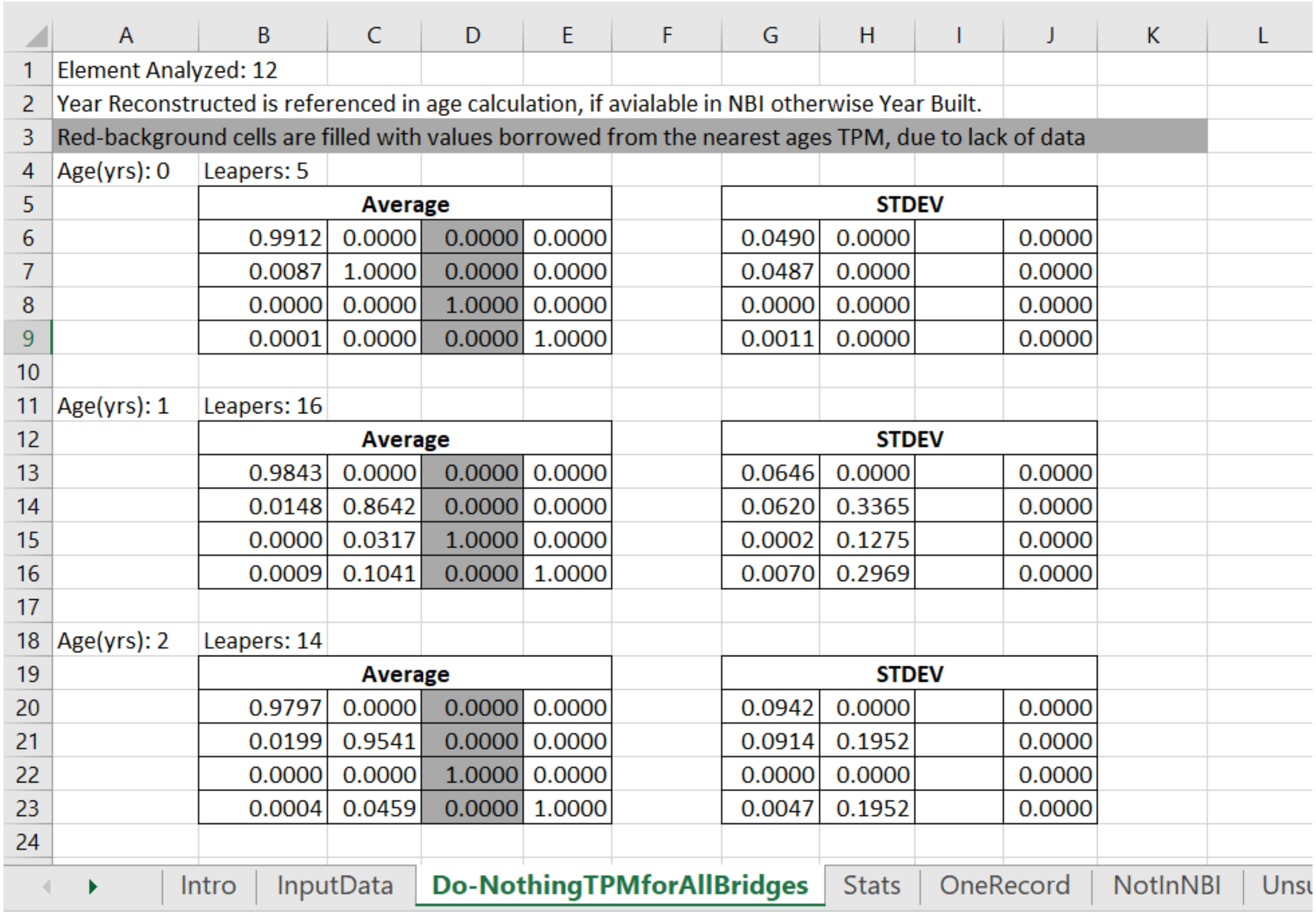
1. If you have a new set of BrM element inspection records, it needs to be formatted as seen in the 'InputData' sheet. Then paste it in the 'InputData' sheet. This sheet currently has the Illinois bridge element inspection records up to 2021.

2. Ensure that the ILNBI.txt file containing the current Illinois NBI is in the same folder where this program is. It provides information for bridge age.

3. Click 'Run Task' below to start calculation. Enter an element ID to focus on when prompted. Then select to use Year Reconstructed or Year Built from NBI for calculating the element age at the next prompt. The TPM depending on age will be generated in the 'Do-NothingTPMforAllBridges' sheet.

4. Other sheets contain intermediate results. They may be used for expert elicitation and/or monitoring the calculation. For more details, the user is referred to the ICT/IDOT project report for R27-238 given above.

Figure 2. Screenshot. Instructions for running the Mansus program.



	A	B	C	D	E	F	G	H	I	J	K	L
1	Element Analyzed: 12											
2	Year Reconstructed is referenced in age calculation, if avialable in NBI otherwise Year Built.											
3	Red-background cells are filled with values borrowed from the nearest ages TPM, due to lack of data											
4	Age(yrs): 0	Leapers: 5										
5		Average					STDEV					
6		0.9912	0.0000	0.0000	0.0000		0.0490	0.0000		0.0000		
7		0.0087	1.0000	0.0000	0.0000		0.0487	0.0000		0.0000		
8		0.0000	0.0000	1.0000	0.0000		0.0000	0.0000		0.0000		
9		0.0001	0.0000	0.0000	1.0000		0.0011	0.0000		0.0000		
10												
11	Age(yrs): 1	Leapers: 16										
12		Average					STDEV					
13		0.9843	0.0000	0.0000	0.0000		0.0646	0.0000		0.0000		
14		0.0148	0.8642	0.0000	0.0000		0.0620	0.3365		0.0000		
15		0.0000	0.0317	1.0000	0.0000		0.0002	0.1275		0.0000		
16		0.0009	0.1041	0.0000	1.0000		0.0070	0.2969		0.0000		
17												
18	Age(yrs): 2	Leapers: 14										
19		Average					STDEV					
20		0.9797	0.0000	0.0000	0.0000		0.0942	0.0000		0.0000		
21		0.0199	0.9541	0.0000	0.0000		0.0914	0.1952		0.0000		
22		0.0000	0.0000	1.0000	0.0000		0.0000	0.0000		0.0000		
23		0.0004	0.0459	0.0000	1.0000		0.0047	0.1952		0.0000		
24												

Figure 3. Screenshot. Mansus final result sheet "Do-NothingTPMforAllBridges."

The TPMs $\mathbf{P}^{M'}$ for age *M'* (M'=0,1,2,3,…) in Figure 3 are presented in the matrix form as defined in Equations 10 and 11. Each TPM is listed with the age identified in Column A and right above each matrix. The standard deviations (STDEV) of the P_{ij} values (i,j=1,2,3,4) in the TPM are also given in the matrix form (Columns G to J) right next to the TPM in Columns B to E. They are there to inform the user how scattered the individual TPM values are. The P_{ij} values are averages over all inspection pairs of all bridges in the BrM inspection records.

The BrM inspection records in the programs cover all state bridges in Illinois up to 2021, when the two programs were delivered to IDOT. The inspection records can be reduced to a route, district, or region. However, when such a reduction is performed, the particular case of EN may provide limited data so that the results become less statistically reliable. Furthermore, it is also possible that an error message pops up and the software program stops, because the averaging process mentioned above needs to be divided by the number of entries. When this number becomes 0 (or 1), an overflow in averaging (or in the STDEV calculation) will occur and some other parts of the program will not be able to function as intended. Note that this can happen even when using the current inspection records in the program for some ENs due to inadequate data.

Also note that the gray-shaded cells in Figure 3 contain TPM values that are not possible to calculate due to lack of data in the provided datasets. Such a situation was seen earlier in Equations 19 and 20 for the illustrative examples in Chapter 3. These cells are then filled with values borrowed from the nearest TPMs (i.e., the TPMs with the nearest ages). Therefore, the corresponding STDEV values are left empty, indicating no STDEV value can be calculated. The cells of these borrowed TPM values are not left empty, because forecasting as formulated in Equations 10 to 11 needs these values to complete computation. As seen there, all terms in the TPMs for different ages from *M′* to *M* need to be available.

These borrowed values do not affect the reliability of forecasting and relevant decision-making for bridge management, although they are needed for the mathematical operations in Equations 10 and 11. For example, as shown in Figure 3, the borrowed values are for a worse CS (CS3) at earlier ages of the element. Practically, bridge elements would not be in such poor condition (CS3) at these early ages. As a result, the borrowed values are never required conceptually for forecasting, although they are needed for executing the algorithm in the computer software.

The following discussion will introduce the other worksheets (or sheets for short) generated by Mansus and illustrate or describe possible uses of the sheets. However, if the reader is only interested in the do-nothing TPM result, they may skip these sheets and the next section of this report.

Mansus computation is divided into two parts. The first part is for data scrubbing and categorizing, and the second part for calculations and formation of TPM as the final result from execution of the program. Figure 4 shows the general architecture of Mansus.

Besides the final result sheet “Do-NothingTPMforAllBridges,” a number of other sheets are also generated to offer information on the used datasets and intermediate results of the computation. These sheets include “Stats,” “OneRecord,” “NotInNBI,” “Unsure,” “NotAddToTotal,” and so on in the tabs at the bottom of the screenshot in Figure 5. These sheets may be used for expert elicitation and/or monitoring the calculation for optimization, as explained below.

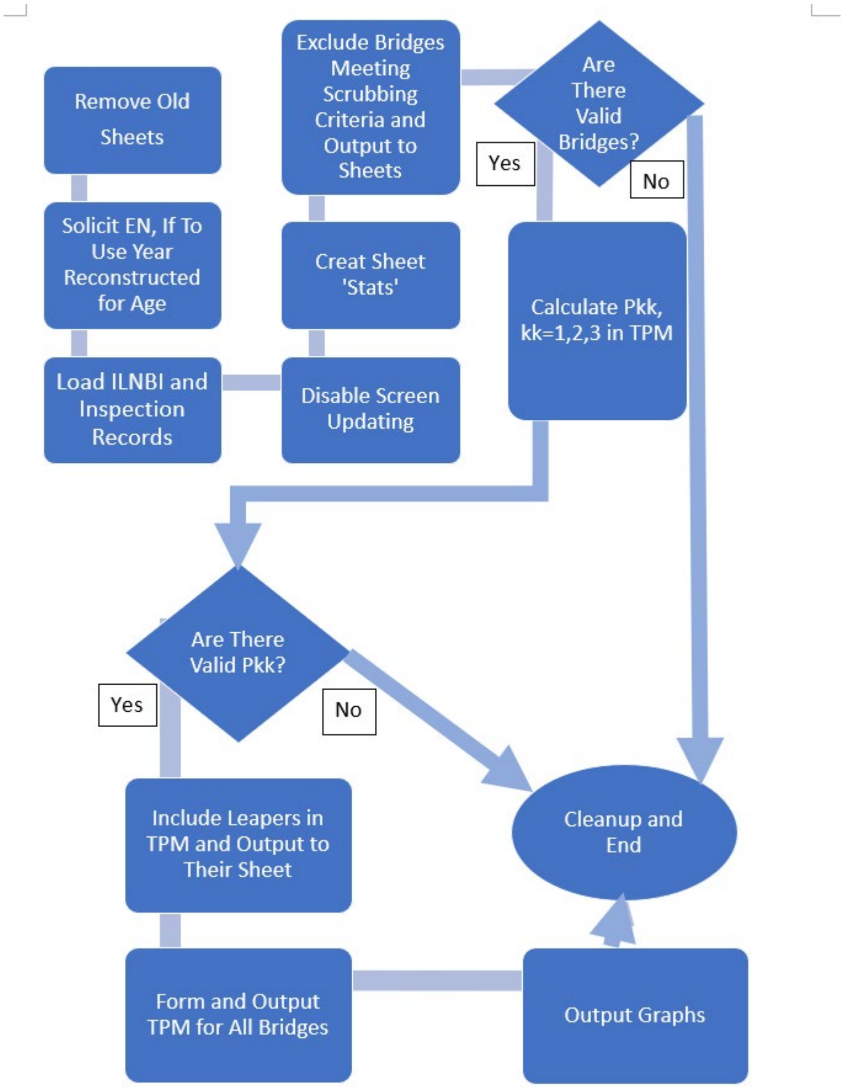
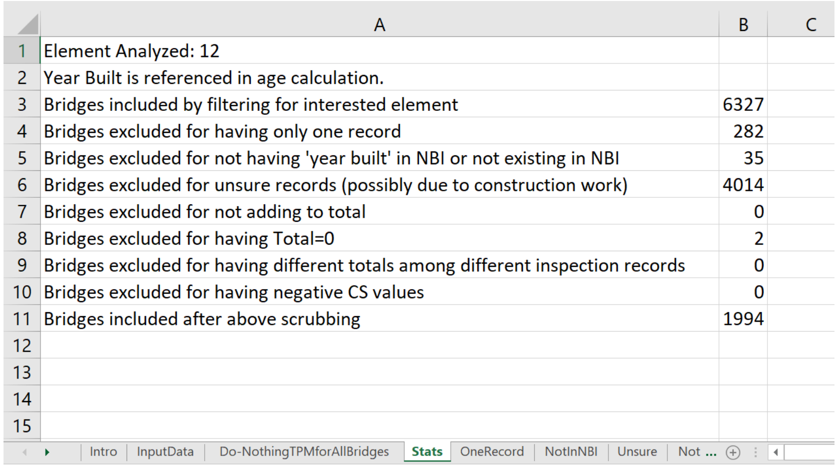


Figure 4. Chart. Calculation process of Mansus.



	A	B	C
1	Element Analyzed: 12		
2	Year Built is referenced in age calculation.		
3	Bridges included by filtering for interested element	6327	
4	Bridges excluded for having only one record	282	
5	Bridges excluded for not having 'year built' in NBI or not existing in NBI	35	
6	Bridges excluded for unsure records (possibly due to construction work)	4014	
7	Bridges excluded for not adding to total	0	
8	Bridges excluded for having Total=0	2	
9	Bridges excluded for having different totals among different inspection records	0	
10	Bridges excluded for having negative CS values	0	
11	Bridges included after above scrubbing	1994	
12			
13			
14			
15			

Figure 5. Screenshot. Mansus sheet "Stats" as a summary of inspection records scrubbing.

The “Stats” sheet shown in Figure 5 contains an overview of the other seven sheets for the data-scrubbing results. It lists how many bridges are excluded because one or more of the seven criteria have been met. The item in Row 11 of Figure 5 is the number of bridges used in calculations for TPM after data scrubbing. The item in Row 3 is the total number of bridges in the used BrM inspection records that have the EN identified in Row 1. Row 2 echoes the message box input regarding which year value from NBI should be used as the reference in the age calculation: Year Reconstructed if available in the NBI or Year Built.

Next to the “Stats” sheet, the “OneRecord” sheet includes bridges that have only one inspection record, which are unable to form a pair of records to allow calculation for TPM. Therefore, these ridges are excluded to this sheet. The next sheet, “NotInNBI,” lists bridges not found in the NBI database or do not have a Year Built, which is expected to provide information on when the bridge was originally constructed and, thus, for computing the age at each inspection. Without such information, the TPM with age cannot be found.

The next sheet, “Unsure,” gathers bridges whose inspection records contain features of enhanced condition status contradicting with do-nothing deterioration, which is the focus here in Mansus. This unsure situation may be caused by renewal construction work, recording errors, other errors, or a combination thereof. Elevatio, the other software module developed in this project and discussed in the next section, will use the bridges in “Unsure” to sort and identify cases of construction work–induced condition improvement. Those cases will be used in Elevatio to calculate TPM for the case of condition improvement.

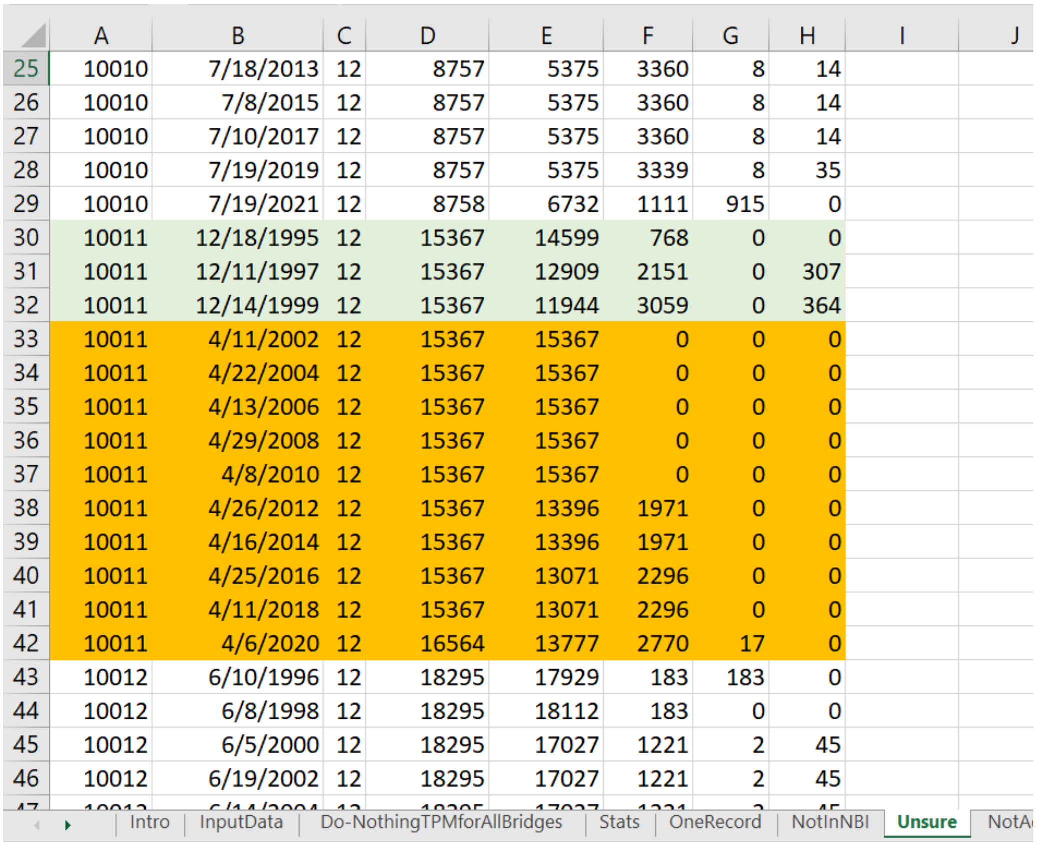
The “NotAddToTotal” sheet includes bridges that have at least one inspection record with quantities at CS1, CS2, CS3, and CS4 that do not add to the total quantity. This situation could cause issues and errors in calculating the TPM, and, thus, the bridge is excluded to this sheet along with its inspection history records.

The “Total=0” sheet contains bridges whose inspection records have a total equal to 0, apparently with the quantities at CS1, CS2, CS3, and CS4 all equal to 0, because they are the only values that could add to a total of 0 since they have passed the check for not adding to the total already.

The “DifferentTotals” sheet gathers bridges whose inspection records have different total quantities at various inspections, although the quantities at CS1 to CS4 do add to the total at each inspection. Thus, they cannot be used for computing TPM because they would not satisfy Equation 6, which requires the total quantity to be unchanged. The sheet “NegativeCS” shows bridges whose quantities at CS_i (i=1,2,3,4) have one or more negative values. Such data violate Equation 7 for probability. Consistently, such data violate the understanding that a bridge element quantity should never be negative.

It is part of the intention of providing these seven sheets to allow elicitation of the software user when desired. When the user finds some of these records in the above seven categories correctable, changes to them can be readily made in the “InputData” sheet or the NBI dataset as appropriate. Using the identified SN and the inspection dates, the bridge along with its inspection records can be easily located in the data files. The effect of such correction can be effortlessly seen after a rerun of the program.

Note that the complete inspection records are included for each bridge listed in these seven sheets to complete recording and identification. Furthermore, this data-scrubbing process excludes a bridge whenever any one of the seven criteria is met. For the excluded bridge, no further check for later criteria will be performed. As a result, a bridge excluded by an earlier criterion may also contain features that qualify for exclusion according to a later criterion(a). However, these later criteria are not checked in Mansus. Therefore, the counting in the "Stats" sheet is exclusive, as seen in Figure 5. The example in Figure 5 shows that the sum of the bridges belonging to these seven categories of improper data plus the remaining ones add to the total: (282 + 35 + 4,014 + 0 + 2 + 0 + 0) + 1,994 = 6,327. In other words, this counting does not double count any bridge that meets more than one scrubbing criterion. An example of meeting multiple criteria is presented in Chapter 5.



	A	B	C	D	E	F	G	H	I	J
25	10010	7/18/2013	12	8757	5375	3360	8	14		
26	10010	7/8/2015	12	8757	5375	3360	8	14		
27	10010	7/10/2017	12	8757	5375	3360	8	14		
28	10010	7/19/2019	12	8757	5375	3339	8	35		
29	10010	7/19/2021	12	8758	6732	1111	915	0		
30	10011	12/18/1995	12	15367	14599	768	0	0		
31	10011	12/11/1997	12	15367	12909	2151	0	307		
32	10011	12/14/1999	12	15367	11944	3059	0	364		
33	10011	4/11/2002	12	15367	15367	0	0	0		
34	10011	4/22/2004	12	15367	15367	0	0	0		
35	10011	4/13/2006	12	15367	15367	0	0	0		
36	10011	4/29/2008	12	15367	15367	0	0	0		
37	10011	4/8/2010	12	15367	15367	0	0	0		
38	10011	4/26/2012	12	15367	13396	1971	0	0		
39	10011	4/16/2014	12	15367	13396	1971	0	0		
40	10011	4/25/2016	12	15367	13071	2296	0	0		
41	10011	4/11/2018	12	15367	13071	2296	0	0		
42	10011	4/6/2020	12	16564	13777	2770	17	0		
43	10012	6/10/1996	12	18295	17929	183	183	0		
44	10012	6/8/1998	12	18295	18112	183	0	0		
45	10012	6/5/2000	12	18295	17027	1221	2	45		
46	10012	6/19/2002	12	18295	17027	1221	2	45		

Figure 6. Screenshot. Mansus "Unsure" sheet of excluded bridges and their inspection records.

Figure 6 displays an example of the "Unsure" sheet. An IDOT bridge SN=10011 is highlighted. The SN in Column A identifies the bridge. Between the two highlighting colors, there is a meaningful enhancement in condition status, where the quantities in CS2 (Column F) and CS4 (Column H) are reduced to 0 from the earlier inspection in 1999 to the later one in 2002. These quantities transitioned to CS1 between the two inspections, which is why this bridge is excluded to the "Unsure" sheet here.

Furthermore, the two pieces of history marked using two different colors of EN=12 for this example bridge could be analyzed separately, both for the case of do-nothing deterioration. If desired, this could be readily accomplished by creating a new and artificial SN in Column A (say 90010012) for one of the two pieces of inspection records. This approach could increase the number of inspection records to be included in the calculation of the do-nothing TPM.

There are many such examples where the inspection records could be corrected so that more data could become available and be included in the TPM calculation to enhance statistical confidence in the result. For some cases of EN with fewer inspection records available, such an action could make a significant difference for the TPM, from not possible to compute to much more statistically reliable results. It is recommended that IDOT personnel perform such elicitation on these data cases and correct some when possible and acceptable to further enhance the quality of the used datasets and, in turn, to improve statistical confidence in the resulting TPM.

The next sheet “BridgesUsedForTPM” lists all bridges with valid inspection records to be analyzed for do-nothing deterioration TPM. The total number is given in the very last row of the “Stats” sheet as “Bridges included after above scrubbing” in Figure 5.

The remaining sheets beyond the seven scrubbed bridges sheets provide some intermediate results for the user to monitor the calculation process. They also offer opportunities for expert elicitation or correction, as discussed next.

The Mansus sheet “Leapers” lists all bridges with inspection records of the focused EN that have experienced transition(s) skipping at least one CS. Namely, these quantity transitions can be from CS1 to CS3, CS1 to CS4, or CS2 to CS4 over the time interval of two inspections. Such pairs of inspection records are referred to as “leapers” herein. These fast transitions can possibly be due to inspection errors as well. For example, a deteriorated quantity may have been missed in one or more previous inspections but then caught attention in a later inspection and recorded when the quantity became worse and more noticeable. Another possibility is that some inspections between the two recorded were simply missed, causing the transitions to look more rapid.

However, this study found these identified leapers to represent a relatively significant population in the inspection records compared with other transitions without leaping. For EN=12, for example, more than 1,000 pairs of inspection records are found and listed in this sheet. Many bridges experienced such leaping deterioration, even more than once, and they were observed over normal inspection intervals not too much away from the required two years. The reader may review each leaper for the two examples EN=12 and EN=107 in the delivered software programs. This large number of leapers appears to show that they do not all result from inspection error, to say the least. Previous research efforts reported in the literature uniformly ignore this leaping behavior by explicitly or implicitly assuming no leaping. This dataset shows that such an assumption is not true, and, thus, that assumption is not used herein. This phenomenon has been covered in the proposed BrM quantity-based TPM calculation and included in Mansus as well.

To offer a visual understanding of the behavior of TPM with age, the Mansus sheet “Graphs” provides respective plots of P_{11}, P_{22}, and P_{33} with age. To a certain extent, these diagonal terms in TPM describe the deterioration behavior of the element. Several off-diagonal terms of TPM are related to the diagonal terms, according to the total probability theorem: $P_{34} = 1 - P_{33}$, $P_{32} + P_{42} = 1 - P_{22}$ and $P_{21} + P_{31} + P_{41} = 1 - P_{11}$. Other off-diagonal terms are 0 for do-nothing deterioration. Comparing these diagonal terms plotted in the Mansus sheet "Graphs" indicates a statistical trend that $P_{11} > P_{22} > P_{33}$. Recall that P_{11} is the probability for a quantity of bridge element to stay in CS1 when previously at CS1. Similarly, P_{22} and P_{33} are probabilities for a quantity to stay at CS2 and CS3 when previously at CS2 and CS3, respectively. This observed statistical trend, that $P_{11} > P_{22} > P_{33}$, is consistent with general observation that RC deck deteriorates faster as age increases. These plots also show that the scatter of P_{11} is smaller than that of P_{22}, which is, in turn, smaller than that of P_{33}. This observation simply says that those quantities at CS3 are less predictable than those at CS2 in terms of which next poorer CS they will become in the future. Analogously, those quantities at CS2 are less predictable than those at CS1 regarding the trend of deterioration/transition.

ELEVATIO FOR CONDITION IMPROVEMENT

Figure 7 displays the flowchart of the software module Elevatio for condition improvement as a result of renewal construction work. Elevatio is a Latin synonym for improvement. Figure 8 shows the first "Intro" sheet of this computer software program with brief instructions. Figure 9 displays four simple instructions for running the program.

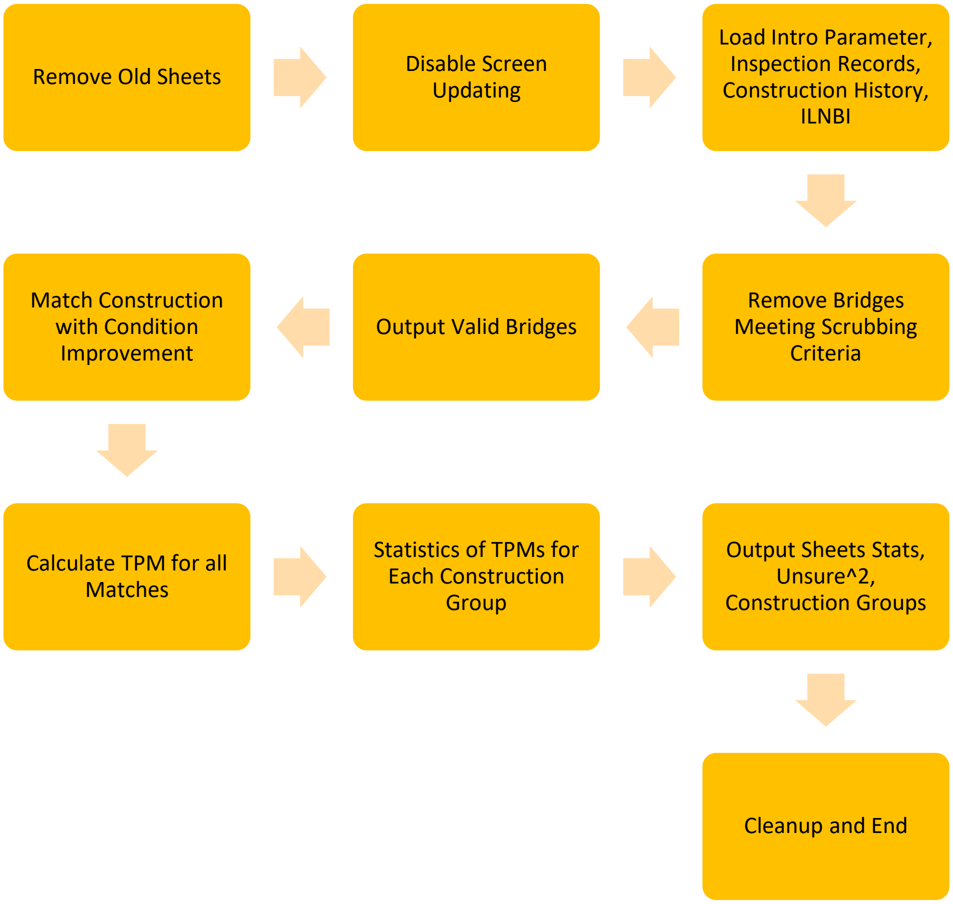
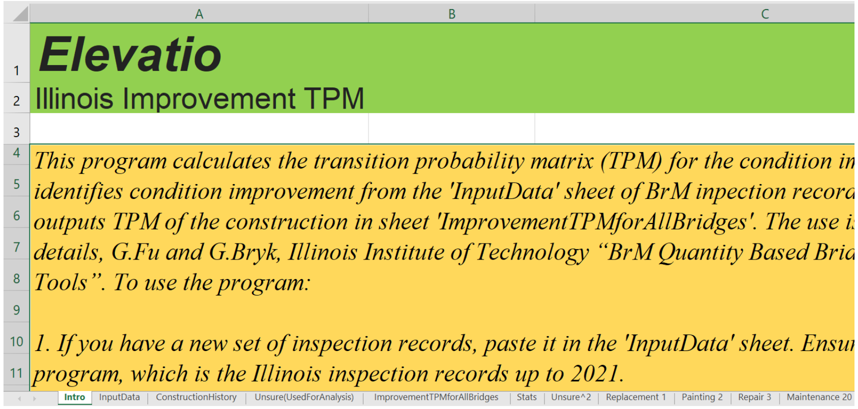


Figure 7. Chart. Calculation process of Elevatio.

