Proceedings of the 2019 Winter Simulation Conference
N. Mustafee, K.-H.G. Bae, S. Lazarova-Molnar, M. Rabe, C. Szabo, P. Haas, and Y-J. Son, eds.

MULTI-CRITERIA-BASED SIMULATION MODEL TO ESTIMATE RESOURCES FOR BRIDGE INSPECTIONS

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ABSTRACT

Bridges are important links in the US infrastructure system, and various inspection activities at different frequencies are needed to maintain and preserve bridges at an acceptable level of service. Recent guidelines by Federal highway administration (FHWA) have mandated state agencies to inspect and manage bridges at an element level. To obtain element-level inspection data, different resources are needed for mobilizing, cleaning, and accessing all elements of a bridge, creating complication in optimizing resource allocation for inspection activities. This study proposes a simulation-based, easy-to-use planning tool for bridge inspection to effectively estimate the minimum resources required to complete all the FHWA mandated inspections using four attributes (deck area, inspection frequency, structure type and scour critical) from bridge inventory database. The results of the simulation model can show resource utilization under different scenarios, which supports the planning of element-level bridge inspection to ensure optimum resource allocation.

1 INTRODUCTION

The Federal Highway Administration (FHWA) under U.S Department of Transportation (USDOT) supports the design, construction, maintenance and preservation of the Nation's transportation infrastructure including highways, bridges and tunnels. There are 607,380 bridges across the country with an average age of 42 years (NBI 2019). In order to maintain these bridges in safe working conditions, FHWA mandates DOTs to conduct bridge inspections biannually (AASHTO 2011).

The FHWA routine inspections cost $2.7 billion with an average inspection cost of between $4,500 to $10,000 per bridge (VDOT 2017). This includes lane closure costs and traffic disruption cost. With aging infrastructure, user safety is becoming a serious concern. The need to inspect bridges before the two-year period (AASHTO, 1982) is rapidly increasing and hence fracture critical inspection is done every 6 months to a year period (Kaviani et al. 2016).

The American Association of State Highways and Transportation Officials (AASHTO) manual classifies bridge elements into National Bridge Elements (NBE), Bridge Management Elements (BME), and Agency Developed Elements (ADE). NBE bridge components are deck, substructure and superstructure representing the primary load carrying elements of a bridge. BME bridge components are elements which protects NBEs, such as wearing surfaces or protective coatings. ADEs are any sub elements of NBEs or BMEs defined by an agency (AASHTO 2013).

Inspector's interpretation of NBE condition ratings are subjective and may not convey the full extent of the distress. BME inspections try to overcome these limitations by collecting element-level quantitative report (Barr 2014). As mandated by MAP-21 (Moving Ahead for Progress in the 21st Century Act), the FHWA uses element-level inspection data to support a ''data-driven, risk-based'' management strategy

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(Campbell et al. 2016). A survey conducted by FHWA among 14 states in 2014 revealed that all states are finding it difficult to implement element-level inspection and two states have not even started to implement element-level inspection. Lack of guidelines and information about resource requirements are some reasons for states falling behind (Campbell et al. 2016).

Inspection planning is an important process for all Department of Transportation (DOT) as they must comply with the FHWA Guidelines. The inspection frequency should not be more than 24 months for routine inspection and critical element inspection while the underwater inspection can be done every 60 months (AASHTO 2011). Each state follows their own frequency of inspection for BMEs and ADEs. Manual process of scheduling bridge inspection following FHWA guidelines is often time consuming, (Pham and La 2016) and doesn't include environmental conditions and uncertainties which leads to many uninspected bridges (MASSDOT 2015; INDOT 2010). In addition, the new regulations prolong the time needed for each inspection, making it difficult to allocate the resources efficiently (Wells 2018).

