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System Dynamics Approach for Bridge Deterioration Monitoring System

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Abstract

Bridge monitoring plays an important role in reducing catastrophic failure. Structural Health Monitoring (SHM) has been performed on one of the bridge components such as decks, girders, abutments/piers independently. However, the failure can be attributed either a component defect or combination among them. Bridge deterioration model requires the analysis of complex and dynamic variables. The system dynamic (SD) is a powerful simulation method to study the dynamic and complex systems. This paper aims to discuss the concept of bridge deterioration monitoring using SD approach. The proposed model utilized variables from the previous studies to represent the bridge component interrelationship, while SD will be used to simulate the probability of bridge failure and to find the dominant bridge component that influences the failure. The model can also be used as guidance for bridge deterioration mitigation and repair program.

Keywords: bridge, deterioration, maintenance, system dynamics

1. Introduction

Recently, the number of bridges has collapsed quickly without prior visual warning. Lee, Mohan, Huang, and Fard [1] describe the collected information of 1.254 bridge failure (1980-2012) are: (i) almost bridges were failure in during service time (94%) and the rest occurred in construction period; (ii) the types of bridge failure are caused by total collapse (37%), partial collapse (29%) and unknown (33%); (iii) the causes of bridge failure are flood (28.3%), scour (18.8%), collision (15%) and the remain due to overload, internal causes, environmental degradation, fire etc. Usually difficult to acquire the data bridge-inspection to predict when the bridge will damage [2].

To prevent a bridge from collapsing, structural health monitoring (SHM) is routinely employed. It utilizes structural data record for monitoring and maintenance purposes as well. At the monitoring stage, SHM can be used to monitor steel bridge parameters [3], masonry structure [4], and a structure's behavior during the natural disaster (wind and earthquake) [5]. Meanwhile, at the maintenance stage, it plays an important role in determining the maintenance strategy [6], in the performance criteria of bridge elements [7], and in predicting the long-term performance of the bridge [8].

Due to the result of the interrelationship among the components of the bridge, the use of SHM is unable to solve problems of bridge collapsed. SHM provides data which can be used to predict damage in every part of the bridge, while the bridge can be failure either partially or totally. So, SHM need a bridge deterioration model to integrate the entire bridge component. This model is developed based on the behavior of each component which has complex and interrelated elements. The model can also analyze the bridge deterioration dynamically during the bridge's lifetime.

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Simulation is a powerful tool to study complex systems. It is utilized to observe the result of the complex system model and the experimental manipulation model. Computer simulation has been used to help make decisions since the mid-1950s. The decision-makers use the building computer models of complex systems to develop an understanding of the performance of systems over time. According to Zhang, Xu, Wu and Li [9], SD is considered to be a way of thinking about the future which focuses on 'stocks' and 'flows' within processes and the relationships between them. The SD approach forces policy-makers to acknowledge up front if there is uncertainty. It also identifies where the uncertainty occurred.

SD has been applied in decision-making in large-scale project management, in the management of human resources [10], in project performance measurement [11], and in construction services in a large shipbuilding project management [12]. Based on the literature studies, SD can also be applied to model the deterioration of complex and dynamic bridges.

This paper aimed to discuss the concept of bridge deterioration monitoring using SD approach. Deterioration bridge can be attributed either a component defect or combination among them. So, the bridge deterioration monitoring needs a simulation to solve the dynamic and complex system. SD can be used to simulate the probability of bridge deterioration to find the dominant bridge component that influences deterioration and to sustain bridge serviceability.

2. Component Interaction Behavior on Bridge Deterioration

Some research about the model of bridge deterioration was developed on each bridge component while all components are physically interconnected in the bridge. So, this model was unable to accurately solve the problems of the bridge deterioration because it does not provide interrelationship of bridge component. These studies include: development of an integrated method for probabilistic bridge-deterioration modelling using the Backward Prediction Model [2], analysis of a structure's collapse using FMEA [13], determination of the probability due to fatigue of bridge materials and maintenance models as well as the costs [14, 15], concrete deterioration using PSO [16], the investigation of a railway bridge failure using Bayesian networks [17], and the infrastructure collapse is anticipated by employing a POMDP model [18].

The bridge condition can reduce its serviceability over time because of the failure of the bridge components themselves or damage to the interrelationship of each element. Bridge deterioration caused by damage to materials is influenced by the environment, such as physical damage to concrete, cracks, concrete wear and others. Failure of the interconnection of elements can occur due to malfunction of the connecting elements, which can accelerate damage to them.

