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Simulation-Based Planning of Concrete Bridge Deck Inspection with Non-Destructive Technologies

By

Sherif Abdelkhalek* and Tarek Zayed

Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong.

ABSTRACT

Inspection process provides beneficial information to assess the current condition of the bridge deck, which is an essential factor in identifying the most appropriate and timely maintenance strategy. Practically, there are a huge number of bridges that need frequent inspection, which makes planning for this process crucial. In this regard, a bridge deck inspection planning (BDIP) model was developed to manage the inspection process of the concrete bridge deck. This model integrates agent-based and discrete event simulation approaches to mimic the sub-processes involved in the inspection using non-destructive technologies. This paper discusses the details and the adopted procedures to build this model starting from real system analysis to model verification, implementation, and validation. Verification and validation of the model demonstrate its ability to accurately estimate inspection duration and cost. The developed model can assist bridge authorities and contractors in planning this process, measure the traffic disorder due to inspection activities, and compare different scenarios for conducting inspection.

Keywords: Concrete bridge deck; Inspection; Non-destructive technologies; Hybrid simulation; Agent-based simulation; Discrete event simulation; Planning.

* Corresponding author at: Department of Building and Real Estate (BRE), Block Z, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong.
E-mail: sherif.abdelkhalek@connect.polyu.hk (S. ABDELKHALEK)

INTRODUCTION

Available budget to conduct maintenance for bridges is insufficient to cover all required maintenance work. According to the USA infrastructure report card, the backlog of rehabilitation projects for the nation's bridges is $123 billion [1]. Thus, priority in conducting needed maintenance is given to vital and extremely defected bridges, while maintenance for less-risky and low-important bridges is usually delayed until new funds are found [2]. Bridge deck represents the most expensive component in the bridge system due to its frequent need for costly maintenance and rehabilitation [3]. Numerically, bridge deck costs between 50 to 80 percent of the overall expenditures on bridges over its service life [4]. Therefore, optimizing maintenance work for such elements can significantly reduce the gap between the available budget and the required maintenance.

To address this challenge, periodical inspection is usually conducted to accurately identify the current condition of the bridge elements, which is an essential factor in determining the most appropriate maintenance strategy on time. Indeed, conducting timely maintenance is a critical step to prevent deterioration proliferation and consequently reduces the required budget for maintenance work in the future. In this regard, non-destructive technologies (NDTs), such as impact echo (IE), ultrasonic pulse echo (UPE), ultrasonic surface wave (USW), half-cell potential (HCP), electrical resistivity (ER) polarization resistance (PR), ground penetrating radar (GPR), infrared thermography (IRT) and image-based techniques, were incorporated in the inspection process to eliminate the limitations of traditional inspection approach (i.e., visual inspection) and to address more accurate assessment for surface and subsurface defects [2].

Nevertheless, there are two main challenges in conducting inspection. Firstly, inspection activities interrupt traffic flow (i.e., especially for vital bridges), which is directly and indirectly related to other vital activities (e.g., commercial and industrial activities). Secondly, the huge number of bridges that need frequent inspection makes planning for this process very important. For example, In the USA, there are 614,387 bridges, 39% of these bridges are more than 50 years old, 15% are between the ages of 40 and 49, and 9.1% of these bridges were structurally deficient in 2016 [1]. This reveals the need for developing a tool that can guide decisions in planning this process, measuring the traffic disorder due to inspection activities, and comparing different scenarios for conducting inspection to optimize the whole process.

Accordingly, a bridge deck inspection planning (BDIP) model was developed to manage the inspection process of the concrete bridge deck. The developed model integrates agent-based and discrete event simulation approaches to mimic the sub-processes involved in the inspection using non-destructive technologies. The developed model can estimate inspection duration and cost, measure traffic disorder due to inspection activities, and compare different inspection scenarios and traffic control strategies to reduce inspection duration and cost. This will contribute to the current situation by providing a decision aiding tool that can be used in planning the forthcoming inspection activities.

BACKGROUND AND RESEARCH GAPS

Few studies have investigated the time and cost of the inspection process for the concrete bridge deck. The applications of the findings of these studies are limited to specific cases. For example, Gucunski, et al. [4] estimated data collection and data analysis speeds for inspection using non-destructive technologies (e.g., half-cell potential and electrical resistivity offer data collection speeds of 1,156 ft^2/hr and 1,415 ft^2/hr, respectively). The proposed speed for different non-destructive technologies was estimated based on 2 ft x 2 ft grid spacing. The data in this study were collected from different participants in the second Strategic Highway Research Program

(SHRP2). Similarly, Benjamin et al. (2016) estimated the speed of data collection and analysis for seven non-destructive technologies by collecting information from Indiana Department of Transportation (INDOT) experts, vendors, and equipment manufacturers (e.g., GPR and Air-coupled GPR offer data collection speeds of 4,800 ft^2/hr and 12,000 ft^2/hr, respectively). The findings of these two studies did not consider several factors that significantly influence the estimated inspection duration, such as preparation time, device characteristics (e.g., mounting the device in a cart or a car), and varying testing grid spacings. Ignoring these factors limits the applications of the developed rates to specific cases.

On the other hand, Chung, et al. [5], and Kim and Frangopol [6] incorporated inspection cost in optimizing the life cycle cost of bridges. The main focus of these studies in estimating inspection cost is to calculate the total inspection cost of a bridge over its service life by considering the number of scheduled inspections and the cost of a single inspection. Agdas, et al. [7] estimated the cost of different items incorporated in visual inspection and wired and wireless structural monitoring systems. The estimated cost includes owning cost of the equipment, installation cost, inspector salary, traffic control cost, maintenance cost, and data analysis cost. The findings showed that visual inspection is less expensive than wired and wireless structural monitoring systems. The estimated cost in this study is limited to the proposed systems and cannot be used for other inspection systems.

Gucunski, et al. [4] estimated cost per unit area (i.e., USD / ft^2) of using different non-destructive technologies in the inspection. The estimated cost includes cost of data collection and data analysis, equipment purchasing cost, maintenance cost, and traffic control cost. The participants in SHRP2 project were asked to provide a cost estimate for the inspection of two bridge decks areas using different non-destructive technologies (i.e., 5,000 ft^2 and 10,000ft^2). The findings of this study showed that chain drag and hammer sounding are the most inexpensive techniques. Nevertheless, the corresponding cost of these techniques increases extremely (i.e., five times) when traffic control cost is considered due to long operation time. The findings also showed that the acoustic techniques (i.e., IE, USW, and UPE) are the most expensive techniques in both cases (i.e., with and without traffic control cost). On the other hand, electrochemical techniques (e.g., half-cell potential) are the cheapest inspection techniques when considering traffic control costs. In addition, GPR and infrared thermography provide reasonable inspection approaches when considering their capabilities.

Benjamin, et al. [3] estimated the cost associated with the inspection using non-destructive technologies. Purchasing cost, maintenance cost, vehicle cost, training cost, inspectors and analysts' salaries, traffic control cost, and travel cost were all considered in estimating the unit price of inspection using non-destructive technologies. The data for unit price estimation was collected from 30 bridges in Indiana's inventory. The findings of this study demonstrate the cost-effectiveness of using infrared thermography test in inspection of concrete bridge deck.

In general, previous studies fixed some factors during estimating the prediction rates for inspection duration and cost, such as testing grid spacing and equipment prices, which significantly biases the assessment of the inspection duration and cost or limits their applications. For example, the proposed cost rates for using NDTs technologies in the inspection process in some studies [3,4] are a function of the bridge area, ignoring the continuous changes in devices purchasing costs, salaries, etc., which makes using these rates nonrepresentative for the real process after a short time. In addition, traffic delay cost was often overlooked in the estimation of inspection cost. Furthermore, non-destructive technologies are usually used together to complement their defect detection capabilities. However, the inspection duration and cost for the whole process that involves several technologies have not been investigated before, since most studies have developed prediction rates to estimate inspection duration and cost for using non-destructive technologies individually. The aforesaid gaps reveal the need to develop a tool that can address more accurate assessment for inspection duration and cost.

Simulation

Computer simulation is an approximate imitation of the behaviour of a real system to predict the outcomes of this system. Simulation models (e.g., discrete event simulation, system dynamic and agent-based simulation) are used for several purposes, such as understanding the underlying behaviour of the real system and optimizing operations inside this system [8]. In 1961, IBM engineer Geoffrey Gordon developed the first discrete event simulation (DES) software, i.e., GPSS (General Purpose Simulation System) [9]. Since then, this technique has gained wide acceptance in both academic and industrial communities and numerous software have been developed to facilitate its implementation (e.g., Arena, WebCYCLONE, and STROBOSCOPE). Accordingly, DES has demonstrated its capabilities in supporting decision-makers and providing solutions for various problems in the real world [10-14].

For example, Zayed and Halpin [10] developed a time-cost-quantity chart that can be used to predict production time and cost of a ready mixed concrete batch plant considering the distance between a construction site and the plant. The chart was developed based on the findings of the sensitivity analysis process of a DES simulation model for the plant developed by MicroCYCLONE simulation software. Marzouk, et al. [11] developed a DES simulation model that can assist government agencies in planning the construction process of a bridge deck by comparing different construction methods. In an interesting study conducted by Balagopalan [14], a DES model was developed to predict time and cost of using an unmanned aerial system (UAS) in bridge inspection. The findings of this study demonstrated the efficiency of implementing UAS in the inspection process compared to visual inspection technique.

DES was integrated with other techniques to strengthen and extend the benefits of the integrated techniques. As an example, ElNimr, et al. [15] integrated 3D visualization and DES to model the movements of a mobile crane on construction sites. The geometrical and special processing strengths of the visualisation were used to identify the shortest obstacle-free path for each mobilization. Alzraiee, et al. [16] integrated DES and system dynamics (SD) to address the operational and strategic aspects of construction projects on a single platform. The developed platform was used to provide a more realistic project schedule and to improve understanding of the project's factors interactions. SD is considered as old as DES. It was developed at the Massachusetts Institute of Technology (MIT) by Professor Jay Forrester in the 1950s (Forrester, 1997). SD is concerned with macro level or strategic level of the system, which includes broad and general details about the processes inside the system. On the other hand, DES focuses on micro level or operational level, where detailed information about the process is the main concern

Despite DES has been widely used in the simulation community for over 40 years, in the early 1990s, the arrival of agent-based simulation (ABS) promised to offer more sophisticated solutions for current problems [17]. It uses a bottom-up approach, where the behaviour of different elements (i.e., agents) in the system and their interactions are modelled. The overall system behaviour emerges as a summary of the actions and interactions of autonomous agents [18]. ABS can model the complexity arising from human behaviour that is either generated from individual actions or from interactions between different agents. For that reason, ABS surpasses DES and SD techniques, since these techniques are not competent enough for these types of problems [17]. For example, Kim and Kim [19] developed a multi-agent-based simulation model to investigate the impact of traffic congestion on the efficiency and productivity of construction equipment, which is not possible to be considered using DES.

Despite the fact that ABS is a very powerful simulation technique, there are some barriers that prevent the wide adoption of this technique. For instance, the lack of experience of academics and practitioners with ABS limits employing this technique in different fields [17]. On the other hand, the practical experience with DES in both academic and industrial communities is now very matured, which increases the popularity of using this technique in many applications.

RESEARCH METHODOLOGY AND MODEL DESIGN

In this part, the main steps of developing the bridge deck inspection planning (BDIP) model will be presented. This model was developed by integrating agent-based and discrete event simulation approaches into a single platform. Anylogic software was used to build this model. The main stages to develop the current model are shown Figure 1 (a). Figure 1 (b) shows the sequences of the main stages and their details. Further details of each stage are illustrated in the next subsections.

Figure 1

System Analysis

System analysis is the first stage to build any model. This stage should receive great attention as it forms the foundation for all upcoming stages. The main goals of this stage are to establish the scope of the model, identify various system aspects that have relationships with this scope, analyse these aspects, put them together to formulate the problem, and finally identify the main steps involved in the process and their sequences. Returning to our problem, inspection of concrete bridge deck using non-destructive technologies represents the main focus of this study. The objectives of this research are to estimate the time and cost of the inspection process and optimize the whole process.

