System Dynamics Approach (SD) for Bridge Deterioration Monitoring System

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Abstract

Bridge monitoring has assumed an important role in reducing catastrophic failure, while safety health monitoring (SHM) has been performed on bridge components. Structural components such as decks, girders, abutments/piers have been attributed as causes of failure. A bridge deterioration model requires the analysis of certain variables, and complex interrelationship and dynamic parameters. A system dynamic (SD) is a simulation that is a powerful tool to study complex and dynamic systems. This paper aims to discuss the concept of bridge deterioration monitoring by using the system dynamics approach, with analysis of the model of the complex and dynamic system behavior based on interrelated and dynamic elements. This framework uses the probabilities of bridge components deterioration from several studies to develop a model using the behavior interrelationship of bridge components. Finally, the bridge deterioration model can be used to find the dominant bridge components that influence bridge failure. Therefore, efforts to mitigate bridge deterioration by repairing bridge components can be carried out annually..

Keywords: bridge, deterioration, maintenance, system dynamics.

1. Introduction

Recently, a number of bridges have collapsed quickly without prior visual warning. The failure did not happen to the whole of the bridge, but only part of it. Scour was responsible for almost 60% of bridge collapses in the USA [1], while the rest were caused by several factors, such as overload during the time of repair [2]. Meanwhile, Indonesia has had 244 cases of bridge failure [3].

To prevent a bridge from collapsing, structural health monitoring (SHM) is routinely employed. SHM utilizes a structural data record to monitor and to maintain the bridge. At the monitoring stage, SHM can be used to monitor steel bridge parameters [4], masonry structure [5], and a structure’s behavior during natural disaster (wind and earthquake) [6]. Meanwhile at the maintenance stage, it plays an important role in determining the maintenance strategy [7], the performance criteria of bridge elements [8], and in predicting the long-term performance of the bridge [9].

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However, the use of SHM is unable to resolve problems that occur related to bridge collapse. This is due to the result of the interrelationship among the components of the bridge. SHM provides data which can be used to predict damage in every part of the bridge. However, to see the behavior of the interrelationship among the components of bridge, there is still a need for a bridge deterioration model to integrate all the bridge components. To determine their interactions requires a model to observe the behavior of the individual components, which have complex and interrelated elements. The model can also analyze the bridge deterioration dynamically during the bridge's lifetime.

Computer simulation is a powerful tool to study complex systems. It is a development of the complex system model and its experimental manipulation to observe the results. Computer simulation has been used to help make decisions since the mid-1950s. Building computer models of complex systems allows decision-makers to develop an understanding of performance of systems over time. According to Zhang, Xu, Wu and Li [10], 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 [11], in project performance measurement [12], and in construction services in a large shipbuilding project management [13]. Based on a literature study, SD can also be applied to model the deterioration of complex and dynamic bridges.

This paper aimed to find a model of the bridge deterioration caused by the interrelationships of each component of a bridge that is very complex and dynamic. Therefore, this research uses a system dynamic which involves simulation models that can analyze complex and dynamic issues.

2. Component Interaction Behavior on Bridge Deterioration

Some research reports on models for the prediction of bridge deterioration showed only the bridge components, without observing the behavior of the interrelationship of each element and component of the bridge. These studies include: collapse of the bridge steel frame with full load due to buckling of a pressed member [2], analysis of a structure's collapse using FMEA [14], determination of the probability due to fatigue of bridge materials and maintenance models as well as the costs [15, 16], concrete deterioration using PSO [17], the investigation of a railway bridge failure using Bayesian networks [18], and the collapse of infrastructure which is anticipated by employing a POMDP model [19].

The bridge condition can reduce its serviceability over time. This occurs 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 [20] and Lagasse, Clopper, Zevenbergen, and Girard [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 was due to malfunctions of bearings and expansion joints.
- Open frame concrete could fail because of traffic (scaling, delamination, spalls, etc.) and the environment (rain, temperature, shrinkage etc.). Other damage could also be caused by the service load on the bridge deck elements, such as cracking because of bending and shear loads.
- Bearing malfunctions occurred 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.