Sianipar and Teresa [19] and Lee, Mohan, Huang, and Fard [1] developed a model of the behavior of bridge deck element interactions to detect the accelerated deterioration of the bridge elements, as follows:

- Accelerated concrete deck deterioration is caused by concrete deck deterioration, bearing malfunctions and expansion joints malfunctions.
- Concrete deck deterioration occurred at open frame concrete because of traffic (scaling, delamination, wearing and spalls) and the environment (rain, temperature, shrinkage etc.) also the load on the bridge deck elements (bearing dan shear areas, flexure cracks, transverse flexure cracks).
- Bearing malfunctions happen when: (i) bearing elements went without maintenance for too long a period; (ii) the function of load transfer to the superstructure did not work as intended (properly); (iii) the redundant bearing support decreased when the traffic volume and load was heavier than its capacity; and (iv) corrosion occurred in the bearings.
- The extended joint malfunction was greatly influenced by: (i) seal joint damage; (ii) the accumulation of dirt disrupting the expansion joint function; (iii) indiscriminate overlay; (iv) deficiencies in joint anchorage due to heavy traffic load and volume causing corrosion on the bearings.

Based on the interaction of bridge deck deterioration, other bridge components can be developed. The variables that affect the process of deterioration can be seen in Table 1.

Table 1 Probability of basic deterioration events occurring at deck, girder and abutment/pier bridge

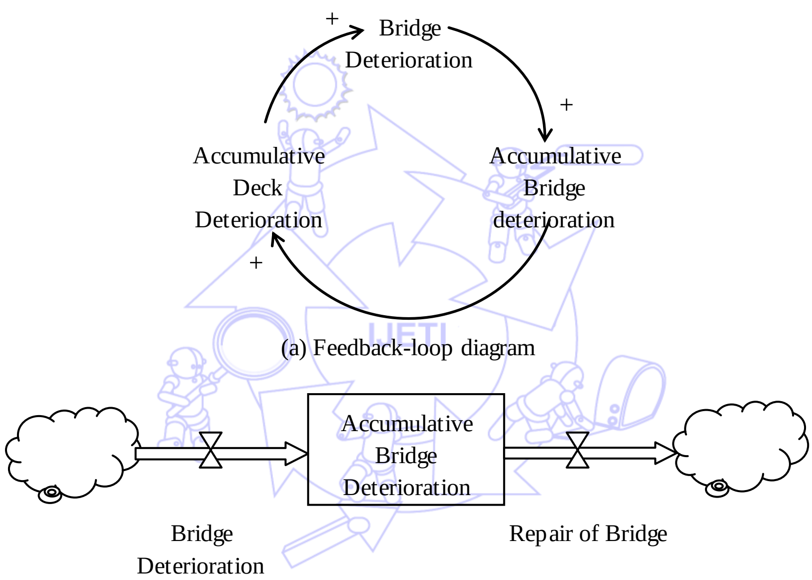
Bridge element deterioration	Bridge Component						Logic
	Deck		Girder		Abutment/Pier		
	Code	Probability	Code	Probability	Code	Probability	
Damage to areas exposed to traffic (scaling, delamination, wearing, spalls)	X1	0.15	-	-	-	-	AND
Damage to areas exposed to drainage (general deterioration of concrete)	X1	0.07	-	-	-	-	AND
Damage to bearing and shear areas (crushing and spalls)	X1	0.01	Y1	0.01	Z1	0.01	AND
Flexure cracks (top over the supports and bottom between the supports of the slab/girder/abutment/pier)	X1	0.25	Y1	0.25	Z1	0.25	AND
Transverse flexure cracks (in the negative moment region of top and bottom of the slab/girder/abutment/pier)	X1	0.27	Y1	0.27	Z1	0.27	AND
Worn bearing elements	X2	0.03	Y2	0.03	Z2	0.03	OR
Loose or missing fasteners (used to attach the bearing to the support or the superstructure)	X2	0.07	Y2	0.07	Z2	0.07	OR
Damage to joint seals	X3	0.10	Y3	0.10	-	-	OR
Dirt accumulation (prevents expansion and contraction)	X3	0.04	Y3	0.04	-	-	OR
Indiscriminate overlay	X3	0.05	Y3	0.05	-	-	OR
High traffic volume causing settlement of the bearing support	X4,X2	0.03	Y4,Y2	0.03	Z4,Z2	0.03	OR
Heavy traffic load causing settlement of the bearing support	X4,X2	0.02	Y4,Y2	0.02	Z4,Z2	0.02	OR
Grates filled with debris causing drainage not to function	X6,X5,X2	0.05	-	-	-	-	OR
Deck inlets not sufficient to carry the runoff causing drainage not to function	X6,X5,X2	0.02	-	-	-	-	OR
Disconnected outlet pipes causing drainage not to function	X6,X5,X2	0.02	-	-	-	-	OR
High traffic volume causing deficiency in joint anchorage	X7,X3	0.03	Y5,Y3	0.03	-	-	OR
Heavy traffic volume causing deficiency in joint anchorage	X7,X3	0.07	Y5,Y3	0.07	-	-	OR
Scouring process	-	-	-	-	Z3	0.21	OR
Occurrence of debris, flood and skew flow	-	-	-	-	Z3	0.04	OR
Water way adequacy	-	-	-	-	Z3	0.04	OR