Considering that state DOTs need to allocate indefinite amount of resource to multiple, simultaneous inspection activities and that characteristics (e.g. productivity, unit costs, etc.) of these activities may vary, there can be an enormous number of possible scenarios for bridge inspection. Modelling and simulation can support decision-making on identifying feasible and optimum solutions. This paper proposes a simulation model suitable for estimating the minimum resources required for element-level bridge inspection activities that take place simultaneously, which improves state DOTs' capabilities of implementing the element-level inspection.

2 MULTI-CRITERIA RESOURCE ESTIMATION FOR BRIDGE INSPECTION

2.1 Graphical Presentation and Concept of Model

The inspection planning is generally based on the bridge characteristics; specifically, the number of lanes on bridge, structure type, scour critical bridges, structure dimensions. These characteristics are the multiple criteria (Fabbri et al. 2019) to plan for the bridge inspection process. The inputs to the model are the resources, such as access equipment, cleaning equipment, and underwater inspection equipment while the availability of these equipment will be a constrain. The resources for model can be modified as per the requirement of the user, and their interdependencies must be designed based on the scenario of that model. A sample model to explain the interdependencies between bridge characteristics and choice of resources is explained in figure 1.

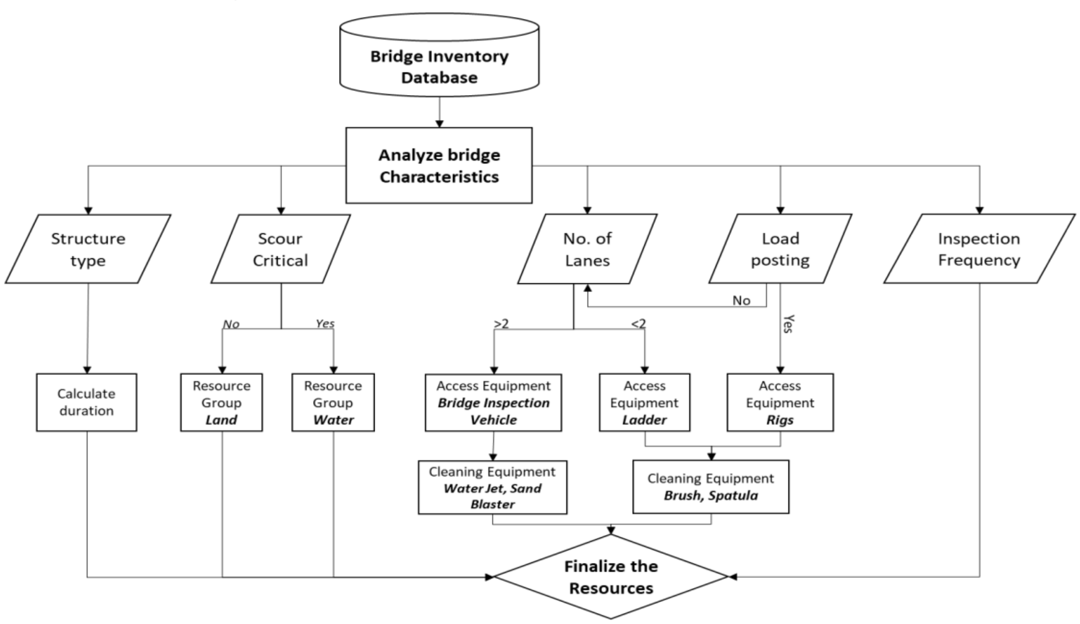

Figure 1: Algorithm for multi-criteria-based resource estimation for bridge inspection.

Based on the resource interdependencies and the number of entities (bridges) to be served, the simulation model was developed using Simphony Modelling environment. This simulation modelling tool has been used in other discrete process simulation (AbouRizk et al. 2011). It is based on Visual Basic (VB) programming language. The model has two components: input parameters and model simulation interface.