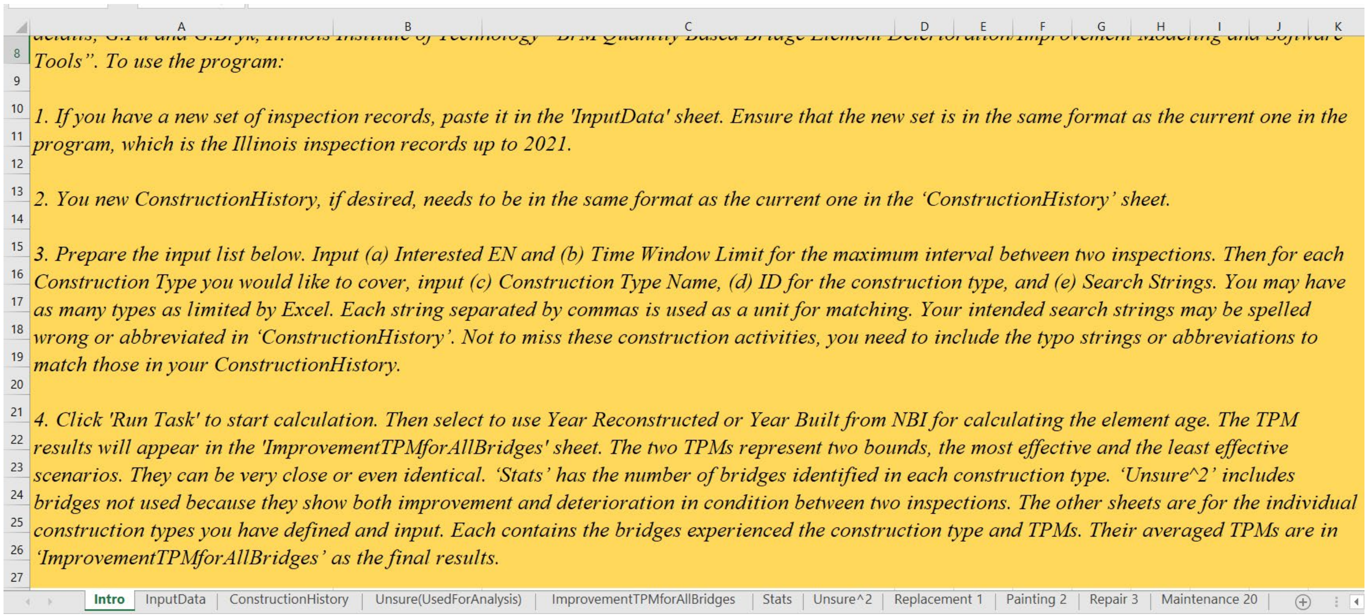
The first two instructions are related to the utilized datasets, similar to the first two instructions in Mansus. They include three sets of input data: IDOT bridge element inspection records, IDOT construction work history, and the Illinois NBI. The first two datasets are in sheets “InputData” and “ConstructionHistory,” respectively. They are placed right after the first sheet, “Intro.” They can continue to be used if updates are not available or not desired. The 2021 Illinois NBI file is named ILNBI.txt. Like in Mansus, it needs to be in the same folder as Elevatio for it to run properly. The usage of ILNBI.txt and the inspection records in “InputData” remains to be unchanged, as in Mensus for the do-nothing case.



This program calculates the transition probability matrix (TPM) for the condition in
identifies condition improvement from the 'InputData' sheet of BrM inpection recor
outputs TPM of the construction in sheet 'ImprovementTPMforAllBridges'. The use i
details, G.Fu and G.Bryk, Illinois Institute of Technology “BrM Quantity Based Bri
Tools”. To use the program:

1. If you have a new set of inspection records, paste it in the 'InputData' sheet. Ensu
program, which is the Illinois inspection records up to 2021.

Figure 8. Screenshot. Front sheet “Intro” of Elevatio for renewal construction work TPM calculation.



details, G.Fu and G.Bryk, Illinois Institute of Technology “BrM Quantity Based Bridge Element Deterioration/Improvement Modeling and Software Tools”. To use the program:

1. If you have a new set of inspection records, paste it in the 'InputData' sheet. Ensure that the new set is in the same format as the current one in the program, which is the Illinois inspection records up to 2021.

2. You new ConstructionHistory, if desired, needs to be in the same format as the current one in the ‘ConstructionHistory’ sheet.

3. Prepare the input list below. Input (a) Interested EN and (b) Time Window Limit for the maximum interval between two inspections. Then for each Construction Type you would like to cover, input (c) Construction Type Name, (d) ID for the construction type, and (e) Search Strings. You may have as many types as limited by Excel. Each string separated by commas is used as a unit for matching. Your intended search strings may be spelled wrong or abbreviated in ‘ConstructionHistory’. Not to miss these construction activities, you need to include the typo strings or abbreviations to match those in your ConstructionHistory.

4. Click 'Run Task' to start calculation. Then select to use Year Reconstructed or Year Built from NBI for calculating the element age. The TPM results will appear in the 'ImprovementTPMforAllBridges' sheet. The two TPMs represent two bounds, the most effective and the least effective scenarios. They can be very close or even identical. ‘Stats’ has the number of bridges identified in each construction type. ‘Unsure^2’ includes bridges not used because they show both improvement and deterioration in condition between two inspections. The other sheets are for the individual construction types you have defined and input. Each contains the bridges experienced the construction type and TPMs. Their averaged TPMs are in ‘ImprovementTPMforAllBridges’ as the final results.

Figure 9. Screenshot. Instructions for running the Elevatio program.

The last two instructions in Figure 9 explain how additional input data need to be entered for a particular EN, in the space right below the instructions in the “Intro” sheet. These input data are for Elevatio to know the EN and search/match condition improvement in the inspection records with recorded relevant construction work. Figure 10 includes an example for EN=12 to illustrate these instructions for the following discussion.

Instruction 3 in Figure 9 identifies two sets of additional input information. The first set includes two items, identified as (a) and (b) in Instruction 3: the EN and a time window, in Rows 29 and 30 in Figure 9 as an example. The time window in years here is to limit the interval length between two inspection records to be included in calculating the TPM for improvement. While the maximum interval of two inspections is generally limited at two years, practically this interval in the inspection records can be excessive. A much larger interval than 2 years can result in misleading or even meaningless TPM for bridge-element condition improvement.

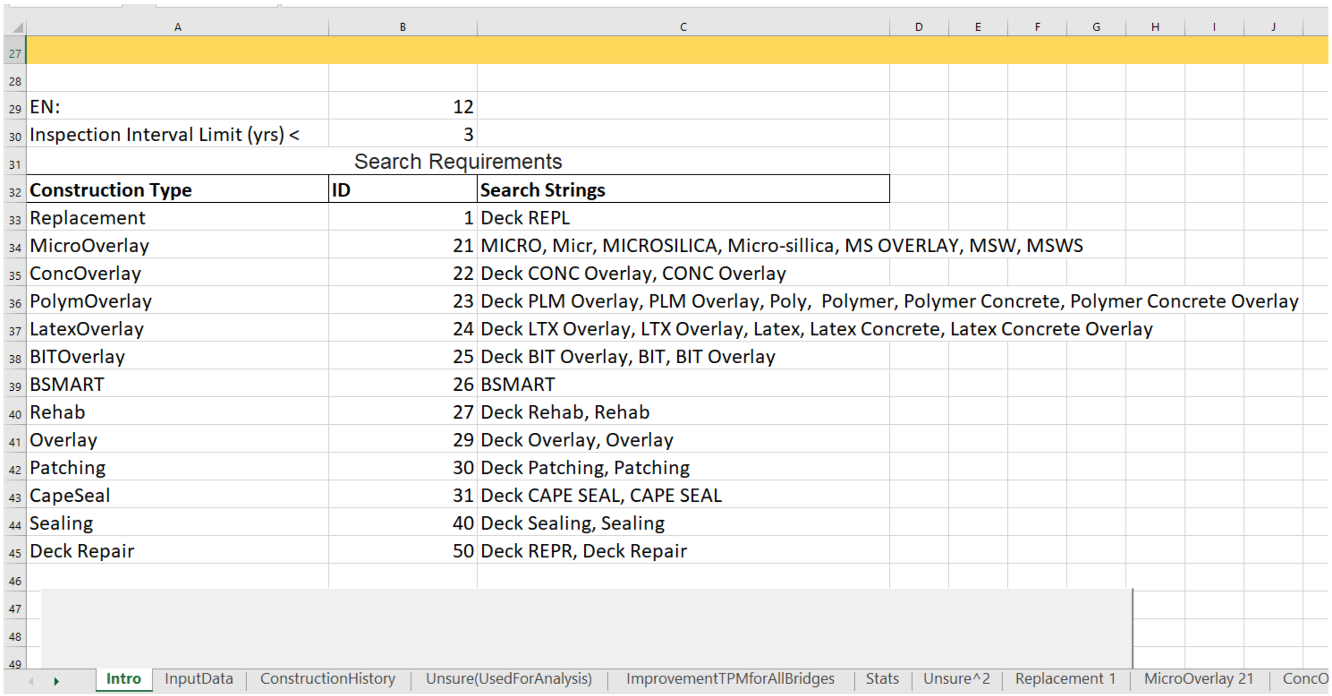
For example, for undocumented reasons, the IDOT inspection records show this interval as long as at least 17.1 years. Within these 17.1 years, for example, many other things than condition improvement may have occurred, been observed, and been recorded as inspection results, such as do-nothing deterioration. Consequently, the resulting TPM based on the two inspection records 17.1 years apart will inevitably mix up and confuse the influence of those things with the effect of renewal construction work. The resulting TPM can be misleading or even completely meaningless. Row 30 in Figure 9 shows three years as the time window limit for this example, to allow inspection cases moderately off the two-year federal maximum interval to be included. The user may enter different values as a sensitivity analysis for the effect of this time limit window regarding the particular EN and the available inspection records.

Many historical factors affecting this inspection interval may have been practiced and recorded. Special needs of the bridge, changes in funding for inspection, scheduling complexity, other construction activities, or record management errors may be among these factors. In addition, in the early stage of BrM element inspection implementation, regularly spaced two-year inspections might not have been fully practiced so that those experimental inspections were not at normal intervals. As a result, this interval changes from several months to 17 or more years, as seen in the IDOT bridge element inspection records. Therefore, Elevatio requests this time window limit to be used in the subsequent search and match. A limit value close to two years is recommended to reasonably minimize the variation in the inspection data and the resulting TPM values. A non-integer for this interval limit is permitted in Elevatio, such as 2.74 years.

Instruction 3 in Figure 9 also addresses the input data table of three more items to enter, identified as items (c), (d), and (e) there, right below Items (a) and (b). How many rows of this table to include depends on how the user wants Elevatio to search and match the inspection records and construction history. The example in Figure 10 includes 13 rows for this table from Row 33 to 45. The search criteria for the software program to search/match between the two databases are the inspection records and the construction history.

The match between the construction work and condition improvement of the element identifies the causal relation. Because these two IDOT datasets were generated for different purposes, the search and match process is needed for calculating the resulting TPM, as explained and illustrated in Equations 36 to 73. More specifically, the IDOT inspection records do not document any construction work and the IDOT construction history does not include bridges that have never experienced any work. The search and match process attempts to identify those intersections of the two databases: condition improvement and construction work for a particular EN. When the condition improvement documented by two consecutive inspections of the EN is matched with the construction work for the scope and the year of work, then the calculation for the corresponding TPM will complete in Elevatio. Figure 10 shows an example table as search requirements for EN=12 (RC deck). The table starting from Row 32 gives three columns of input data by the user for the search scope and definition.

For this particular example of RC deck, a number of relevant construction renewal work are seen in the IDOT construction history. Several typical ones are listed in Rows 33 to 45 as an illustrative example. Depending on the need and purpose, these rows may be modified, increased, or reduced. Each row is for a type of construction renewal work, whose name is identified in Column A as Item (c) in Instruction 3, along with a numeral ID in Column B as Item (d). Column C as Item (e) lists search strings for this row of specific construction work, such as Microsilica Overlay for RC deck in Row 35.


EN: 12

Inspection Interval Limit (yrs) < 3

Search Requirements

Construction Type	ID	Search Strings
Replacement	1	Deck REPL
MicroOverlay	21	MICRO, Micr, MICROSILICA, Micro-sillica, MS OVERLAY, MSW, MSWS
ConcOverlay	22	Deck CONC Overlay, CONC Overlay
PolymOverlay	23	Deck PLM Overlay, PLM Overlay, Poly, Polymer, Polymer Concrete, Polymer Concrete Overlay
LatexOverlay	24	Deck LTX Overlay, LTX Overlay, Latex, Latex Concrete, Latex Concrete Overlay
BITOverlay	25	Deck BIT Overlay, BIT, BIT Overlay
BSMART	26	BSMART
Rehab	27	Deck Rehab, Rehab
Overlay	29	Deck Overlay, Overlay
Patching	30	Deck Patching, Patching
CapeSeal	31	Deck CAPE SEAL, CAPE SEAL
Sealing	40	Deck Sealing, Sealing
Deck Repair	50	Deck REPR, Deck Repair

Figure 10. Screenshot. Elevatio user input to identify construction work as cause for condition improvement.

It should be stressed that the example table in Figure 10 is not the only option for EN=12. The user may choose a different set of search requirements. For example, Groups 21 to 29 in Figure 10 may be regrouped into one “Overlay” or into two: “ConcreteOverlay” and “BituminousOverlay.” When inspection records are limited for certain ENs, such aggregate grouping may become necessary because too many construction types can cause each to have very few matches. The TPMs for these construction types will then be less reliable.

Note that the search strings will be used in Elevatio by comma-separated phrases. When one of these strings/phrases is exactly matched (case insensitive) along with the year the work was done, the case's TPM is then calculated for the particular inspection record pair. It should be stressed that the string/phrase needs to be exactly the same to match. For example, an extra space between two words will lead to unmatching.

Note that IDOT "ConstructionHistory" is a freely written record, not a coded database. As a result, the software user needs to design the search with consideration to how "ConstructionHistory" can be used to maximum effect. For example, a word "replacement" can be abbreviated as "REPL" or alternatively recorded as "REMOVED & REPLACED." Further note that the intended string/phrase may be misspelled or may include an extra space. Thus, the search strings will need to be carefully designed and possibly reiterated to catch all interested cases in the construction history to maximize the reliability of the resulting TPM. Figure 10's example demonstrates the result of such an iteration.

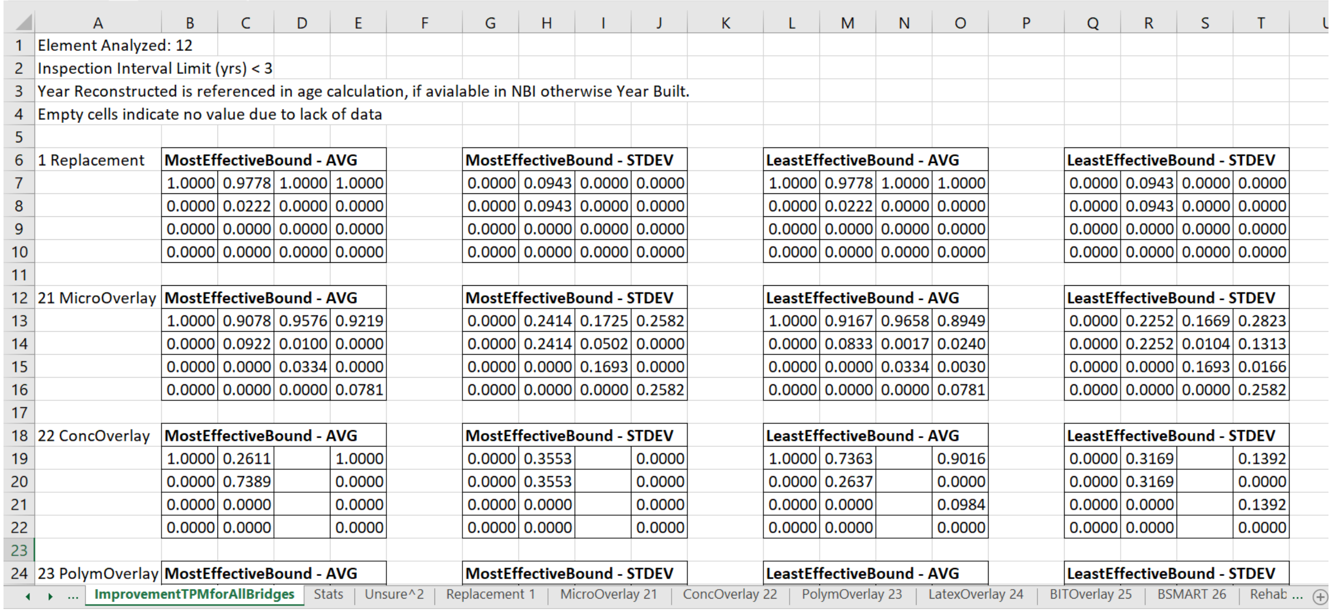
For instance, micro-sillica is a typo for micro-silica. This typo was observed in the IDOT construction history, and, thus, it was included here for the search because it is present in the database. Another search design example is the abbreviations MSW (micro-silica wearing) and MSWS (micro-silica wearing surface), which were identified by manually scanning the IDOT construction history. Thus, they are also included as search strings in Row 34 in Figure 10.

It is therefore recommended that IDOT change the construction history to a coded record for a more precise and exhaustive search/match in the future. Such a change will help exact identification of the construction work for optimized resulting TPMs.

After the search requirement table is entered, Instruction 4 in Figure 9 provides the simple steps to run Elevatio. Elevatio does not require much instruction to run, because all steps are prompted after clicking the "Run Task" button. Instruction 4 also includes a brief introduction to the final result as the two bounds, introduced and illustrated earlier in Chapter 3. It also refers to this report for more details.

The sheet "Unsure(UsedForAnalysis)" contains the inspection records used in the TPM calculations as a result of running the program. These bridges are identical to those identified in Mansus' "Unsure" sheet, excluding those also meeting one or more of the other scrubbing criteria. Furthermore, some of the bridges in the Mansus' "Unsure" sheet are also excluded to the sheet "Unsure^2," meaning double unsure. These bridges are categorized as such because their inspection records indicate not only condition improvement, but also deterioration. Elevatio is designed exclusively for condition improvement. So, the Unsure^2 bridges do not satisfy this requirement and are excluded. Some examples, along with possible causes, are discussed in Chapter 5.

Each individual TPM for the inspection record pair matched with the construction work is calculated as illustrated in Chapter 3 in Equations 57 to 73. Then, these TPMs are averaged within the construction type group as the TPM for the type. This final result is reported in the "ImprovementTPMforAllBridges" sheet (Figure 11) as the output for the EN12 example, whose input for search requirement are shown in Figure 10.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Element Analyzed: 12																			
2	Inspection Interval Limit (yrs) < 3																			
3	Year Reconstructed is referenced in age calculation, if avialable in NBI otherwise Year Built.																			
4	Empty cells indicate no value due to lack of data																			
5																				
6	1 Replacement	**MostEffectiveBound - AVG**					**MostEffectiveBound - STDEV**					**LeastEffectiveBound - AVG**					**LeastEffectiveBound - STDEV**			
7		1.0000	0.9778	1.0000	1.0000		0.0000	0.0943	0.0000	0.0000		1.0000	0.9778	1.0000	1.0000		0.0000	0.0943	0.0000	0.0000
8		0.0000	0.0222	0.0000	0.0000		0.0000	0.0943	0.0000	0.0000		0.0000	0.0222	0.0000	0.0000		0.0000	0.0943	0.0000	0.0000
9		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000	0.0000	0.0000
10		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000	0.0000	0.0000
11																				
12	21 MicroOverlay	**MostEffectiveBound - AVG**					**MostEffectiveBound - STDEV**					**LeastEffectiveBound - AVG**					**LeastEffectiveBound - STDEV**			
13		1.0000	0.9078	0.9576	0.9219		0.0000	0.2414	0.1725	0.2582		1.0000	0.9167	0.9658	0.8949		0.0000	0.2252	0.1669	0.2823
14		0.0000	0.0922	0.0100	0.0000		0.0000	0.2414	0.0502	0.0000		0.0000	0.0833	0.0017	0.0240		0.0000	0.2252	0.0104	0.1313
15		0.0000	0.0000	0.0334	0.0000		0.0000	0.0000	0.1693	0.0000		0.0000	0.0000	0.0334	0.0030		0.0000	0.0000	0.1693	0.0166
16		0.0000	0.0000	0.0000	0.0781		0.0000	0.0000	0.0000	0.2582		0.0000	0.0000	0.0000	0.0781		0.0000	0.0000	0.0000	0.2582
17																				
18	22 ConcOverlay	**MostEffectiveBound - AVG**					**MostEffectiveBound - STDEV**					**LeastEffectiveBound - AVG**					**LeastEffectiveBound - STDEV**			
19		1.0000	0.2611		1.0000		0.0000	0.3553		0.0000		1.0000	0.7363		0.9016		0.0000	0.3169		0.1392
20		0.0000	0.7389		0.0000		0.0000	0.3553		0.0000		0.0000	0.2637		0.0000		0.0000	0.3169		0.0000
21		0.0000	0.0000		0.0000		0.0000	0.0000		0.0000		0.0000	0.0000		0.0984		0.0000	0.0000		0.1392
22		0.0000	0.0000		0.0000		0.0000	0.0000		0.0000		0.0000	0.0000		0.0000		0.0000	0.0000		0.0000
23																				
24	23 PolymOverlay	**MostEffectiveBound - AVG**					**MostEffectiveBound - STDEV**					**LeastEffectiveBound - AVG**					**LeastEffectiveBound - STDEV**			

Figure 11. Screenshot. Elevatio final TPM output for example EN12 using input in Figure 10.

The individual terms of TPMs are random variables with variation. Thus, their standard deviation (STDEV) values are also included next to the average values, in Figure 11 for this example. The STDEVs offer information on the final TPM (average) values for each construction type, so that the user is aware of the associated variation. Such information can help the user make decisions based on the provided TPMs and compare and possibly redesign the search for improved results. Two bounds for TPM are seen in Figure 11—MostEffectiveBound and LeastEffectiveBound—as presented in Chapter 3. Each construction type is identified in Column A along with its numerical ID for easy reference, as defined in the "Intro" sheet by the user. In some cases, the two bounds are identical, as seen in this example.

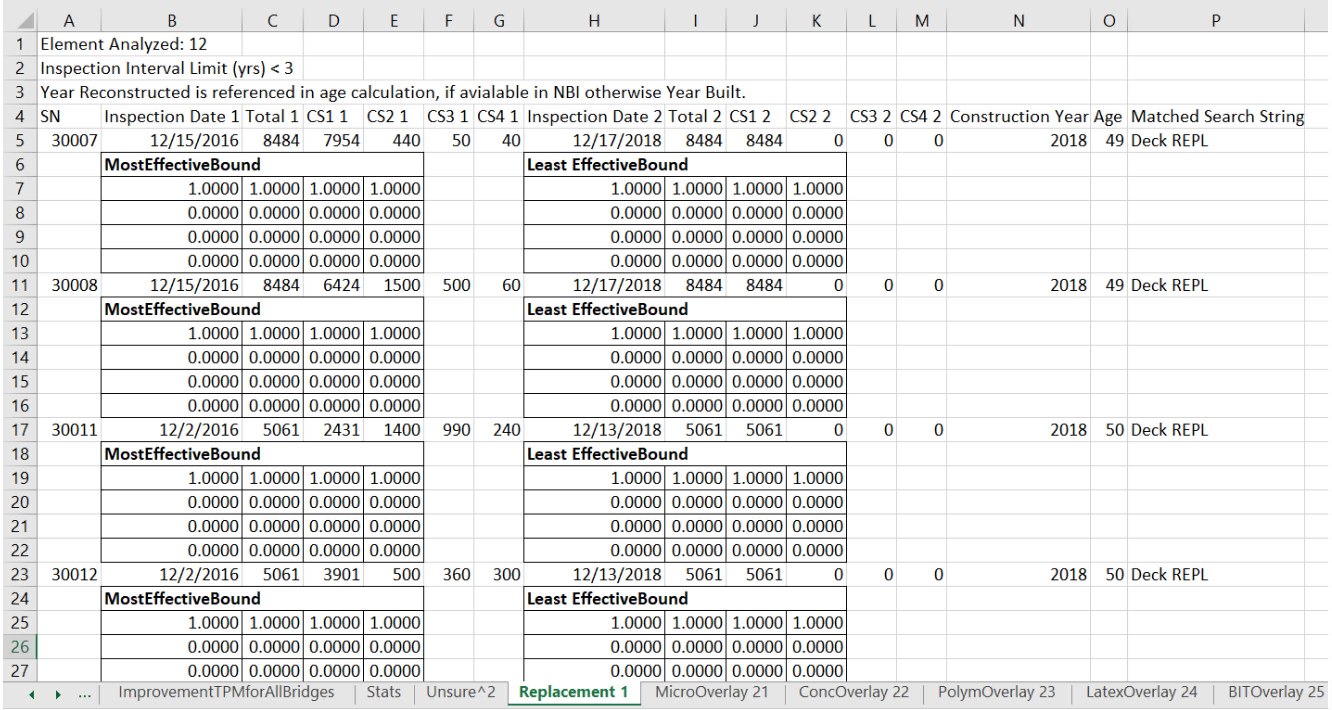
For instance, for RC deck replacement as Construction Type 1 in Rows 5 to 9, the calculated TPMs are the same for the two bounds. This is expected because RC deck replacement is expected to transition all quantities back to CS1 no matter where they were before the construction work, leading to the two bounds identical. An exception in this example is the TPM column for CS2 in Columns C and M, where P_{12} is shown as 0.9778 not 1, while P_{11}, P_{13}, and P_{14} are all 1 as expected.

This exception is perhaps due to a number of reasons as follows:

- Within the time interval between the two inspections and after the construction work, some minor deterioration or imperfect work was noticed and recorded as the bridge element's condition.
- Some errors occurred in the inspection or recording processes.
- A combination of the above reasons.

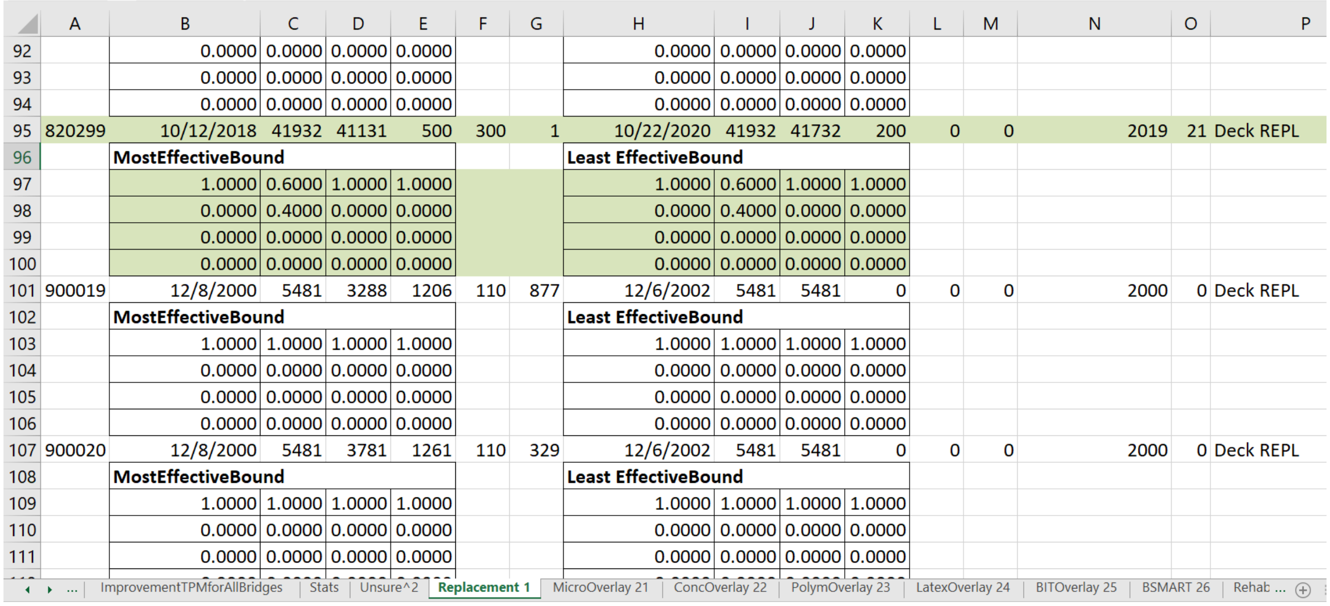
The sheet “Replacement 1” in Figure 12 for this particular construction type lists all matched cases of bridges contributing to the final result TPM and STDEV in Rows 6 to 10 in Figure 11. Each bridge occupies six rows in the sheet in Figure 12. In the first row, the SN is identified along with the first inspection date and the quantities at CS1 to CS4 then. The same information for the second inspection then follows. The second row identifies the two bounds as headings, followed by the two TPMs for the two bounds found for this pair of inspection records. They occupy the remaining four rows, for the 4 × 4 matrices.

Inspection of the “Replacement 1” sheet indicates that the only bridge contributing to the final non-1 value of P_{12} is SN=820299, as seen in Figure 13-a and highlighted green. Further examination of this case is recommended to IDOT to clarify the reason why the recorded quantity at CS2 did not all transition to CS1 after deck replacement. The result can be helpful in enhancing not only the reliability of the calculated TPMs here, but also possibly the quality of the inspection process, construction, and other aspects of the IDOT bridge inspection and preservation operation.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Element Analyzed: 12															
2	Inspection Interval Limit (yrs) < 3															
3	Year Reconstructed is referenced in age calculation, if avialable in NBI otherwise Year Built.															
4	SN	Inspection Date 1	Total 1	CS1 1	CS2 1	CS3 1	CS4 1	Inspection Date 2	Total 2	CS1 2	CS2 2	CS3 2	CS4 2	Construction Year	Age	Matched Search String
5	30007	12/15/2016	8484	7954	440	50	40	12/17/2018	8484	8484	0	0	0	2018	49	Deck REPL
6		MostEffectiveBound						Least EffectiveBound								
7		1.0000	1.0000	1.0000	1.0000			1.0000	1.0000	1.0000	1.0000					
8		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
9		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
10		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
11	30008	12/15/2016	8484	6424	1500	500	60	12/17/2018	8484	8484	0	0	0	2018	49	Deck REPL
12		MostEffectiveBound						Least EffectiveBound								
13		1.0000	1.0000	1.0000	1.0000			1.0000	1.0000	1.0000	1.0000					
14		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
15		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
16		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
17	30011	12/2/2016	5061	2431	1400	990	240	12/13/2018	5061	5061	0	0	0	2018	50	Deck REPL
18		MostEffectiveBound						Least EffectiveBound								
19		1.0000	1.0000	1.0000	1.0000			1.0000	1.0000	1.0000	1.0000					
20		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
21		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
22		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
23	30012	12/2/2016	5061	3901	500	360	300	12/13/2018	5061	5061	0	0	0	2018	50	Deck REPL
24		MostEffectiveBound						Least EffectiveBound								
25		1.0000	1.0000	1.0000	1.0000			1.0000	1.0000	1.0000	1.0000					
26		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
27		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					

Figure 12. Screenshot. Elevatio “Replacement 1” sheet for bridge details of example EN12 in Figures 10 and 11.