3. System Dynamics (SD) Model

System dynamics is a simulation technique used as a tool to investigate complex systems feedback [20]. The basic assumptions of SD are theories of control and modern nonlinear dynamics. Therefore, SD has an accurate mathematical base for both theories and models [21]. The basic principles of dynamics will create the structure of the system behavior [22]. The complexity of the behavior is the outcome of the interactions between certain components. Therefore, to analyze these interactions and connections among components in the system, feedback structures should be identified using causes and effects when examined over time [22]. In other words, this method aims to recognize, understand and analyze the behavior of system components. It can be said that this method is an approach to analyzing complex system behavior that makes it possible to get a strong perception of the events involved in the process.

This study utilizes Vensim software to simulate system dynamics approach which it is a user-friendly tool for visual modeling. The user can develop the model starting from developing concept, simulation, analyzing, optimization, and documentation. Running Vensim requires parameters interrelationships. The parameter relations will be determined by the bridge component behaviour. Fig. 1a, for example, shows Vensim feedback-loop diagram where deterioration of the bridge and its component slippage recurring cycle. The arrows represent influence between the parameters which they have the plus or minus sign indicate whether a positive change in the preceding parameter has a positive or negative effect on the next. Fig. 1b, the stock-flow diagram, gives flexible way to make simulation models from the feedback-loop diagram. The stock-flow diagram has stock and rate variable that the stock variable accumulate value of the rate variable while the variable rate is an equation to analyze inflow and outflow value in the stock. The stock is governed by simple formula as follow:

$$stock(t_1) = stock(t_0) + inflows(t_0,t_1) - outflows(t_0,t_1) \quad (1)$$



(a) Feedback-loop diagram

(b) Stock flow diagram

Fig. 1 SD diagram

3.1. Structure of the SD Model

The SD model of bridge deterioration was built based on the behavior of bridge element interactions to detect the accelerated deterioration of the bridge. This simulation model has 4 variables: (1) accelerated deck deterioration, (2) accelerated girder deterioration, (3) accelerated abutment/pier deterioration, and (4) accelerated bridge deterioration. The shape of the causal-loop diagram (CLD) can be seen in Fig. 2.

Accelerated deck deterioration is stock which will receive a deterioration value from Deck deterioration rate (sign "+"). Accelerated deck deterioration will be reduced by Repair of the deck (sign "–"). Repair of the deck is achieved by concrete healing, replacing the device causing failure, and traffic regulation. This also applies to the Accelerated girder and abutment/pier deterioration. Bridge deterioration obtains a deterioration value from accelerated deterioration of the deck, girders and abutment/pier (sign "+") while a reduction value of bridge deterioration is obtained from repair of the bridge. The residual of Accelerated bridge deterioration becomes the input of deterioration of the deck, girder and abutment/pier, respectively. These models have three loops: (i) The 1st loop describe the interrelation between accumulative accelerated bridge deterioration, accumulative accelerated girder deterioration and bridge deterioration; (ii) The 2nd loop illustrates the interrelated among accumulative accelerated bridge deterioration, accumulative accelerated deck deterioration and bridge deterioration; and (iii) The 3rd loop shows complexity connection of accumulative accelerated bridge deterioration, accumulative accelerated abutment/pier deterioration and bridge deterioration.