Input parameters include the resource interdependencies and the bridge characteristics. National Bridge Inventory is the information repository for all the FHWA-administrated bridges. Each bridge has more than 100 characteristics, from which deck area, inspection frequency, structure type, and waterflow under the bridge are the ones used in this model (figure 1), and more characteristics can be incorporated when the resource interdependencies are properly identified and developed. The resources required for bridge inspection include mobilization trucks to carry all the tools for inspection, boats and chest waders for under water inspection for scour, and under bridge inspection vehicles. The productivity and duration of inspection is summarized in Table 1 (Emal Masoud et al. 2017).

Table 1: Input parameters for bridge inspection based on bridge type.

Structure Type	**Bridge Material**	**Sq.ft/Minutes**	
		Mean	**Standard Deviation**
1	Concrete	24.2	20.8
2	Steel	17.7	19.6
3	Prestressed Concrete	32.7	25.9
4	Masonry	28.7	21.2
5	Timber	36.5	22.1
Mobilization		120 minutes/bridge	
Cleaning		10% of inspection time	

2.2 Input Data to Simphony Model from Bridge Inventory Database

Simphony.NET 4.6 is a simulation tool which allows the user to manually define the local attributes for entities flowing in the model, which is appropriate for entities with one local variable. Each bridge has four attributes which cannot be entered manually as these data are unique for every bridge. The transferring of data, including those related to deck area, inspection frequency, structure type and scour critical, from bridge inventory to Simphony simulation engine is achieved through Microsoft SQL Server, as shown in Figure 2. This approach enables the model to incorporate all the bridges in the Virginia State bridge inventory and constitutes a practical way of processing large amount of data in a simulation model. Sample input data is shown in Table 2.

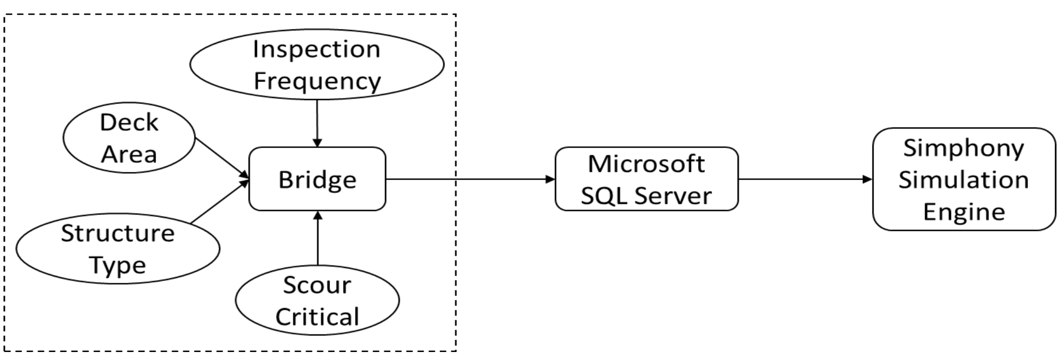

Figure 2: Data transfer from Bridge Inventory to simulation model.

Table 2: Sample input data for Simulation model.

LX(1)	LX(2)	LX(3)	LX(4)
Deck Area	**Inspection Frequency**	**Structure Type**	**Scour Critical**
5732.4	24	3	1
283.65	24	4	1
179.08	12	2	1
106.25	24	2	1

2.3 Simulation Model

The database has bridges that needs inspection once a year (12 months) and once every two years (24 months). Bridges that need more frequent inspections are separated using a conditional branch and after inspection the bridge is made to wait for a year until its inspected next time as shown in figure 3. The code below returns true for bridges that need inspection once in 24 months.

```
START
   if inspection frequency in 24, then
      allow entity through loop A
   else
      allow entity through loop B
FINISH
```