To achieve the aforesaid objectives, the inspection process was carefully analysed and broken down into small parts to identify the process environment. Process environment contains different parameters that influence the objectives. Figure 2 summarizes these parameters according to the three objectives: time, cost, and process optimization. As shown in Figure 2, there are several parameters that control the inspection duration, such as bridge characteristics, number of technicians, test characteristics, preparation time, working hours per day, and possibility of closing several lanes at the same time for inspection. The last parameter is concerned with the opportunity to close more than one lane at the same time to perform inspection, which depends on the status of traffic (i.e. low or high traffic density) and the adopted strategy to control the traffic (i.e. rerouting or partial lane closure).

Similarly, inspection cost is a function of several parameters, which include inspection duration, transportation cost, devices renting cost, technician salary, traffic control cost, bridge user cost, other costs (i.e. tools cost, indirect cost, etc.), and working start time. Working start time determines when the work will start every day. In fact, this is a critical factor in determining the impact of the inspection activities on traffic flow. The starting time for inspection is preferably chosen at low-traffic density hours to reduce the disturbance of the traffic flow and accordingly reduces excessive user cost due to this disturbance.

Figure 2

Finally, adjusting process parameters to optimize the outputs of the system is considered an essential step during planning. Nevertheless, there are some parameters that have constant values, such as bridge length and width, test speed, devices rental cost, and technician salary. On the other hand, some parameters can be adjusted to optimize the process, such as number of technicians, overtime length, working start time, traffic control strategy, and possibility of closing several lanes at the same time for inspection (Figure 2).

The final procedure in this stage (i.e., system analysis) is to identify the main steps involved in the process. Inspection process includes several tasks which can be categorized into two sub-processes: preparation and testing. Figure 3 shows the tasks included in each sub-process. Preparation of each lane starts with lane closure, then cleaning and preparing the surface of the bridge deck if needed, and finally marking testing grid. On the other hand, testing comprises three tasks: device setup, testing, and moving to the next line/point to test. The last two tasks are repeated until finishing all test lines or points.

Figure 3

Generally, there are two approaches for performing inspection using non-destructive technologies: line-based test and point-based test. In the line-based test, the technician stirs the device through marked lines on the surface of the bridge. The technician with the device moves continuously through each line at a specific speed. This approach includes two methods for testing: forward and zigzag. In the forward method, the technician always moves to the start line in order to start testing a new line, while in the zigzag method, the technician reverses the direction of the movement with each new line (Figure 4). GPR, infrared camera mounted on a car, and some types of half-cell potential (i.e., wheeled half-cell potential) are used according to the line-based test method. On the other hand, in the point-based test approach, the technician tests marked points on the surface of the bridge using the device (e.g., IE and USW). At each point, the technician puts the device over the point for several seconds to measure a specific property, and then moves to the next point.

Figure 4

Conceptual Design

Conceptual design comprises three main steps: establishing the process framework, developing the cost estimating model, and choosing the most appropriate technique(s) to build the final model. The details of each step are described in the next subsections.

Process Framework (Time Model)

The first step in the conceptual design focuses on identifying the key elements in the process, investigating their behaviours during the process, examining their relationships, and establishing a framework for the process including all these aspects (i.e., conceptual model). Figure 5 shows the inspection process framework. As shown in Figure 5, inspection process includes six main elements: daily working hours, inspection, technician, preparation, device, and traffic flow. Daily working hours are the summation of the normal working hours per day and the overtime hours. This element circulates between three states: mobilization, testing, and demobilization. Every day, the inspection team starts mobilizing the required tools and devices for inspection. Then, inspection activities are commenced. Finally, when the working hours in the current day are finished, the inspection team demobilizes the inspection tools and devices. These tasks are repeated every day until the end of the inspection. This element determines the daily time window for the inspection activities. Therefore, it controls the cycles of all other elements directly or indirectly (i.e., through another element).

Figure 5

The second element is the inspection process. It includes all inspection activities, such as preparation and testing activities using different non-destructive technologies. This element influences all other elements, since it holds all inspection information, such as number of technicians, tests incorporated in the inspection, tests order, etc. The inspection cycle is repeated every lane (i.e., when the inspection of one lane is finished, the inspection team moves to the next lane to inspect). The work in this element is mainly influenced by the daily working hours element as the daily working hours element stops the inspection activities when daily testing time in the daily working hours element is finished (i.e., total working hour minus mobilization and demobilization times) and resumes the inspection activities when testing time starts in the next cycle (i.e. day).

The third element is the technician, who do all inspection activities, starting from mobilization till the end of the inspection. There are two state for this element: working and idle (Figure 5). The latter case occurs when there are more than one technician involved in the inspection process as the technician should wait for the previous test to provide enough space to start another test (i.e., there is always a gap between different tests if they can start at the same time). This is considered a precaution condition to prevent test collisions. In working state, the technician will be involved in one of the following tasks: mobilization, demobilization, preparation, and NDT tests. Therefore, there is a strong relation between technician cycle and daily working hours, inspection, preparation, and device cycles. Inspection cycle provides the technician with the sequence of inspection activities (e.g., after preparation, GPR test should start, then IE test, and finally HCP test). After the completion of the preparation process or any test, the device and preparation elements inform the technician element that the process is finished, which allows the technician to start a new test. Consequently, the technician checks if there is another test ready to start or becomes idle.

The fourth element is preparation. This process includes several tasks, such as setup lane closure tools, cleaning and preparing the deck surface, and grid marking. The cycle of this element includes two states: waiting and preparing (Figure 5). This cycle is repeated every lane until the end of the inspection process. The inspection element indirectly determines the current state of the preparation element through the technician element. Similarly, daily working hours element indirectly stops and resumes the work in this element through technician element.

The fifth element includes the devices used in the inspection. There are several non-destructive technologies that are commonly used in the inspection of concrete bridge deck, such as GPR, IE, USW, UPE, HCP, ER, PR, IRT, and images [2]. The cycle of any device includes two main states: waiting and testing (Figure 5). The device switches between these two states until the end of the inspection process. When the test in progress provides enough space to start a new test, the next test checks the availability of the technician to start the test. If there is no technician available, the device will stay in the waiting state until a technician becomes available (this proves the relationship between this element and the technician element). After finishing testing with a specific device, this device releases the technician to do another job. Similar to the preparation element, the daily working hours and the inspection elements control the current state of this element.

The last element is the traffic flow, which includes two states: normal flow and flow under inspection. Starting the inspection activities converts the traffic flow from normal condition to flow under inspection. There are two cases of traffic flow under inspection. The first one is partial direction closure, in which some lanes are closed, while the remaining are opened for traffic. The car driver, in this case, has two options: driving beside the working area or taking another route. The second case is complete closure for the entire lanes in this direction, which may convert the traffic flow to the other direction or convert the traffic in this direction to another route. Inspection element determines if there are inspection activities in progress in this direction or not. On the other hand, daily working hours element interrupts the inspection activities and returns the traffic flow to the normal condition after the working hours on that day are finished. On the next day, the inspection work is resumed, and the traffic flow is affected again. The cycle of traffic element is repeated every day until the completion of the inspection activities in this direction.

Cost Model

Inspection cost can be divided into six parts: technicians cost (C_{tech}), devices cost (C_{dev}), transportation cost (C_{transp}), lane closure control cost (C_{lc}), bridge user cost (C_{BU}), and other costs (C_{oth}). The total inspection cost can be calculated from the following equation:

$$TC_{insp} = C_{tech} + C_{dev} + C_{transp} + C_{lc} + C_{BU} + C_{oth} \qquad [1]$$

Technicians cost is the expenses paid for the inspection team to do inspection. This part considers normal and overtime pay rates for the inspection team. It is a function of technicians number (N_{tech}), technician normal and overtime pay rates, total normal working hours, and total overtime working hours. It can be calculated according to the following equation:

$$C_{tech} = N_{tech}\{(S_{tech} * (T_{insp} - OT_{insp})) + (OS_{tech} * OT_{insp})\} \qquad [2]$$

where S_{tech} = hourly salary of technician, T_{insp} = inspection duration in hours, OS_{tech} = overtime hourly salary for technician, OT_{insp} = total overtime hours.

Devices cost is the cost associated with the use of NDTs in the inspection. It depends on the number of NDTs used in the inspection, the rental rate for each technology, and inspection duration. The following equation can be used to calculate this term:

$$C_{dev} = \sum_{i=1}^{n} (R_{d_i} * T_{insp}) \qquad [3]$$

where n = number of utilized devices in inspection, R_{d_i} = hourly rental cost of device i.

Transportation cost is the cost corresponding to transporting the inspection team, devices, and tools from the depot to the inspection site and vice versa. This term considers two cost sources: renting cost and operation cost of the vehicle. It is a function of the number of trips to the inspection site (i.e., equal to the inspection working days), rental cost of the vehicle, operation cost of the vehicle, and traveling distance to inspection site. It is assumed that the inspection team takes the same route in traveling to the inspection site and returning to the depot. Transportation cost can be calculated using the following equation:

$$C_{transp} = [R_{veh} + (OC_{veh} * 2 * L_t)] * number\ of\ working\ days \qquad [4]$$

where R_{veh} = daily rental cost for the vehicle, OC_{veh} = operation cost of the vehicle per kilometre, L_t = traveling distance between depot and inspection site in kilometre.

Lane closure cost is the cost of using lane closure tools during inspection process. It can be calculated using the following equation:

$$C_{lc} = R_{lc} * number\ of\ working\ days \qquad [5]$$

where R_{lc} = daily rental cost for the lane closure tools.

Other costs include cost of the tools used in marking testing grid, lighting, tools for cleaning, and all items that are not related to the other five parts. Other costs may include fixed costs, such as painting used in marking, and/or time dependent costs, such as rental cost of lighting tools. The following equation can be used to calculate other costs:

$$C_{oth} = \sum_{j=1}^{m} F_j + \sum_{k=1}^{p} R_k * T_{insp} \qquad [6]$$

where F_j = fixed cost of item j, R_k = hourly time dependent cost of item k, m = number of fixed cost items, p = number of time dependent cost items.

Finally, bridge user cost is the cost that bridge users incur due to the reduced travel speed at the work zone or rerouting to avoid the work zone. Excess user cost includes two sources: traffic delay cost and additional vehicle operation cost [20]. Traffic delay cost is the value of delay time to the vehicle's driver, while additional vehicle operation cost is the cost incurred due to consuming a longer time to travel through the work zone.

The main parameter in calculating the bridge user cost is the amount of delay caused by speed changes at the work zone or travelling longer distance to avoid the work zone (i.e. rerouting). Generally, there are three traffic flow cases that cause delays in case of a work zone: rerouting, signalized (i.e. complete direction closure), and partial lane closure. Rerouting is selecting another route to drive through instead of driving beside the work zone. The signalized flow occurs when the lane in one direction is closed and the traffic in the affected direction is converted to the other direction (i.e., in the case of a two-direction bridge with one lane in each direction). In that case, the vehicles in both directions will drive through the same lane. Therefore, a green time is adjusted for both directions to control the traffic flow. The Last case is closing some lanes against traffic flow, but keeping the remaining lanes opened for traffic. The total traffic delay (D_T) can be calculated using the following equation:

$$D_T = \sum_{h=1}^{T_{insp}} \left(D_{re_h} \; or \; D_{lc_h} \; or \; D_{s_h}\right) * TD_h \qquad [7]$$

where TD_h = hourly traffic demand for hour h, D_{re_h} = vehicle delay due to rerouting flow for hour h, D_{lc_h} = vehicle delay due to partial lane closure flow for hour h, D_{s_h} = vehicle delay due to signalized flow for hour h.