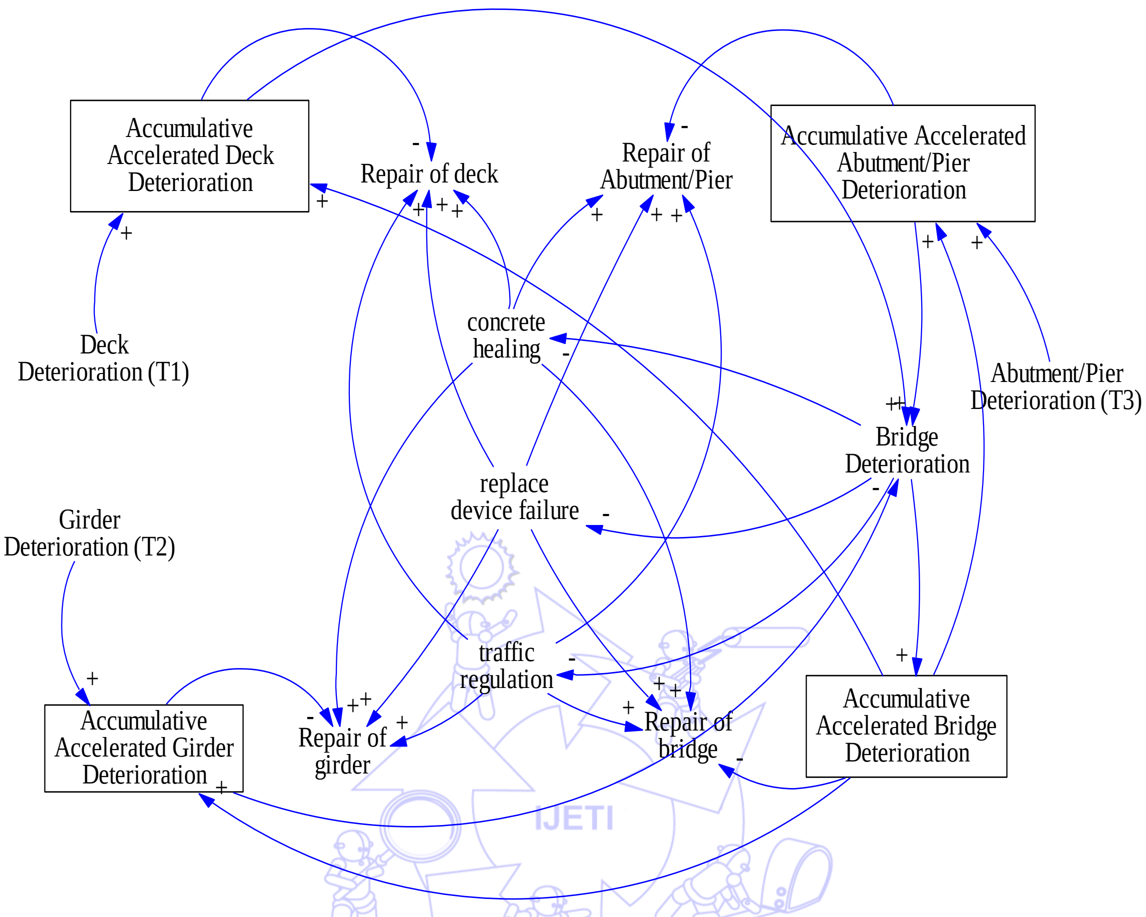


Fig. 2 CLD model for bridge deterioration

3.2. Stock Flow Diagram SD Model

The Stock-Flow Diagram (SFD) is used to create correlation between parameter based on the bridge components relationships behaviour which has already described in section 2. So, SFD will produce the frame of model as well as the behavior of the bridge and its components. The SFD diagram of bridge deterioration needs data from the deterioration parameters for each bridge component. It includes the deck which has 17 parameters, the girder - 12 parameters, abutment/pier - 10 parameters, and bridge repair function - 5 parameters. The parameters of each bridge element are values of probability deterioration as shown in Table 1. SFD is arranged by the using Vensim program and the shape of the SFD can be seen in Fig. 3.