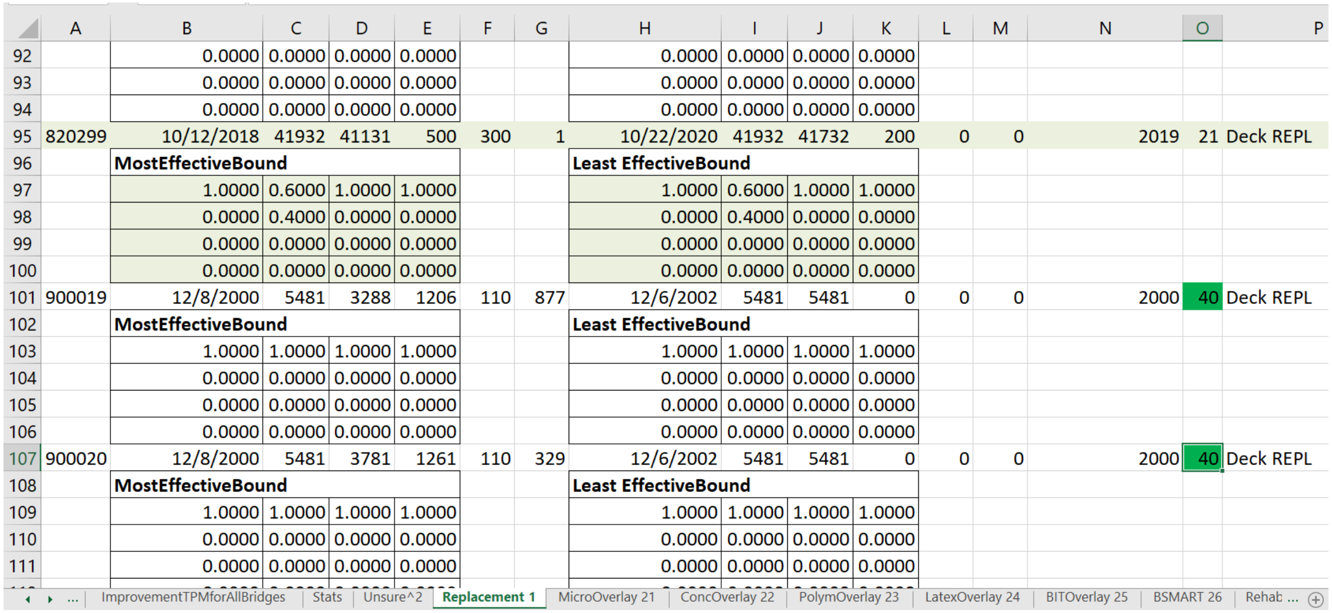


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
92		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
93		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
94		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
95	820299	10/12/2018	41932	41131	500	300	1	10/22/2020	41932	41732	200	0	0	2019	21	Deck REPL
96		**MostEffectiveBound**						**Least EffectiveBound**								
97		1.0000	0.6000	1.0000	1.0000			1.0000	0.6000	1.0000	1.0000					
98		0.0000	0.4000	0.0000	0.0000			0.0000	0.4000	0.0000	0.0000					
99		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
100		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
101	900019	12/8/2000	5481	3288	1206	110	877	12/6/2002	5481	5481	0	0	0	2000	0	Deck REPL
102		**MostEffectiveBound**						**Least EffectiveBound**								
103		1.0000	1.0000	1.0000	1.0000			1.0000	1.0000	1.0000	1.0000					
104		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
105		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
106		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
107	900020	12/8/2000	5481	3781	1261	110	329	12/6/2002	5481	5481	0	0	0	2000	0	Deck REPL
108		**MostEffectiveBound**						**Least EffectiveBound**								
109		1.0000	1.0000	1.0000	1.0000			1.0000	1.0000	1.0000	1.0000					
110		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
111		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					

Figure 13-a. Screenshot. A bridge in Elevatio "Replacement 1" sheet contributing to P_{12} not equal to 1 (Year Reconstructed from NBI used for age calculation if available otherwise Year Built).

Note that for each matched bridge in Figures 12 and 13-a, Columns O and P provide the element/bridge age at the first inspection date and the matched string, respectively. This information is uniformly included in the sheets for all other construction types for each identified match bridge. This information can be particularly helpful for the software user when designing and redesigning the search and its requirements (search strings). The information may also serve as confirmation or denial for a pre-design to see whether the search design could be effective in identifying the intended matches.

It was then noticed that some of the ages in Column O are identified as 0 years or very young ages, which were caused by using the Year Reconstructed (instead of Year Built) as inputted by the user for this example. Figure 13-b offers a comparison using Year Built for the same example. The two 0-year ages in Figure 13-a have been changed to 40-year ages in Figure 13-b, highlighted dark green. The other age for SN=820299 did not change, because this SN has no Year Reconstructed in ILNBI.txt. As a result, Year Built was defaulted to, although Year Reconstructed was selected by the user resulting in Figure 13-a.

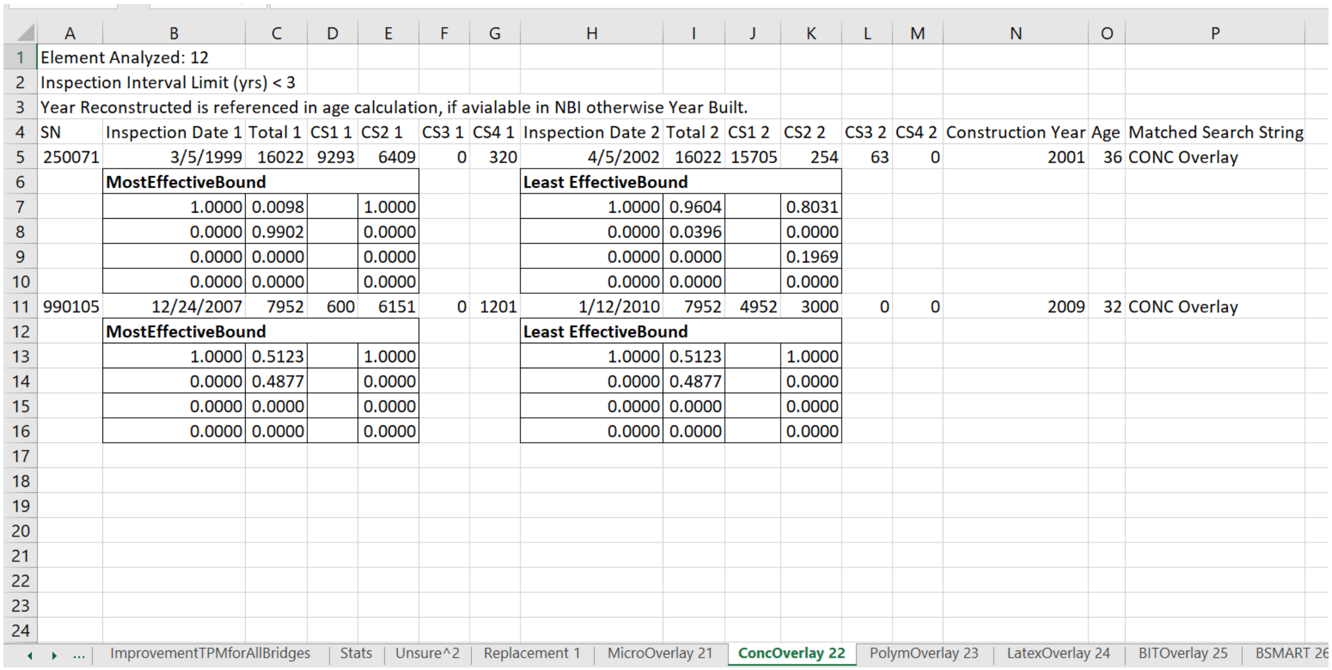


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
92		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
93		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
94		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
95	820299	10/12/2018	41932	41131	500	300	1	10/22/2020	41932	41732	200	0	0	2019	21	Deck REPL
96		**MostEffectiveBound**						**Least EffectiveBound**								
97		1.0000	0.6000	1.0000	1.0000			1.0000	0.6000	1.0000	1.0000					
98		0.0000	0.4000	0.0000	0.0000			0.0000	0.4000	0.0000	0.0000					
99		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
100		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
101	900019	12/8/2000	5481	3288	1206	110	877	12/6/2002	5481	5481	0	0	0	2000	40	Deck REPL
102		**MostEffectiveBound**						**Least EffectiveBound**								
103		1.0000	1.0000	1.0000	1.0000			1.0000	1.0000	1.0000	1.0000					
104		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
105		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
106		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
107	900020	12/8/2000	5481	3781	1261	110	329	12/6/2002	5481	5481	0	0	0	2000	40	Deck REPL
108		**MostEffectiveBound**						**Least EffectiveBound**								
109		1.0000	1.0000	1.0000	1.0000			1.0000	1.0000	1.0000	1.0000					
110		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					
111		0.0000	0.0000	0.0000	0.0000			0.0000	0.0000	0.0000	0.0000					

Figure 13-b. Screenshot. A bridge in Elevatio "Replacement 1" sheet contributing to P_{12} not equal to 1 (Year Built from NBI used for the age calculation).

The "ImprovementTPMForAllBridges" sheet, shown in Figure 11, also displays empty TPM cells for a few cases and their STDEVs (e.g., Rows 18 to 21). The empty cells indicate no available data; all are for the transition probabilities from CS3. Sometimes, the TPM cells are not empty, but the corresponding STDEV cells are, indicating there is only one entry to result in TPM (averaging with one entry) but not enough for STDEV, which requires at least two entries.

The empty cells in Figure 11, for the concrete overlay construction type, highlight no quantity in CS3 recorded to have transitioned to another CS or even stay in CS3. More details about the identified individual bridges in that construction type and their inspection records contributing to these final results can be found in sheet (Figure 14). Two bridges are identified there as the contributors to the empty cells in Figure 11. The setting of this sheet is identical to all other sheets for various construction types. The information there can be utilized by the software user to further track down for clarification and/or understanding. Additional datasets with the bridge owner may be needed for this purpose. They may include, and are not limited to, information on the inspection team/contractor, consistency of other inspection results for the same bridge and/or by the same team/contractor, etc.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Element Analyzed: 12															
2	Inspection Interval Limit (yrs) < 3															
3	Year Reconstructed is referenced in age calculation, if avialable in NBI otherwise Year Built.															
4	SN	Inspection Date 1	Total 1	CS1 1	CS2 1	CS3 1	CS4 1	Inspection Date 2	Total 2	CS1 2	CS2 2	CS3 2	CS4 2	Construction Year	Age	Matched Search String
5	250071	3/5/1999	16022	9293	6409	0	320	4/5/2002	16022	15705	254	63	0	2001	36	CONC Overlay
6		**MostEffectiveBound**						**Least EffectiveBound**								
7		1.0000	0.0098		1.0000			1.0000	0.9604		0.8031					
8		0.0000	0.9902		0.0000			0.0000	0.0396		0.0000					
9		0.0000	0.0000		0.0000			0.0000	0.0000		0.1969					
10		0.0000	0.0000		0.0000			0.0000	0.0000		0.0000					
11	990105	12/24/2007	7952	600	6151	0	1201	1/12/2010	7952	4952	3000	0	0	2009	32	CONC Overlay
12		**MostEffectiveBound**						**Least EffectiveBound**								
13		1.0000	0.5123		1.0000			1.0000	0.5123		1.0000					
14		0.0000	0.4877		0.0000			0.0000	0.4877		0.0000					
15		0.0000	0.0000		0.0000			0.0000	0.0000		0.0000					
16		0.0000	0.0000		0.0000			0.0000	0.0000		0.0000					
17																
18																
19																
20																
21																
22																
23																
24																

Figure 14. Screenshot. Bridge- and inspection-record details for concrete overlay in Elevatio.

CHAPTER 5: TWO APPLICATION EXAMPLES OF SOFTWARE TOOLS

Two examples are included here to illustrate application of the proposed approach to calculate TPM for the do-nothing and improvement cases using Mansus and Elevatio, respectively. They also demonstrate possible applications of the obtained TPMs for forecasting and other bridge management decisions. Potential further applications are also foreseeable, with the future condition probability distribution vectors **q** made available through the TPMs found as described in Equations 10 and 11.

EXAMPLE 1: EN = 12 RC DECK

The RC deck, as the most popular roadway bridge deck, receives significant attention in bridge management. It is subject to deterioration due to weather-pertinent factors, such as freeze-thaw cycles and salt usage for deicing in winter. Truck wheel loads are also perceived to lead to deterioration in RC decks. In addition, the deck serves as the roof of the bridge. Its condition and life span may affect many other bridge elements' conditions and life spans. As such, a great deal of maintenance effort and expenditure have been devoted to the deck. Furthermore, the condition state data for the deck may be the most extensive and complete part in the available BrM databases among all bridge elements. Thus, this element is selected for application illustration.

Do-Nothing Deterioration TPM for EN12 Using Mansus

Figure 15 shows the start of this application example in Mansus. The user begins by typing the EN in the pop-up window that is prompted by clicking the "Run Task" button on the "Intro" sheet. Figure 16 displays the answer choices to the question on whether to use Year Reconstructed or Year Built in NBI to calculate the age. Select "Yes" to use Year Reconstructed here as the base for age calculation if it is available in ILNBI.txt. Year Reconstructed is often recorded in NBI for a major reconstruction, which most likely has included significant or major work to the deck, signaling the restart of its life span. Therefore, the answer "Yes" is selected here to use Year Reconstructed as the base for age calculation if it is available in ILNBI. In case Year Reconstructed is not available in ILNBI, then Year Built will be used as the default, even if "Yes" is answered. The answer "No" means to use Year Built for age calculation, which will completely ignore Year Reconstructed. For some other elements, "No" may be more appropriate for reality, because reconstruction more likely does not include a significant renewal for them. Some examples can include abutment, pile, etc.

It took about 50 seconds on a 4 GHz/128 GB RAM computer to complete this Mansus calculation. Figure 18 presents the final results in the sheet "Do-NothingTPMForAllBridges." Figure 17 shows an overview of the IDOT inspection records used for the calculation of TPM for RC deck using Mansus. This "Stats" sheet indicates that 6,327 bridges in IDOT inspection records were found to have EN12.

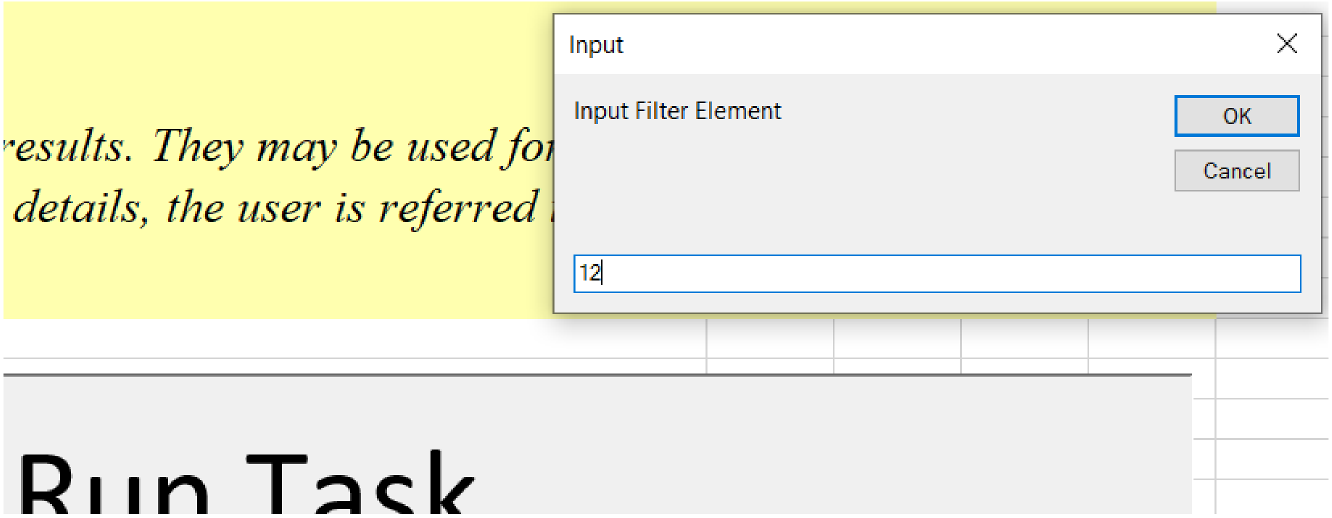
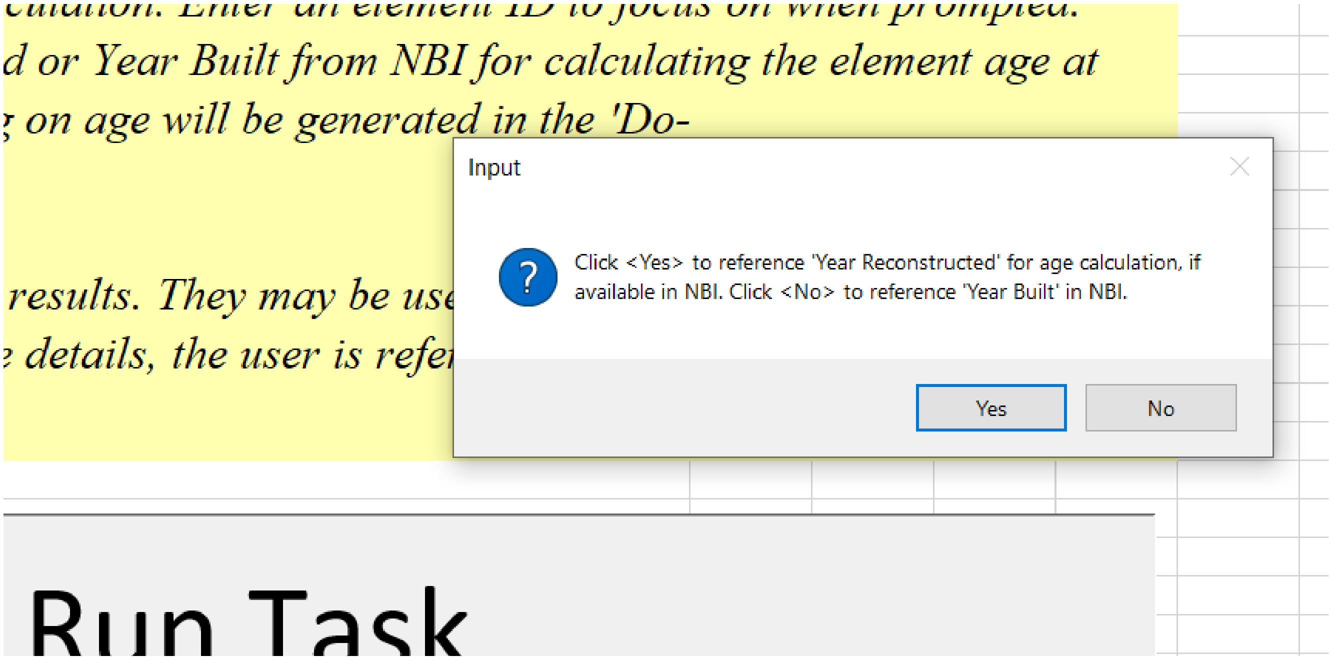


Figure 15. Screenshot. Enter EN=12 after clicking the Run Task button in Mansus “Intro” sheet.



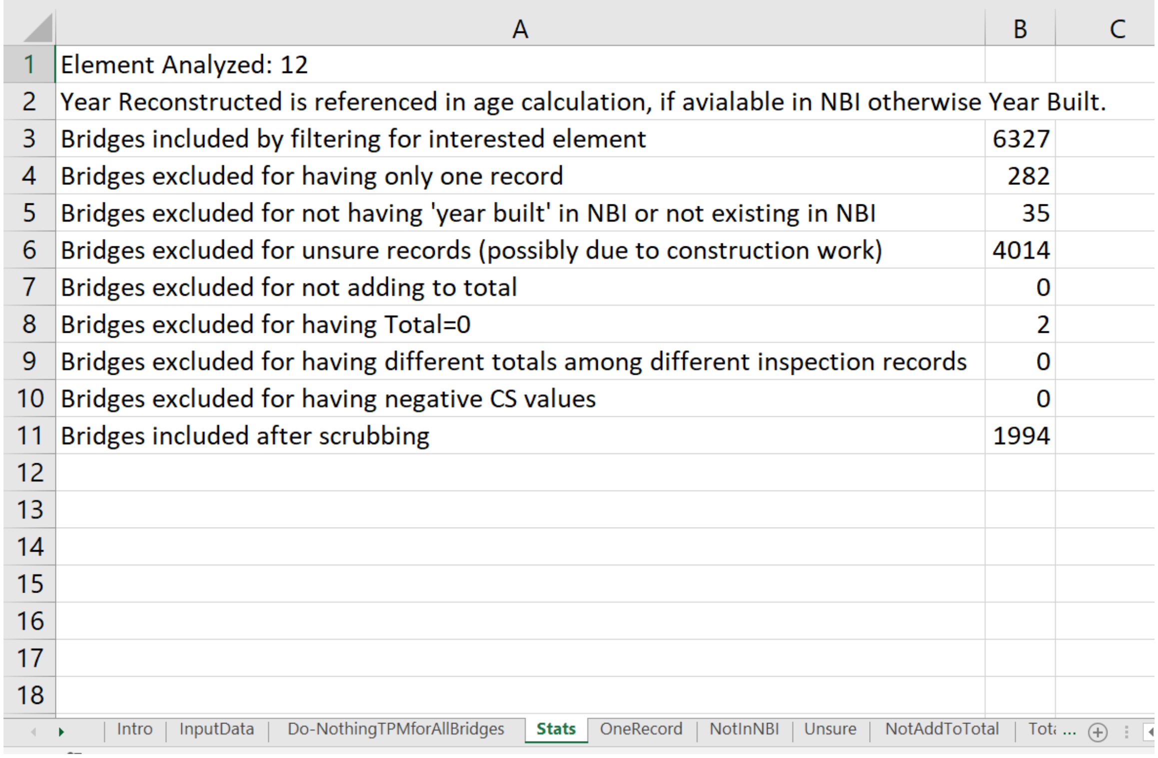
Click <Yes> to reference 'Year Reconstructed' for age calculation, if available in NBI. Click <No> to reference 'Year Built' in NBI.

Figure 16. Screenshot. Select answer about age calculation reference in Mansus.

However, a large number of these bridges have inspection records that do not qualify for the following calculations in Mansus. As seen, 282 of these 6,327 bridges have only one inspection recorded. Thus, they are unable to form a pair of before and after inspection records required for the TPM calculation, as illustrated in all numerical examples in Chapter 3. Thirty-five of them were not found in the Illinois NBI record of 2021. As a result, their age would not be available, so they were excluded from further calculation.

Through the data-scrubbing process described in Chapter 4, a large number (4,014) of these 6,327 bridges were found to have records indicating condition improvement or other than deterioration. This inspection record category is labeled “unsure” because Mansus is not certain at this point whether they can be used in Elevatio calculations for TPMs for renewal construction work. They will be accepted or denied in the Elevatio application later. Again, note that some of these bridge inspection records may also meet the criteria of exclusion to be checked later than this criterion for “unsure” records. These criteria are the following: (a) the quantities at CS1 to CS4 do not add to the total, (b) the total quantity is equal to 0, (c) the total quantities vary from one inspection to another, and (d) there is(are) negative quantity(ies). The order of these criterion checks for data scrubbing is the same as they are listed in Figure 17.

Two of the 6,327 bridges are listed in Figure 17 as having the total quantity equal to 0. However, as mentioned earlier, there may be more bridges having the total quantity equal to 0, which were identified to meet the other scrubbing criteria checked earlier, in Rows 4 to 6 in Figure 17. Those that are included in the unsure category (Row 6 in Figure 17) will be double checked in Elevatio. Elevatio will screen them and only use those that do not meet any of the scrubbing criteria.



	A	B	C
1	Element Analyzed: 12		
2	Year Reconstructed is referenced in age calculation, if avialable in NBI otherwise Year Built.		
3	Bridges included by filtering for interested element	6327	
4	Bridges excluded for having only one record	282	
5	Bridges excluded for not having 'year built' in NBI or not existing in NBI	35	
6	Bridges excluded for unsure records (possibly due to construction work)	4014	
7	Bridges excluded for not adding to total	0	
8	Bridges excluded for having Total=0	2	
9	Bridges excluded for having different totals among different inspection records	0	
10	Bridges excluded for having negative CS values	0	
11	Bridges included after scrubbing	1994	
12			
13			
14			
15			
16			
17			
18			

Figure 17. Screenshot. Mansus sheet “Stats” for EN12 for do-nothing TPM.

As mentioned earlier in Chapter 4, the resulting bridges with their inspection records used in TPM calculation are listed in the sheet “BridgesUsedForTPM.” The final results of TPM for all these bridges as a function of age are output in the sheet “Do-NothingTPMForAllBridges,” as seen in Figure 18.

One of the recommended applications of the TPMs is to forecast from the perfect initial condition represented by the following condition probability distribution vector:

$$\mathbf{q}^0 = \{1,0,0,0\}^{t,0} \tag{77}$$

to estimate, on average, how long the element will take to reach a predefined end of expected service life. Figure 18 includes this forecasting computation, starting from the perfect initial condition in Cells L6 to L9, highlighted in green. Equations 10 and 11 state that this forecasting involves simple matrix multiplication. It requires TPMs now available in the Mansus "Do-NothingTPMForAllBridges" sheet in Figure 18. As a result, the condition probability distribution $\mathbf{q}^1$ as a column vector at the first year is computed as

$$\mathbf{q}^1 = \mathbf{P}^0\,\mathbf{q}^0 = \mathbf{P}^0\,\{1,0,0,0\}^{t,0} \tag{78}$$

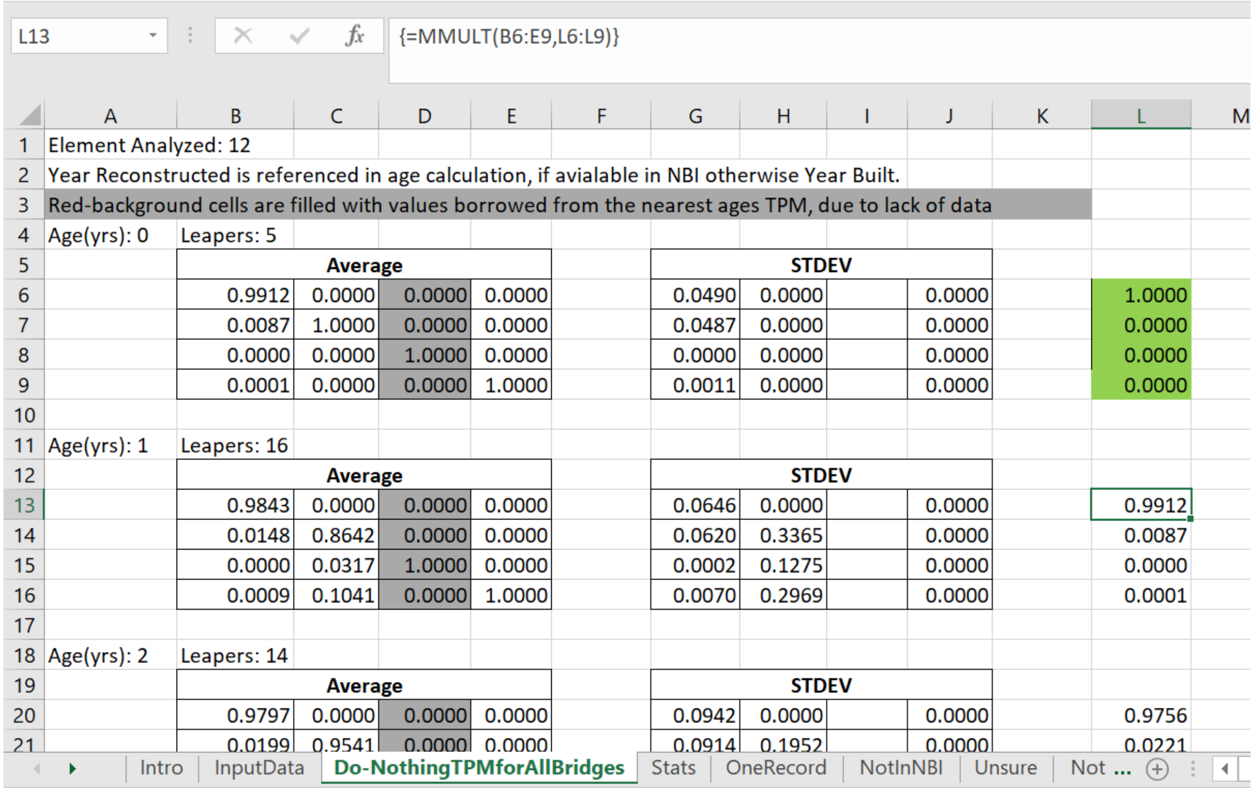
This column vector is shown in Cells L13 to L16 in Figure 18. Cell L13 also has the Excel formula for matrix multiplication MMULT() shown in the formula space. The formula indicates the matrix in Cells B6 to E9 multiplied by the vector matrix in Cells L6 to L9 highlighted green. This can be readily performed by the user. Note that this forecasting calculation is not included in Mansus because it is very easy for the user to do and such applications may vary widely. Mansus includes calculations to provide the needed TPMs for such forecasting.

The same is then repeated for

$$\mathbf{q}^j = \mathbf{P}^{j-1}\,\mathbf{q}^{j-1} \qquad (j=2,3,4,\ldots,N) \tag{79}$$

In Figure 18, all computed condition probability distribution vectors $\mathbf{q}^j$ are given in Column L with *j* (age) indicated in Column A. The life span *N* is then found by identifying the value of *j* when the predetermined q_4 = 15% threshold is reached. This *N* value often is not an integer, as seen in Figure 19 for this example, because it is unlikely an integer would happen to result in the exact target value (15% here). Therefore, linear interpolation is recommended to find this *N* value as a real number for the expected life.

For this example, linear interpolation between 36 and 37 years in Figure 19 finds *N* in Equation 79 at 36.8 years. This expected life span for RC deck without renewal construction work is close to that found using the NBI rating system for deck (Fu, 2021). However, the RC deck here with EN=12 is a subset of deck in the NBI system in Fu (2021). Similar forecasting can be done for EN12 of bridges on a route, in a district, or in a region, when the TPMs are found using only those bridges of the corresponding route, district, or region.



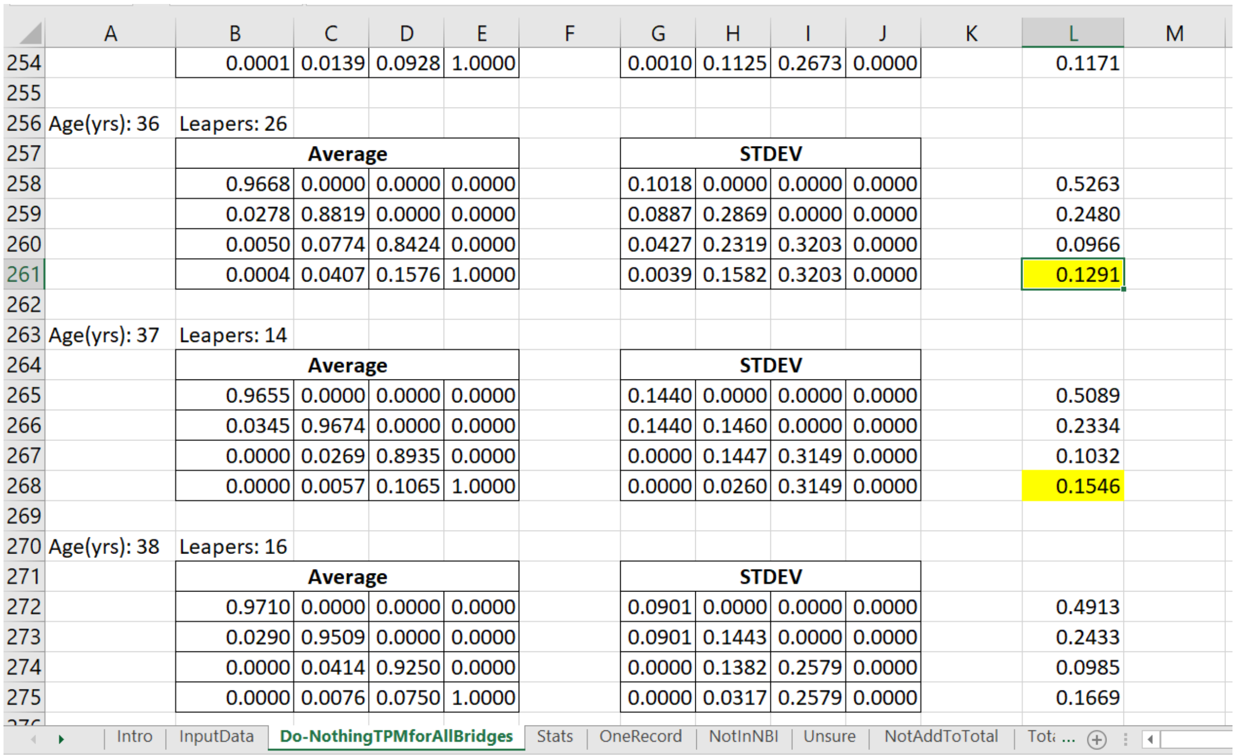
{=MMULT(B6:E9,L6:L9)}

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Element Analyzed: 12												
2	Year Reconstructed is referenced in age calculation, if avialable in NBI otherwise Year Built.												
3	Red-background cells are filled with values borrowed from the nearest ages TPM, due to lack of data												
4	Age(yrs): 0	Leapers: 5											
5		Average					STDEV						
6		0.9912	0.0000	0.0000	0.0000		0.0490	0.0000		0.0000		1.0000	
7		0.0087	1.0000	0.0000	0.0000		0.0487	0.0000		0.0000		0.0000	
8		0.0000	0.0000	1.0000	0.0000		0.0000	0.0000		0.0000		0.0000	
9		0.0001	0.0000	0.0000	1.0000		0.0011	0.0000		0.0000		0.0000	
10													
11	Age(yrs): 1	Leapers: 16											
12		Average					STDEV						
13		0.9843	0.0000	0.0000	0.0000		0.0646	0.0000		0.0000		0.9912	
14		0.0148	0.8642	0.0000	0.0000		0.0620	0.3365		0.0000		0.0087	
15		0.0000	0.0317	1.0000	0.0000		0.0002	0.1275		0.0000		0.0000	
16		0.0009	0.1041	0.0000	1.0000		0.0070	0.2969		0.0000		0.0001	
17													
18	Age(yrs): 2	Leapers: 14											
19		Average					STDEV						
20		0.9797	0.0000	0.0000	0.0000		0.0942	0.0000		0.0000		0.9756	
21		0.0199	0.9541	0.0000	0.0000		0.0914	0.1952		0.0000		0.0221	

Figure 18. Screenshot. Do-nothing TPM result and its forecast application initiated for example EN12 in Mansus.