Further details about how to calculate the delay time in the three cases (i.e., rerouting, signalized, and partial lane closure) can be found in appendix A. According to equation 7, the delay time in each traffic flow case is calculated based on a one-hour interval, since the traffic demand is changing along the day. The amount of delay determined in equation 7 can be used to calculate the excess bridge user cost incurred due to this delay as shown in the following equations [21]:

$$C_{BU} = C_D + C_{op} \qquad [8]$$

$$C_D = D_T * [P_{HV} * W_{HV} + (1 - P_{HV}) * W_p] \qquad [9]$$

$$C_{op} = D_T * [P_{HV} * OC_{HV} + (1 - P_{HV}) * OC_p] \qquad [10]$$

C_D = traffic delay cost, C_{op} = vehicle operation cost due to delay, W_{HV} = hourly time value for heavy vehicle, W_P = hourly time value for passenger vehicle, OC_{HV} = hourly operation cost for heavy vehicle, OC_P = hourly operation cost for passenger vehicle, P_{HV} = proportion of heavy vehicles.

Modeling Techniques

Based on the findings of the system analysis and the conceptual design, the modelling techniques for the current problem were chosen. A hybrid simulation model was developed to mimic the inspection process. Agent-based simulation and discrete event simulation techniques were integrated to develop this hybrid simulation model. Agent-based simulation was used to model the behaviour of real system elements (i.e. inspection, daily working hours, traffic flow, devices, preparation, and technicians) and their interaction. Each element was presented as an agent and these different agents were connected to each other to consider the interactions between them in the real process. On the other hand, discrete event simulation was built inside the agent-based model to mimic the different activities in sub-processes of the inspection (Figure 3), such as preparation steps, GPR testing steps, etc. Further details about the computerized system will be provided in the next section.

Computerized Model (Programming)

The hybrid model was developed using Anylogic simulation software. Anylogic is a very powerful simulation software, since it supports three types of simulation (i.e. agent-based, discrete event and system dynamic) and provides the capability to integrate these different types of simulation techniques. This section elaborates on the details of the developed hybrid simulation model. It is divided into two parts: agent based and discrete event integration framework and input parameters.

Agent Based and Discrete Event Integration Framework

As shown in Figure 6, The design of the model comprises three layers. The first layer includes all process statistics (e.g., inspection duration, inspection cost and resources utilization efficiency), the main input parameters (i.e., bridge length and width, number of lanes, traffic direction, number of technicians, and utilized technologies), and the four main agents (i.e., working hours, inspection, left traffic, right traffic).

In the second layer, the behaviours of the four agents were presented using several parameters and state charts. The state chart is a graph that presents possible states that the agent may stay on and the movement logic between these states. Agent's parameters and its interactions with other agents control how much time the agent spent in each state and how the agent moves between different states. For example, inspection starts with mobilizing the required tools and devices for inspection and then inspection activities start. When the working hours in the current day are finished, the daily working hours agent sends a message to the inspection agent to stop all inspection activities in progress and move to the demobilization state. Further details about the behaviour of each agent will be discussed next.

Inspection agent includes other agents that are needed for inspection, such as different devices agents (i.e., GPR, IE, USW, UPE, HCP, ER, PR, image), preparation agent, and technicians' agents. The characteristics and behaviour of these agents are presented in layer three (Figure 6). As shown in Figure 6, discrete event models are embedded in the devices and preparation agents. Discrete event model is used to mimic the preparation/ test steps in the real process.

Figure 6

Figure 7 shows the state charts for different agents and their interaction. Starting with daily working hours agent which is initiated at "waitToStartInspection" waiting to set process parameters for all agents. After that, the agent moves to mobilization, then inspection, and finally demobilization. The values of mobilization time, demobilization time, and daily working hours parameters are set before running the model, which determine how much time the agent will stay in each state. The cycle of this agent is repeated every day.

Inspection agent starts from “waitToStartInspection” state waiting to set process parameters for all agents. Next, the agent moves to “waitingNewLane” state to set /update the parameters of the lane that will be inspected. Then, the agent moves to “mobilization” state. After that, it moves to “laneInspectionStarted” state. At the end of each day, the inspection activities are stopped, and the agent goes to “demobilization” state. Daily working hours agent determines how much time inspection agent spent in “mobilization”, “laneInspectionStart”, and “demobilization” states. The agent switches between these three states every day under the control of daily working hours agent (i.e., relationship 1).

After finishing lane inspection, the agent moves from “laneInspectionStarted” state to “waitingNewLane” state to start the inspection activities in a new lane. The agent switch between these two states every lane until the end of inspection. While conducting inspection activities, device agent informs the inspection agent that the next test can start (i.e., relationship 9). Consequently, the inspection agent notifies the next test (i.e. device) agent to be ready for testing (i.e., relationship 9). If the current test is the last test in the inspection process, the test agent sends a message to the inspection agent to switch to another lane to start inspection activities.

There are two traffic agents in the model: left traffic and right traffic. Traffic agents are involved in the model to measure the disruption in traffic flow due to inspection activities and consequently determine excess bridge user cost due to this disruption. There are three states in the traffic agent: “normalFlow”, “flowUnderInspection”, and “changeTrafficDemand”. The first state indicates that inspection activities in this direction have not started yet or have been finished. The agent moves to the second state "flowUnderInspection", when the inspection activities start in this direction. In this case, the inspection agent sends a message to the traffic agent stating that the inspection activities have started in this direction and the traffic flow will be affected (i.e., relationship 10). The agent moves to the third state "changeTrafficDemand" to change the traffic demands. This happens every hour as the average traffic flow density usually changes every hour. At the end of the day or after finishing the inspection of this direction, the traffic flow in this direction returns to the normal operation condition.

Figure 7

Technician agent switches between eight states under the control of daily working hours, inspection, devices, preparation agents (Figure 7). In the beginning, technician agent is initiated at "waitToStartInspection" waiting to set process parameters for all agents. Based on the number of technicians involved in the process, the agent may or may not leave this state (i.e., there are eight technicians' agents in the model). The states in area 1 in Figure 8 are controlled by daily working hours agent as every day, the technician does mobilization, then testing (i.e. includes preparation, testing, and waiting), and finally demobilization. If a lane inspection is finished and the remaining time for working in that day is less than a predetermined value (i.e. in our experiment, this value was adjusted to the summation of lane closure, cleaning, and demobilization times), the agent waits in waste time state until the finish of daily testing time.

Switching between testing states (i.e. area 2 in Figure 8) are determined by the preparation agent, the device agent, and the inspection agent. The preparation agent determines the finishing time for preparation activities (i.e., relationship 5) as all details about the preparation process are built in the preparation agent. Therefore, after finishing the preparation activities, the preparation agent sends a message to the technician agent to inform the technician that testing activities could start. After that, the technician agent checks the availability of the devices that are ready for testing and based on that, the technician agent goes to “NDTTesting” state or “waitingNDTTesting” state (i.e., relationship 6). When the agent goes to “NDTTesting” state, the device agent (involved in the testing at that time) determines how much time the technician agent will stay in this state (i.e., relationship 7). On the other hand, the technician agent stays in “waitingNDTTesting” state until a device becomes available for conducting inspection (i.e., relationship 6). In general, the sequences of testing activities and lanes are determined by the inspection agent (i.e., relationship 3).

The device agent is also initiated at “waitToStartInspection” waiting to set process parameters for all agents. If the test is included in the inspection process (i.e., HCP test), inspection agent sends a message to the device agent to move to “waitingPreviousTest” state. In this state, the agent waits for the completion of preparation activities (or the previous test to provide enough space to start another test). Device agent stay in this state waiting for another message from the inspection agent to start the test. When the device agent receives this message, the agent checks the availability of technicians (i.e., relationship 6). If there is a technician available, the test starts, and the agent goes to “NDTTesting” state. If there is no technician available, the device agent goes to “waitingTechnician” state waiting for a technician to become available. During the test, the daily testing time may finish. If this happens, the daily working hours agent interrupts the device agent and stops the test until the beginning of a new day. The working hours agent is connected indirectly to the device agent through the technician agent (i.e., relationships 2 and 8). During this time, the agent stays in “waitingNewDay” state waiting for a new day to resume testing activities. After finishing the test, the agent releases the technician that was involved in this test (i.e., relationship

7), and the device agent either returns to “waitingPreviousTest” state waiting for its turn of the testing in the next lane or goes to “inspectionCompleted” state, if the inspection is over.

In the model, there are eight agents for devices. The user can define the characteristic of each agent, such as line-based or point-based test, forward or zigzag methods, the device mounted on a cart or a car, etc. Each device agent includes a discrete event simulation model that involves all tasks needed to complete the test procedures. The DES model is working only when the agent enters “NDTTesting” state. For example, In GPR device (Figure 7), when the agent reaches “NDTTesting” state, the number of testing lines per lane are initiated in the DES model (i.e., relationship 11). These lines go to “waitTechnician” queue waiting the technician to finish testing the previous line to start the next line. In DES model, setup task (e.g., switching on the device, setting all testing parameters in the software, and conducting calibration) is repeated once per lane as the branch for this task is closed after passing of the first entity (i.e. line). The procedures for GPR test include adjusting the device to the start line, testing (i.e. moving the GPR cart through the test line), and moving to the next line (Figure 7). These three tasks are repeated for each line until the end of lane testing. When the test is finished, the DES model sends a message to the device agent stating that the test is completed (i.e., relationship 12).

Preparation agent circulates between three states: “waiting”, “Preparing”, and “waitingNewDay”. This agent is initiated in the first state “waiting” until the technician agent calls the preparation agent to start the process (i.e., relationship 4), which makes the agent moves to “Preparing” state. Inside this agent, there is also a DES model that includes all steps involved in this sub-process (e.g., lane closure, cleaning, and testing grid marking). When the agent reach “Preparing” state, the agent starts running the DES model to determine the time needed for preparation. Similar to the device agent, if the daily testing time is over in that day, the daily working hours agent stops the preparation process and the preparation agents moves to "waitingNewDay" (i.e., relationships 2 and 4). After finishing the process, the DES model notifies the agent that the process is finished to move again to the "waiting" state waiting the new lane. Accordingly, the preparation agent notifies the technician agent that the process is finished (i.e., relationship 5).

Figure 8

Input Parameters

Several inspection parameters were considered to develop the model. As shown in Figure 9, there are five main categories for these parameters. The first group includes bridge characteristics parameters, such as bridge length, bridge width, traffic direction (i.e. one way or two ways) and number of lanes. In the second category, general inspection information parameters are provided, such as grid spacing, number of technicians, working hours per day, etc.

Figure 9

The third group determines the prospective strategy to control traffic while performing the inspection activities. As mentioned before, there are two conditions for the work zone area: complete direction closure and partial direction closure. In the first condition, there are two strategies to control traffic: rerouting the traffic flow in that direction to an alternate route or rerouting the traffic flow to the opposite direction (i.e., in this case, the traffic may be subjected to signalized flow rules). On the other hand, in partial direction closure, two strategies can be adopted to control the traffic flow. The first one is rerouting the traffic flow in that direction to an alternate route, while the second strategy is letting the traffic flows beside the work zone, which will disturb the flow and may form a traffic queue. Decision-makers should adopt the most appropriate strategy that has the least impact on the traffic flow and consequently on the user cost.

The fourth category comprises the bridge user parameters, such as daily traffic density, traffic distribution along the day, proportion of heavy vehicle to the total traffic, permitted vehicle speeds in different cases, and time value and operation cost for different vehicles types. Finally, the last group includes the parameters related to the implementation of different inspection activities, such as test approach (i.e., point-based test or line-based test), test methods (i.e., forward or zigzag), test speed, etc.

Model Verification and Case Studies

Verification process aims at ensuring that the computerized model performs as intended and has been programmed and implemented correctly [22,23]. The verification of the computerized model was divided into two stages: logic verification and calculations verification. In the first stage, the relationships between model inputs (i.e., model parameters in Figure 9) and the model outputs (i.e., inspection duration and cost) were analysed from a logical perspective rather than a value perspective. On the other hand, calculations verification intends to ensure the integrity of the model calculations and identify error sources.

Figure 10 shows the relationships between five inspection parameters and the model outputs. Figure 10 (a) shows the relationship between inspection duration and four cases of bridge area. The four cases have the same bridge length but vary in bridge width (i.e., number of lanes: one, two, three, and four lanes). The relationship proves that increasing the bridge area increases the inspection duration.