- 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

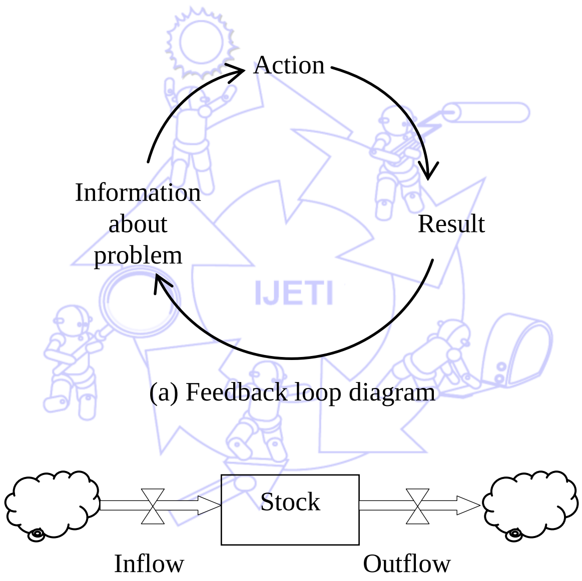
System dynamics is a simulation technique used as a tool to investigate complex systems feedback [21]. The basic assumptions of SD are theories of control and modern nonlinear dynamics. This means that there is an accurate mathematical base for both theories and models [22]. The basic principles of dynamics will create the structure of the system behavior [23].

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 [23]. 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 uses a system dynamics approach that has been used widely to analyze complex systems dynamics and has many nonlinear interactions. To simulate the system dynamics model, existing computing software includes Dynamo, Vensim, Stella, and Matlab. Vensim is a visual modeling tool that makes it possible to conceptualize, document, simulate, analyze, and optimize the models of the system dynamics. Vensim provides a simple tool to build a model (see Fig. 1a), and a flexible way to make simulation models from a causal loop or stock and flow diagrams (Fig. 1b). Vensim needs formulas to run their programs. The parameter formula depends on their behavior, while the variables formula can use a simple equation on Vensim's system, as seen in Equation 1.

The stock can be calculated using formula (1):

$$stock(t_1) = stock(t_0) + inflows(t_0,t_1) - outflows(t_0,t_1) \tag{1}$$



(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 the deck deterioration rate (sign "+"). Accelerated deck deterioration will be reduced by repair of the deck (sign "–"). Repair of the deck concrete is achieved by concrete healing, replacing the device causing failure, and traffic regulation. This also applies to the accumulative accelerated girder and abutment/pier deterioration. Accumulative accelerated bridge deterioration obtain deterioration rate from deterioration rate of the deck, girders and abutment/pier (sign "+") and the reduction in the rate of deterioration is obtained from the rate of repair of the bridge, while the rate of repair of bridge decks is obtained from the deck, girder and abutment/pier repair. The residual of accumulative accelerated bridge deterioration becomes the input of deterioration of the deck, girder and abutment/pier respectively. These models have three loops: (i) Loop Number 1: accumulative accelerated bridge deterioration - accumulative accelerated girder deterioration – bridge deterioration; (ii) Loop Number 2: accumulative accelerated bridge deterioration - accumulative accelerated deck deterioration – bridge deterioration; and (iii) Loop Number 3: accumulative accelerated bridge deterioration - accumulative accelerated abutment/pier deterioration – bridge deterioration.