It is interesting to see how many years it may take for the 100% quantity at CS1 to become 50%. This criterion has been used overwhelmingly in the literature to find the so-called transition time between CS1 and CS2. For this example of EN12, the 100% quantity at CS1 at the beginning of service or age of 0 years will become 50% at about 37 years of age (between Cells L258 and L265). At that age, the quantity at CS4 will reach 15.5%, exceeding the IDOT threshold of 15% for expected life. Apparently, IDOT does not use this reduction from 100% to 50% as the criterion for transition from CS1 and CS2, and this transition time exceeds the expected life according to the IDOT threshold so there is no time left to transition from CS2 to CS3 and from CS3 to CS4 to complete the life.

As discussed earlier, the transition from CS1 to CS2 is not well defined in this context of BrM inspection data, because not the entire element (i.e., 100% of deck area here for EN12) is tracked for condition deterioration but individual sqft of it. However, the entire element's transition from CS1 to CS2 is almost always perceived when the transition from CS1 to CS2 is mentioned. This contradiction is the root of the observed inconsistency or confusion with reality.



	A	B	C	D	E	F	G	H	I	J	K	L	M
254		0.0001	0.0139	0.0928	1.0000		0.0010	0.1125	0.2673	0.0000		0.1171	
255													
256	Age(yrs): 36	Leapers: 26											
257		**Average**					**STDEV**						
258		0.9668	0.0000	0.0000	0.0000		0.1018	0.0000	0.0000	0.0000		0.5263	
259		0.0278	0.8819	0.0000	0.0000		0.0887	0.2869	0.0000	0.0000		0.2480	
260		0.0050	0.0774	0.8424	0.0000		0.0427	0.2319	0.3203	0.0000		0.0966	
261		0.0004	0.0407	0.1576	1.0000		0.0039	0.1582	0.3203	0.0000		0.1291	
262													
263	Age(yrs): 37	Leapers: 14											
264		**Average**					**STDEV**						
265		0.9655	0.0000	0.0000	0.0000		0.1440	0.0000	0.0000	0.0000		0.5089	
266		0.0345	0.9674	0.0000	0.0000		0.1440	0.1460	0.0000	0.0000		0.2334	
267		0.0000	0.0269	0.8935	0.0000		0.0000	0.1447	0.3149	0.0000		0.1032	
268		0.0000	0.0057	0.1065	1.0000		0.0000	0.0260	0.3149	0.0000		0.1546	
269													
270	Age(yrs): 38	Leapers: 16											
271		**Average**					**STDEV**						
272		0.9710	0.0000	0.0000	0.0000		0.0901	0.0000	0.0000	0.0000		0.4913	
273		0.0290	0.9509	0.0000	0.0000		0.0901	0.1443	0.0000	0.0000		0.2433	
274		0.0000	0.0414	0.9250	0.0000		0.0000	0.1382	0.2579	0.0000		0.0985	
275		0.0000	0.0076	0.0750	1.0000		0.0000	0.0317	0.2579	0.0000		0.1669	

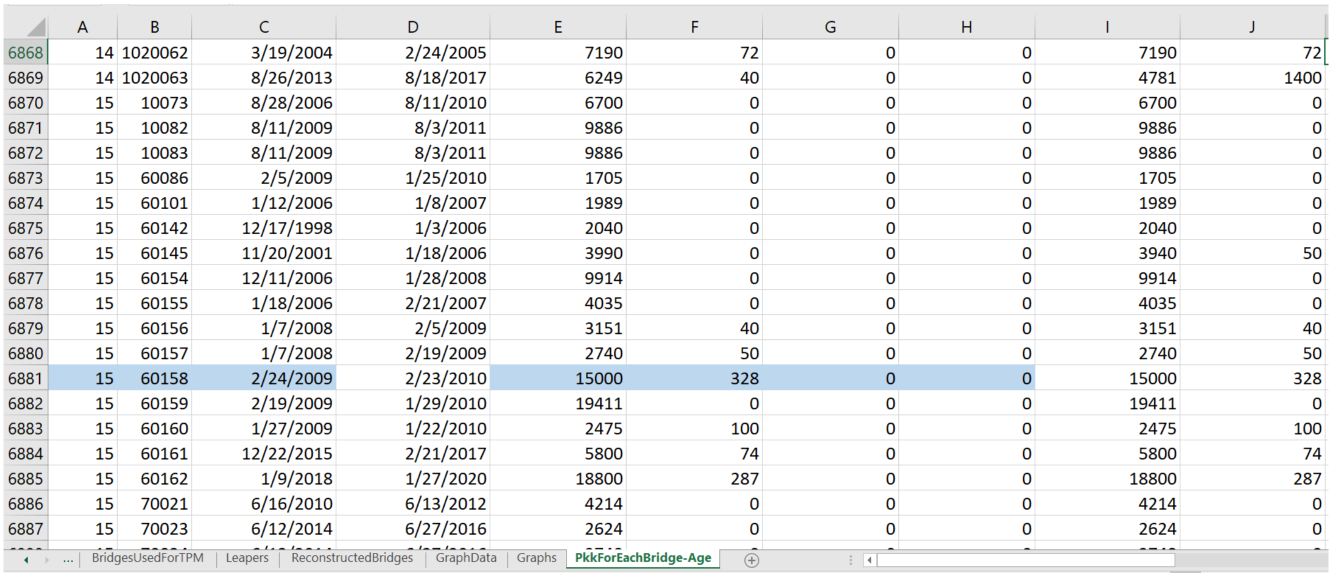
Figure 19. Screenshot. Life span forecast for Illinois EN12 interpolated between 36 and 37 years.

The forecasting above can be readily performed for a single bridge as well. It could answer such questions as how many more years (i.e., remaining service life) on average the bridge may still have before reaching the end of this element's expected service life. Then, its current CS quantities for the interested element along with its age can be readily used to derive the vector condition probability distributions to the life end. Figure 20 shows a randomly selected example bridge with an RC deck highlighted blue at an age of 15 years for forecasting the element's expected remaining service life as follows.

$$\mathbf{q}^{j} = \mathbf{P}^{j-1}\,\mathbf{q}^{j-1} \qquad (j=16,17,18,\ldots,K) \tag{80}$$

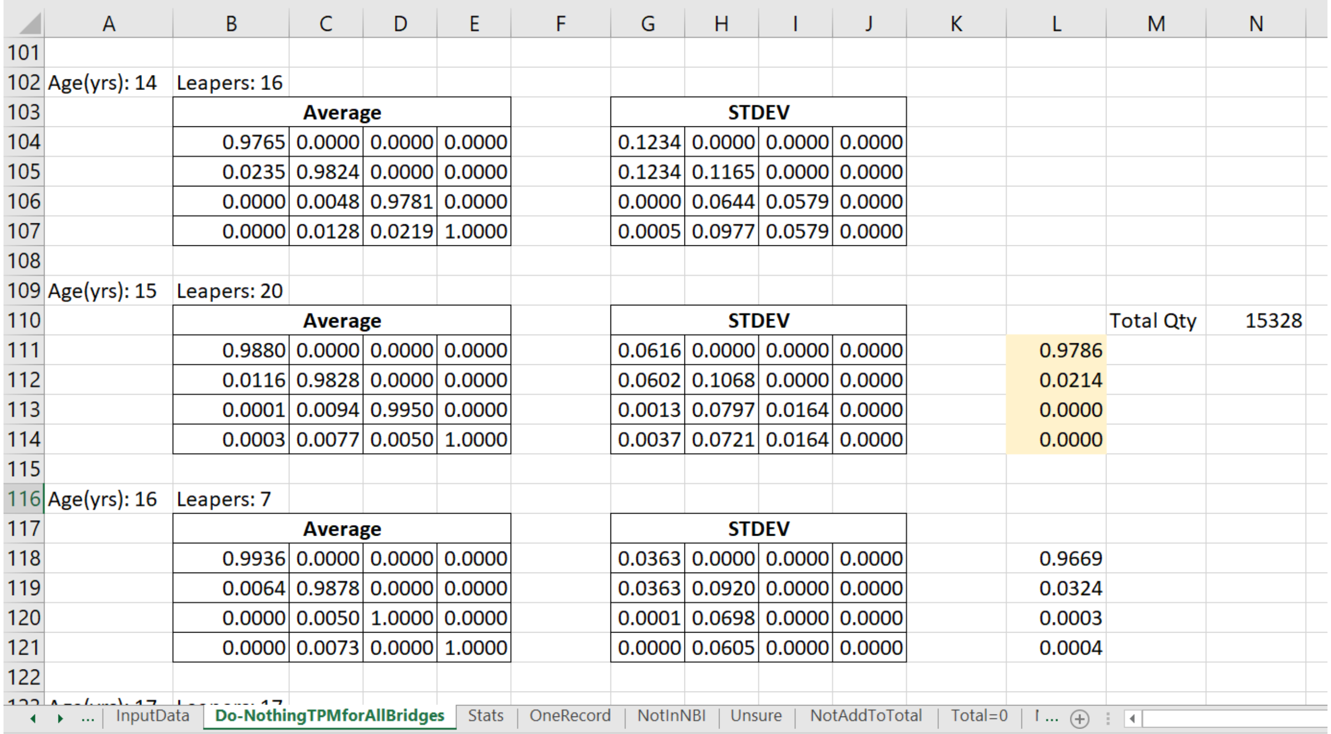
Figure 21 shows the forecasting computation starting at 15 years, according to Equation 80. This computation of matrix multiplication is repeated for consecutive *j* values until the targeted q_4 = 15% is reached, as seen in Figure 22. Linear interpolation between years 45 and 46 finds the *K* of Equation 80 at 45.7 years. The expected remaining service life is then 45.7 − 15 = 30.7 years for EN12 of this bridge.

Nevertheless, it should be stressed that such forecasting is based on the performance of the deck under historical environmental factors, such as truck loading, freeze-thaw cycling and behavior, etc., which are perceived to be important for RC deck performance. In the next 30.7 years, these factors will likely change, affecting the real performance of the RC deck element. As such, it is critical to update such forecasting when new inspection results become available. When the horizon for forecasting becomes closer, the credibility of forecasting will increase accordingly. An analogy exists with weather forecasting, which becomes more credible and accurate when getting closer to the forecast horizon. For example, today's forecast for tomorrow's weather is certainly more reliable than that of a month ago for tomorrow's weather.



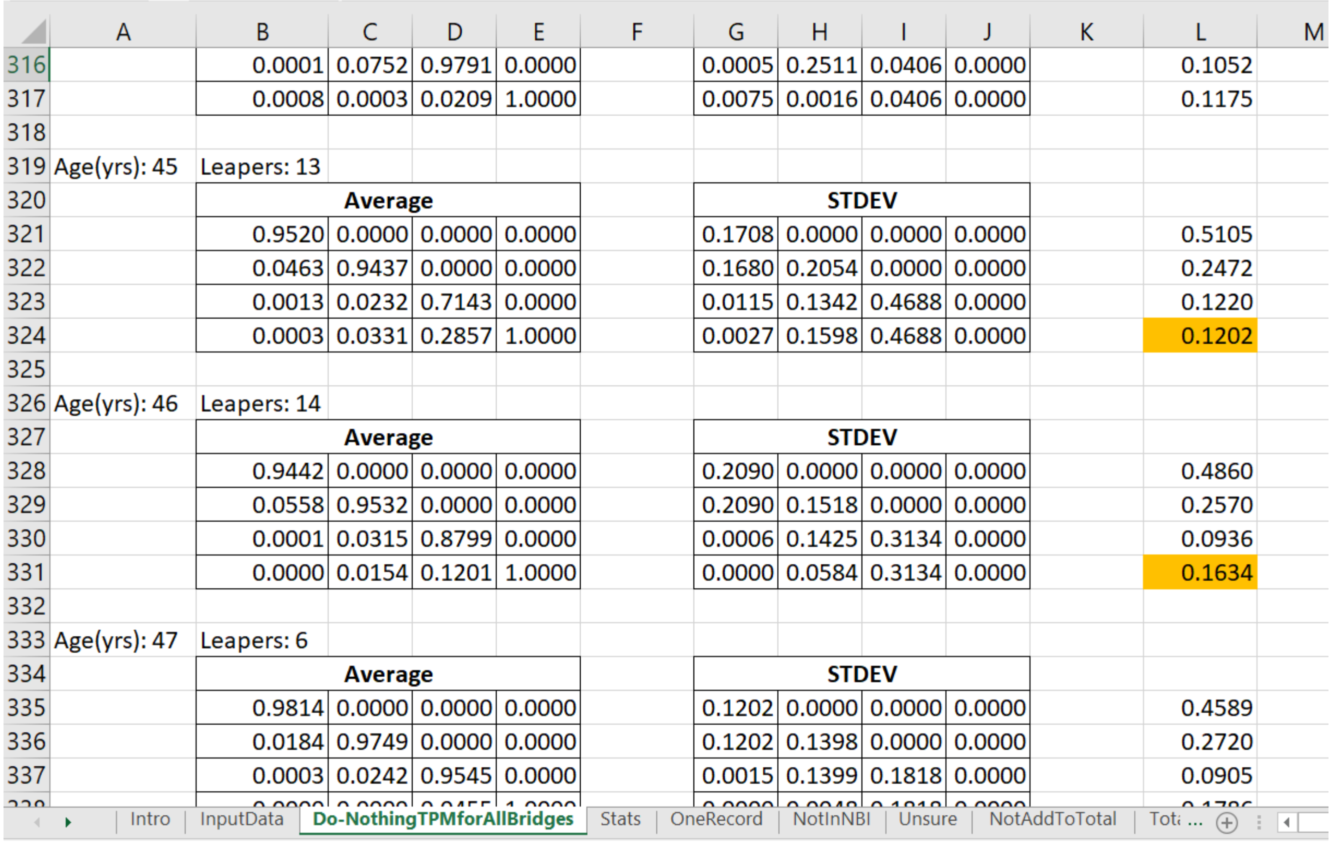
	A	B	C	D	E	F	G	H	I	J
6868	14	1020062	3/19/2004	2/24/2005	7190	72	0	0	7190	72
6869	14	1020063	8/26/2013	8/18/2017	6249	40	0	0	4781	1400
6870	15	10073	8/28/2006	8/11/2010	6700	0	0	0	6700	0
6871	15	10082	8/11/2009	8/3/2011	9886	0	0	0	9886	0
6872	15	10083	8/11/2009	8/3/2011	9886	0	0	0	9886	0
6873	15	60086	2/5/2009	1/25/2010	1705	0	0	0	1705	0
6874	15	60101	1/12/2006	1/8/2007	1989	0	0	0	1989	0
6875	15	60142	12/17/1998	1/3/2006	2040	0	0	0	2040	0
6876	15	60145	11/20/2001	1/18/2006	3990	0	0	0	3940	50
6877	15	60154	12/11/2006	1/28/2008	9914	0	0	0	9914	0
6878	15	60155	1/18/2006	2/21/2007	4035	0	0	0	4035	0
6879	15	60156	1/7/2008	2/5/2009	3151	40	0	0	3151	40
6880	15	60157	1/7/2008	2/19/2009	2740	50	0	0	2740	50
6881	15	60158	2/24/2009	2/23/2010	15000	328	0	0	15000	328
6882	15	60159	2/19/2009	1/29/2010	19411	0	0	0	19411	0
6883	15	60160	1/27/2009	1/22/2010	2475	100	0	0	2475	100
6884	15	60161	12/22/2015	2/21/2017	5800	74	0	0	5800	74
6885	15	60162	1/9/2018	1/27/2020	18800	287	0	0	18800	287
6886	15	70021	6/16/2010	6/13/2012	4214	0	0	0	4214	0
6887	15	70023	6/12/2014	6/27/2016	2624	0	0	0	2624	0

Figure 20. Screenshot. Example bridge with EN12 in service at age of 15 years.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
101														
102	Age(yrs): 14	Leapers: 16												
103		Average					STDEV							
104		0.9765	0.0000	0.0000	0.0000		0.1234	0.0000	0.0000	0.0000				
105		0.0235	0.9824	0.0000	0.0000		0.1234	0.1165	0.0000	0.0000				
106		0.0000	0.0048	0.9781	0.0000		0.0000	0.0644	0.0579	0.0000				
107		0.0000	0.0128	0.0219	1.0000		0.0005	0.0977	0.0579	0.0000				
108														
109	Age(yrs): 15	Leapers: 20												
110		Average					STDEV						Total Qty	15328
111		0.9880	0.0000	0.0000	0.0000		0.0616	0.0000	0.0000	0.0000		0.9786		
112		0.0116	0.9828	0.0000	0.0000		0.0602	0.1068	0.0000	0.0000		0.0214		
113		0.0001	0.0094	0.9950	0.0000		0.0013	0.0797	0.0164	0.0000		0.0000		
114		0.0003	0.0077	0.0050	1.0000		0.0037	0.0721	0.0164	0.0000		0.0000		
115														
116	Age(yrs): 16	Leapers: 7												
117		Average					STDEV							
118		0.9936	0.0000	0.0000	0.0000		0.0363	0.0000	0.0000	0.0000		0.9669		
119		0.0064	0.9878	0.0000	0.0000		0.0363	0.0920	0.0000	0.0000		0.0324		
120		0.0000	0.0050	1.0000	0.0000		0.0001	0.0698	0.0000	0.0000		0.0003		
121		0.0000	0.0073	0.0000	1.0000		0.0000	0.0605	0.0000	0.0000		0.0004		
122														

Figure 21. Screenshot. Forecasting remaining life initiated for example bridge in Figure 20 at age of 15 years.

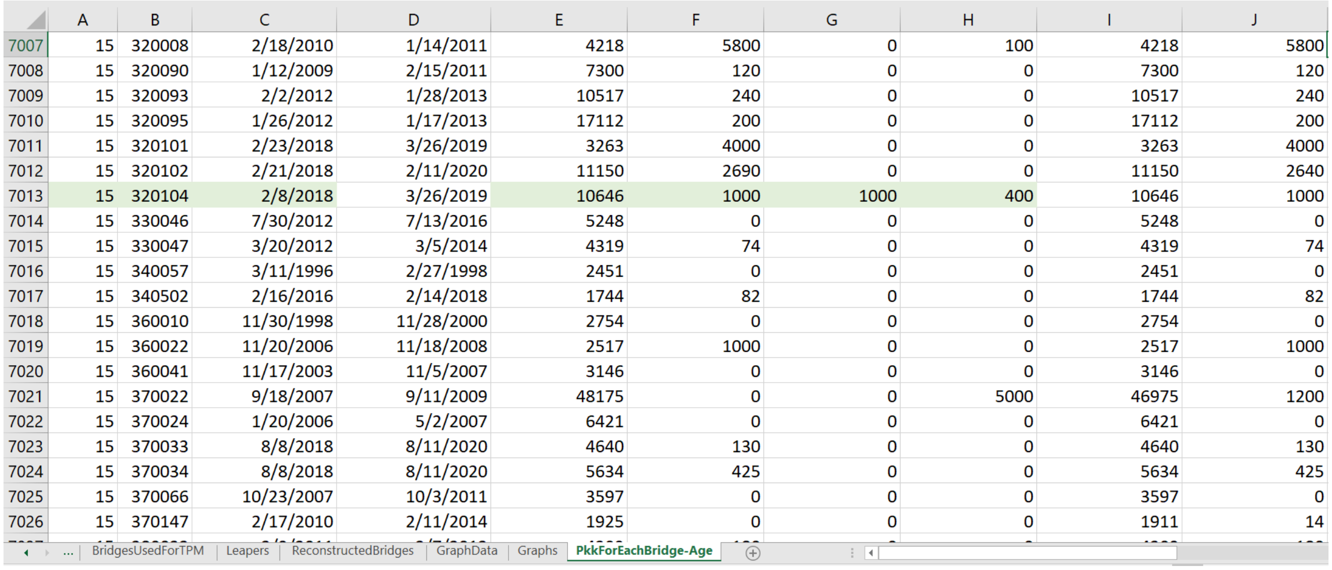


	A	B	C	D	E	F	G	H	I	J	K	L	M
316		0.0001	0.0752	0.9791	0.0000		0.0005	0.2511	0.0406	0.0000		0.1052	
317		0.0008	0.0003	0.0209	1.0000		0.0075	0.0016	0.0406	0.0000		0.1175	
318													
319	Age(yrs): 45	Leapers: 13											
320		Average					STDEV						
321		0.9520	0.0000	0.0000	0.0000		0.1708	0.0000	0.0000	0.0000		0.5105	
322		0.0463	0.9437	0.0000	0.0000		0.1680	0.2054	0.0000	0.0000		0.2472	
323		0.0013	0.0232	0.7143	0.0000		0.0115	0.1342	0.4688	0.0000		0.1220	
324		0.0003	0.0331	0.2857	1.0000		0.0027	0.1598	0.4688	0.0000		0.1202	
325													
326	Age(yrs): 46	Leapers: 14											
327		Average					STDEV						
328		0.9442	0.0000	0.0000	0.0000		0.2090	0.0000	0.0000	0.0000		0.4860	
329		0.0558	0.9532	0.0000	0.0000		0.2090	0.1518	0.0000	0.0000		0.2570	
330		0.0001	0.0315	0.8799	0.0000		0.0006	0.1425	0.3134	0.0000		0.0936	
331		0.0000	0.0154	0.1201	1.0000		0.0000	0.0584	0.3134	0.0000		0.1634	
332													
333	Age(yrs): 47	Leapers: 6											
334		Average					STDEV						
335		0.9814	0.0000	0.0000	0.0000		0.1202	0.0000	0.0000	0.0000		0.4589	
336		0.0184	0.9749	0.0000	0.0000		0.1202	0.1398	0.0000	0.0000		0.2720	
337		0.0003	0.0242	0.9545	0.0000		0.0015	0.1399	0.1818	0.0000		0.0905	

Figure 22. Screenshot. Forecasted end of expected service life identified between 45 and 46 years for bridge in Figure 20.

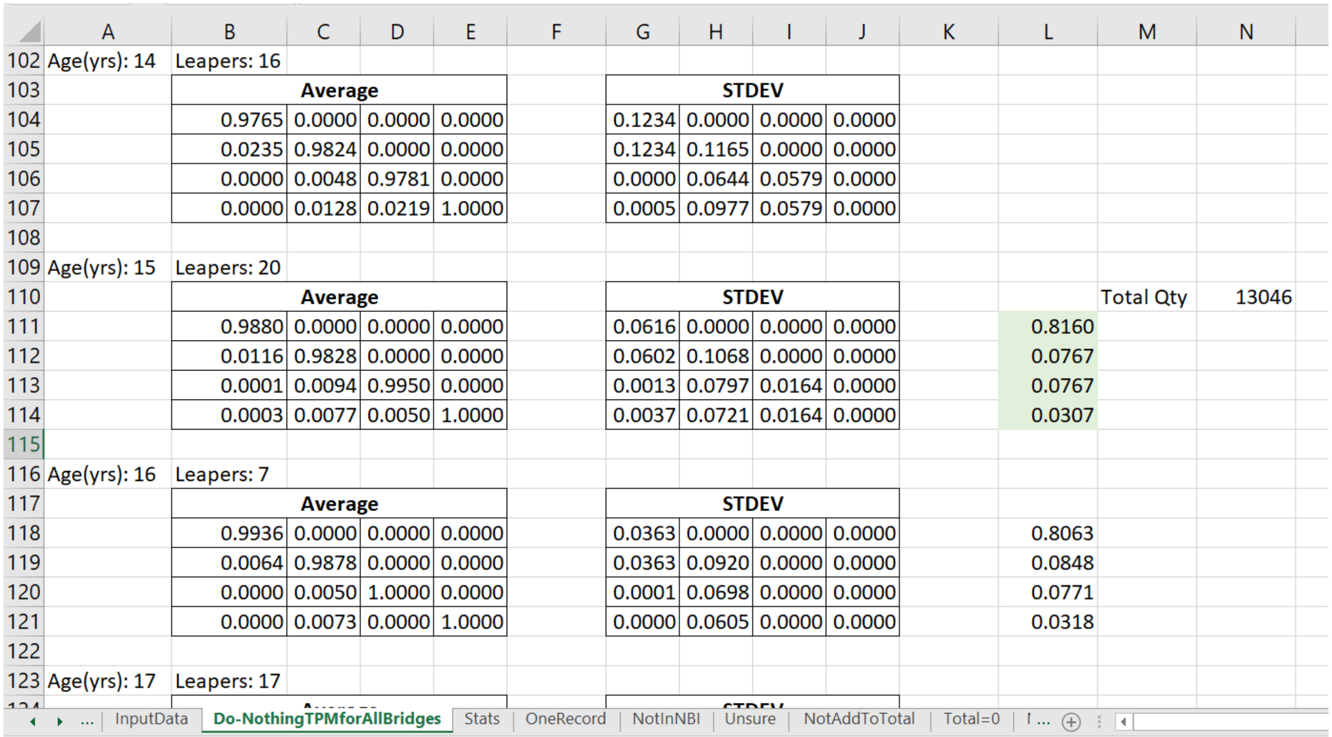
Another example with a worse starting condition probability distribution $\mathbf{q}^{15}$ at 15 years is selected, as seen in Figure 23. Its EN12 15-year condition probability distribution vector $\mathbf{q}^{15}$ is in Cells L103 to L106. These q_i values for i=1,2,3,4 are calculated using the quantities in Cells E7013 to H7013 of Figure 23 according to Equation 9. The resulting column vector is in Cells L111 to L114 in Figure 24, highlighted light green. The computation according to Equation 80 for forecasting is displayed in Figures 24 and 25 to the ages of 35 and 36 years. Linear interpolation for q_4=15% gives the end of expected service life at 35.6 years. Thus, the expected remaining service life is 35.6 − 15 = 20.6 years.

These two examples of individual bridge's RC decks also highlight the statistical scatter for the end of the expected service life. This needs to be accounted for when forecasting and bridge management decision-making.



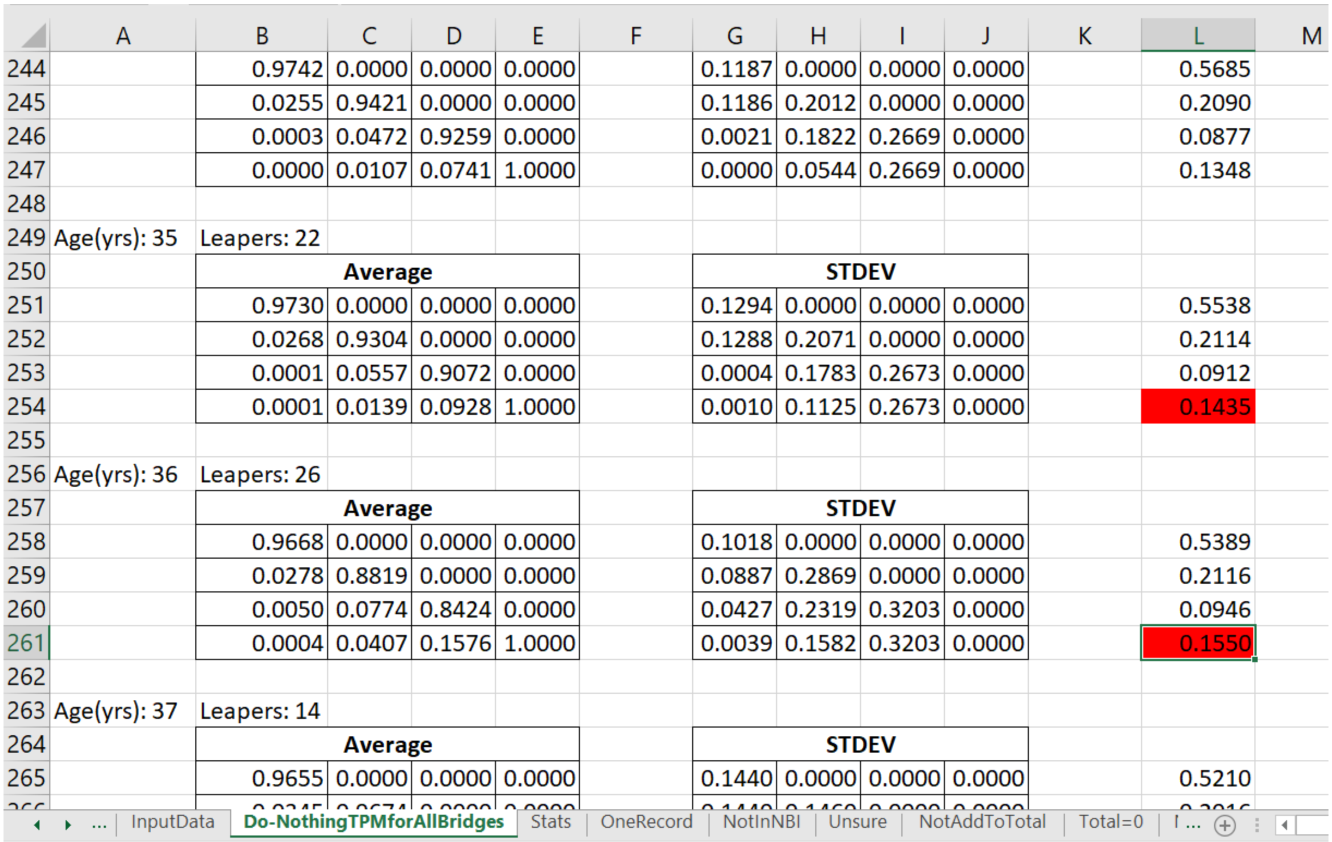
	A	B	C	D	E	F	G	H	I	J
7007	15	320008	2/18/2010	1/14/2011	4218	5800	0	100	4218	5800
7008	15	320090	1/12/2009	2/15/2011	7300	120	0	0	7300	120
7009	15	320093	2/2/2012	1/28/2013	10517	240	0	0	10517	240
7010	15	320095	1/26/2012	1/17/2013	17112	200	0	0	17112	200
7011	15	320101	2/23/2018	3/26/2019	3263	4000	0	0	3263	4000
7012	15	320102	2/21/2018	2/11/2020	11150	2690	0	0	11150	2640
7013	15	320104	2/8/2018	3/26/2019	10646	1000	1000	400	10646	1000
7014	15	330046	7/30/2012	7/13/2016	5248	0	0	0	5248	0
7015	15	330047	3/20/2012	3/5/2014	4319	74	0	0	4319	74
7016	15	340057	3/11/1996	2/27/1998	2451	0	0	0	2451	0
7017	15	340502	2/16/2016	2/14/2018	1744	82	0	0	1744	82
7018	15	360010	11/30/1998	11/28/2000	2754	0	0	0	2754	0
7019	15	360022	11/20/2006	11/18/2008	2517	1000	0	0	2517	1000
7020	15	360041	11/17/2003	11/5/2007	3146	0	0	0	3146	0
7021	15	370022	9/18/2007	9/11/2009	48175	0	0	5000	46975	1200
7022	15	370024	1/20/2006	5/2/2007	6421	0	0	0	6421	0
7023	15	370033	8/8/2018	8/11/2020	4640	130	0	0	4640	130
7024	15	370034	8/8/2018	8/11/2020	5634	425	0	0	5634	425
7025	15	370066	10/23/2007	10/3/2011	3597	0	0	0	3597	0
7026	15	370147	2/17/2010	2/11/2014	1925	0	0	0	1911	14

Figure 23. Screenshot. Another bridge with EN12 in service at age of 15 years.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
102	Age(yrs): 14	Leapers: 16												
103		Average					STDEV							
104		0.9765	0.0000	0.0000	0.0000		0.1234	0.0000	0.0000	0.0000				
105		0.0235	0.9824	0.0000	0.0000		0.1234	0.1165	0.0000	0.0000				
106		0.0000	0.0048	0.9781	0.0000		0.0000	0.0644	0.0579	0.0000				
107		0.0000	0.0128	0.0219	1.0000		0.0005	0.0977	0.0579	0.0000				
108														
109	Age(yrs): 15	Leapers: 20												
110		Average					STDEV						Total Qty	13046
111		0.9880	0.0000	0.0000	0.0000		0.0616	0.0000	0.0000	0.0000		0.8160		
112		0.0116	0.9828	0.0000	0.0000		0.0602	0.1068	0.0000	0.0000		0.0767		
113		0.0001	0.0094	0.9950	0.0000		0.0013	0.0797	0.0164	0.0000		0.0767		
114		0.0003	0.0077	0.0050	1.0000		0.0037	0.0721	0.0164	0.0000		0.0307		
115														
116	Age(yrs): 16	Leapers: 7												
117		Average					STDEV							
118		0.9936	0.0000	0.0000	0.0000		0.0363	0.0000	0.0000	0.0000		0.8063		
119		0.0064	0.9878	0.0000	0.0000		0.0363	0.0920	0.0000	0.0000		0.0848		
120		0.0000	0.0050	1.0000	0.0000		0.0001	0.0698	0.0000	0.0000		0.0771		
121		0.0000	0.0073	0.0000	1.0000		0.0000	0.0605	0.0000	0.0000		0.0318		
122														
123	Age(yrs): 17	Leapers: 17												

Figure 24. Screenshot. Forecasting remaining life initiated for example bridge in Figure 23 at age of 15 years.