Figure 10 (b) demonstrates the relationship between the number of technicians and the inspection duration in case of utilizing three technologies in the inspection process. The findings show that increasing the number of technicians from one to two technicians reduces the inspection duration by approximately 40 %. Hiring a third technician also reduces the inspection duration however, the improvement of results is less than the first case (i.e., around 17%). Employing more than three technicians in the inspection process slightly reduces the inspection duration because only three technologies are being utilized in the inspection process and the slight improvement comes from reducing the preparation duration. Indeed, increasing the number of technicians reduces preparation time and creates an overlap between different testing methods (Figure 11). However, when the number of technicians becomes bigger than the number of utilized testing methods, creating further overlaps between the inspection activities will not be possible and the improvement in the inspection duration will come only from reducing preparation time.

Figure 10

Figure 10 (c) shows the impact of increasing daily traffic density on the bridge user cost. More vehicles drive beside the work zone means more delayed vehicles and longer delay time. The formation of traffic queue is more likely to happen in the case of increasing traffic density than the current bridge capacity. This is clearly noticed in the figure at a traffic rate equal to 19000 vehicle/day/lane. Figure 10 (d) and (e) illustrate the impact of testing grid spacing and test speed on the inspection duration. Using narrow grid spacing increases the inspection duration and vice versa. On the other hand, increasing the test speed by using faster NDT technology, such as GPR and infrared camera, reduces the inspection duration.

Figure 11

The second verification stage is calculations verification, where the values of the model outputs are being traced and checked using hand calculations. Hand calculations provide detailed calculations for the model outputs, which is a perfect tool to review all aspects of the model outputs to identify error sources. Therefore, the details of the computerized model’s calculations are needed to manage this objective. In this regard, the detailed calculations of the computerized model were exported to excel sheets.

Three cases and eight scenarios were used to compare the results of the hand calculations and the computerized model outputs. These cases are shown in Table 1. The area of the bridge in the three cases are 4385, 2192, and 6580 ft^2, respectively. Number of lanes are 4, 2, and 6 lanes, respectively. The first case is one-way bridge, while the other two cases are two-way bridges. GPR was used to inspect the bridge in the first case, while eight technologies were used to inspect the bridges in the other cases. All NDT tests were conducted based on 1 ft test spacing, except image technique, which was implemented based on three paths per lane. Three scenarios (i.e., 1.1,1.2 and 1.3) were used to check the total inspection duration in the first case: inspecting one lane per time, inspecting two lane per time, and inspecting three lanes per time. Since the total number of lanes in this case is four, in the first scenario, four equal stages for inspection process were considered (one lane per stage), in the second scenario, two equal stages for inspection process were considered (two lanes per stage), and in the third scenario, two unequal stages for inspection process were considered (inspecting three lanes in the first stage and one lane in the second stage). Four scenarios were proposed for the second case (i.e., 2.1, 2.2, 2.3, and 2.4): signalized traffic control strategy/one technician, rerouting traffic control strategy/one technician, signalized traffic control strategy/three technician, and rerouting traffic control strategy/three technician. Only one scenario for the third case study was adopted due to the complexity of the hand calculations, especially for large bridges.

To use the computerized model in estimating the duration and cost of forthcoming inspection tasks, the user should first input the inspection parameters, such as bridge length, bridge width, number of lanes, traffic control strategy, traffic density, and so forth (Figure 9). The outputs of the computerized model for the third and fourth scenarios in case study 2 are shown in Figure 12. The outputs include the most important input parameters, such as bridge length and width, number of lanes, and traffic direction (i.e., upper left part of Figure 12), detailed information about the inspection duration and cost (i.e., upper right part of Figure 12), and resource utilization efficiency (i.e., lower part of Figure 12). In addition, detailed information about each agent in the inspection process is exported to an excel sheet. Figure 13 shows movement details of the first technician in case 2.3 (Table 1).

Figure 12

Figure 13

The findings of the different scenarios in the first and the second case studies aimed to optimize the inspection process by altering the number of lanes that can be closed simultaneously for inspection (i.e., 1 to 3), traffic control strategy (i.e., signalized and rerouting), and technicians' number (i.e., 1 to 3). In the first case study, increasing the number of lanes that can be closed simultaneously for inspection reduced the inspection duration (i.e., scenarios 1.2 and 1.3). This in turn cut in the inspection cost in scenario 1.2. Nevertheless, inspection cost extremely increased in scenario 1.3 due to the formed traffic queue during inspection. The findings of the proposed scenarios in the second case study show that using three technicians (i.e., cases 2.3 and 2.4) reduced the inspection duration from 59.21 hours to 29.44 hours and consequently reduced the corresponding cost. Most of time-dependent cost items were reduced, such as cost of devices, transportation, bridge user, traffic control, and other (Figure 14), while technician cost was increased due to idle or waiting time that can be clearly noticed on the performance of the second and the third technicians (Figure 12). Furthermore, choosing rerouting scenario (i.e., cases 2.2 and 2.4) as a traffic control strategy gave the least bridge users cost (Figure 14). Combining the two inputs produced the optimum inspection cost and duration (i.e., case 2.4). This example demonstrated the capability of the hybrid model to compare the proposed scenarios for inspection and to optimize the inspection process.

Table 1

Going back to the second main stage in the verification process, where these cases and their different scenarios were used, calculations verification step highlighted some problems in the results of the computerized model. The data in the excel sheets (e.g., Figure 13) were used to trace each aspect in the computerized model outputs to identify the source of the problem. After several iterations of editing and running the model, the results of the computerized model proved a considerable amount of compatibility with the results of hand calculations. As shown in Table 1, the inspection duration of both computerized model and hand calculations are almost the same. The small differences in the inspection cost between the computerized model and the hand calculations are due to the approximation in hand calculations.

Figure 14

Model Implementation and Validation

Model validation aims at ensuring that the conceptual model and its application (i.e., computerized model) provide an accurate representation of the real system [22,23]. Two field tests were conducted to validate the developed model. The areas of the two tests are 336 and 828 square feet, respectively. Each test comprises three main tasks: preparation, GPR test, and infrared thermography test. Further details about the field tests are provided in Table 2.

Table 2

Preparation task includes marking grid points on the tested surface. The two test approaches (i.e., point-based and line-based test approaches) were considered while conducting the field tests. As listed in Table 2, GPR test (i.e., line-based test) was conducted in the first field test in a forward order, while in the second field test, a zigzag order was adopted. In both field tests, the spacing between GPR test lines was 2 ft. On the other hand, infrared thermography test (i.e., point-based test) was conducted in a forward order in both field tests. In the first field test, 2 ft spacing was considered to conduct infrared thermography test, while 4 ft spacing was adopted for the second field test.

Table 3 shows the results of both field test and model outputs. The total durations for the two field tests are 29.24 and 46.31 minutes, respectively. Despite the area of the second field test is almost 2.5 times the area of the first field test, the duration for GPR tests and infrared tests in the two field tests are very close. Indeed, using the zigzag test procedure for GPR test in the second field test saved the returning time to the first line to start testing the next line, which accumulated and consequently reduced the total duration. On the other hand, infrared thermography test was conducted in the first field test based on 2 feet test spacing making the total tested lines and points in the first field test equal to 5 and 135, respectively, while in the second test, the test spacing was adjusted to 4 feet, which reduced these numbers to 2 lines and 68 points and consequently reduced the total infrared test duration.

Table 3

The total durations of the two field tests from the hybrid simulation model outputs are 28.51 and 46.8 minutes, respectively. The percentages of error between actual duration and estimated duration are 2.5% and 1.06%, respectively. The difference between actual duration and estimated duration for infrared thermography test gave the largest error in the estimated durations (i.e., 4.71%). All difference rates are less than 5%, which reflects the accuracy of the computerized model in estimating inspection duration.

CONCLUSION AND FUTURE WORK

This paper illustrated and discussed the hybrid simulation model (i.e., BDIP) that was developed to facilitate planning the inspection process of concrete bridge deck using non-destructive technologies. The developed model integrates agent based and discrete event simulation approaches into a single platform. Agent based simulation is used to imitate the behaviour of different elements involved in the process and their interactions, such as technicians, NDT devices, and traffic. On the other hand, discrete event simulation is used to mimic the sub-processes inside the inspection considering different tasks and their sequences (e.g., preparation, GPR test, and HCP test). Two approaches were adopted to verify the developed model: logic verification and calculations verification. The findings of the verification process demonstrated the capability of the developed model to accurately estimate inspection duration and cost, effectively measure traffic disorder, and compare different scenarios for implementing inspection. On the other hand, two field tests were used to validate the model. The comparison between the results of the field tests and the hybrid simulation model proved the capability of the developed model to precisely represent the real process.

In verification process, three cases with different scenarios to implement inspection were used. Based on the findings of these cases, image and GPR testing techniques proved their capabilities to offer high inspection speed. Possibility to simultaneously close several lanes for inspection can reduce inspection duration (i.e., cases 1.2 and 1.3) and cost (i.e., case 1.2). Nevertheless, it may significantly impact traffic flow (i.e., forming traffic queue) and increase bridge user cost (i.e., case 1.3). Hiring more technicians can reduce inspection duration (i.e., cases 2.3 and 2.4) but some factors should be considered to determine the optimum technicians' number, such as number of utilized tests and inspection duration and cost.

Overall, the developed hybrid model can support decision-makers during planning the forthcoming inspection activities by examining the impact of adopting different traffic control strategies and considering various scenarios to implement inspection, which include utilized technologies, inspection team size, working for overtime, inspection start time, and so forth. Nevertheless, two more aspects need to be considered in future research. The first one is process visualization, which can provide an in-depth understanding of what is going on in the process instead of getting only numerical outputs. The second aspect is to consider other bridge components (e.g., bridge piers and beams), which will support the wide application of the developed model.

APPENDIX A

This section is devoted to illustrating how to calculate delay terms in equation 7, which include delay due to rerouting flow, delay due to partial direction closure flow, and delay due to signalized flow.

<u>Rerouting</u>

Delay due to rerouting traffic (D_{re}) is the difference between the original travel time (T_{or}) and travel time required for the new route (T_{re}). It can be calculated using the following equation:

$$D_{re} = T_{re} - T_{or} \quad [11]$$

<u>Partial Direction Closure</u>

The traffic capacity of the bridge after partial direction closure controls the traffic flow during inspection activities. If the hourly direction capacity of the bridge during inspection (*TC*) is less than the hourly traffic demand (*TD*), vehicles queue will be generated increasing traffic delays. Bridge direction capacity can be calculated from the following equation [24,25]:

$$TC = Q_{lane} * F_{HV} * N_{l(opened)} \quad [12]$$

where Q_{lane} = hourly passenger-car equivalent capacity per lane (i.e. 1600 car/hour/lane), $N_{l(opened)}$ = number of opened lanes, F_{HV} = adjusted factor for heavy vehicles (i.e. buses and trucks) and can be calculated using the following equation:

$$F_{HV} = \frac{1}{1+P_{HV}(E_R-1)} \quad [13]$$

where P_{HV} = proportion of heavy vehicles, E_R = passenger-car equivalent for heavy vehicles.

While determining traffic delays, there are two cases in partial lane closure: traffic flow when no queue exist ($TC \geq TD$) and traffic flow subjected to queue ($TC < TD$). The delay calculations were adopted from [20,21,24,26] as follows:

No queue ($TC \geq TD$)

Speed changes are the main source of delays in this case. First, the vehicles reduce their driving speed from the normal speed (i.e., freeway speed) to the work zone speed before reaching the work zone by a specific distance (i.e., deceleration distance). Second, the vehicles move beside the work zone for a distance equal to work zone length at the reduced speed. Finally, the vehicles accelerate from the work zone speed to the freeway speed to continue their trips. The total delay due to speed changes, in this case, can be calculated as follow:

$$D_{lc} = D_{decc_1} + D_{rs} + D_{acc_1} \quad [14]$$

where D_{decc1} = delay time due to reducing speed from freeway speed (V_f) to work zone speed (V_{wz}), D_{rs} = delay time due to driving the car with work zone speed instead of freeway speed, D_{acc1} = delay time due to acceleration from work zone speed to the freeway speed. Equations 15 to 17 can be used to calculate these parameters.

$$D_{decc_1} = \frac{2L_{decc}}{V_f+V_{wz}} - \frac{L_{decc}}{V_f} \quad [15]$$

$$D_{rs} = L_{wz}\left(\frac{1}{V_{wz}} - \frac{1}{V_f}\right) \quad [16]$$

$$D_{acc_1} = \frac{V_f^2 - V_{fwz}^2}{2aV_f} \quad [17]$$

where L_{decc} = deceleration distance, L_{wz} = work zone length, a = vehicle acceleration rate (2.28 m/sec^2).