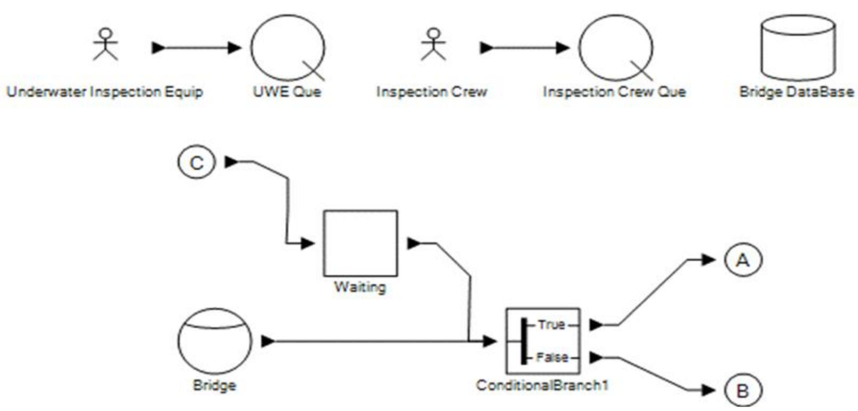

Figure 3: Simphony model interface to separate frequent inspected bridges.

The Inspection crew consists of two bridge inspectors and one inspection truck with basic tools for inspection. The underwater inspection equipment contains an inspection boat, probe and chest wader. The bridges entering the simulation model will capture the required resources and the simulation model will execute the inspection process as shown in figure 4. The entities in the model capture resources based on the structure type and scour critical. A series of conditional branches are used to separate the bridges based on the material types. The code returns the type 1 bridges and those in fail loop are passed to next conditional branch.

```
START
   if structure type is concrete, then
      allow entity through Type 1 bridge loop
   else
      return to next loop
FINISH
```

Based on scour critical condition the underwater inspection resource for a bridge is allocated. The entity will capture the resource only if the bridge has underwater flow. Then all the entity captures the inspection crew after which the process for inspection begins.

```
START
   if the bridge is scour critical, then
      entity request underwater inspection equipment and waits in UWE Que
   else
      entity flows
FINISH
```

The duration of the inspection is calculated based on the normal distribution of rate of inspection for each structure type as mentioned in Table 1. Absolute values of the normal distribution are used for the model to avoid negative values. Duration is the product of inspection rate and deck area as shown in the code below.

```
Sample Normal (0.462,0.42) /60 * LX(1))
```

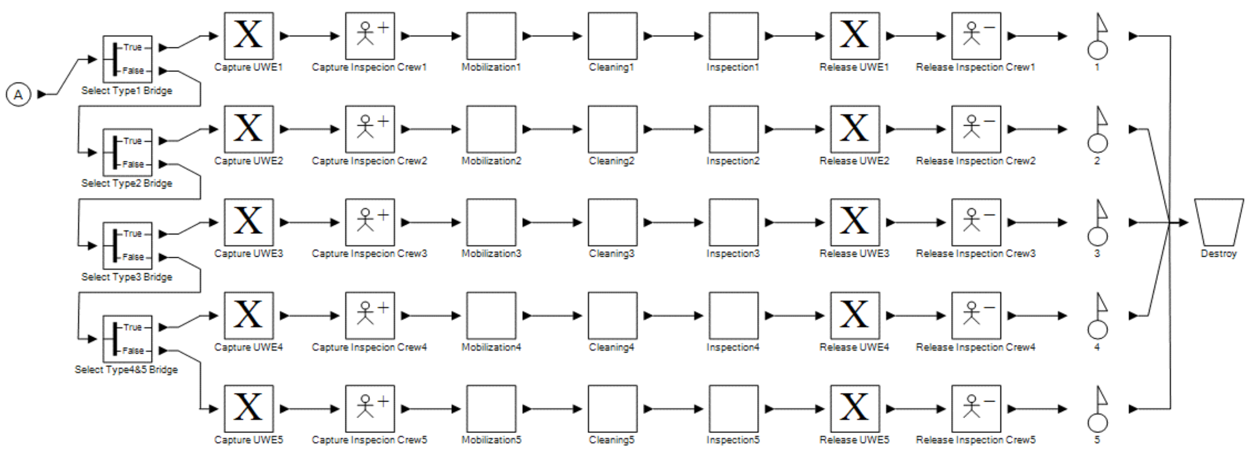

Figure 4: Simphony model interface for routine inspection.