	A	B	C	D	E	F	G	H	I	J	K	L	M
244		0.9742	0.0000	0.0000	0.0000		0.1187	0.0000	0.0000	0.0000		0.5685	
245		0.0255	0.9421	0.0000	0.0000		0.1186	0.2012	0.0000	0.0000		0.2090	
246		0.0003	0.0472	0.9259	0.0000		0.0021	0.1822	0.2669	0.0000		0.0877	
247		0.0000	0.0107	0.0741	1.0000		0.0000	0.0544	0.2669	0.0000		0.1348	
248													
249	Age(yrs): 35	Leapers: 22											
250		**Average**					**STDEV**						
251		0.9730	0.0000	0.0000	0.0000		0.1294	0.0000	0.0000	0.0000		0.5538	
252		0.0268	0.9304	0.0000	0.0000		0.1288	0.2071	0.0000	0.0000		0.2114	
253		0.0001	0.0557	0.9072	0.0000		0.0004	0.1783	0.2673	0.0000		0.0912	
254		0.0001	0.0139	0.0928	1.0000		0.0010	0.1125	0.2673	0.0000		0.1435	
255													
256	Age(yrs): 36	Leapers: 26											
257		**Average**					**STDEV**						
258		0.9668	0.0000	0.0000	0.0000		0.1018	0.0000	0.0000	0.0000		0.5389	
259		0.0278	0.8819	0.0000	0.0000		0.0887	0.2869	0.0000	0.0000		0.2116	
260		0.0050	0.0774	0.8424	0.0000		0.0427	0.2319	0.3203	0.0000		0.0946	
261		0.0004	0.0407	0.1576	1.0000		0.0039	0.1582	0.3203	0.0000		0.1550	
262													
263	Age(yrs): 37	Leapers: 14											
264		**Average**					**STDEV**						
265		0.9655	0.0000	0.0000	0.0000		0.1440	0.0000	0.0000	0.0000		0.5210	

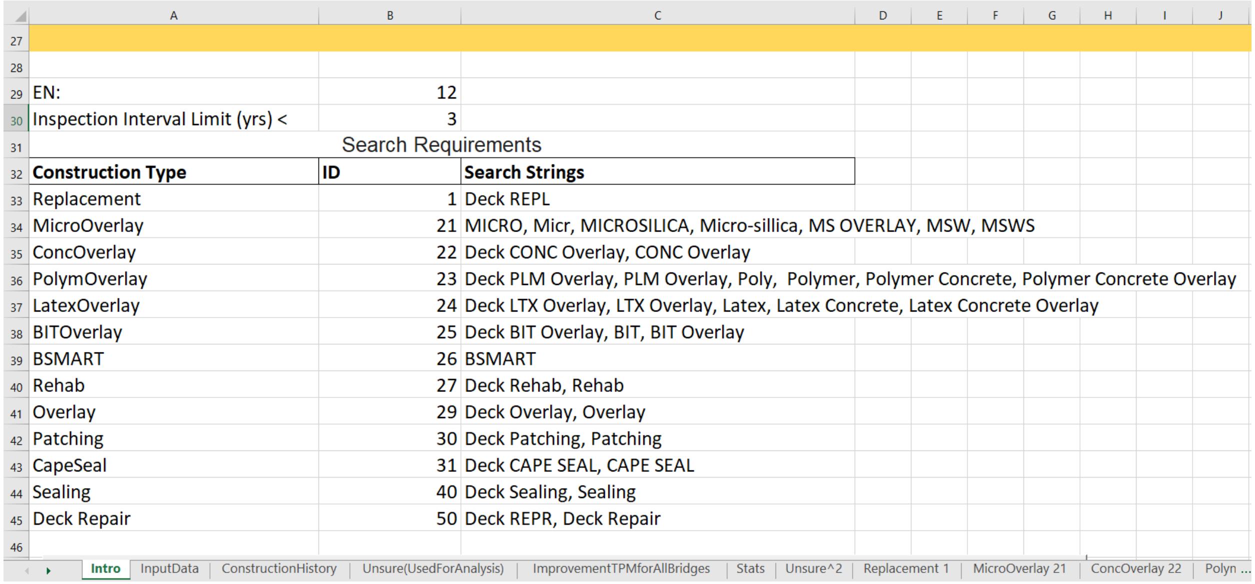
Figure 25. Screenshot. Forecasted end of expected service life identified between 35 and 36 years for bridge in Figure 23.

Condition Improvement TPM for EN12 Using Elevatio

Figure 26 displays Elevatio's front "Intro" sheet for an example of EN=12. This sheet provides the scope of how the search and match between the two major datasets is organized, with regard to how the types of construction work are grouped and then matched between the two datasets: the inspection records and the construction history. As discussed in Chapter 4, this example of grouping is not the only way to perform and find improvement TPM for EN12, but merely one of possibly many options for illustration.

Nevertheless, this particular choice of grouping in Figure 26 is possibly more detailed than many other options. For example, Construction Types 21, 22, 23, and 24 in Figure 26 may be combined into one type: concrete overlay. Type 29 Overlay may also be used to cover Types 21, 22, 23, 24, 25, and even some of Types 26 and 27 (BSMART and Rehab). Other minor work in Types 30, 40, and 50 may be combined as well into a new type, Maintenance, depending on the specific purpose of application at hand.

The present grouping for construction type may not be logical enough because different construction types appear to overlap. Nevertheless, this selection was made according to the remarks present in the IDOT construction history, which was not developed for the purposes here but is the only dataset available and useful for the research objective. The following analyses will further illustrate the advantages and disadvantages of this grouping to facilitate the user of Elevatio in designing his or her own application of the software program.



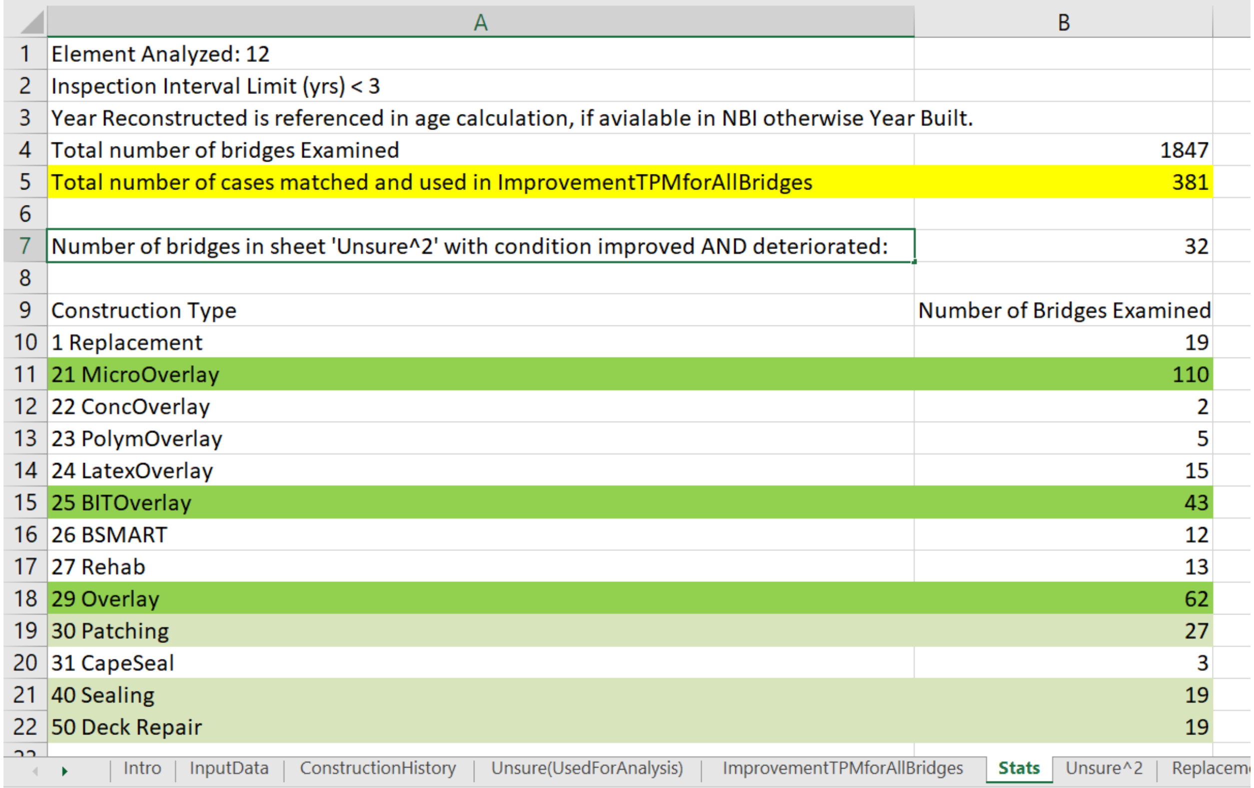
EN: 12

Inspection Interval Limit (yrs) < 3

Search Requirements

Construction Type	ID	Search Strings
Replacement	1	Deck REPL
MicroOverlay	21	MICRO, Micr, MICROSILICA, Micro-sillica, MS OVERLAY, MSW, MSWS
ConcOverlay	22	Deck CONC Overlay, CONC Overlay
PolymOverlay	23	Deck PLM Overlay, PLM Overlay, Poly, Polymer, Polymer Concrete, Polymer Concrete Overlay
LatexOverlay	24	Deck LTX Overlay, LTX Overlay, Latex, Latex Concrete, Latex Concrete Overlay
BITOverlay	25	Deck BIT Overlay, BIT, BIT Overlay
BSMART	26	BSMART
Rehab	27	Deck Rehab, Rehab
Overlay	29	Deck Overlay, Overlay
Patching	30	Deck Patching, Patching
CapeSeal	31	Deck CAPE SEAL, CAPE SEAL
Sealing	40	Deck Sealing, Sealing
Deck Repair	50	Deck REPR, Deck Repair

Figure 26. Screenshot. Causal construction types identified for example EN12 condition improvement TPM in Elevatio sheet "Intro."



Element Analyzed: 12

Inspection Interval Limit (yrs) < 3

Year Reconstructed is referenced in age calculation, if avialable in NBI otherwise Year Built.

Total number of bridges Examined	1847
Total number of cases matched and used in ImprovementTPMforAllBridges	381
Number of bridges in sheet 'Unsure^2' with condition improved AND deteriorated:	32

Construction Type	Number of Bridges Examined
1 Replacement	19
21 MicroOverlay	110
22 ConcOverlay	2
23 PolymOverlay	5
24 LatexOverlay	15
25 BITOverlay	43
26 BSMART	12
27 Rehab	13
29 Overlay	62
30 Patching	27
31 CapeSeal	3
40 Sealing	19
50 Deck Repair	19

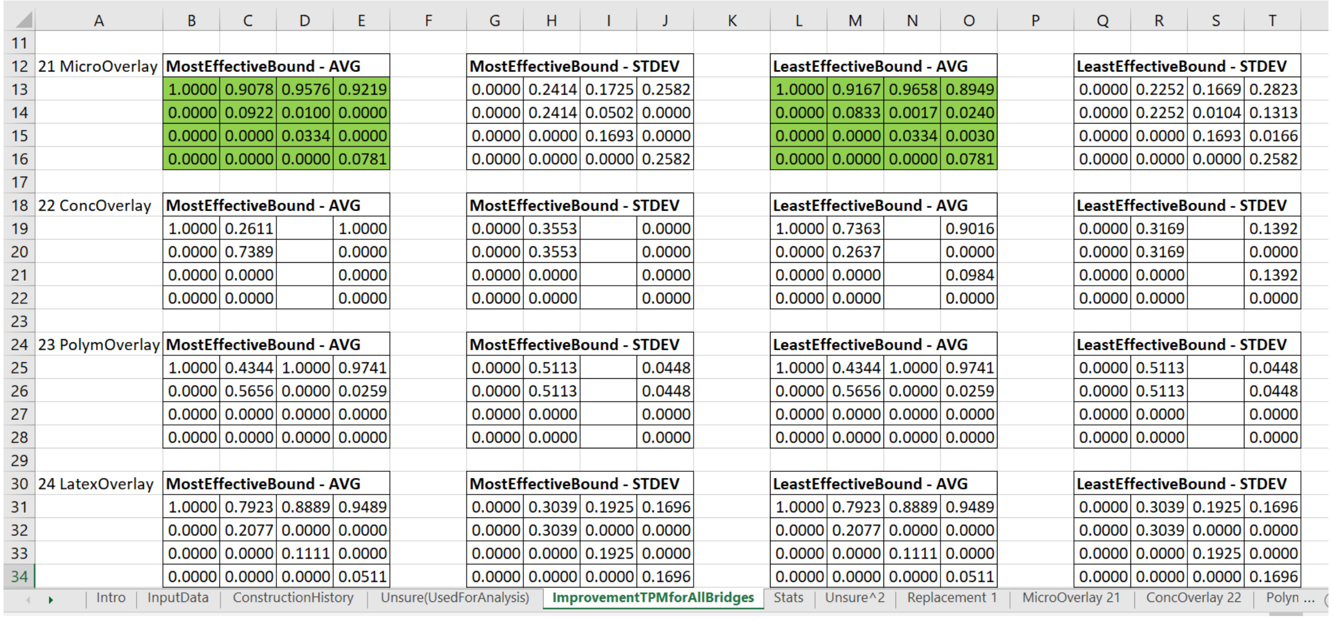
Figure 27. Screenshot. Overview of data utilization in Elevatio for example EN12 in Figure 26.

Figure 27 displays the numbers of bridges identified as matches between the construction history and condition improvement in the BrM element inspection records. The sheet named “Stats” in Elevatio contains important information for interpreting the TPM results provided in other sheets. It also pertains to the reliability of the Elevatio results with respect to how many data points were available and used, contributing to the final results as expected TPMs for the respective construction work.

A total of 1,847 bridges were identified as showing condition improvement (Figure 27) in EN12 and were used for the search and match. Of the 1,847 bridges, 381 were matched with construction work for relevant features with the focused element EN12 and the year of work was deemed to be related to the recorded condition improvement. Calculations were then performed for the TPMs for these bridges and inspection records regarding EN12 condition improvement. The TPMs for individual bridges were averaged within each construction type defined in Figure 26.

Figure 27 also identifies the numbers of the matched individual bridges for each construction type. In general, a large number of individual bridges in the type is expected to produce a higher reliability in the TPM for the construction type. Thus, these numbers can also be used to redesign grouping by redefining their scope in terms of search strings. For example, as stated above, Construction Types 21, 22, 23, and 24 may be combined into one type: ConcreteOverlay. This can mitigate the issue that the numbers of bridges in Types 22, 23, and 24 are relatively small compared with Type 21. In Figure 27, those construction types with relatively larger numbers of bridges found are highlighted green, and those in the next tier are highlighted light green. TPMs from those types with a relatively large population are considered more reliable.

A special case of construction type in Figure 27 is “Replacement 1.” Conceptually, the TPM for this construction type would not need calculation but expert elicitation, because replacement of the element is expected to change all quantities at CS2, CS3, and CS4 to CS1, and the CS1 quantity is expected to stay in CS1. With such a certain expectation, this group is used here merely for verification of the algorithm and programming. The TPM final results shown in Rows 6 to 10 of Figure 11 earlier for the Elevatio sheet “ImprovementTPMforAllBridges” states a successful validation, for both the algorithm and programming implementation. Figures 11 to 13 in Chapter 4 and their discussions presented more details on this subject of replacement as construction work for the same numerical example.

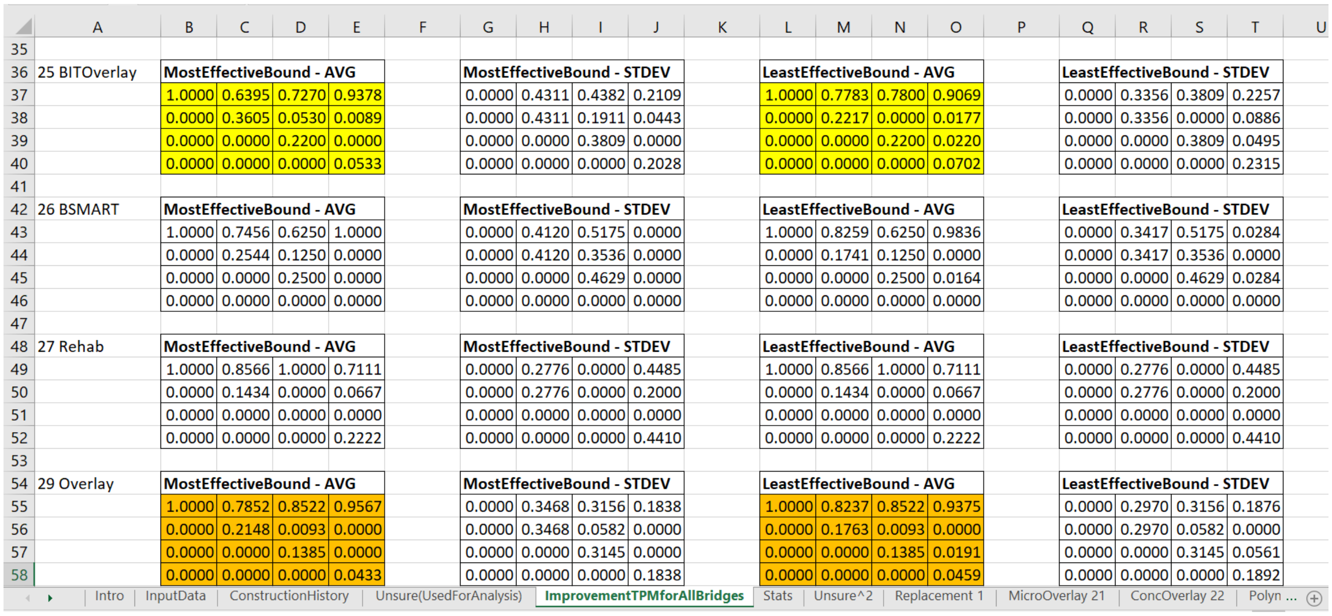


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
11																				
12	21 MicroOverlay	MostEffectiveBound - AVG					MostEffectiveBound - STDEV					LeastEffectiveBound - AVG					LeastEffectiveBound - STDEV			
13		1.0000	0.9078	0.9576	0.9219		0.0000	0.2414	0.1725	0.2582		1.0000	0.9167	0.9658	0.8949		0.0000	0.2252	0.1669	0.2823
14		0.0000	0.0922	0.0100	0.0000		0.0000	0.2414	0.0502	0.0000		0.0000	0.0833	0.0017	0.0240		0.0000	0.2252	0.0104	0.1313
15		0.0000	0.0000	0.0334	0.0000		0.0000	0.0000	0.1693	0.0000		0.0000	0.0000	0.0334	0.0030		0.0000	0.0000	0.1693	0.0166
16		0.0000	0.0000	0.0000	0.0781		0.0000	0.0000	0.0000	0.2582		0.0000	0.0000	0.0000	0.0781		0.0000	0.0000	0.0000	0.2582
17																				
18	22 ConcOverlay	MostEffectiveBound - AVG					MostEffectiveBound - STDEV					LeastEffectiveBound - AVG					LeastEffectiveBound - STDEV			
19		1.0000	0.2611		1.0000		0.0000	0.3553		0.0000		1.0000	0.7363		0.9016		0.0000	0.3169		0.1392
20		0.0000	0.7389		0.0000		0.0000	0.3553		0.0000		0.0000	0.2637		0.0000		0.0000	0.3169		0.0000
21		0.0000	0.0000		0.0000		0.0000	0.0000		0.0000		0.0000	0.0000		0.0984		0.0000	0.0000		0.1392
22		0.0000	0.0000		0.0000		0.0000	0.0000		0.0000		0.0000	0.0000		0.0000		0.0000	0.0000		0.0000
23																				
24	23 PolymOverlay	MostEffectiveBound - AVG					MostEffectiveBound - STDEV					LeastEffectiveBound - AVG					LeastEffectiveBound - STDEV			
25		1.0000	0.4344	1.0000	0.9741		0.0000	0.5113		0.0448		1.0000	0.4344	1.0000	0.9741		0.0000	0.5113		0.0448
26		0.0000	0.5656	0.0000	0.0259		0.0000	0.5113		0.0448		0.0000	0.5656	0.0000	0.0259		0.0000	0.5113		0.0448
27		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000		0.0000		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000		0.0000
28		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000		0.0000		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000		0.0000
29																				
30	24 LatexOverlay	MostEffectiveBound - AVG					MostEffectiveBound - STDEV					LeastEffectiveBound - AVG					LeastEffectiveBound - STDEV			
31		1.0000	0.7923	0.8889	0.9489		0.0000	0.3039	0.1925	0.1696		1.0000	0.7923	0.8889	0.9489		0.0000	0.3039	0.1925	0.1696
32		0.0000	0.2077	0.0000	0.0000		0.0000	0.3039	0.0000	0.0000		0.0000	0.2077	0.0000	0.0000		0.0000	0.3039	0.0000	0.0000
33		0.0000	0.0000	0.1111	0.0000		0.0000	0.0000	0.1925	0.0000		0.0000	0.0000	0.1111	0.0000		0.0000	0.0000	0.1925	0.0000
34		0.0000	0.0000	0.0000	0.0511		0.0000	0.0000	0.0000	0.1696		0.0000	0.0000	0.0000	0.0511		0.0000	0.0000	0.0000	0.1696

Figure 28. Screenshot. TPM results of construction types for example EN12 in Elevatio.

A comparison of TPM results for these different construction options is of interest to bridge management practice. The results are in the Elevatio "ImprovementTPMforAllBridges" sheet. Figure 28 shows TPMs of both bounds for Construction Types 21 to 24, MostEffectiveBound and LeastEffectiveBound in Columns B to E and Columns L to O, respectively, for their averaged TPMs. Next to these columns are the STDEV for the TPM values. The two bounds are very close to each other. Type 21 is highlighted in green in Figure 28, as also in Figure 27 for its large number of entries/bridges, compared with the other three construction types. The top row (Row 13) of the TPMs in Figure 28 for this construction type exhibits those transition probabilities to CS1 being all close to or higher than 90%, with some higher than 95%. These high values being close to 1, their possible maximum, highlight the effectiveness of the particular construction work, Micro-Silica Overlay, for RC deck.

The other overlay works in Construction Types 22, 23, and 24 are seen less effective in terms of the TPM values in the first row of the matrices. Note that these TPM values are based on relatively smaller populations of bridges, as discussed earlier for the "Stats" sheet in Figure 27. They are respectively 2, 5, and 15 bridges vs. 110 in Type 21. Among Types 22, 23, and 24, Type 24's (LatexOverlay) TPMs are most close to those for Type 21, suggesting it to be the next effective treatment for RC deck. Needless to say, Type 22 ConcOverlay must have overlaps with the other three concrete overlay types.

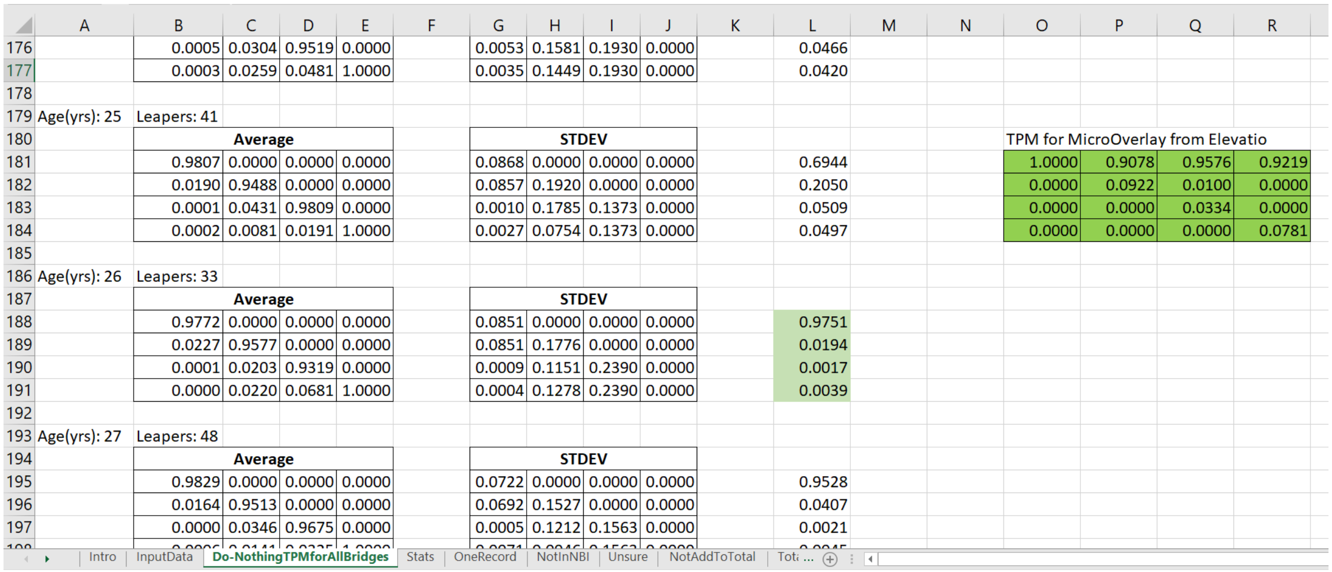


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
35																					
36	25 BITOverlay	**MostEffectiveBound - AVG**					**MostEffectiveBound - STDEV**					**LeastEffectiveBound - AVG**					**LeastEffectiveBound - STDEV**				
37		1.0000	0.6395	0.7270	0.9378		0.0000	0.4311	0.4382	0.2109		1.0000	0.7783	0.7800	0.9069		0.0000	0.3356	0.3809	0.2257	
38		0.0000	0.3605	0.0530	0.0089		0.0000	0.4311	0.1911	0.0443		0.0000	0.2217	0.0000	0.0177		0.0000	0.3356	0.0000	0.0886	
39		0.0000	0.0000	0.2200	0.0000		0.0000	0.0000	0.3809	0.0000		0.0000	0.0000	0.2200	0.0220		0.0000	0.0000	0.3809	0.0495	
40		0.0000	0.0000	0.0000	0.0533		0.0000	0.0000	0.0000	0.2028		0.0000	0.0000	0.0000	0.0702		0.0000	0.0000	0.0000	0.2315	
41																					
42	26 BSMART	**MostEffectiveBound - AVG**					**MostEffectiveBound - STDEV**					**LeastEffectiveBound - AVG**					**LeastEffectiveBound - STDEV**				
43		1.0000	0.7456	0.6250	1.0000		0.0000	0.4120	0.5175	0.0000		1.0000	0.8259	0.6250	0.9836		0.0000	0.3417	0.5175	0.0284	
44		0.0000	0.2544	0.1250	0.0000		0.0000	0.4120	0.3536	0.0000		0.0000	0.1741	0.1250	0.0000		0.0000	0.3417	0.3536	0.0000	
45		0.0000	0.0000	0.2500	0.0000		0.0000	0.0000	0.4629	0.0000		0.0000	0.0000	0.2500	0.0164		0.0000	0.0000	0.4629	0.0284	
46		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000	0.0000	0.0000	
47																					
48	27 Rehab	**MostEffectiveBound - AVG**					**MostEffectiveBound - STDEV**					**LeastEffectiveBound - AVG**					**LeastEffectiveBound - STDEV**				
49		1.0000	0.8566	1.0000	0.7111		0.0000	0.2776	0.0000	0.4485		1.0000	0.8566	1.0000	0.7111		0.0000	0.2776	0.0000	0.4485	
50		0.0000	0.1434	0.0000	0.0667		0.0000	0.2776	0.0000	0.2000		0.0000	0.1434	0.0000	0.0667		0.0000	0.2776	0.0000	0.2000	
51		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000	0.0000	0.0000	
52		0.0000	0.0000	0.0000	0.2222		0.0000	0.0000	0.0000	0.4410		0.0000	0.0000	0.0000	0.2222		0.0000	0.0000	0.0000	0.4410	
53																					
54	29 Overlay	**MostEffectiveBound - AVG**					**MostEffectiveBound - STDEV**					**LeastEffectiveBound - AVG**					**LeastEffectiveBound - STDEV**				
55		1.0000	0.7852	0.8522	0.9567		0.0000	0.3468	0.3156	0.1838		1.0000	0.8237	0.8522	0.9375		0.0000	0.2970	0.3156	0.1876	
56		0.0000	0.2148	0.0093	0.0000		0.0000	0.3468	0.0582	0.0000		0.0000	0.1763	0.0093	0.0000		0.0000	0.2970	0.0582	0.0000	
57		0.0000	0.0000	0.1385	0.0000		0.0000	0.0000	0.3145	0.0000		0.0000	0.0000	0.1385	0.0191		0.0000	0.0000	0.3145	0.0561	
58		0.0000	0.0000	0.0000	0.0433		0.0000	0.0000	0.0000	0.1838		0.0000	0.0000	0.0000	0.0459		0.0000	0.0000	0.0000	0.1892	

Figure 29. Screenshot. Comparison of TPMs for different construction options for EN12.