<u>Traffic flow under queue ($TC < TD$)</u>

In this case, the vehicles reduce their speeds from the freeway speed to near zero speed (when approaching the traffic queue formed before the work zone). Then, the vehicles move at the reduced speed (i.e., queue speed) during the queuing time before entering the work zone. Next, the vehicles accelerate from the queue speed to the work zone speed. After that, the vehicles move beside the work zone at the reduced speed (i.e., work zone speed). Finally, the vehicles accelerate from the work zone speed to the freeway speed to continue their trips. The total delay can be calculated as follow:

$$D_{lc} = D_{decc_2} + D_q + D_{acc_2} + D_{rs} + D_{acc_1} \quad [18]$$

where D_{decc2} = delay time due to car stopping, D_q = delay time due to driving in queue speed instead of freeway speed, D_{acc2} = delay time due to acceleration from queue speed to the work zone speed. The parameters in equation 18 can be calculated using equations 16, 17, (19-23).

$$D_{decc_2} = \frac{L_{decc}}{V_f} \quad [19]$$

$$Q = (TD - TC) * T_{insp}/N_{l(opened)} \quad [20]$$

$$L_q = Q_{avg} * L_v \quad [21]$$

$$D_q = L_q\left(\frac{1}{V_q} - \frac{1}{V_f}\right) \quad [22]$$

$$D_{acc_2} = \frac{V_{wz}^2 - V_q^2}{2aV_{wz}} \quad [23]$$

where Q = number of vehicles in queue per lane, Q_{avg} = average number of vehicles in calculation interval, L_q = queue length, L_v = average distance for each vehicle (i.e., 12 m), V_q = queue speed.

Signalized Flow

In signalized flow, green times (*g*) are adjusted for both directions, in which vehicles are permitted to drive beside work zone. Cycle time (*C*) is the required time to reopen the bridge in a specific direction to traffic flow, which is the summation of green times in both directions. During signalized flow, the hourly direction capacity of the bridge (TC_s) is reduced due to interrupting traffic flow in that direction to allow for traffic flow in the opposite direction (equation 24). In this case, the total delay includes four terms (equation 25): non-random delay (D_1), overflow delay (D_2), delay time due to driving the car with work zone speed instead of freeway speed, and delay time due to acceleration from work zone speed to the freeway speed. Equations (25-27) are dedicated to calculate delays due to signalized flow (D_s) as follows [27-29]:

$$TC_s = (TC * g)/C \qquad [24]$$

$$D_s = D_1 + D_2 + D_{rs} + D_{acc_1} \qquad [25]$$

$$D_1 = \begin{cases} \frac{0.5*C(1-u)^2}{1-(xu)} & x \le 1 \\ 0.5(C-g) & x > 1 \end{cases} \qquad [26]$$

$$D_2 = \begin{cases} 0 & x \le x_0 \\ 900 * T_{insp}[(x-1) + \sqrt{(x-1)^2 + \frac{8k(x-x_0)}{TC_s*T_{insp}}}\ ] & x \le 1 \\ 1800\,(x-1) & x > 1 \end{cases} \qquad [27]$$

where x = degree of saturation = TD/TC_s, u = ratio of effective green time = g/C, *k (constant)=1.5 and* $x_0=0.67+TC_{s*}$(g/600) according to Australian code.

Further information about the aforementioned equations (12 to 27) can be found in [20,21,24-29].

REFERENCES

[1] American Society of Civil Engineers (ASCE), Infrastructure Report Card, Available at https://www.infrastructurereportcard.org/cat-item/bridges/, (2017), Accessed date: 27 February 2020.

[2] S. Abdelkhalek, T. Zayed, Comprehensive Inspection System for Concrete Bridge Deck Application: Current Situation and Future Needs, Journal of Performance of Constructed Facilities, (2020), https://doi.org/10.1061/(ASCE)CF.1943-5509.0001484.

[3] R.T. Benjamin, Q. Yu, D.B. Mark, L. Samuel, The Economic Impact of Implementing Nondestructive Testing of Reinforced Concrete Bridge Decks in Indiana, Technical report, Available at Purdue University, https://docs.lib.purdue.edu/jtrp/1635/, (2016), Accessed date: 27 February 2020.

[4] N. Gucunski, A. Imani, F. Romero, S. Nazarian, D. Yuan, H. Wiggenhauser, P. Shokouhi, A. Taffe, D. Kutrubes, Nondestructive Testing to Identify Concrete Bridge Deck Deterioration, Technical report, Available at Transportation Research Board, http://www.trb.org/Main/Blurbs/167278.aspx, (2013), Accessed date: 27 February 2020.

[5] H.-Y. Chung, L. Manuel, H. Frank Karl, Optimal Inspection Scheduling of Steel Bridges Using Nondestructive Testing Techniques, Journal of Bridge Engineering 11 (3), (2006), pp. 305-319, https://doi.org/10.1061/(ASCE)1084-0702(2006)11:3(305).

[6] S. Kim, D.M. Frangopol, Decision Making for Probabilistic Fatigue Inspection Planning Based on Multi-Objective Optimization, International Journal of Fatigue 111, (2018), pp. 356-368, https://doi.org/10.1016/j.ijfatigue.2018.01.027.

[7] D. Agdas, J.A. Rice, J.R. Martinez, I.R. Lasa, Comparison of Visual Inspection and Structural-Health Monitoring As Bridge Condition Assessment Methods, Journal of Performance of Constructed Facilities 30 (3), (2016), 04015049, https://doi.org/10.1061/(ASCE)CF.1943-5509.0000802.

[8] S. AbouRizk, Role of Simulation in Construction Engineering and Management, Journal of Construction Engineering and Management 136 (10), (2010), pp. 1140-1153, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000220.

[9] R.E. Nance, A history of discrete event simulation programming languages, Sigplan Notices 28 (3), (1993), pp. 149–175, https://doi.org/10.1145/155360.155368.

[10] T.M. Zayed, D. Halpin, Simulation of Concrete Batch Plant Production, Journal of Construction Engineering and Management 127 (2), (2001), pp. 132-141, https://doi.org/10.1061/(ASCE)0733-9364(2001)127:2(132)

[11] M. Marzouk, H. Said, M. El-Said, Special-Purpose Simulation Model for Balanced Cantilever Bridges, Journal of Bridge Engineering 13 (2), (2008), pp. 122-131, https://doi.org/10.1061/(ASCE)1084-0702(2008)13:2(122)

[12] C. Zhang, T. Zayed, A. Hammad, Resource Management of Bridge Deck Rehabilitation: Jacques Cartier Bridge Case Study, Journal of Construction Engineering and Management 134 (5), (2008), pp. 311-319, https://doi.org/10.1061/(ASCE)0733-9364(2008)134:5(311)

[13] A. Alvanchi, R. Azimi, S. Lee, S.M. AbouRizk, P. Zubick, Off-Site Construction Planning Using Discrete Event Simulation, Journal of Architectural Engineering 18 (2), (2012), pp. 114-122, https://doi.org/10.1061/(ASCE)AE.1943-5568.0000055

[14] R.K. Balagopalan, Simulation Based Cost-Benefit Analysis for the Inspection of Highway Bridges using Small Unmanned Aerial Systems, M.Sc. Thesis, Available at Florida Institute of Technology, http://hdl.handle.net/11141/2333, (2018), Accessed date: 27 February 2020.

[15] A. ElNimr, M. Fagiar, Y. Mohamed, Two-way integration of 3D visualization and discrete event simulation for modeling mobile crane movement under dynamically changing site layout, Automation in Construction 68, (2016), pp. 235-248, https://doi.org/10.1016/j.autcon.2016.05.013.

[16] H. Alzraiee, T. Zayed, O. Moselhi, Dynamic planning of construction activities using hybrid simulation, Automation in Construction 49, (2015), pp. 176-192, https://doi.org/10.1016/j.autcon.2014.08.011.

[17] P.O. Siebers, C.M. Macal, J. Garnett, D. Buxton, M. Pidd, Discrete-event simulation is dead, long live agent-based simulation!, Journal of Simulation 4 (3), (2010), pp. 204-210, https://doi.org/10.1057/jos.2010.14.

[18] E. Bonabeau, Agent-based modeling: Methods and techniques for simulating human systems, Proceedings of the National Academy of Sciences 99 (suppl 3), (2002), pp. 7280-7287, https://doi.org/10.1073/pnas.082080899.

[19] K. Kim, K.J. Kim, Multi-agent-based simulation system for construction operations with congested flows, Automation in Construction 19 (7), (2010), pp. 867-874, https://doi.org/10.1016/j.autcon.2010.05.005.

[20] Y. Jiang, A Model for Estimating Excess User Costs at Highway Work Zones, Transportation Research Record 1657 (1), (1999), pp. 31-41, https://doi.org/10.3141/1657-05.

[21] M. Safi, Bridge Life Cycle Cost Optimization: Analysis, Evaluation, & Implementation, M.Sc. Thesis, Available at Royal Institute of Technology (KTH), https://www.diva-portal.org/smash/get/diva2:289293/FULLTEXT01.pdf,, (2009), Accessed date: 27 February 2020.

[22] J.P.C. Kleijnen, Verification and validation of simulation models, European Journal of Operational Research 82 (1), (1995), pp. 145-162, https://doi.org/10.1016/0377-2217(94)00016-6.

[23] R.G. Sargent, Verification and validation of simulation models, Proceedings of the 2011 Winter Simulation Conference (WSC), Arizona, USA, Dec. 11-14, (2011), pp. 183–198, https://doi.org/10.1109/WSC.2011.6147750.

[24] D.A. Curry, D.G. Anderson, Procedures for Estimating Highway User Costs, Air Pollution, and Noise Effects, Technical report, Available at Transportation Research Board, https://trid.trb.org/view/115937, (1972), Accessed date: 27 February 2020.

[25] Transportation Research Board, Highway Capacity Manual 2000, Transportation Research Board, National Research Council, Washington, D.C., USA, (2000), ISBN: 0-309-06681-6.

[26] J.L. Memmott, C.L. Dudek, Queue and User Cost Evaluation of Work Zones (QUEWZ), 63rd Annual Meeting of the Transportation Research Board, Washington, D.C., USA, Jan. 16-20, (1984), pp. 12-19, Available at: https://trid.trb.org/view/217832, Accessed date: 27 February 2020.

[27] R. Akçelik, N.M. Rouphail, Estimation of Delays at Traffic Signals for Variable Demand Conditions, Transportation Research Part B: Methodological 27 (2), (1993), pp. 109-131, https://doi.org/10.1016/0191-2615(93)90003-S.

[28] M.J. Cassidy, Y. Son, D.V. Rosowsky, Estimating Motorist Delay at Two-Lane Highway Work Zones, Transportation Research Part A: Policy and Practice 28 (5), (1994), pp. 433-444, https://doi.org/10.1016/0965-8564(94)90025-6.