The accelerated deck deterioration variable is the level of *deck deterioration* rate with the *deck repair* rate subtracted (Eq. 1). The deck deterioration rate is affected by concrete deck deterioration; bearing malfunction and expansion joint malfunction (see section 2). The parameter correlation has been built by SFD above, but assessment *accelerated deck deterioration* rate need a method which is able to solve basic event probabilities the using probability of occurrence. The Fault Tree Analysis (FTA) can be chosen because of its ability to identify events something failure process. So that the *accelerated deck deterioration* rate can be obtained by computing using the logic of OR and AND on FTA. The OR gate is the union operation of the event. The AND gate is the intersection operation of the event. Probability evaluation on FTA uses Boolean algebraic equations. The basic mathematical rules of Boolean algebra are given as follows:

(1) The logical OR operator can use equation (2):

$$P(a)\ OR\ P(b) = P(a)\ U\ P(b) = P(a)+P(b) - P(a)*P(b) \quad (2)$$

(2) The logical AND operator can be calculated using equation (3):

$$P(a)\ AND\ P(b) = P(a) \cap P(b) = P(a)*P(b) \quad (3)$$

The probability of deck deterioration is either due to the probability of concrete deck deterioration and the probability of bearing malfunction or due to the probability of concrete deck deterioration and the probability of expansion joint malfunction. Following Eq. 2 and 3, the deck deterioration probability can be expressed as ("Deck deterioration (T1)") = "Concrete deck deterioration (X1)" AND ("Bearing malfunction (X2)" OR "Expansion joint malfunction (X3)". This relation can be presented into the formula as follows:

$$T1 = X1 * [X2 + X3 - (X2 * X3)] \quad (4)$$

All the symbol used in Eq. 4 are found in Fig. 3.

Following the deck deterioration formulation, the probability relationships of the accelerated girder and abutment/pier deterioration respectively can be written as follow:

$$T2 = Y1 * [Y2 + Y3 - (Y2 * Y3)] \quad (5)$$

$$T3 = Z1 * [Z2 + Z3 - (Z2 * Z3)] \quad (6)$$

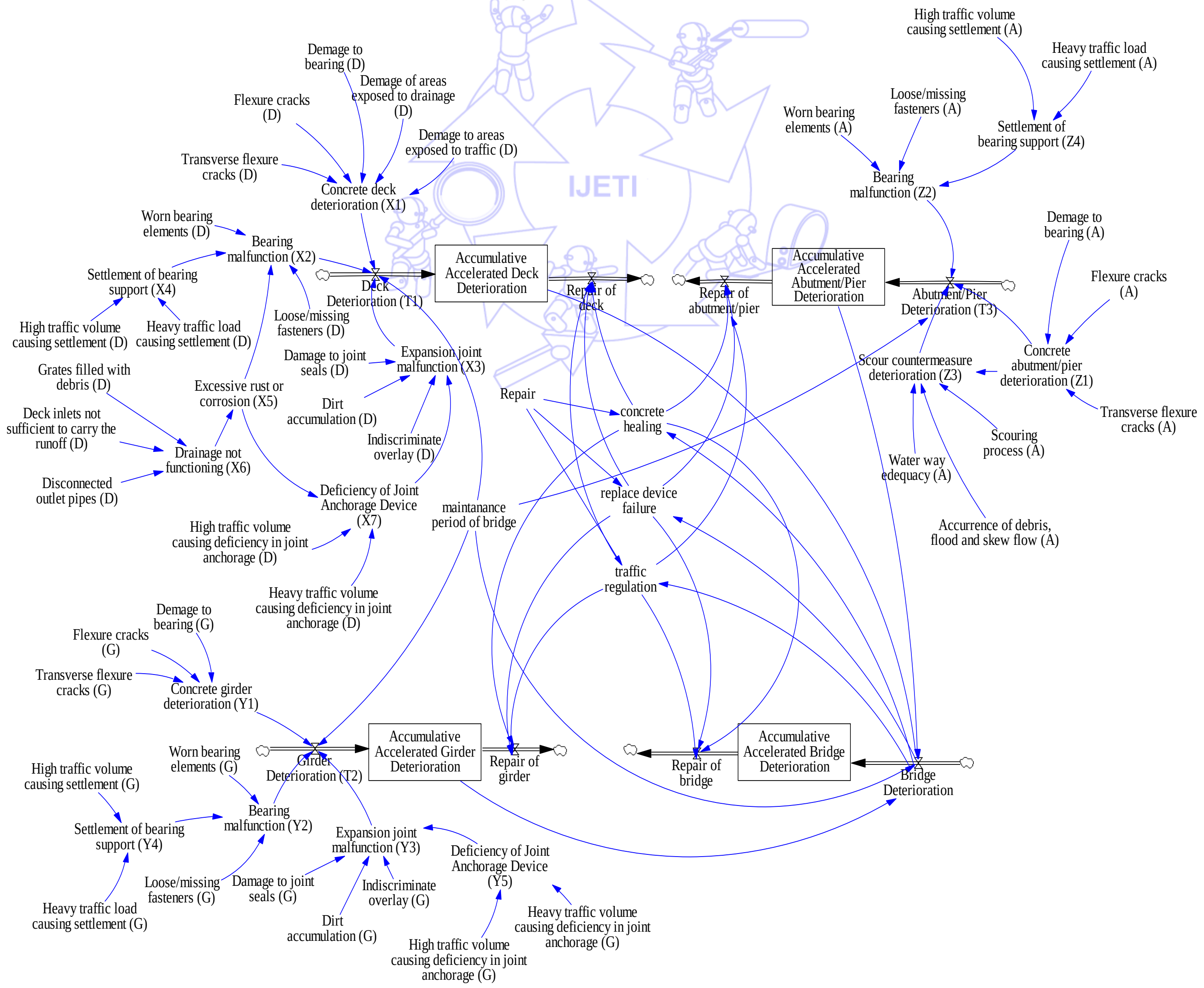


Fig. 3 SD model for bridge deterioration

3.3. Simulation and verification of SD model

The SD model can be accepted if it has passed the verification. This is carried out to make sure of four things: (1) the model is programmed correctly; (2) the algorithms have been implemented properly; (3) the model does not contain errors or bugs; and (4) specification and implementation of the model have been completed. Therefore, the SD model must be run to see what the model has worked properly. This process is called the simulation model.

The SD simulation model was performed by using a preliminary data input and its prediction which the output of the running program would be validated. The preliminary data used the values of the probabilities of deterioration of deck, girder, and abutment/pier elements (Table 1). To compute the deck deterioration, the logic of OR and AND as in Eqs. (2) and (3) is used depending on which states we wish to apply to influence the deck deterioration. The result of this simulation model showed a 0.40 probability of deck deterioration in the 15th year (Fig. 4(a) and Table 2). To validate this model can use previous findings [19] in which the probability of deck deterioration is 0.40. So, this model can be developed to calculate the girder and abutment/pier deterioration.

Table 2 Simulation and verification model of SD

No	Variable	Output	Note
1	Accelerated deck deterioration	0.40	The model can be run; The model has good validation; There are no bugs/errors
2	Accelerated girder deterioration	0.21	
3	Accelerated abutment/pier deterioration	0.45	

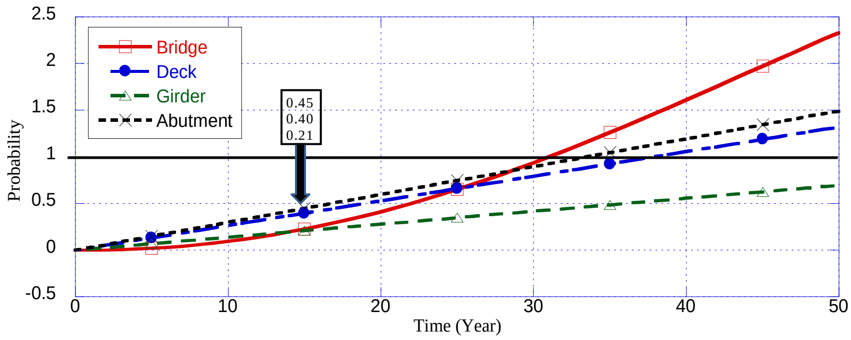
3.4. Scenario of SD model

The purpose of the scenario of this model was to see changes of the model output if the variables were adjusted. The scenario was chosen based on the use of suitable purposes for the model. Two scenario models were set: (1) the purpose of the first scenario was to show which bridge components performed as the dominant factors in the prevention of deterioration; (2) the second scenario was to show how to maintain the bridge from collapse. The percentage of repair depended on the annual rate of deterioration probability.