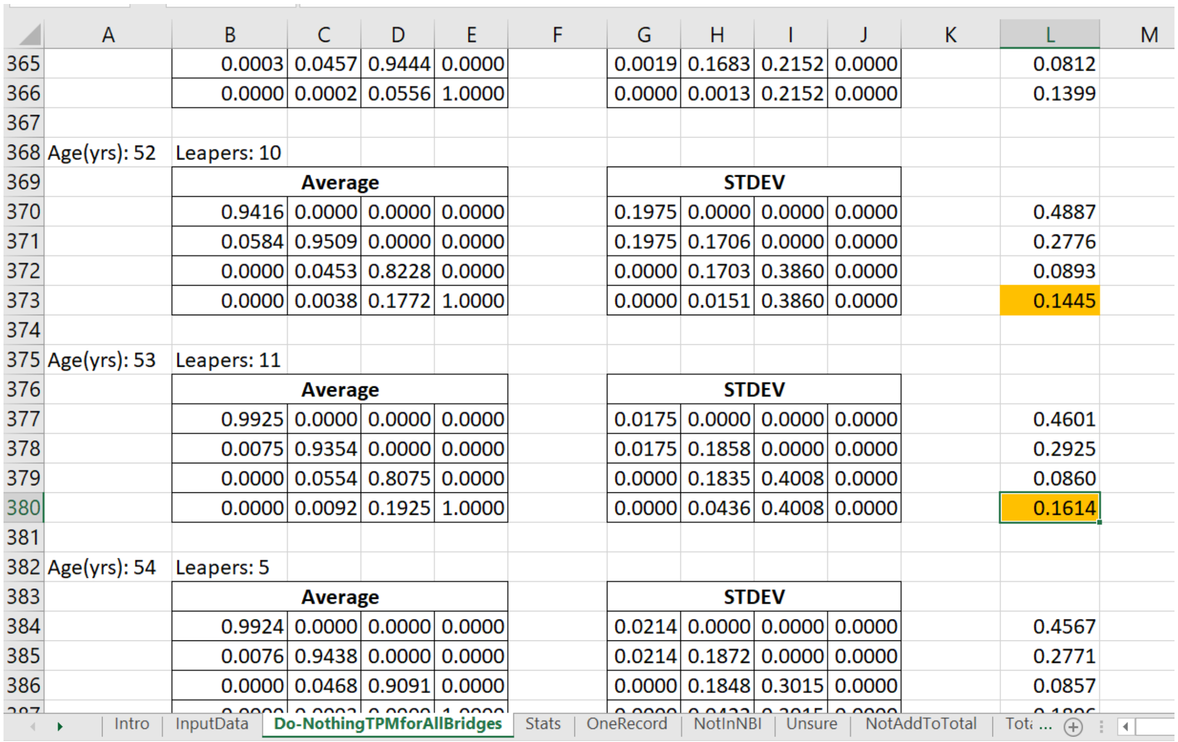
Figure 29 continues this comparison using BITOverlay. The TPM results from relatively more bridges contributing to them are highlighted, Types 25 BITOverlay (yellow) and 29 Overlay (orange). Type 29 may have overlaps with other construction types, such as Types 21 to 25, possibly 26 and 27 as well. In the IDOT construction history, "Overlay" is noted separately from other more specific overlays, such as Micro(-silica)Overlay, ConcOverlay, and PolymOverlay. The grouping here merely follows these remarks in ConstructionHistory for illustration purposes and is not claimed to be rational for other ENs or other bridge owners.

The values P_{12}, P_{13}, and P_{14} in the first row of TPMs in Figures 11 to 13 and 28 to 29 show that these construction options have accomplished condition improvement as intended. Besides replacement, Type 21's (Micro-Silica Overlay) TPMs show most effective than the other construction types, for their higher values of P_{12}, P_{13}, and P_{14} (with P_{11} always at 1 for all construction types and thus no need for comparison). While Type 21 includes more bridges (110) than the other types, Types 25 and 29 also have statistically significant entries of 43 and 62 bridges, respectively. Type 25 BITOverlay is seen noticeably less effective than Type 21 MicroOverlay by comparing the P_{12}, P_{13}, and P_{14} values of the two groups. This is not a surprise to many experienced bridge engineers, but demonstrating this well-known fact based on BrM quantity analysis developed and presented herein is certainly a plausible accomplishment. Therefore, this approach of BrM-data-based TPMs is quite effective and practical for forecasting and decision-making in bridge management.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
176		0.0005	0.0304	0.9519	0.0000		0.0053	0.1581	0.1930	0.0000		0.0466						
177		0.0003	0.0259	0.0481	1.0000		0.0035	0.1449	0.1930	0.0000		0.0420						
178																		
179	Age(yrs): 25	Leapers: 41																
180		Average					STDEV								TPM for MicroOverlay from Elevatio			
181		0.9807	0.0000	0.0000	0.0000		0.0868	0.0000	0.0000	0.0000		0.6944			1.0000	0.9078	0.9576	0.9219
182		0.0190	0.9488	0.0000	0.0000		0.0857	0.1920	0.0000	0.0000		0.2050			0.0000	0.0922	0.0100	0.0000
183		0.0001	0.0431	0.9809	0.0000		0.0010	0.1785	0.1373	0.0000		0.0509			0.0000	0.0000	0.0334	0.0000
184		0.0002	0.0081	0.0191	1.0000		0.0027	0.0754	0.1373	0.0000		0.0497			0.0000	0.0000	0.0000	0.0781
185																		
186	Age(yrs): 26	Leapers: 33																
187		Average					STDEV											
188		0.9772	0.0000	0.0000	0.0000		0.0851	0.0000	0.0000	0.0000		0.9751						
189		0.0227	0.9577	0.0000	0.0000		0.0851	0.1776	0.0000	0.0000		0.0194						
190		0.0001	0.0203	0.9319	0.0000		0.0009	0.1151	0.2390	0.0000		0.0017						
191		0.0000	0.0220	0.0681	1.0000		0.0004	0.1278	0.2390	0.0000		0.0039						
192																		
193	Age(yrs): 27	Leapers: 48																
194		Average					STDEV											
195		0.9829	0.0000	0.0000	0.0000		0.0722	0.0000	0.0000	0.0000		0.9528						
196		0.0164	0.9513	0.0000	0.0000		0.0692	0.1527	0.0000	0.0000		0.0407						
197		0.0000	0.0346	0.9675	0.0000		0.0005	0.1212	0.1563	0.0000		0.0021						

Figure 30. Screenshot. Modeling EN12 condition improvement by multiplying MicroOverlay’s TPM.



	A	B	C	D	E	F	G	H	I	J	K	L	M
365		0.0003	0.0457	0.9444	0.0000		0.0019	0.1683	0.2152	0.0000		0.0812	
366		0.0000	0.0002	0.0556	1.0000		0.0000	0.0013	0.2152	0.0000		0.1399	
367													
368	Age(yrs): 52	Leapers: 10											
369		Average					STDEV						
370		0.9416	0.0000	0.0000	0.0000		0.1975	0.0000	0.0000	0.0000		0.4887	
371		0.0584	0.9509	0.0000	0.0000		0.1975	0.1706	0.0000	0.0000		0.2776	
372		0.0000	0.0453	0.8228	0.0000		0.0000	0.1703	0.3860	0.0000		0.0893	
373		0.0000	0.0038	0.1772	1.0000		0.0000	0.0151	0.3860	0.0000		0.1445	
374													
375	Age(yrs): 53	Leapers: 11											
376		Average					STDEV						
377		0.9925	0.0000	0.0000	0.0000		0.0175	0.0000	0.0000	0.0000		0.4601	
378		0.0075	0.9354	0.0000	0.0000		0.0175	0.1858	0.0000	0.0000		0.2925	
379		0.0000	0.0554	0.8075	0.0000		0.0000	0.1835	0.4008	0.0000		0.0860	
380		0.0000	0.0092	0.1925	1.0000		0.0000	0.0436	0.4008	0.0000		0.1614	
381													
382	Age(yrs): 54	Leapers: 5											
383		Average					STDEV						
384		0.9924	0.0000	0.0000	0.0000		0.0214	0.0000	0.0000	0.0000		0.4567	
385		0.0076	0.9438	0.0000	0.0000		0.0214	0.1872	0.0000	0.0000		0.2771	
386		0.0000	0.0468	0.9091	0.0000		0.0000	0.1848	0.3015	0.0000		0.0857	

Figure 31. Screenshot. Forecasting EN12 expected service life resulting from MicroOverlay between 52 and 53 years.

Figures 30 and 31 show a forecasting exercise while including the effect of micro-silica overlay for RC decks of Illinois, based on the results above using Mansus and Elevatio. Figure 30 shows multiplication of the micro-silica overlay TPM (highlighted green and taken from Figure 11) with the condition probability distribution vector $\mathbf{q}^{25}$ of Illinois RC decks at the age of 25 years, according to

Equation 80 with $j = 25$. Mathematically, this replaces the TPM for do-nothing deterioration at the age of 25 years in forecasting the life span, as seen in Figure 30. This age of 25 years is selected because it is close to the average age when micro-silica overlay is applied, as recorded in the IDOT construction history and matched with condition improvement. As mentioned earlier, the sheet for this construction work "MicroOverlay 21" includes the ages of individual bridges that have experienced renewal work in Column O of Figures 11 to 13.

After the inspection at 25 years, where MicroOverlay TPM was multiplied, multiplication of do-nothing TPMs resumes, modeling deterioration restarting and continuing without further construction work. Figure 31 displays the last few multiplications reaching the targeted $q_4 = 15\%$ used by IDOT as the indication of an RC deck's end of expected service life.

Linear interpolation between the found 52 and 53 years from Figure 31 results in 52.3 years as the new expected life span if micro-silica overlay is applied at 25 years. An increase of expected life span of $52.3 - 36.8 = 15.5$ years is then concluded, from the expected life of 36.8 years in Figure 19 without renewal construction work. When associated costs are considered, this framework can be used to identify optimized strategies considering life cycle cost for maintenance, repair, and rehabilitation (MR&R) for all elements covered in the current BrM system.

When the health index and damage index presented in Chapter 3 are applied to this example, the condition improvement of this element can be readily presented and intuitively seen in a 2D graph in Figures 32 and 33 for comparison of do-nothing deterioration vs MicroOverlay at age of 25. The former exhibits the two indices as functions of age without renewal construction work and the latter with micro-silica overlay applied at 25 years, an effort of preservation or interference to do-nothing deterioration.

In Figure 32, the rate of deterioration increases with age at approximately 20 years. The rate of deterioration is expressed graphically as the slope of the health and damage indices. This is consistent with field observations of many experienced bridge engineers that an RC deck deteriorates faster with age under the condition of do-nothing deterioration. This rate change is also recognizable in Figure 33, except at the point when micro-silica concrete overlay is applied at an age of 25 years.

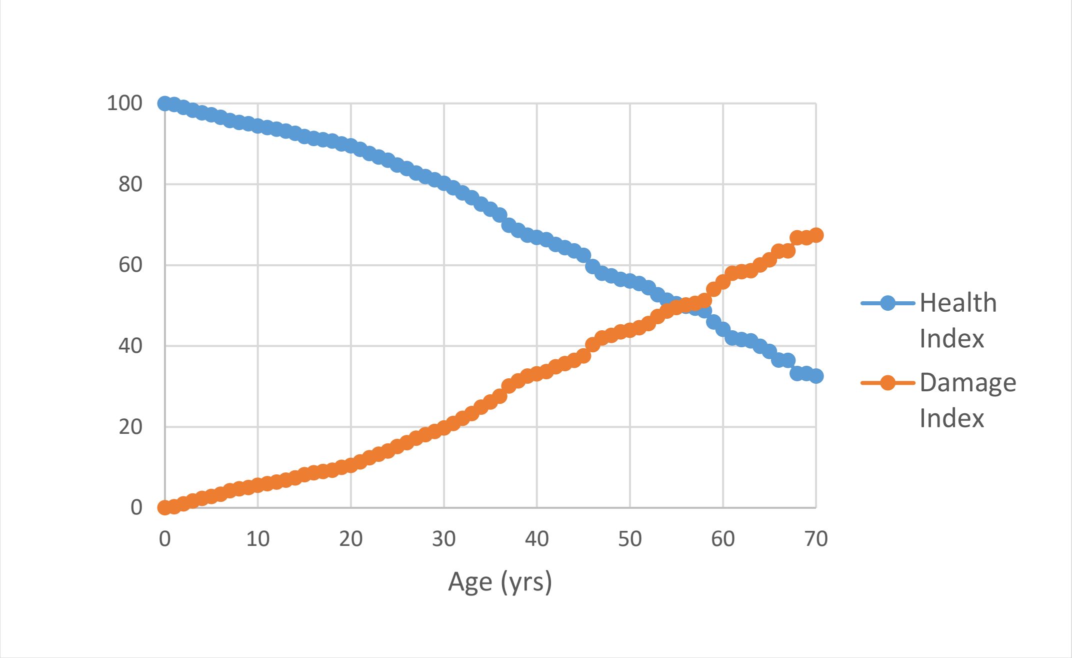


Figure 32. Chart. Health and damage indices for EN12 without construction work.

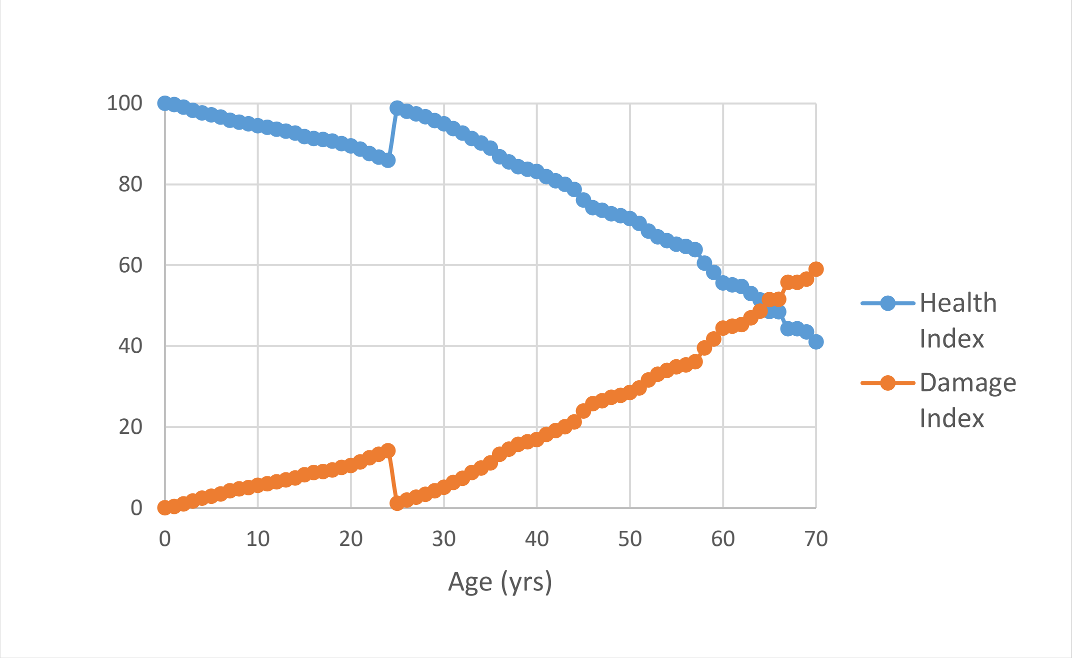
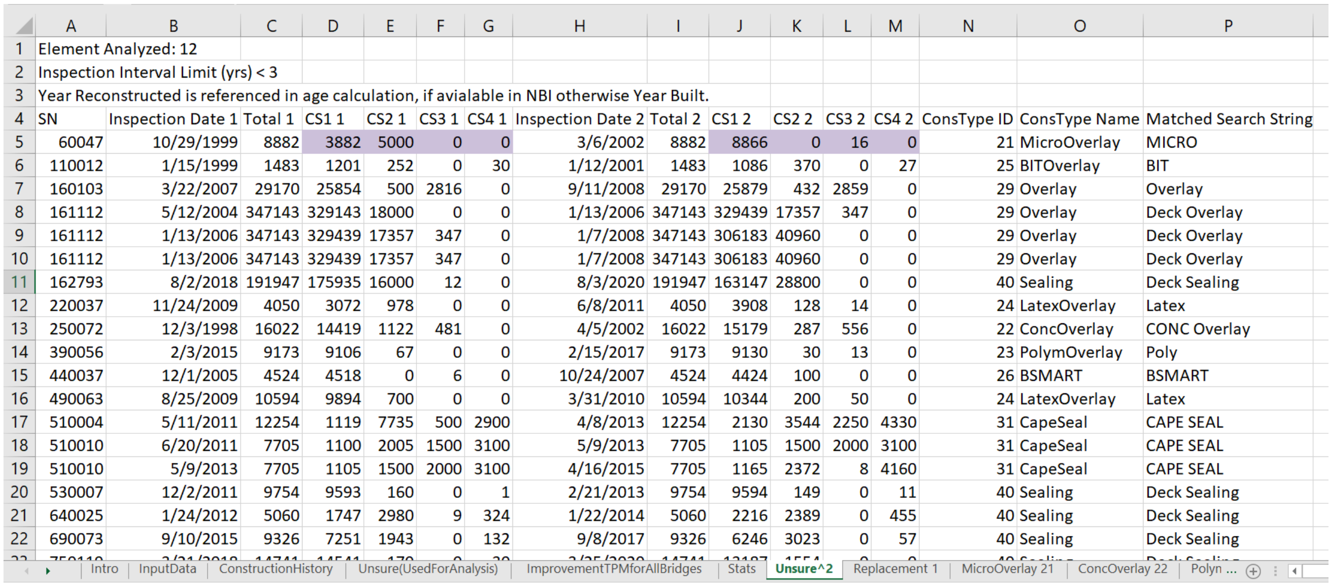


Figure 33. Chart. Health and damage indices for EN12 with MicroOverlay at age of 25 years.

Figure 34 displays the “Unsure^2” listing of excluded bridges due to further unsure features of both deterioration and improvement in condition. For this application example of EN12, the purple highlighted cells in Figure 34 contain a typical example for discussion. The bridge’s before and after quantities at the four CSs resulting from the two inspections are highlighted. As seen, its CS3 quantity increased from 0 sqft in 1999 to 16 sqft in 2002, indicating net deterioration in condition. However, the CS1 quantity also increased from 3,882 sqft in 1999 to 8,866 sqft in 2002, highlighting significant improvement in condition as well. This situation may be caused by a number of factors, or a combination thereof, as follows:

- One or both of the two inspection teams made a mistake or mistakes.
- Different condition state definitions were used in the two inspections by different teams/contractors.
- Inspection recording errors.
- Both improvement and deterioration took place within the interval of the two inspections.

Further examination of these records is worth pursuing by IDOT to make an appropriate decision as to how these Unsure^2 inspection records can be treated and used in TPM derivations. Such an effort could also help the bridge owner enhance the quality of inspection as well as bridge management practice.



Element Analyzed: 12
Inspection Interval Limit (yrs) < 3
Year Reconstructed is referenced in age calculation, if avialable in NBI otherwise Year Built.

SN	Inspection Date 1	Total 1	CS1 1	CS2 1	CS3 1	CS4 1	Inspection Date 2	Total 2	CS1 2	CS2 2	CS3 2	CS4 2	ConsType ID	ConsType Name	Matched Search String
60047	10/29/1999	8882	3882	5000	0	0	3/6/2002	8882	8866	0	16	0	21	MicroOverlay	MICRO
110012	1/15/1999	1483	1201	252	0	30	1/12/2001	1483	1086	370	0	27	25	BITOverlay	BIT
160103	3/22/2007	29170	25854	500	2816	0	9/11/2008	29170	25879	432	2859	0	29	Overlay	Overlay
161112	5/12/2004	347143	329143	18000	0	0	1/13/2006	347143	329439	17357	347	0	29	Overlay	Deck Overlay
161112	1/13/2006	347143	329439	17357	347	0	1/7/2008	347143	306183	40960	0	0	29	Overlay	Deck Overlay
161112	1/13/2006	347143	329439	17357	347	0	1/7/2008	347143	306183	40960	0	0	29	Overlay	Deck Overlay
162793	8/2/2018	191947	175935	16000	12	0	8/3/2020	191947	163147	28800	0	0	40	Sealing	Deck Sealing
220037	11/24/2009	4050	3072	978	0	0	6/8/2011	4050	3908	128	14	0	24	LatexOverlay	Latex
250072	12/3/1998	16022	14419	1122	481	0	4/5/2002	16022	15179	287	556	0	22	ConcOverlay	CONC Overlay
390056	2/3/2015	9173	9106	67	0	0	2/15/2017	9173	9130	30	13	0	23	PolymOverlay	Poly
440037	12/1/2005	4524	4518	0	6	0	10/24/2007	4524	4424	100	0	0	26	BSMART	BSMART
490063	8/25/2009	10594	9894	700	0	0	3/31/2010	10594	10344	200	50	0	24	LatexOverlay	Latex
510004	5/11/2011	12254	1119	7735	500	2900	4/8/2013	12254	2130	3544	2250	4330	31	CapeSeal	CAPE SEAL
510010	6/20/2011	7705	1100	2005	1500	3100	5/9/2013	7705	1105	1500	2000	3100	31	CapeSeal	CAPE SEAL
510010	5/9/2013	7705	1105	1500	2000	3100	4/16/2015	7705	1165	2372	8	4160	31	CapeSeal	CAPE SEAL
530007	12/2/2011	9754	9593	160	0	1	2/21/2013	9754	9594	149	0	11	40	Sealing	Deck Sealing
640025	1/24/2012	5060	1747	2980	9	324	1/22/2014	5060	2216	2389	0	455	40	Sealing	Deck Sealing
690073	9/10/2015	9326	7251	1943	0	132	9/8/2017	9326	6246	3023	0	57	40	Sealing	Deck Sealing

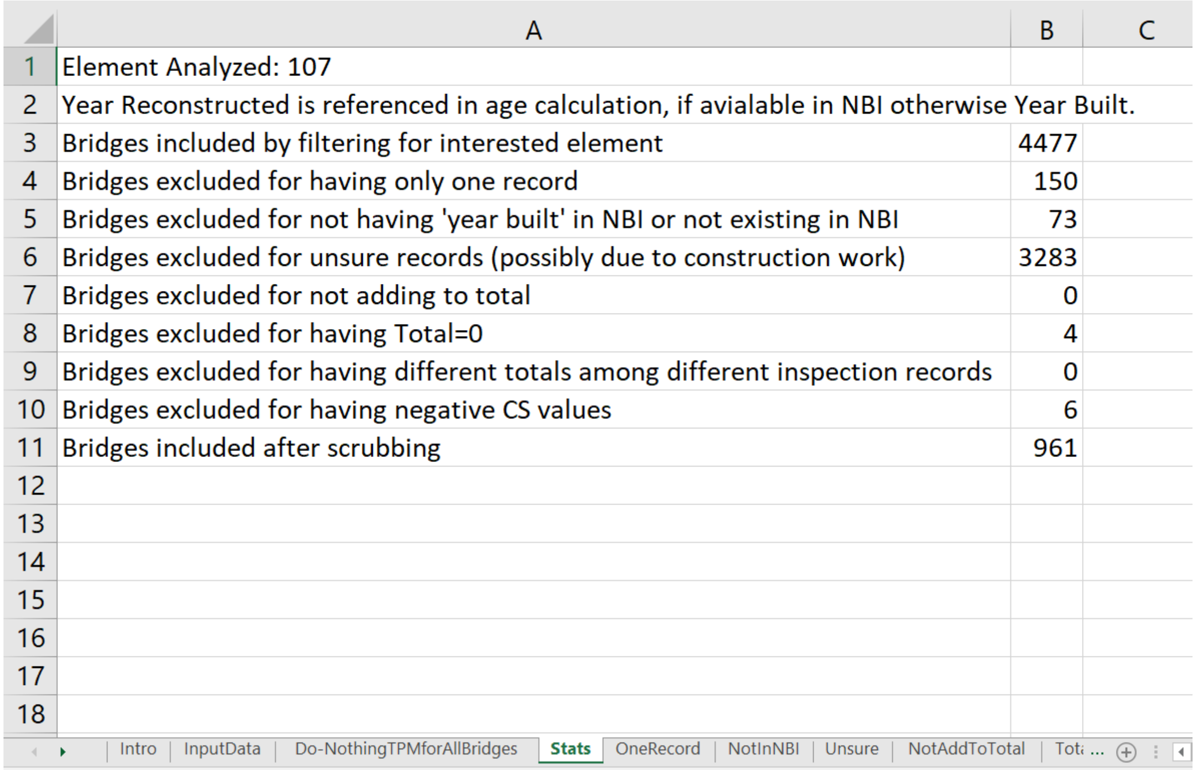
Figure 34. Screenshot. Elevatio sheet “Unsure^2” for bridges excluded from TPM calculation.

EXAMPLE 2: EN = 107 STEEL GIRDER BEAM

Steel girder beam is another popular superstructure element in Illinois and many other US states. As a result, more inspection records exist for steel girder beams than many other bridge elements in the Illinois BrM system. Hence, this element is used as an example application of the two software modules produced from this research project.

Do-Nothing Deterioration TPM for EN107 Using Mansus

Running Mansus for EN107 is the same as for EN12 except the step of input EN. Figure 35 presents the Mansus sheet “Stats” for EN107. As seen, a large number of bridges (3,283) are excluded from this calculation of do-nothing TPMs. The reasons for exclusion are also listed in Figure 35 corresponding to the exhibited numbers of bridges excluded. It is worth noting that each bridge contributes often much more than just one data point to the TPMs, because each bridge’s IDOT inspection records contain often tens of pairs of inspections. Each pair of records contributes an entry to the TPM of the age. As such, a bridge with *L* valid inspection records contributes *L*-1 pairs of inspection and, thus, *L*-1 data points for TPMs. For IDOT bridges, *L* is usually between 10 and 20 for EN12 and EN107.

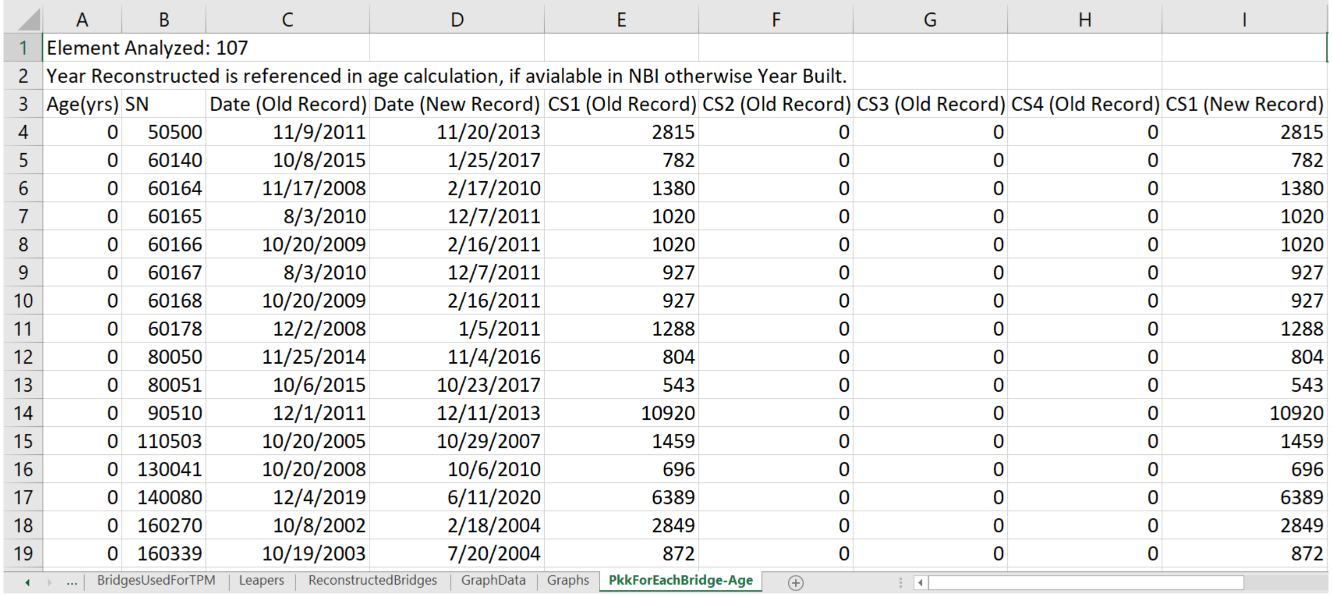


	A	B	C
1	Element Analyzed: 107		
2	Year Reconstructed is referenced in age calculation, if avialable in NBI otherwise Year Built.		
3	Bridges included by filtering for interested element	4477	
4	Bridges excluded for having only one record	150	
5	Bridges excluded for not having 'year built' in NBI or not existing in NBI	73	
6	Bridges excluded for unsure records (possibly due to construction work)	3283	
7	Bridges excluded for not adding to total	0	
8	Bridges excluded for having Total=0	4	
9	Bridges excluded for having different totals among different inspection records	0	
10	Bridges excluded for having negative CS values	6	
11	Bridges included after scrubbing	961	
12			
13			
14			
15			
16			
17			
18			

Figure 35. Screenshot. Data usage overview of Mansus calculation for EN107.

The Mansus sheet named “PkkForEachBridge-Age” in Figure 36 lists all bridges contributing valid inspection pairs to the values P_{kk} (k=1,2,3). P_{44} is not included here because it is always 1 for do-nothing deterioration, as the absorbing state of the four. The phrase “absorbing state” means a state that only receives quantities and never transitions out quantities. This is because there is no driving force for transitioning out any quantity to become better for do-nothing deterioration. The list in Figure 36 can also serve as a debugging tool to see all valid pairs of inspection records for each individual bridge, if the software user encounters any issue with the final results in the sheet “Do-NothingTPMforAllBridges.”

For each exclusion criterion in the "Stats" sheet in Figure 35, there is a corresponding sheet listing all bridges, with at least one inspection record pair meeting the criterion. This corresponding sheet's count is included in the sheet "Stats" in Figure 35. Note that only one such event of meeting the criterion is needed for the bridge to be excluded along with its entire inspection record history, because such a case of violation would cause the consequential calculation to stop or to produce erroneous results. As a result, some bridges in the earlier categories such as Rows 4 to 6 likely also meet the later criteria for exclusion. Figure 37 includes an example for this situation.

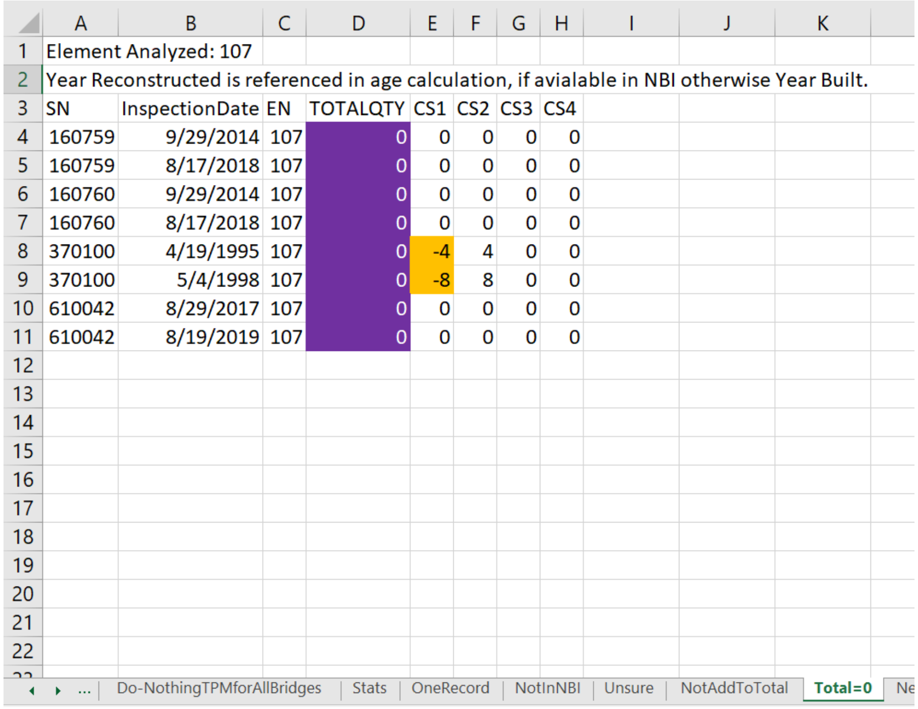


	A	B	C	D	E	F	G	H	I
1	Element Analyzed: 107								
2	Year Reconstructed is referenced in age calculation, if avialable in NBI otherwise Year Built.								
3	Age(yrs)	SN	Date (Old Record)	Date (New Record)	CS1 (Old Record)	CS2 (Old Record)	CS3 (Old Record)	CS4 (Old Record)	CS1 (New Record)
4	0	50500	11/9/2011	11/20/2013	2815	0	0	0	2815
5	0	60140	10/8/2015	1/25/2017	782	0	0	0	782
6	0	60164	11/17/2008	2/17/2010	1380	0	0	0	1380
7	0	60165	8/3/2010	12/7/2011	1020	0	0	0	1020
8	0	60166	10/20/2009	2/16/2011	1020	0	0	0	1020
9	0	60167	8/3/2010	12/7/2011	927	0	0	0	927
10	0	60168	10/20/2009	2/16/2011	927	0	0	0	927
11	0	60178	12/2/2008	1/5/2011	1288	0	0	0	1288
12	0	80050	11/25/2014	11/4/2016	804	0	0	0	804
13	0	80051	10/6/2015	10/23/2017	543	0	0	0	543
14	0	90510	12/1/2011	12/11/2013	10920	0	0	0	10920
15	0	110503	10/20/2005	10/29/2007	1459	0	0	0	1459
16	0	130041	10/20/2008	10/6/2010	696	0	0	0	696
17	0	140080	12/4/2019	6/11/2020	6389	0	0	0	6389
18	0	160270	10/8/2002	2/18/2004	2849	0	0	0	2849
19	0	160339	10/19/2003	7/20/2004	872	0	0	0	872

Figure 36. Screenshot. Intermediate results contributing to do-nothing TPM for EN107.