[29] W. Zhu, Z. Li, J. Ash, Y. Wang, X. Hua, Capacity Modeling and Control Optimization for a Two-Lane Highway Lane-Closure Work Zone, Journal of Transportation Engineering, Part A: Systems 143 (12), (2017), 04017059, https://doi.org/10.1061/JTEPBS.0000078

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Table 1: Different cases for model calculations verification

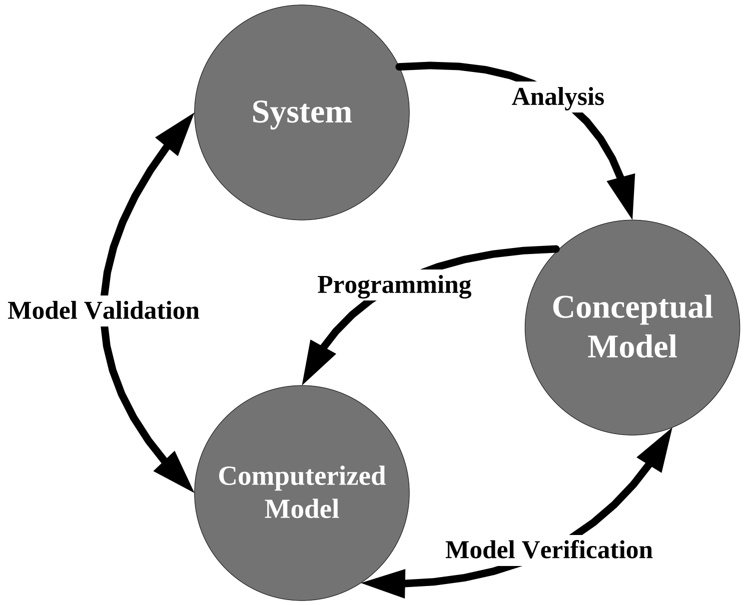
Case	Bridge area (ft^2)	Number of Lane	Traffic direction	Testing technologies	Traffic control Strategy	Number of closed lanes for inspection	Number of technicians	Hand calculations		Computerized model	
								Duration (hr)	Cost ($)	Duration (hr)	Cost ($)
1.1	4385	4	1	GPR	Partial direction closure	1	1	9.54	3,691.04	9.53	3,690.96
1.2	4385	4	1	GPR	Partial direction closure	2	1	7.6	2,793.62	7.59	2,793.92
1.3	4385	4	1	GPR	Partial direction closure	3	1	7.6	16,698.16	7.59	16,686.36
2.1	2192	2	2	GPR-IE-USW-UPE-HCP-ER-PR-Image	Signalized	1	1	59.2	65,846.32	59.21	65,836.98
2.2	2192	2	2	GPR-IE-USW-UPE-HCP-ER-PR-Image	Rerouting	1	1	59.2	42,204.00	59.21	42,212.25
2.3	2192	2	2	GPR-IE-USW-UPE-HCP-ER-PR-Image	Signalized	1	3	29.47	34,027.70	29.44	33,949.44
2.4	2192	2	2	GPR-IE-USW-UPE-HCP-ER-PR-Image	Rerouting	1	3	29.47	23,010.20	29.44	23,022.16
3	6580	6	2	GPR-IE-USW-UPE-HCP-ER-PR-Image	Partial direction closure	1	1	175.79	126,171.31	175.81	125,452.15

Table 2: Field tests details

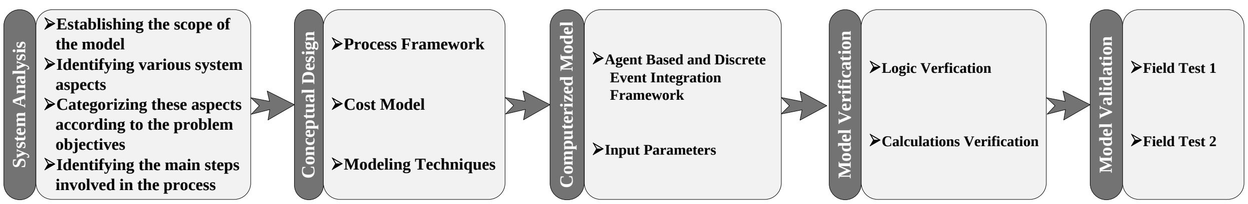
Parameter	Field test 1	Field test 2
Area	336 ft^2	828 ft^2
Number of grid lines	5	5
Number of points per line	27	68
Spacing between points	2 ft	2 ft
GPR testing spacing	2 ft	2 ft
GPR testing approach	forward	zigzag
Infrared testing spacing	2 ft	4 ft
Infrared testing approach	forward	forward

Table 3: Results of field tests and computerized model

Parameter	Field test 1	Model output	% Error
Preparation duration (min.)	11.81	11.63	1.53
GPR test duration (min.)	6.65	6.5	2.26
Infrared test duration (min.)	10.78	10.38	3.72
Total duration (min.)	29.24	28.51	2.5
Parameter	**Field test 2**	**Model output**	**% Error**
Preparation duration (min.)	29.12	28.84	< 1
GPR test duration (min.)	7.41	7.72	4.19
Infrared test duration (min.)	9.78	10.24	4.71
Total duration (min.)	46.31	46.8	1.06



a) Main stages



b) Detailed steps and sequences of main stages

Figure 1: Methodology to develop the hybrid model: a) Main stages and b) Detailed steps and sequences of main stages