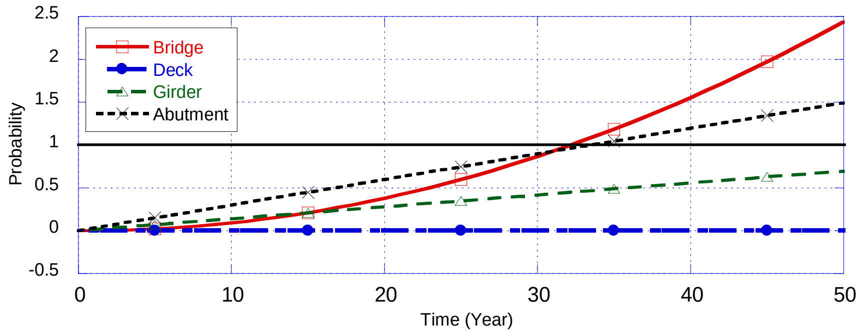
Furthermore, it can be explained that, for the first scenario, the probabilities for the parameters of the bridge components were changed. This model used four types of inputs: (i) the values of preliminary probability were given to all components; (ii) the bridge deck did not collapse (the value of the probability for the deck [P(d)] = 0); (iii) the girder bridge was considered no collapse (hence the probability value for the girder [P(g)] = 0); and (iv) the abutment/pier bridge was assumed no collapse (the value of the probability of the abutment/pier [P(a)] = 0). The results of these scenarios can be seen in Fig. 4 below.

The result of first scenario were: (1) the longest time of the bridge serviceability was 50 years if the bridge abutment/pier construction was assumed to be very strong ([P(a)] = 0) (Fig. 4d); (2) the shortest time of the bridge serviceability was 31 years if all bridge components was given the value of preliminary probability (Fig. 4a); (3) the bridge will collapse in 33 years later if it is assumed the bridge deck or bridge girder considered no damage ([P(d)] = 0 and [P(g)]=0) (Fig. 4b and Fig. 4c); and (4) the bridge was a collapse in variety time periods for a different scenario (Fig. 4e).

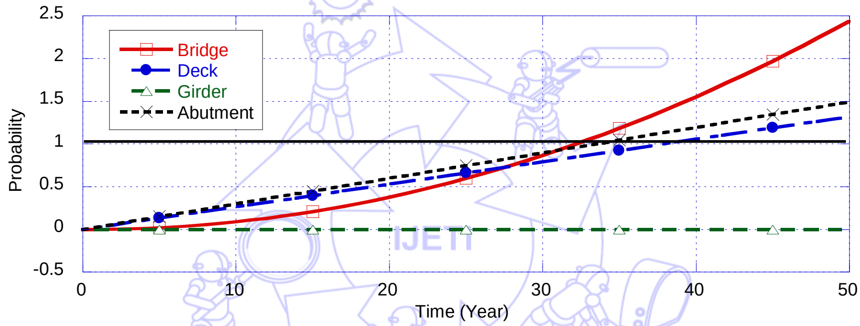
Based on the first scenario, the bridge deterioration highly depended on the abutment/pier deterioration which the stronger abutment/pier will make the longer bridge deterioration. The bridge serviceability could be extended until 19 years or 61.29% if abutment/pier had no damage.



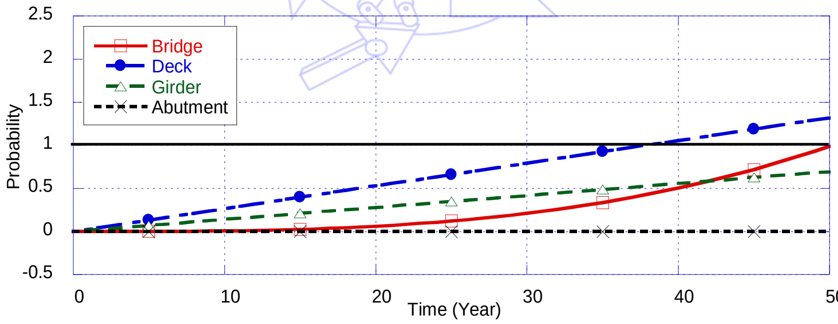
(a) Accelerated bridge and components deterioration [P(d), P(g), P(a) = preliminary probabilities]