Figures 37 and 38 show examples of Mansus sheets for total quantity equal to 0 and negative CS quantity. The identified cases meeting the respective criteria are highlighted purple and orange, respectively. It is recommended that IDOT personnel re-examine these excluded records and correct them if warranted or delete the erroneous portions of the records. Such action could increase the usable data in the TPM calculation and, in turn, enhance the reliability of the results. For some ENs with smaller datasets, this can make a critical difference.

Figure 37 also shows that a bridge may have inspection records meeting more than one scrubbing criterion. These cases of SN=370100 are highlighted purple and orange, each color for a different criterion. When that happens, the bridge with all of its inspection records are excluded from further calculation and are listed in the first checked criterion's sheet in Figure 37. The counting in the "Stats" sheet is also not repeated for the later criterion because exclusion has taken place whenever the first criterion was met. Thus, the excluded bridge will not be subject to any further check for the later criteria. Figure 37 also shows the other three bridges highlighted purple for only one criterion (total=0) met.

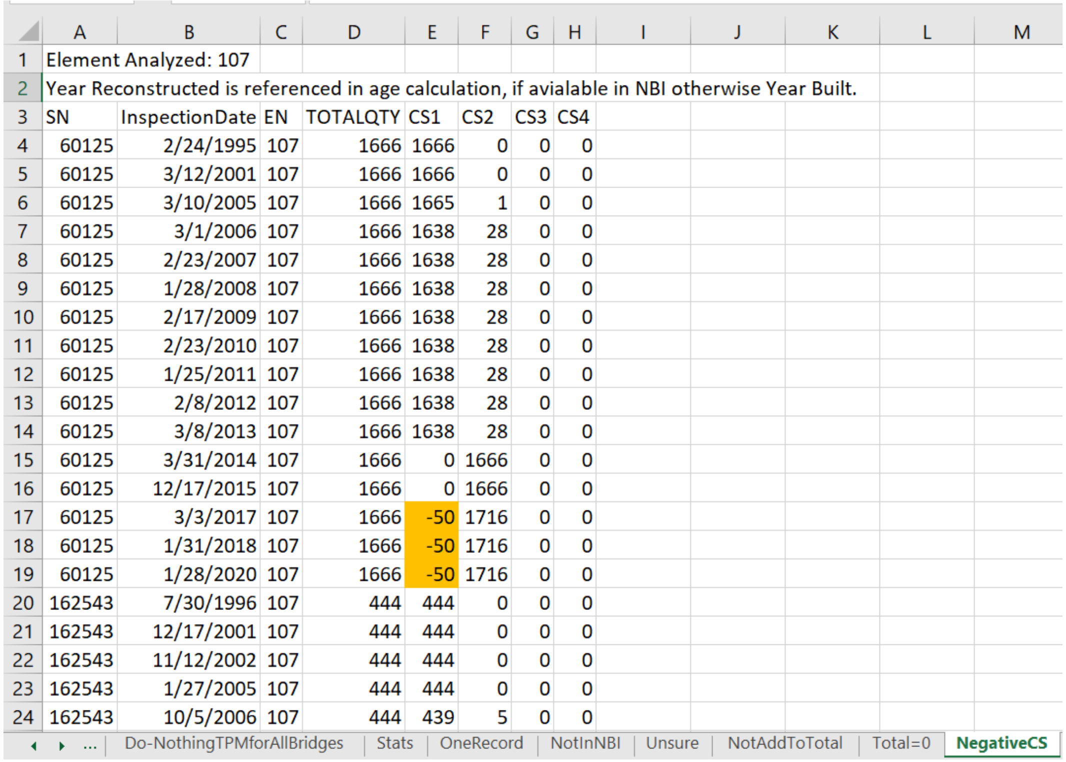


Element Analyzed: 107

Year Reconstructed is referenced in age calculation, if avialable in NBI otherwise Year Built.

SN	InspectionDate	EN	TOTALQTY	CS1	CS2	CS3	CS4
160759	9/29/2014	107	0	0	0	0	0
160759	8/17/2018	107	0	0	0	0	0
160760	9/29/2014	107	0	0	0	0	0
160760	8/17/2018	107	0	0	0	0	0
370100	4/19/1995	107	0	-4	4	0	0
370100	5/4/1998	107	0	-8	8	0	0
610042	8/29/2017	107	0	0	0	0	0
610042	8/19/2019	107	0	0	0	0	0

Figure 37. Screenshot. Four bridges with 0 total quantity and one with negative CS quantities in Mansus sheet "Total=0" for EN107.

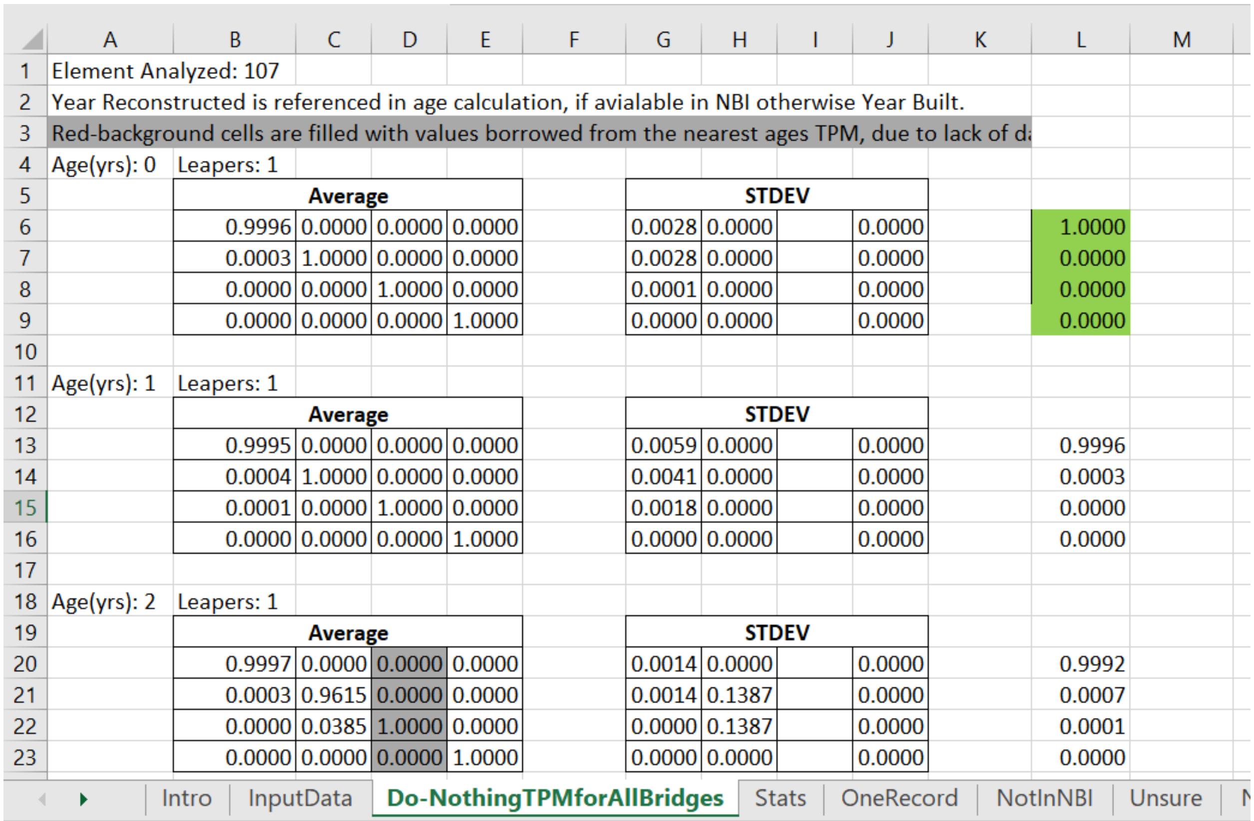


Element Analyzed: 107

Year Reconstructed is referenced in age calculation, if avialable in NBI otherwise Year Built.

SN	InspectionDate	EN	TOTALQTY	CS1	CS2	CS3	CS4
60125	2/24/1995	107	1666	1666	0	0	0
60125	3/12/2001	107	1666	1666	0	0	0
60125	3/10/2005	107	1666	1665	1	0	0
60125	3/1/2006	107	1666	1638	28	0	0
60125	2/23/2007	107	1666	1638	28	0	0
60125	1/28/2008	107	1666	1638	28	0	0
60125	2/17/2009	107	1666	1638	28	0	0
60125	2/23/2010	107	1666	1638	28	0	0
60125	1/25/2011	107	1666	1638	28	0	0
60125	2/8/2012	107	1666	1638	28	0	0
60125	3/8/2013	107	1666	1638	28	0	0
60125	3/31/2014	107	1666	0	1666	0	0
60125	12/17/2015	107	1666	0	1666	0	0
60125	3/3/2017	107	1666	-50	1716	0	0
60125	1/31/2018	107	1666	-50	1716	0	0
60125	1/28/2020	107	1666	-50	1716	0	0
162543	7/30/1996	107	444	444	0	0	0
162543	12/17/2001	107	444	444	0	0	0
162543	11/12/2002	107	444	444	0	0	0
162543	1/27/2005	107	444	444	0	0	0
162543	10/5/2006	107	444	439	5	0	0

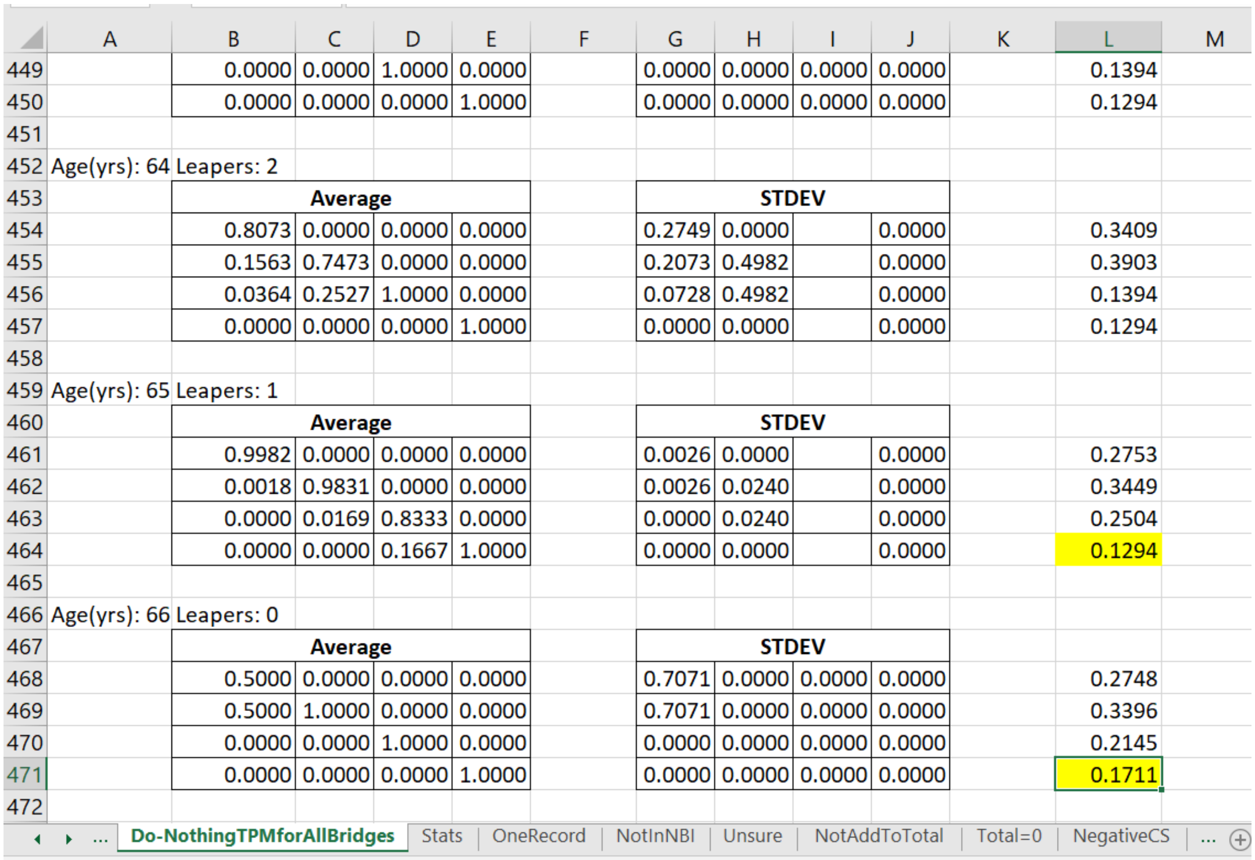
Figure 38. Screenshot. Bridges with negative quantities in Mansus Sheet "NegativeCS" for EN107.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Element Analyzed: 107												
2	Year Reconstructed is referenced in age calculation, if avialable in NBI otherwise Year Built.												
3	Red-background cells are filled with values borrowed from the nearest ages TPM, due to lack of d												
4	Age(yrs): 0	Leapers: 1											
5		Average					STDEV						
6		0.9996	0.0000	0.0000	0.0000		0.0028	0.0000		0.0000		1.0000	
7		0.0003	1.0000	0.0000	0.0000		0.0028	0.0000		0.0000		0.0000	
8		0.0000	0.0000	1.0000	0.0000		0.0001	0.0000		0.0000		0.0000	
9		0.0000	0.0000	0.0000	1.0000		0.0000	0.0000		0.0000		0.0000	
10													
11	Age(yrs): 1	Leapers: 1											
12		Average					STDEV						
13		0.9995	0.0000	0.0000	0.0000		0.0059	0.0000		0.0000		0.9996	
14		0.0004	1.0000	0.0000	0.0000		0.0041	0.0000		0.0000		0.0003	
15		0.0001	0.0000	1.0000	0.0000		0.0018	0.0000		0.0000		0.0000	
16		0.0000	0.0000	0.0000	1.0000		0.0000	0.0000		0.0000		0.0000	
17													
18	Age(yrs): 2	Leapers: 1											
19		Average					STDEV						
20		0.9997	0.0000	0.0000	0.0000		0.0014	0.0000		0.0000		0.9992	
21		0.0003	0.9615	0.0000	0.0000		0.0014	0.1387		0.0000		0.0007	
22		0.0000	0.0385	1.0000	0.0000		0.0000	0.1387		0.0000		0.0001	
23		0.0000	0.0000	0.0000	1.0000		0.0000	0.0000		0.0000		0.0000	

Figure 39. Screenshot. Modeling do-nothing deterioration by matrix multiplication of Equations 10 and 11 for EN107.

For application of the obtained TPMs to forecasting, Figure 39 shows a snapshot of the modeled process of do-nothing deterioration according to Equations 10 and 11. This modeled process starts at an intact condition $\mathbf{q}^0 = \{1,0,0,0\}^{t,0}$. It can also be viewed as a simulation of do-nothing deterioration, using the TPMs obtained based on the inspection records for the EN107 population of Illinois state bridges. When this process continues to the point when a threshold is reached for the end of the expected service life, the expected life span for the element is then established. If q_4=15% continues to be used here for this purpose, Figure 40 displays the conclusion of this modeling or simulation process between 65 and 66 years. Linear interpolation finds the expected life span at 65.5 years for EN107.

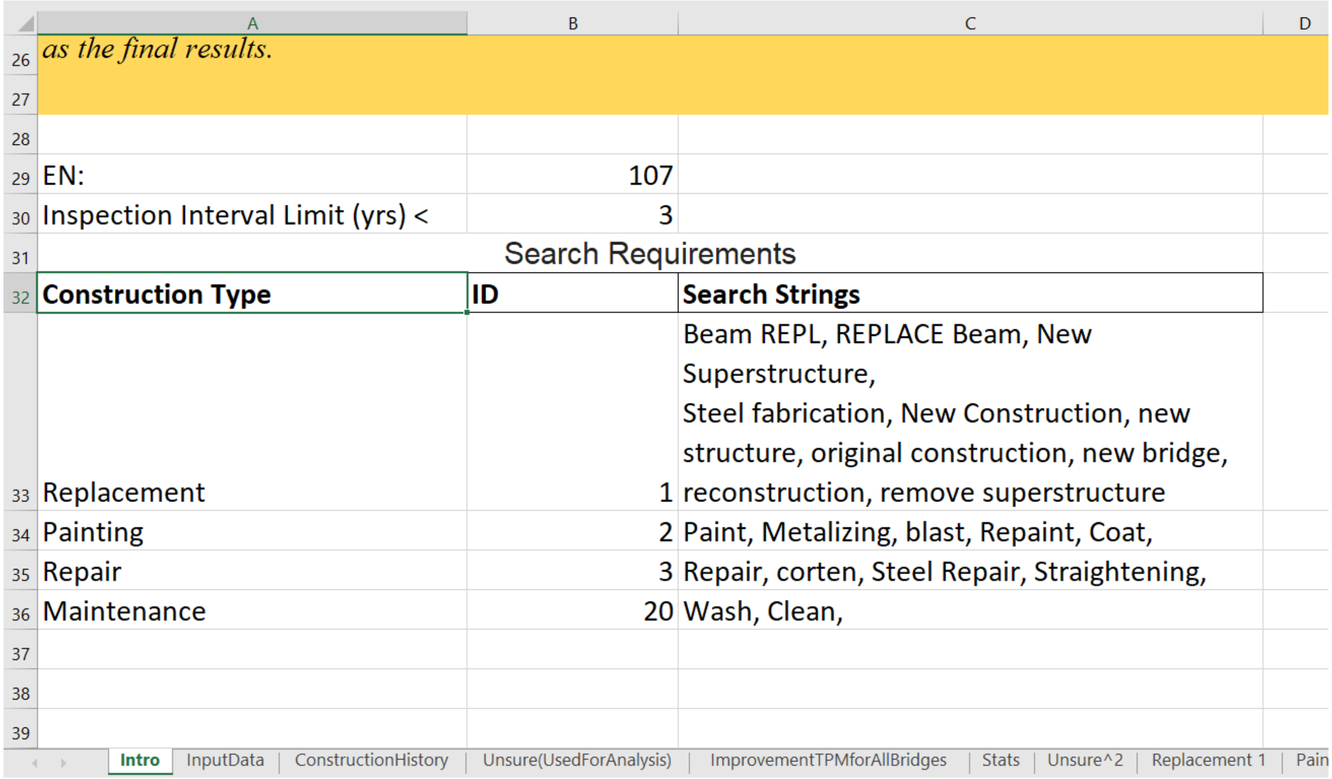


	A	B	C	D	E	F	G	H	I	J	K	L	M
449		0.0000	0.0000	1.0000	0.0000		0.0000	0.0000	0.0000	0.0000		0.1394	
450		0.0000	0.0000	0.0000	1.0000		0.0000	0.0000	0.0000	0.0000		0.1294	
451													
452	Age(yrs): 64 Leapers: 2												
453		Average					STDEV						
454		0.8073	0.0000	0.0000	0.0000		0.2749	0.0000		0.0000		0.3409	
455		0.1563	0.7473	0.0000	0.0000		0.2073	0.4982		0.0000		0.3903	
456		0.0364	0.2527	1.0000	0.0000		0.0728	0.4982		0.0000		0.1394	
457		0.0000	0.0000	0.0000	1.0000		0.0000	0.0000		0.0000		0.1294	
458													
459	Age(yrs): 65 Leapers: 1												
460		Average					STDEV						
461		0.9982	0.0000	0.0000	0.0000		0.0026	0.0000		0.0000		0.2753	
462		0.0018	0.9831	0.0000	0.0000		0.0026	0.0240		0.0000		0.3449	
463		0.0000	0.0169	0.8333	0.0000		0.0000	0.0240		0.0000		0.2504	
464		0.0000	0.0000	0.1667	1.0000		0.0000	0.0000		0.0000		0.1294	
465													
466	Age(yrs): 66 Leapers: 0												
467		Average					STDEV						
468		0.5000	0.0000	0.0000	0.0000		0.7071	0.0000	0.0000	0.0000		0.2748	
469		0.5000	1.0000	0.0000	0.0000		0.7071	0.0000	0.0000	0.0000		0.3396	
470		0.0000	0.0000	1.0000	0.0000		0.0000	0.0000	0.0000	0.0000		0.2145	
471		0.0000	0.0000	0.0000	1.0000		0.0000	0.0000	0.0000	0.0000		0.1711	
472													

Figure 40. Screenshot. Identification of expected service life end according to q_4=15% for EN107.

Condition Improvement TPM for EN107 Using Elevatio

Figure 41 shows the search and match parameter input sheet for the Elevatio application to EN107 improvement TPM calculation. Four construction types are selected for inclusion, although fewer or more may be used depending on the user intention or need. The four types here are replacement, painting, repair, and maintenance. Maintenance refers to minor correction work compared with the first three types of renewal efforts. As seen in Figure 41, Column C contains the search strings developed for the respective types of construction work. As discussed earlier, this parameter input went through a few rounds of trial and error to maximize the match results.



as the final results.

EN: 107

Inspection Interval Limit (yrs) < 3

Search Requirements

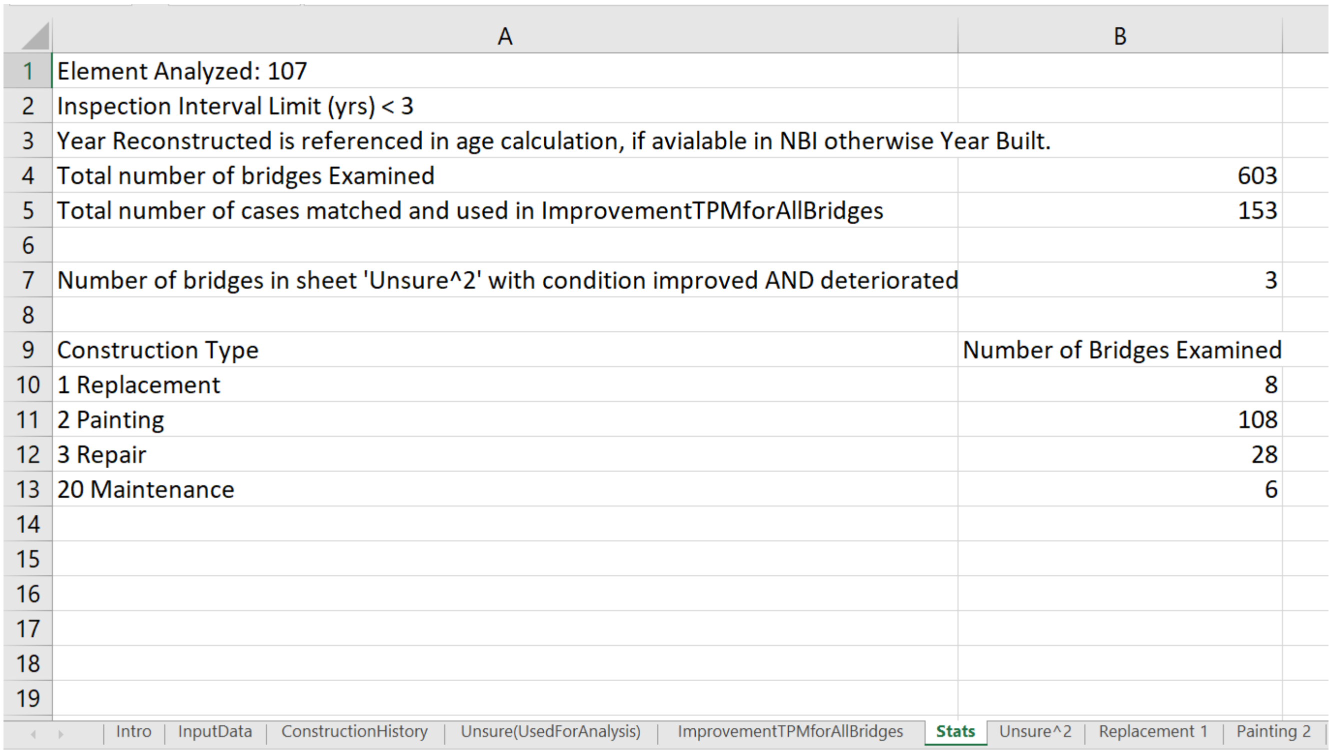
Construction Type	**ID**	**Search Strings**
Replacement	1	Beam REPL, REPLACE Beam, New Superstructure, Steel fabrication, New Construction, new structure, original construction, new bridge, reconstruction, remove superstructure
Painting	2	Paint, Metalizing, blast, Repaint, Coat,
Repair	3	Repair, corten, Steel Repair, Straightening,
Maintenance	20	Wash, Clean,

Figure 41. Screenshot. Causal construction types identified for EN107 improvement TPM in Elevatio sheet "Intro."

The research team established the listed search strings in Figure 41 based on experience as well as spotty manual checks of the "ConstructionHistory." Further expanding this list of search strings may result in more complete match results and further optimized TPM values for this EN and relevant construction work types.

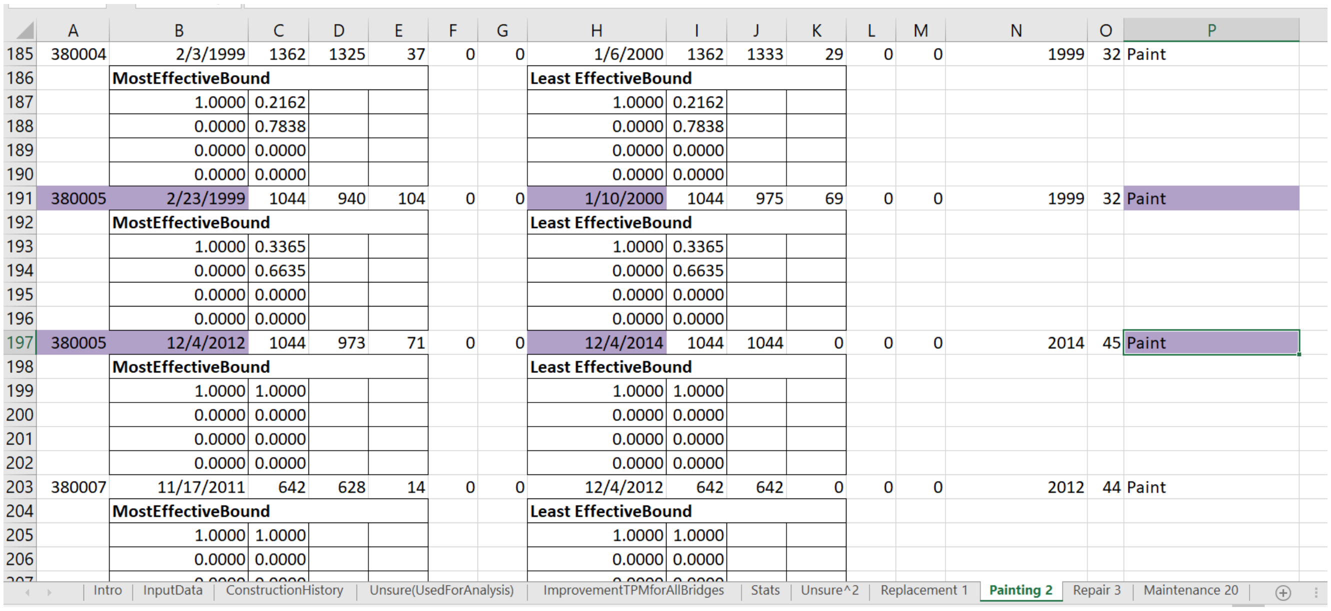
Figure 42 shows a summary of the search/match for this element, steel girder beam, in the population of Illinois state bridges. It took about 30 seconds on a 4 GHz/128 GB RAM computer to complete the calculations by Elevatio. A total of 603 bridges are filtered from those in the Mansus "Unsure" sheet, and then further scrubbing was applied to eliminate those that also meet another scrubbing criterion or criteria, as discussed in Chapter 4.

All bridges with their inspection record(s) matched with construction work are listed in the sheet "Unsure(UsedForTPM)." It is possible that a bridge contributes to the final TPM more than once because its inspection records were matched more than once with construction history data. Figure 43 for the sheet "Painting 2" shows such an example for SN=380005. Its EN107 was painted twice 13+ years apart, as recorded and shown in Figure 43. Apparently, less expensive work may be done more frequently, such as painting and cleaning. This kind of work then has more opportunities to have been recorded if construction / maintenance recording is exhaustive.



	A	B
1	Element Analyzed: 107	
2	Inspection Interval Limit (yrs) < 3	
3	Year Reconstructed is referenced in age calculation, if avialable in NBI otherwise Year Built.	
4	Total number of bridges Examined	603
5	Total number of cases matched and used in ImprovementTPMforAllBridges	153
6		
7	Number of bridges in sheet 'Unsure^2' with condition improved AND deteriorated	3
8		
9	Construction Type	Number of Bridges Examined
10	1 Replacement	8
11	2 Painting	108
12	3 Repair	28
13	20 Maintenance	6
14		
15		
16		
17		
18		
19		

Figure 42. Screenshot. Match result overview for EN107 in Elevatio sheet "Stats."