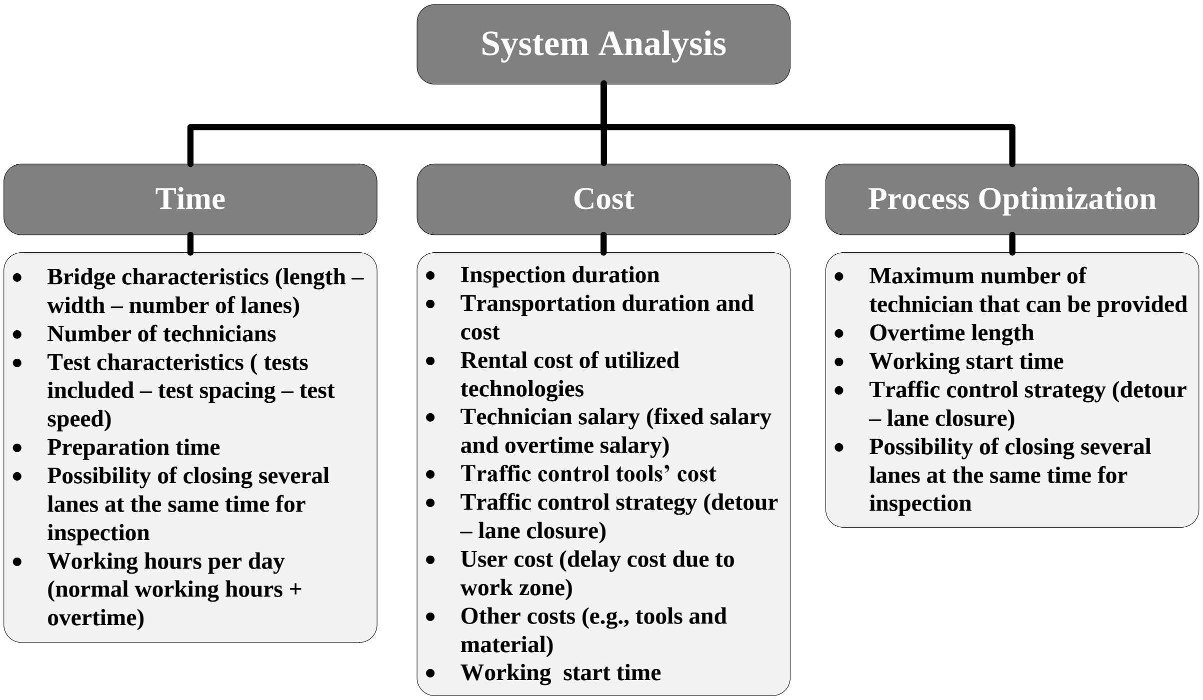


Figure 2: Parameters influence model objectives

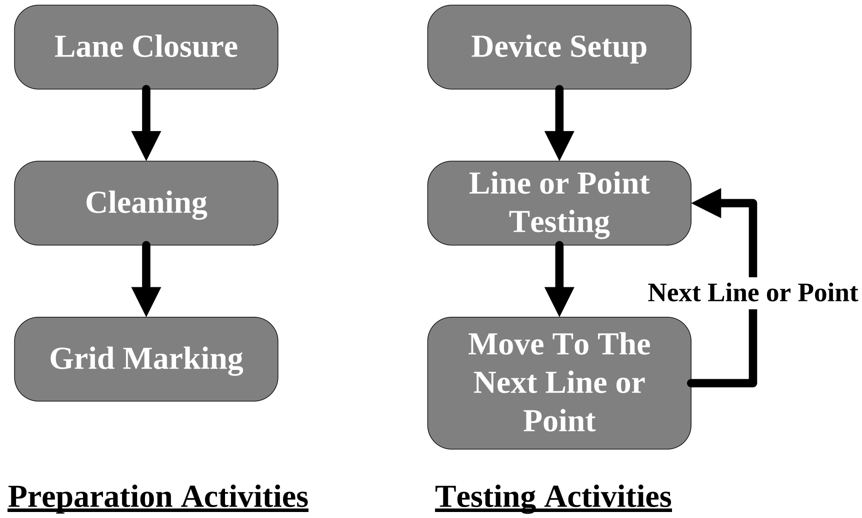


Figure 3: Inspection activities

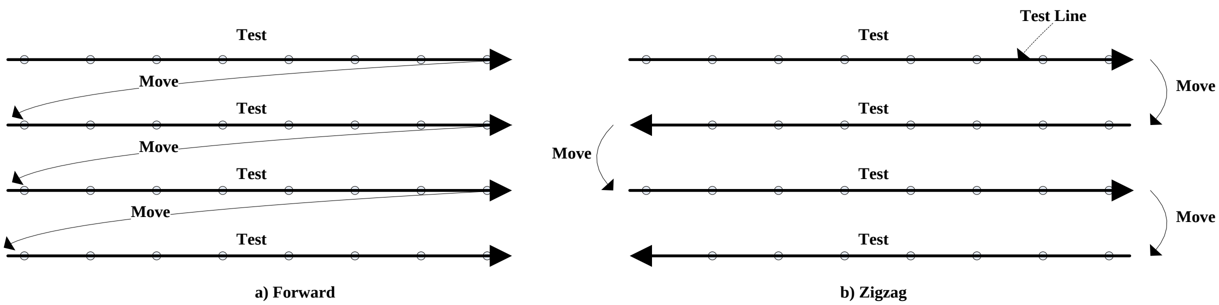


Figure 4: Line-based test methods: a) Forward, b) Zigzag

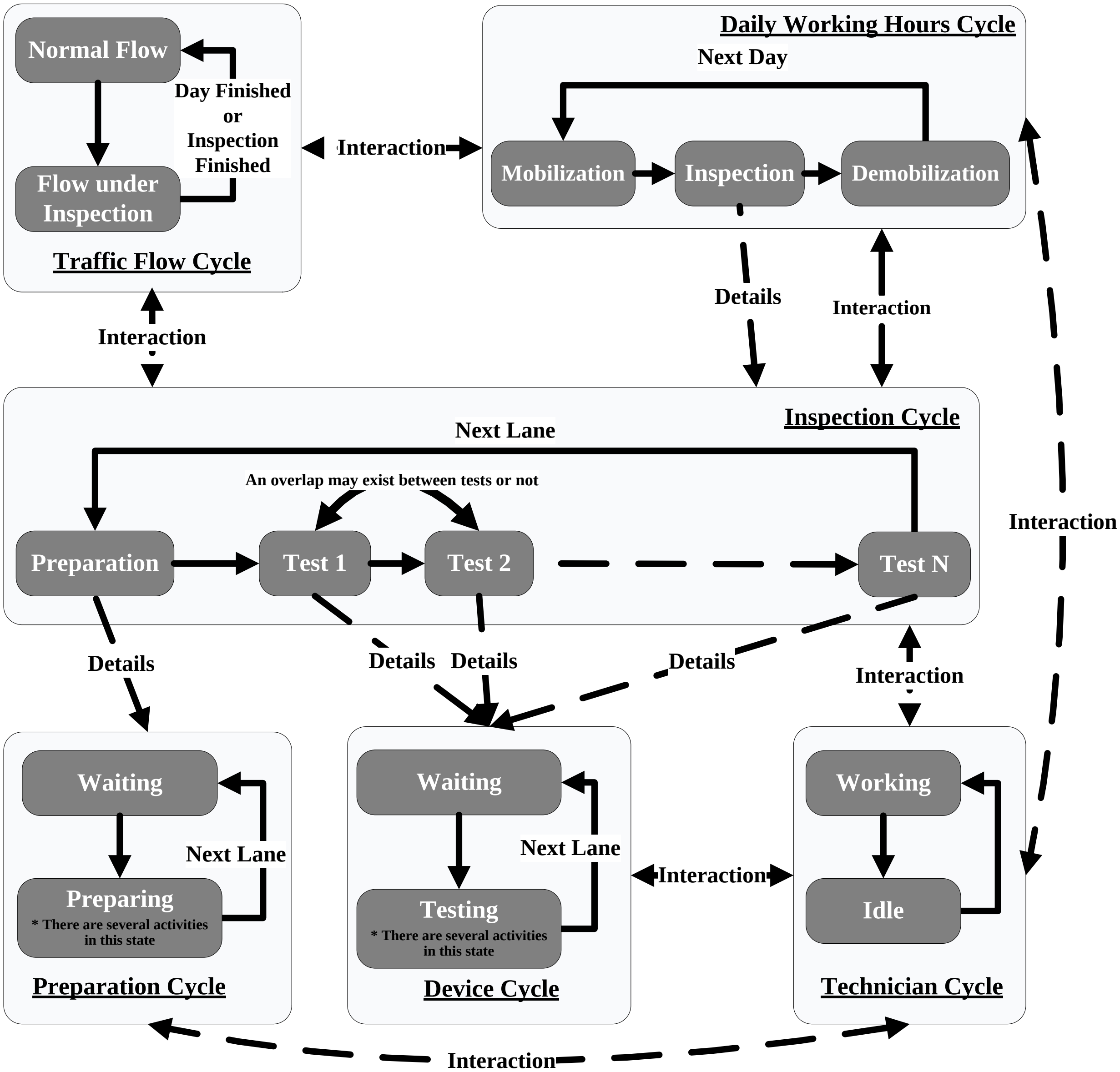


Figure 5: Conceptual model of inspection process

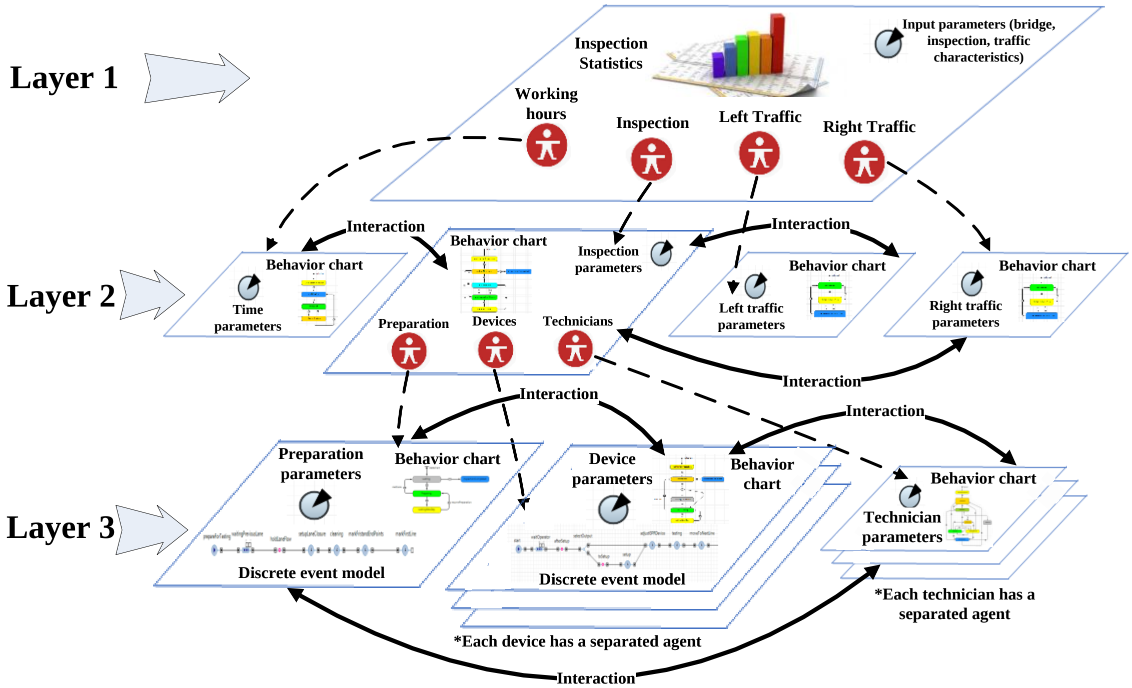


Figure 6: Anylogic framework for hybrid model

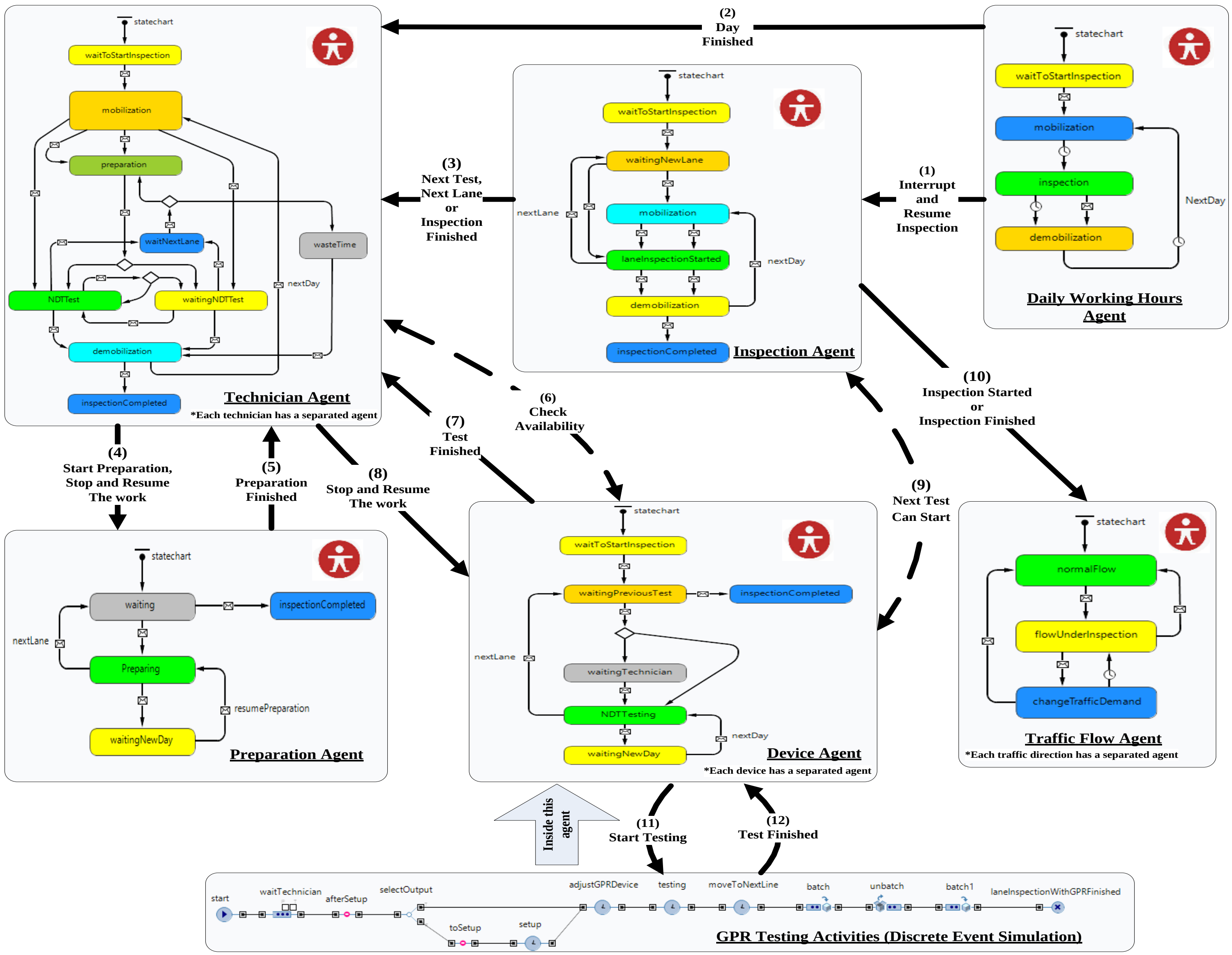


Figure 7: Different agents in hybrid model

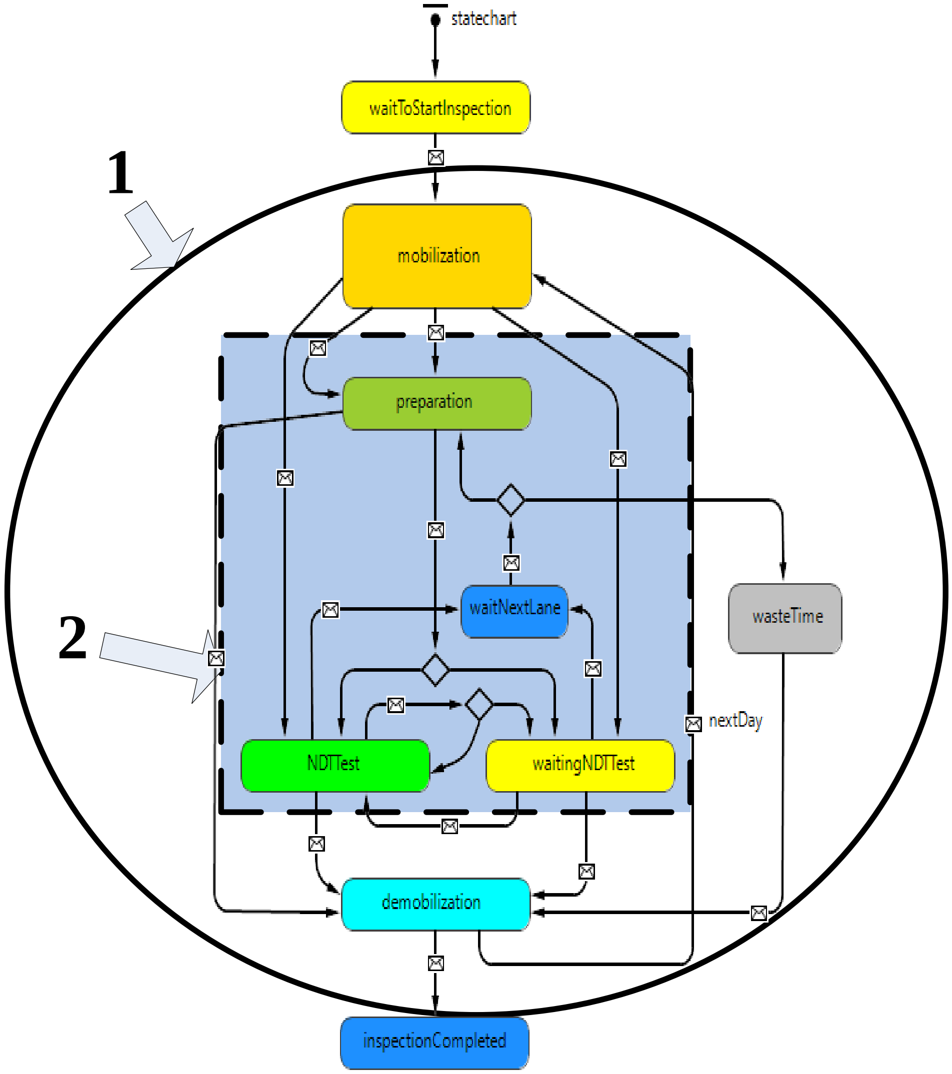


Figure 8: Technician agent

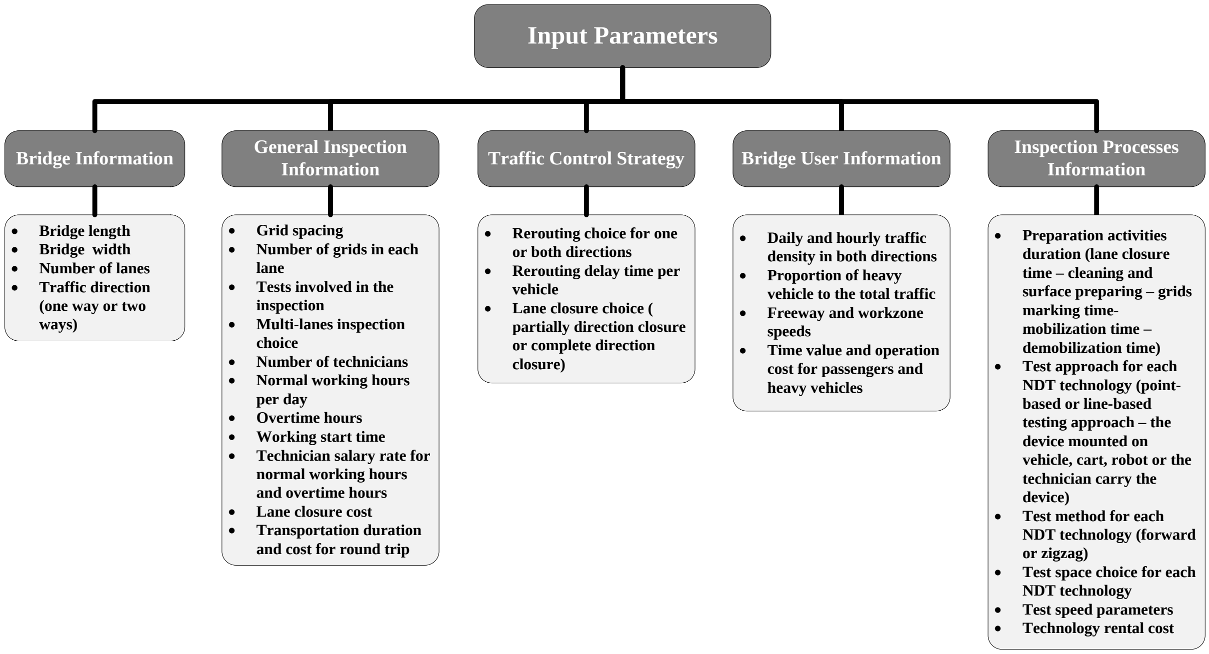


Figure 9: Inspection parameters involved in the developed model

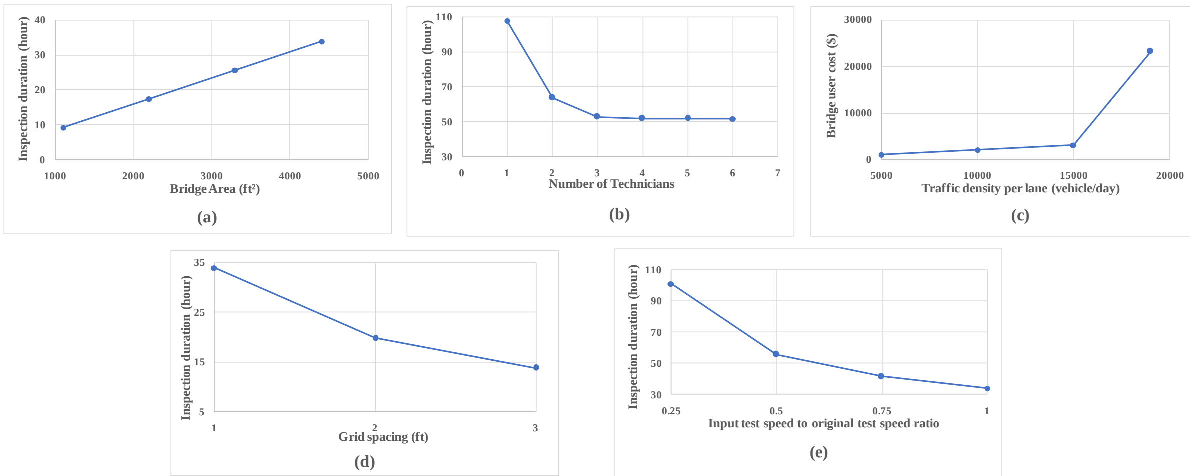


Figure 10: Logic verification: a) relationship between bridge area and inspection duration, b) relationship between number of technicians and inspection duration, c) relationship between traffic density per lane and bridge user cost, d) relationship between testing grid spacing and inspection duration, e) relationship between input test speed to original test speed ratio and inspection duration

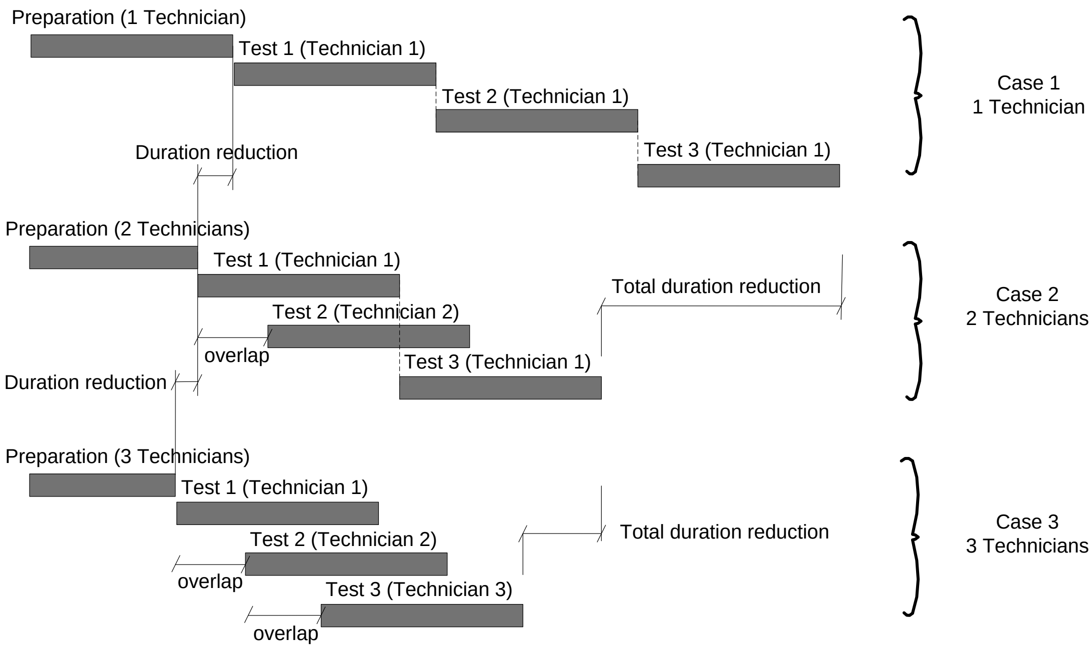


Figure 11: Relationship between number of technicians and inspection duration

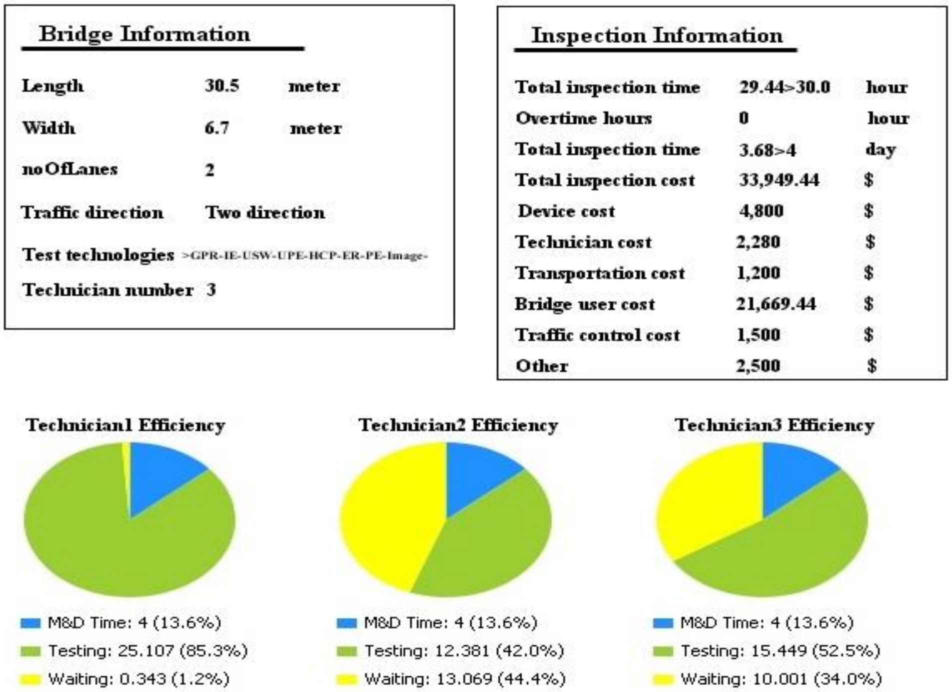


Figure 12: Outputs of the computerized model (case 2.3 in Table 1)

Activity	Day	Start	Finish	Duration	Device
Mobilization	1	8.00	8.50	0.50	
Preparation	1	8.50	9.16	0.65	
Waiting NDT Testing	1	9.16	9.33	0.17	
NDT Testing	1	9.33	10.11	0.79	GPR
NDT Testing	1	10.11	12.92	2.81	IE
NDT Testing	1	12.92	15.50	2.58	PE
Demobilization	1	15.50	16.00	0.50	
Mobilization	2	8.00	8.50	0.50	
NDT Testing	2	8.50	14.22	5.72	PE
Waiting Next Lane	2	14.22	14.22	0.00	
Preparation	2	14.22	14.88	0.65	
Waiting NDT Testing	2	14.88	15.05	0.17	