3 RESULTS, DISCUSSIONS AND FUTURE STUDIES

The simulation model is tested using State of Virginia bridges. Excluding culverts that span less than 20 feet in length, the total number of bridges for the study is 8022 (VDOT 2017), out of which 630 bridges need to be inspected frequently. The simulation model has been tested for different scenarios by changing the number of resources available. Monte-Carlo simulation results for different scenarios are shown in Table 3.

The normal statistic tests give misleading results when used for validating the simulation models (Mass et al. 1978). The model validation is subjective to user view. A valid model is the one that can be used with confidence as defined by Forrester et al. 1978. The structure of the simulation model can be validated by extreme condition test (Bell et al. 1980). It is carried out to check the model performance at extreme resource quantities i.e., no resources or infinite resources and the model performed as expected. The performance of the simulation model can be validated by Degenerate Test (Sargent R.G, 2010, 2007, 2003).

By checking the resource allocation in Table 3 the test can be conducted. Irrespective of the number of resources available the simulation performs all the critical element inspection first and then moves to routine inspection. Internal Validity was tested to check the consistency of the model (Sargent R.G, 2011, 2007, 2003). By running the model several times for same number of resources and it was found the resource utilization was found to be consistent across different runs.

Table 3: Simulation results for different scenarios.

Resource Available		**Routine Inspection**					**Critical Element Inspection**					**No. of Inspected Bridges**	**Resource Utilization**	
UWE	**IC**	**1**	**2**	**3**	**4**	**5**	**11**	**12**	**13**	**14**	**15**		**UWE**	**IC**
0	**0**	0	0	0	0	0	0	0	0	0	0	0	-	-
1	**1**	11	0	0	0	0	314	776	17	8	6	576	100	100
2	**2**	720	0	0	0	0	314	812	38	17	13	1317	100	100
4	**9**	1785	4086	1245	19	13	328	858	42	18	14	7778	88.5	100
4	**10**	1786	4142	1286	19	13	328	858	42	18	14	7876	83	100
4	**11**	1785	4142	1430	21	13	328	858	42	18	14	8021	77	98.7
5	**9**	1785	4142	1271	19	13	328	858	42	18	14	7860	91.9	100
5	**10**	1786	4142	1430	21	13	328	858	42	18	14	8022	80.5	91.9
6	**12**	1786	4142	1430	21	13	328	858	42	18	14	8022	71	78.3

Routine inspection indicates the inspection is done every two years. The model completes all the critical element inspection first because a high priority is given for these bridges during resource allocation. By doing so all the critical bridges can be inspected once a year. The utilization of the underwater equipment (UWE) doesn't get better after 5 resources but we need at least 10 inspection crew (IC) to successfully complete the inspection within 2 years. This is because the inspection crew will be used by all the bridges, but the underwater equipment will be used only by the bridges that are built over water bodies or is scour critical. Having more resources than 5 UWE and 10 IC will result in increased idling time, which reduces the resource utilization (below 100%).

A well-designed resource selection and allocation plan is important to successfully design the simulation model. For simplicity considerations, this simulation model did not consider Non-Destructive Examination (NDE) techniques. Future studies can expand the simulation model by including (1) more resources such as NDE equipment (e.g. drones and Ground Penetration Radar [GPR]) and access equipment (e.g. cranes and ladders) and (2) more information about bridges (e.g. the number of lanes that affects the practicality of using bridge inspection trucks) that may influence time needed for inspection.

The calendar used in this study to estimate the average working days in a year only considers the federal holidays and weekends into account. However, manual bridge inspection is an outdoor job that is accompanied with many safety concerns for the inspectors. Weather plays a very important role in the decision whether a day counts as a working day for inspection or not. Areas with harsh weather conditions should consider potential, weather-related delays in the simulation model. This issue could be addressed in future by defining the minimum weather condition requirements for safe bridge inspections probability of extreme weather occurrence by incorporating historical weather data.

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