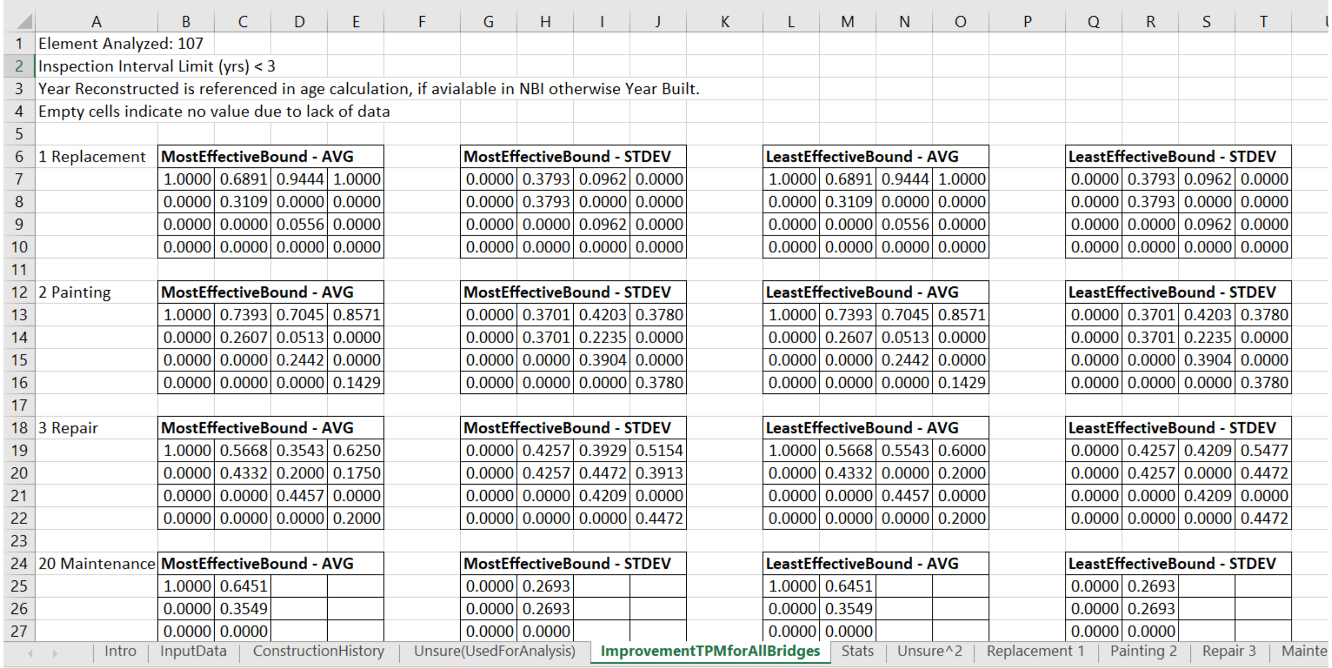
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
185	380004	2/3/1999	1362	1325	37	0	0	1/6/2000	1362	1333	29	0	0	1999	32	Paint
186		**MostEffectiveBound**						**Least EffectiveBound**								
187		1.0000	0.2162					1.0000	0.2162							
188		0.0000	0.7838					0.0000	0.7838							
189		0.0000	0.0000					0.0000	0.0000							
190		0.0000	0.0000					0.0000	0.0000							
191	380005	2/23/1999	1044	940	104	0	0	1/10/2000	1044	975	69	0	0	1999	32	Paint
192		**MostEffectiveBound**						**Least EffectiveBound**								
193		1.0000	0.3365					1.0000	0.3365							
194		0.0000	0.6635					0.0000	0.6635							
195		0.0000	0.0000					0.0000	0.0000							
196		0.0000	0.0000					0.0000	0.0000							
197	380005	12/4/2012	1044	973	71	0	0	12/4/2014	1044	1044	0	0	0	2014	45	Paint
198		**MostEffectiveBound**						**Least EffectiveBound**								
199		1.0000	1.0000					1.0000	1.0000							
200		0.0000	0.0000					0.0000	0.0000							
201		0.0000	0.0000					0.0000	0.0000							
202		0.0000	0.0000					0.0000	0.0000							
203	380007	11/17/2011	642	628	14	0	0	12/4/2012	642	642	0	0	0	2012	44	Paint
204		**MostEffectiveBound**						**Least EffectiveBound**								
205		1.0000	1.0000					1.0000	1.0000							
206		0.0000	0.0000					0.0000	0.0000							

Figure 43. Screenshot. Bridge identified for improved EN107 condition painted twice about 13 years apart.

Figure 42 shows that 153 − 3 (Row 5 minus Row 7) = 150 of the 603 bridges were matched with a record of renewal construction work deemed to be the cause of condition improvement. Three of the

603 bridges (in Row 7) are still unsure, showing both condition improvement and deterioration, and therefore were marked as unsure^2. This result could be due to the following causal factors:

1. Inspection error
2. Recording error
3. Occurrence of condition improvement and deterioration within the time interval between two inspections. This is possible when the renewal work is not significant and the inspection interval is relatively long.
4. A combination of the above factors.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Element Analyzed: 107																			
2	Inspection Interval Limit (yrs) < 3																			
3	Year Reconstructed is referenced in age calculation, if avialable in NBI otherwise Year Built.																			
4	Empty cells indicate no value due to lack of data																			
5																				
6	1 Replacement	**MostEffectiveBound - AVG**					**MostEffectiveBound - STDEV**					**LeastEffectiveBound - AVG**					**LeastEffectiveBound - STDEV**			
7		1.0000	0.6891	0.9444	1.0000		0.0000	0.3793	0.0962	0.0000		1.0000	0.6891	0.9444	1.0000		0.0000	0.3793	0.0962	0.0000
8		0.0000	0.3109	0.0000	0.0000		0.0000	0.3793	0.0000	0.0000		0.0000	0.3109	0.0000	0.0000		0.0000	0.3793	0.0000	0.0000
9		0.0000	0.0000	0.0556	0.0000		0.0000	0.0000	0.0962	0.0000		0.0000	0.0000	0.0556	0.0000		0.0000	0.0000	0.0962	0.0000
10		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000	0.0000	0.0000		0.0000	0.0000	0.0000	0.0000
11																				
12	2 Painting	**MostEffectiveBound - AVG**					**MostEffectiveBound - STDEV**					**LeastEffectiveBound - AVG**					**LeastEffectiveBound - STDEV**			
13		1.0000	0.7393	0.7045	0.8571		0.0000	0.3701	0.4203	0.3780		1.0000	0.7393	0.7045	0.8571		0.0000	0.3701	0.4203	0.3780
14		0.0000	0.2607	0.0513	0.0000		0.0000	0.3701	0.2235	0.0000		0.0000	0.2607	0.0513	0.0000		0.0000	0.3701	0.2235	0.0000
15		0.0000	0.0000	0.2442	0.0000		0.0000	0.0000	0.3904	0.0000		0.0000	0.0000	0.2442	0.0000		0.0000	0.0000	0.3904	0.0000
16		0.0000	0.0000	0.0000	0.1429		0.0000	0.0000	0.0000	0.3780		0.0000	0.0000	0.0000	0.1429		0.0000	0.0000	0.0000	0.3780
17																				
18	3 Repair	**MostEffectiveBound - AVG**					**MostEffectiveBound - STDEV**					**LeastEffectiveBound - AVG**					**LeastEffectiveBound - STDEV**			
19		1.0000	0.5668	0.3543	0.6250		0.0000	0.4257	0.3929	0.5154		1.0000	0.5668	0.5543	0.6000		0.0000	0.4257	0.4209	0.5477
20		0.0000	0.4332	0.2000	0.1750		0.0000	0.4257	0.4472	0.3913		0.0000	0.4332	0.0000	0.2000		0.0000	0.4257	0.0000	0.4472
21		0.0000	0.0000	0.4457	0.0000		0.0000	0.0000	0.4209	0.0000		0.0000	0.0000	0.4457	0.0000		0.0000	0.0000	0.4209	0.0000
22		0.0000	0.0000	0.0000	0.2000		0.0000	0.0000	0.0000	0.4472		0.0000	0.0000	0.0000	0.2000		0.0000	0.0000	0.0000	0.4472
23																				
24	20 Maintenance	**MostEffectiveBound - AVG**					**MostEffectiveBound - STDEV**					**LeastEffectiveBound - AVG**					**LeastEffectiveBound - STDEV**			
25		1.0000	0.6451				0.0000	0.2693				1.0000	0.6451				0.0000	0.2693		
26		0.0000	0.3549				0.0000	0.2693				0.0000	0.3549				0.0000	0.2693		
27		0.0000	0.0000				0.0000	0.0000				0.0000	0.0000				0.0000	0.0000		

Figure 44. Screenshot. Improvement TPMs of four construction options for EN107 in Elevatio.

Figure 44 displays the final result of TPM as the average of individual TPM values for the considered four treatments to steel girder beam EN107. Results for the two bounds are included in the Elevatio sheet "ImprovementTPMforAllBridges." Columns B to E are for the MostEffectiveBound, introduced in Chapter 3. Columns L to O are for the LeastEffectiveBound. Columns G to J and Q to T are their respective standard deviations to indicate variation from the averages.

Note that the two bounds are identical for this EN for these treatments, except a few terms in "3 Repair" in Rows 18 to 22. There are also empty cells for the Maintenance work in the listed TPM and STDEV values for transitions from CS3 and CS4, because there is not enough data available to compute them. If these values are ever needed for forecasting formulated in Equations 10 and 11, expert elicitation will be needed to fill these cells so that the matrix multiplication can proceed. Such elicitation has been made easier by some of the results here. For example, the P_{ij} values in TPM for maintenance may be extrapolated by referencing or considering those for repair. Nevertheless, these values are not expected to be critically needed for the physical condition prediction, because minor maintenance work is not likely to be expected or intended to meaningfully change the current condition of the element at CS3 or CS4. This is reflected by the fact that no data are available because such activity has not happened often.

Figure 44 also contrasts the effectiveness of these construction options represented by the resulting TPM for condition improvement. Focus on Columns B to E for this discussion, because Columns L to O for the LeastEffectiveBound are correspondingly identical or similar. Columns B to E for the TPMs appear to indicate the order of effectiveness from the top to bottom (i.e., from replacement to maintenance). This is seen by comparing the values in TPM in the first row, P_{11}, P_{12}, P_{13}, and P_{14}—the larger, the more effective of the work. The first row of TPM means physically the chance of the quantities at CS1 to CS4 to stay in or transition to CS1. The higher value (closer to 1) the better chance (i.e., the more effective).

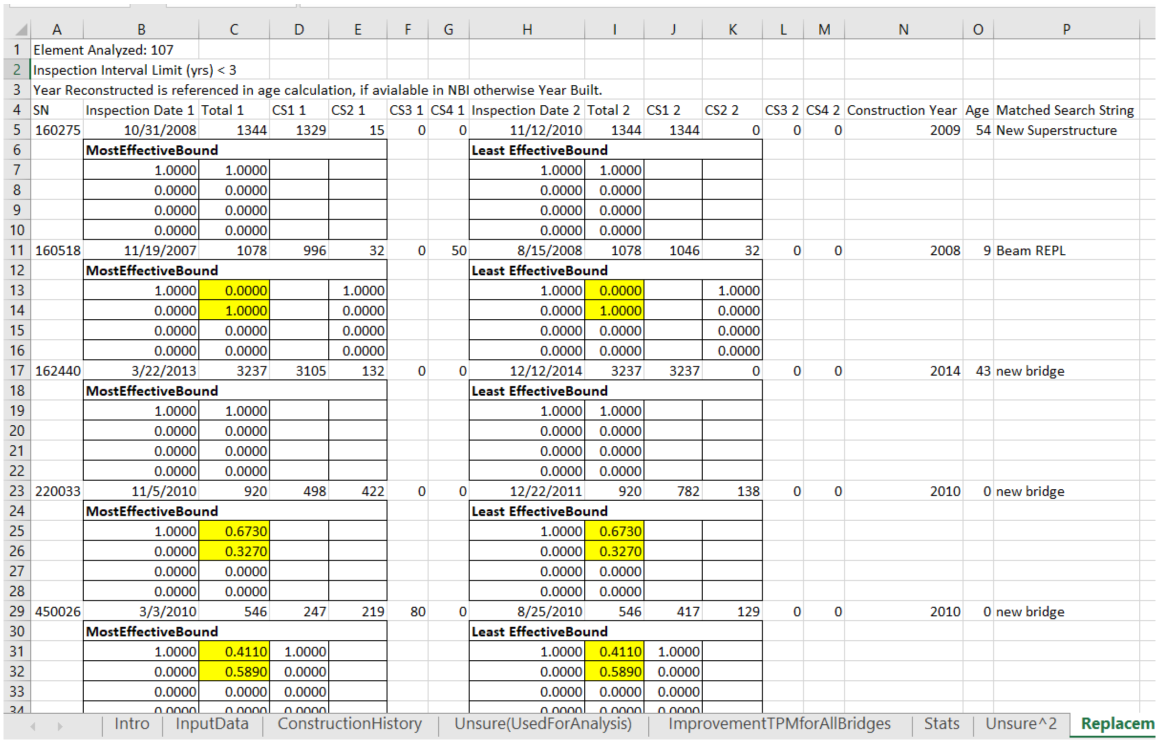
Figure 44 also demonstrates that the TPMs for replacement do not exhibit the expected effectiveness. The perfect or expected result would be 1 for all terms in the first row of the TPM. To further examine the causes of these imperfect TPM terms, the sheet “Replacement 1” for this particular construction type is available for investigation as follows.

Examination of the “Replacement 1” sheet indicates that four of the eight bridges contributing to the replacement TPM have P_{12} being an unexpected value. One of the four bridges in Figure 45-a gives 0, indicating no chance for the quantity at CS2 to transition to CS1, as highlighted yellow in cells C13 and I13 in Figure 45-a. Two other non-1 P_{12} are also highlighted yellow. It is recommended that IDOT personnel continue this investigation using more background information and data to determine the cause(s) of these inspection results as recorded. This investigative effort is expected to positively contribute to preventing such records in the future.

This situation has been discussed in detail for Figures 11, 13-a, and 13-b for EN12. The discussion is still applicable here. Further data or information than what has been used here will be needed to help identify the real causes. Such information may include, but is not limited to:

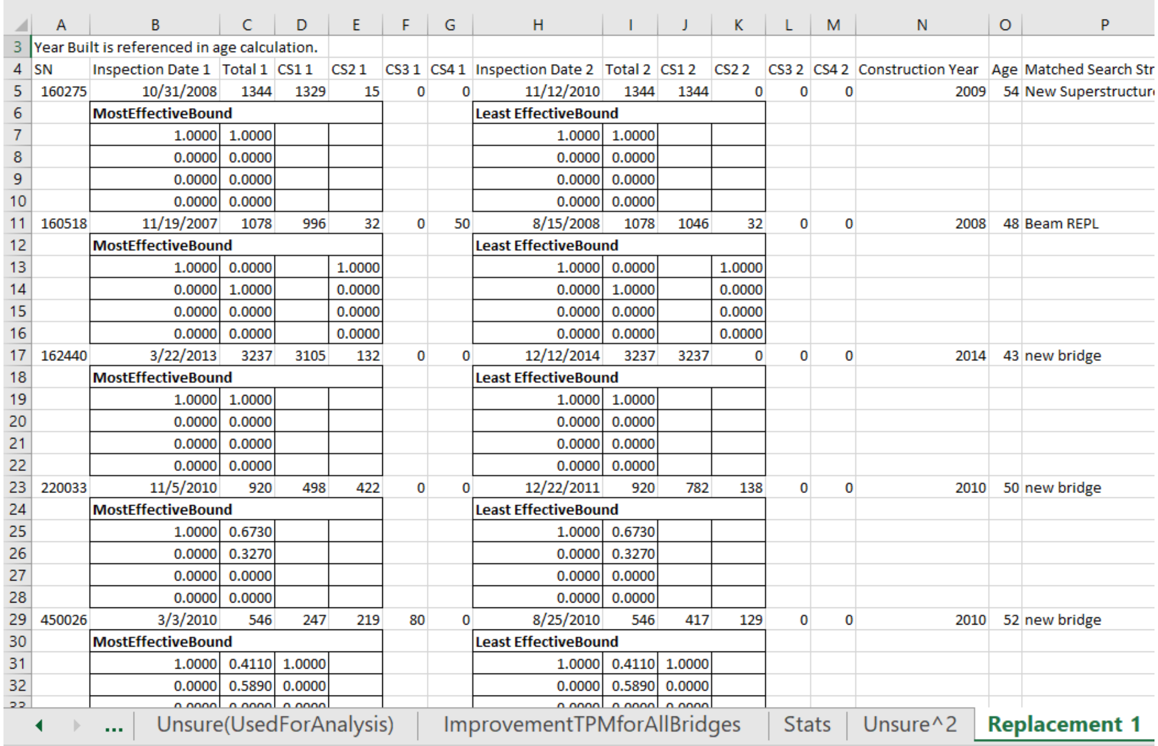
- The scope of construction work as possibly documented in the plans and construction logs.
- Records for how the planned scope was implemented.
- Qualifications of the inspection team and possibly its record of past performance.

Figure 45-a also shows some bridges’ EN107 was replaced at very early ages (for example, nine years in cell O11, 0 years in cells O23 and O29). They are obtained using Year Reconstructed in the NBI dataset, since the user input requested this approach. These values do not make sense, indicating that the earlier selection in parameter input was wrong. Elevatio was then rerun with that selection reversed to Year Built. Figure 45-b displays the corresponding results for comparison with Figure 45-a. Note that Row 3 of both figures echoes for recording the selection decision for how the age is computed.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Element Analyzed: 107															
2	Inspection Interval Limit (yrs) < 3															
3	Year Reconstructed is referenced in age calculation, if avialable in NBI otherwise Year Built.															
4	SN	Inspection Date 1	Total 1	CS1 1	CS2 1	CS3 1	CS4 1	Inspection Date 2	Total 2	CS1 2	CS2 2	CS3 2	CS4 2	Construction Year	Age	Matched Search String
5	160275	10/31/2008	1344	1329	15	0	0	11/12/2010	1344	1344	0	0	0	2009	54	New Superstructure
6		MostEffectiveBound						Least EffectiveBound								
7		1.0000	1.0000					1.0000	1.0000							
8		0.0000	0.0000					0.0000	0.0000							
9		0.0000	0.0000					0.0000	0.0000							
10		0.0000	0.0000					0.0000	0.0000							
11	160518	11/19/2007	1078	996	32	0	50	8/15/2008	1078	1046	32	0	0	2008	9	Beam REPL
12		MostEffectiveBound						Least EffectiveBound								
13		1.0000	0.0000		1.0000			1.0000	0.0000		1.0000					
14		0.0000	1.0000		0.0000			0.0000	1.0000		0.0000					
15		0.0000	0.0000		0.0000			0.0000	0.0000		0.0000					
16		0.0000	0.0000		0.0000			0.0000	0.0000		0.0000					
17	162440	3/22/2013	3237	3105	132	0	0	12/12/2014	3237	3237	0	0	0	2014	43	new bridge
18		MostEffectiveBound						Least EffectiveBound								
19		1.0000	1.0000					1.0000	1.0000							
20		0.0000	0.0000					0.0000	0.0000							
21		0.0000	0.0000					0.0000	0.0000							
22		0.0000	0.0000					0.0000	0.0000							
23	220033	11/5/2010	920	498	422	0	0	12/22/2011	920	782	138	0	0	2010	0	new bridge
24		MostEffectiveBound						Least EffectiveBound								
25		1.0000	0.6730					1.0000	0.6730							
26		0.0000	0.3270					0.0000	0.3270							
27		0.0000	0.0000					0.0000	0.0000							
28		0.0000	0.0000					0.0000	0.0000							
29	450026	3/3/2010	546	247	219	80	0	8/25/2010	546	417	129	0	0	2010	0	new bridge
30		MostEffectiveBound						MostEffectiveBound								
31		1.0000	0.4110	1.0000				1.0000	0.4110	1.0000						
32		0.0000	0.5890	0.0000				0.0000	0.5890	0.0000						
33		0.0000	0.0000	0.0000				0.0000	0.0000	0.0000						

Figure 45-a. Screenshot. Elevatio TPMs for bridges needing further investigation for EN107 replacement (Year Reconstructed from NBI used for age calculation if available otherwise Year Built).



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
3	Year Built is referenced in age calculation.															
4	SN	Inspection Date 1	Total 1	CS1 1	CS2 1	CS3 1	CS4 1	Inspection Date 2	Total 2	CS1 2	CS2 2	CS3 2	CS4 2	Construction Year	Age	Matched Search Str
5	160275	10/31/2008	1344	1329	15	0	0	11/12/2010	1344	1344	0	0	0	2009	54	New Superstructur
6		MostEffectiveBound						Least EffectiveBound								
7		1.0000	1.0000					1.0000	1.0000							
8		0.0000	0.0000					0.0000	0.0000							
9		0.0000	0.0000					0.0000	0.0000							
10		0.0000	0.0000					0.0000	0.0000							
11	160518	11/19/2007	1078	996	32	0	50	8/15/2008	1078	1046	32	0	0	2008	48	Beam REPL
12		MostEffectiveBound						Least EffectiveBound								
13		1.0000	0.0000		1.0000			1.0000	0.0000		1.0000					
14		0.0000	1.0000		0.0000			0.0000	1.0000		0.0000					
15		0.0000	0.0000		0.0000			0.0000	0.0000		0.0000					
16		0.0000	0.0000		0.0000			0.0000	0.0000		0.0000					
17	162440	3/22/2013	3237	3105	132	0	0	12/12/2014	3237	3237	0	0	0	2014	43	new bridge
18		MostEffectiveBound						Least EffectiveBound								
19		1.0000	1.0000					1.0000	1.0000							
20		0.0000	0.0000					0.0000	0.0000							
21		0.0000	0.0000					0.0000	0.0000							
22		0.0000	0.0000					0.0000	0.0000							
23	220033	11/5/2010	920	498	422	0	0	12/22/2011	920	782	138	0	0	2010	50	new bridge
24		MostEffectiveBound						Least EffectiveBound								
25		1.0000	0.6730					1.0000	0.6730							
26		0.0000	0.3270					0.0000	0.3270							
27		0.0000	0.0000					0.0000	0.0000							
28		0.0000	0.0000					0.0000	0.0000							
29	450026	3/3/2010	546	247	219	80	0	8/25/2010	546	417	129	0	0	2010	52	new bridge
30		MostEffectiveBound						Least EffectiveBound								
31		1.0000	0.4110	1.0000				1.0000	0.4110	1.0000						
32		0.0000	0.5890	0.0000				0.0000	0.5890	0.0000						

Figure 45-b. Screenshot. Elevatio TPMs for bridges needing further investigation for EN107 replacement (Year Built from NBI used for age calculation).

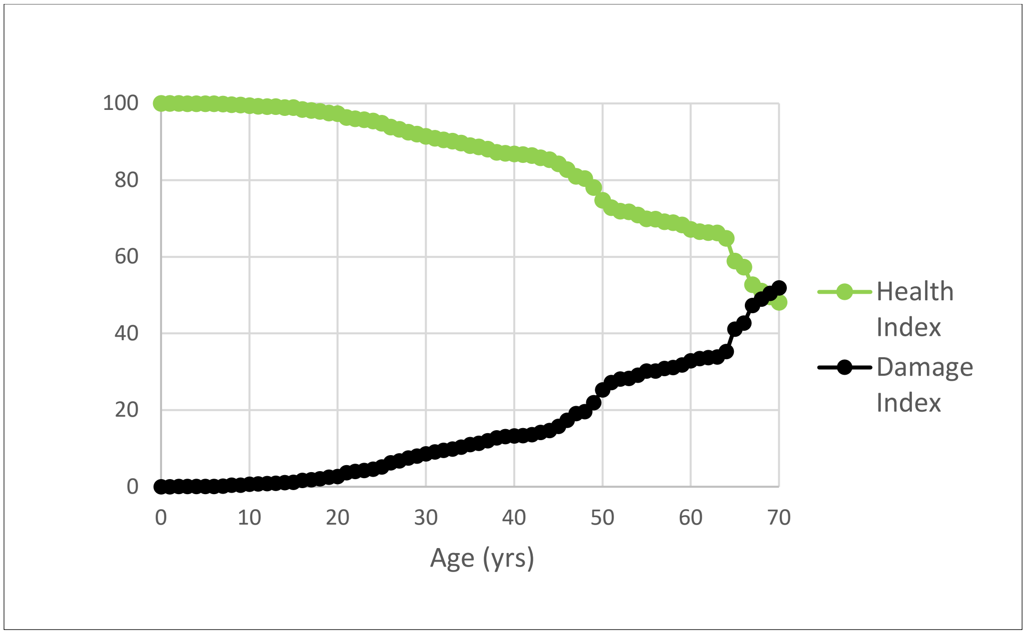


Figure 46. Chart. Health and damage indices for EN107 without renewal construction work.

The health and damage indices presented in Chapter 3 are also calculated here as functions of age in Figure 46 for the do-nothing case. Furthermore, an example construction work of painting is assumed to be performed at the age of 35 years. This is simulated using matrix multiplication formulated in Equations 10 and 11, but the do-nothing TPM at the age of 35 years is substituted by the painting TPM in Figure 44 (Cells B13 to E16). Then, the process of matrix multiplication resumes using the do-nothing TPMs. At every age, the health index and damage index are computed and plotted in Figure 47. The discontinuous behavior of these curves at age 35 is due to the painting work for EN107.

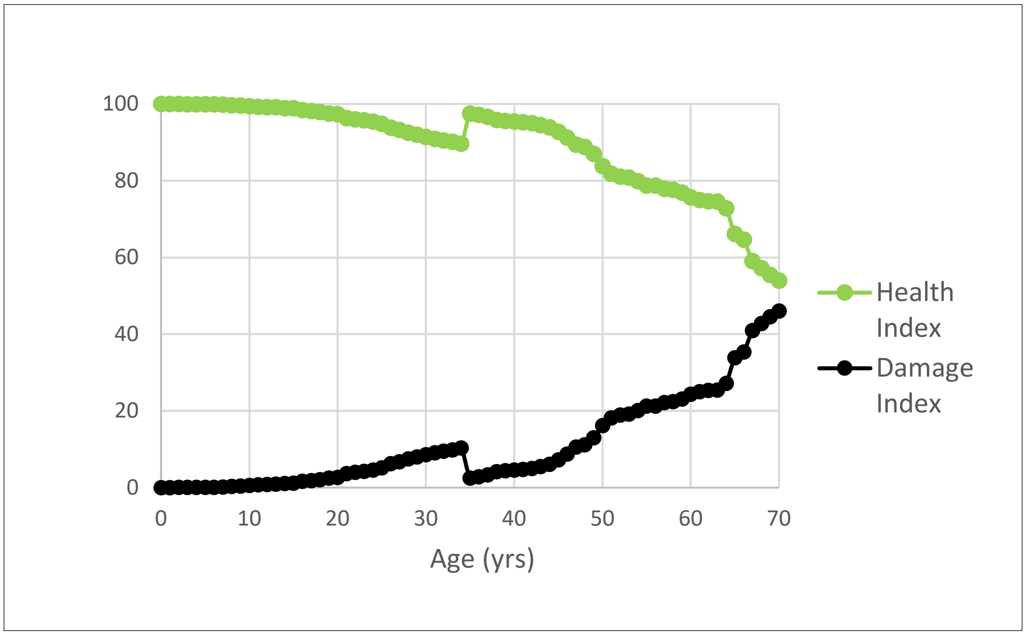


Figure 47. Chart. Health and damage indices for EN107 with painting at age of 35 years.

Note that the increase in deterioration rate with age, noted earlier for EN12, is also seen here for EN107, but at a much slower rate. Both Figures 46 and 47 show that in the first 20 years of service life, EN107 experiences very little deterioration. The health and damage indices in both figures do not show much change in this period. Equivalently, the deterioration rate is at about 0 points per 20 years, as graphically shown by the flap slope of the curves from 0 years to about 20 years. This 0-point change refers to the change in health index or the damage index.

Beyond that point of 20 years to about 40 years of age, the deterioration rate was about 10 points per 20 years. For the health index, this 10 means −10 points, or a reduction of 10 points per 20 years. For the damage index, this 10 indicates +10 points, or an increase of 10 points per 20 years. Between the ages of 40 to 60 years, this rate becomes about ±20 points per 20 years. This observation also highlights the capability of the proposed BrM quantity-based approach for modeling deterioration / improvement, carried by the new software tools Mansus and Elevatio.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

The conclusions of this study can be summarized as follows.

1. The proposed BrM quantity-based analysis approaches have been shown to be able to avoid the issues associated with the previous methods reported in the literature. They include, but are not limited to, (a) negative transition probabilities; (b) transition probabilities from one CS do not add to 1, violating the total probability theorem; (c) no solution from the solver algorithm for transition probabilities; (d) among neighboring states for do-nothing deterioration, order-of-magnitude different transition times from one CS to next poorer CS; (e) inability to capture and model quantity transitions skipping one or more CSs; (f) inability to replicate age-dependent deterioration for do-nothing; and (g) inability to demonstrate the preservation work's effect by TPM. These issues are presented and discussed in Chapter 2. Two computer software programs based on the new analysis approach, Mansus and Elevatio, were developed to carry the proposed approaches and were effective and efficient in producing TPMs for do-nothing deterioration and condition improvement, respectively.

2. In particular, the new algorithm for TPM in Mansus is designed to replicate the BrM quantity transitions for each individual bridge's element, recorded in its inspection history. The original algorithm is also able to capture the leaping behavior of quantity transitions from a CS to another poorer CS, skipping one or more CSs in between. These recorded leaping transitions represent one of the driving forces in do-nothing deterioration. The proposed algorithm is competent to describe do-nothing deterioration as age dependent, evidenced in the field and recorded condition history.

3. For the EN12 and EN107 examples under the do-nothing condition, the diagonal terms of TPM have this statistical trend: $P_{11} > P_{22} > P_{33}$. This trend indicates a higher deterioration rate at poorer CSs (i.e., faster deterioration with age increase). The uncertainty in P_{11} is lower than that in P_{22}, which is in turn lower than that in P_{33}. This indicates statistically less predictable deterioration behavior at a poorer CS. This trend is consistent with the behavior of faster element deterioration with age increase.

4. The new algorithm implemented in Elevatio for condition improvement is shown for the first time in history to be able to model the situation effectively and efficiently using inspection records. It avoids a number of assumptions in previous methods reported in the literature. It is also able to differentiate different levels of preservation work, such as replacement vs. concrete overlay vs. bituminous overlay vs. patching, and vs. sealing for RC deck (EN12). For example, micro-silica concrete overlay is more effective in enhancing condition for EN12 than bituminous overlay by the obtained TPMs using the IDOT BrM inspection history data. This simulated effect is consistent with field observations of bridge engineers.

5. The obtained TPMs via the proposed approaches are effective in forecasting expected element life span, expected remaining life, the effectiveness of preservation construction work in life extension, etc.

Accordingly, this research effort has produced the following recommendations:

A. Data quality is critical for modeling bridge element deterioration/improvement as well as for the proposed BrM quantity-based approaches. IDOT is recommended to further examine available datasets (BrM inspection records, construction history, and Illinois NBI) and to correct or address found errors or identified issues to enhance the data quality. This will maximize the potential of the innovative approaches and the software tools. Ultimately, the BrM's potential will be maximized.

B. It is recommended to change the IDOT construction history to a coded database for more accurate and complete identification of the effect of construction work on bridge element condition improvement. More details of the work are desired—for example, affected ENs, affected quantities of the ENs, unchanged quantities of the affected ENs (if any), work completion date, etc. It is also desirable to include a typical element inspection upon completion of the work as part of acceptance (like that for a new construction initiating the condition history).

C. A record check is recommended when a new inspection gets recorded for its consistency with the previous records. The check items should cover the seven scrubbing criteria in Mansus as well as other criteria possibly identified in the future when the current IDOT datasets have been fully used and examined in recommendation D. This new check can be automated into a computer software program to trigger a need for human check when warranted.

D. More applications of the developed software programs Mansus and Elevatio are recommended to other ENs and more groupings of various construction types, especially those ENs with fewer inspection records. This effort will explore not only the potential of these software tools, but also possible inadequacies and issues with the datasets. As reported herein, some unexpected issues have been identified such as negative quantities, total quantity equal to 0, and different total quantities for a bridge. There could be other issues with the datasets that have not been exposed. The two application examples for EN12 and EN107 used herein represent only a small portion of inspection records and are involved with perhaps a small portion of construction history as well. This recommended effort for more applications is expected to enhance and demonstrate the programs' capabilities and greatly enhance the IDOT operation of bridge management using BrM. The outcomes of these applications will also help recommendation C as to what else may need to be included as additional checks in the future for improved data quality.

E. When data errors or issues are exhaustively identified in more applications and how to treat the observed data errors becomes clear, further research/development effort is recommended to add more functions into Mansus and Elevatio to automate such treatments. For example, isolated records of negative quantities may be deleted as a function in the software, if no other more appropriate solution is identified. Such deletion can make use of the remaining portions of the inspection records. It will function as if more data are made available for the TPM calculation. The potential gain is quite significant, given that a large number of bridges now are excluded due to their small segments of invalid data.

F. Further optimization of Mansus and Elevatio is recommended to make them more efficient, especially when more functions are added to them, as recommended above.

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