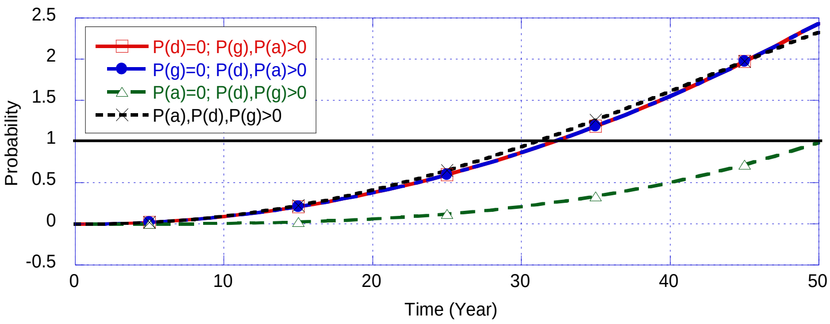
(b) Accelerated bridge and components deterioration [P(d) = 0, P(g), P(a) = preliminary probabilities]



(c) Accelerated bridge and components deterioration [P(g) = 0, P(d), P(a) = preliminary probabilities]



(d) Accelerated bridge and components deterioration [P(a) = 0, P(d), P(g) = preliminary probabilities]



(e) Comparison of the first scenario bridge deterioration

Fig. 4 The first scenario SD models

The second scenario was developed to find means how to maintain the bridge from collapse. To avoid failure in the bridge was needed repair action. These repair treatments were executed by healing the concrete, replacing failed elements, applying traffic regulation, etc. However, at the time of this research, the repair treatments have not yet been developed to heal concrete, to replace failed elements, to arrange traffic regulation, etc. To simplify this simulation, the repair was arranged to reduce the rate of bridge deterioration by using a percentage from the rate of bridge deterioration itself. The percentages of repair used in this study were respectively 0%, 5%, 10%, 15%, 20% and 25% of the rate of bridge deterioration probabilities.

The probabilities of bridge deterioration of ≤ 0.75 was achieved in the years as follows: (i) 27th (do nothing in the models); (ii) 31st (with 5% repair from the annual rate of deterioration); (iii) 36.5th (with 10% repair from the annual rate of deterioration); (iv) 45th (with 15% repair from the annual rate of deterioration); (v) > 50th (with repair of ≥ 20% of the annual rate of deterioration)..

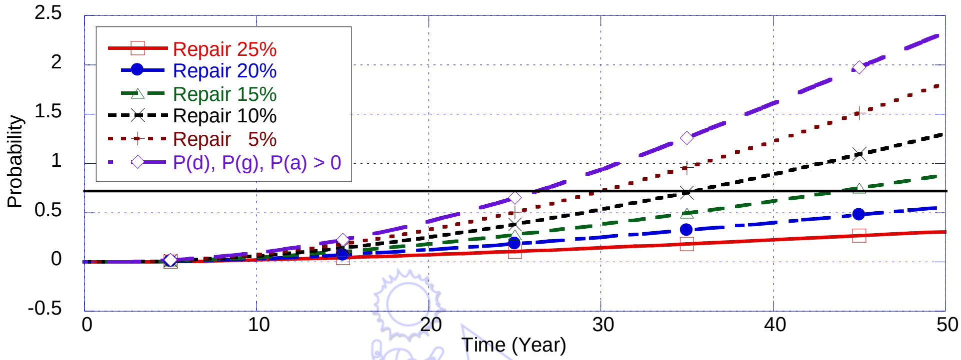


Fig. 5 The second scenario SD model, varying the bridge repair

4. Conclusion

The model of bridge deterioration in this study was initiated by investigating the behavior of the elements interacting in every bridge component. In this model, 4 variables and 44 parameters were run dynamically. The SD successfully developed the bridge deterioration model by using the logic of OR and AND on a FTA. The SD models yielded the following results: (1) the longest deterioration if the abutment/pier probability value = 0 was happen in the 50th year or an additional 19 years longer (61.29%) from bridge deterioration using the preliminary probability values; (2) bridge deterioration could be prevented under conditions with both the level of probabilities = 0.75 and the time period of the bridge more than 50 years, by repair ≥ 20% of the annual rate of bridge deterioration probability. The repair was arranged to reduce the rate of bridge deterioration by using the rate percentage of the bridge deterioration itself, for example, through concrete healing, replacement of failed elements, traffic regulation, etc. However, the real impacts of repair in this study have not been calculated yet. It is, therefore, recommended to carry out further research so that the SD model findings can be explored more widely by including the real impacts of repair.

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