NDT Testing	2	15.05	15.50	0.45	GPR
Demobilization	2	15.50	16.00	0.50	
Mobilization	3	8.00	8.50	0.50	
NDT Testing	3	8.50	8.83	0.33	GPR
NDT Testing	3	8.83	11.64	2.81	IE
NDT Testing	3	11.64	15.50	3.86	PE
Demobilization	3	15.50	16.00	0.50	
Mobilization	4	8.00	8.50	0.50	
NDT Testing	4	8.50	12.95	4.45	PE
Demobilization	4	12.95	13.45	0.50	

Mobilization and Demobilization Time	4.00
Preparation and Testing Time	25.11
Waiting Time	0.34

Figure 13: Detailed movements of technician1 during the inspection (case 2.3 in Table 1)

Inspection Information

Total inspection time	59.21>60.0	hour
Overtime hours	0	hour
Total inspection time	7.4>8	day
Total inspection cost	65,836.98	$
Device cost	9,600	$
Technician cost	1,520	$
Transportation cost	2,400	$
Bridge user cost	45,316.99	$
Traffic control cost	3,000	$
Other	4,000	$

a) case 2.1

Inspection Information

Total inspection time	59.21>60.0	hour
Overtime hours	0	hour
Total inspection time	7.4>8	day
Total inspection cost	42,212.25	$
Device cost	9,600	$
Technician cost	1,520	$
Transportation cost	2,400	$
Bridge user cost	21,692.26	$
Traffic control cost	3,000	$
Other	4,000	$

b) case 2.2

Inspection Information

Total inspection time	29.44>30.0	hour
Overtime hours	0	hour
Total inspection time	3.68>4	day
Total inspection cost	33,949.44	$
Device cost	4,800	$
Technician cost	2,280	$
Transportation cost	1,200	$
Bridge user cost	21,669.44	$
Traffic control cost	1,500	$
Other	2,500	$

c) case 2.3

Inspection Information

Total inspection time	29.44>30.0	hour
Overtime hours	0	hour
Total inspection time	3.68>4	day
Total inspection cost	23,022.16	$
Device cost	4,800	$
Technician cost	2,280	$
Transportation cost	1,200	$
Bridge user cost	10,742.16	$
Traffic control cost	1,500	$
Other	2,500	$

d) case 2.4

Figure 14: Cost items of different scenarios in the second case study: a) case 2.1, b) case 2.2, c) case 2.3, d) case 2.4