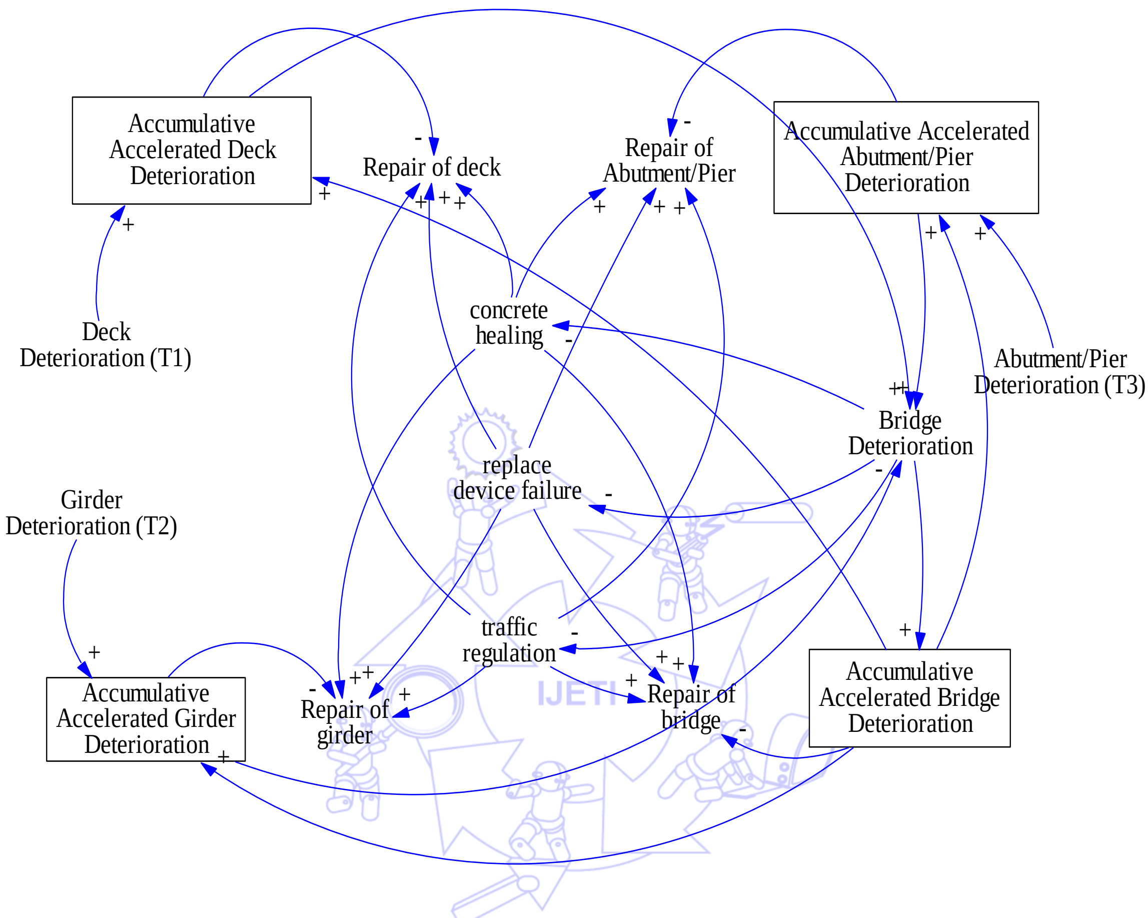


Fig. 2 CLD model for bridge deterioration

3.2. Stock Flow Diagram SD Model

The Stock Flow Diagram (SFD) is arranged by using a Vensim program based on the CLD. SFD is a causal relationship diagram with feedback on the simulation model of bridge deterioration. The SFD diagram of bridge deterioration needs data input 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 probability values as shown in Table 1. 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 value of this variable is the deck deterioration probability. The deck repair rate concerns repair attempts to decrease the probability of deck deterioration, while the deck deterioration rate is obtained by computing using logic of OR and AND on the fault tree analysis. The OR gate is the union operation of the event. The AND gate is the intersection operation of the event. Probability evaluation on a fault tree analysis uses Boolean algebraic equations. The basic mathematical rules of Boolean algebra are given as follows:

(i) The logical OR operator can use formula (2):

$$P(a)\ OR\ P(b) = P(a)\ U\ P(b) = P(a)+P(b) - (P(a)*P(b)) \tag{2}$$

(ii) The logical AND operator can be calculated using formula (3):

$$P(a)\ AND\ P(b) = P(a) \cap P(b) = P(a)*P(b) \tag{3}$$

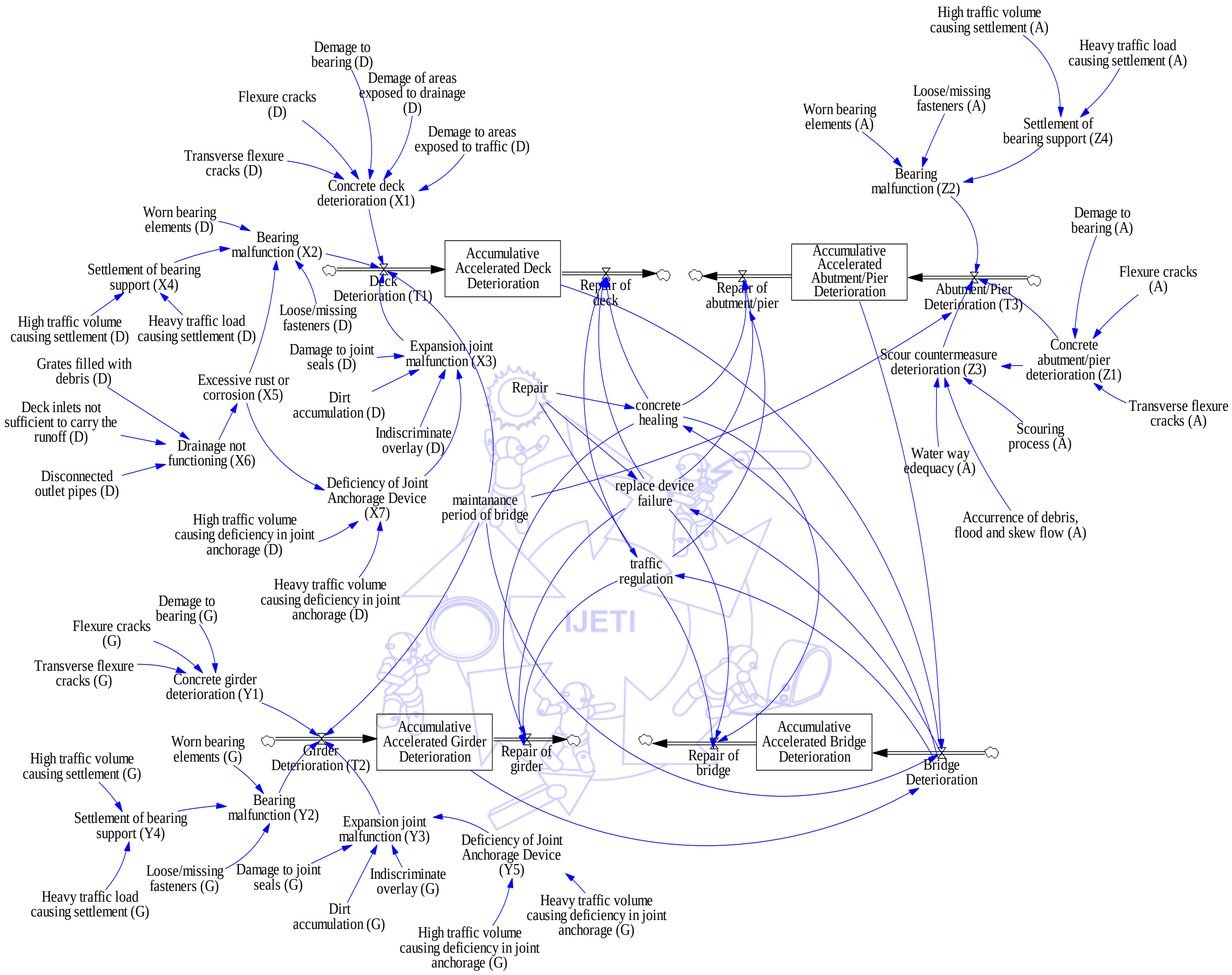


Fig. 3 SD model for bridge deterioration

The probability of deck deterioration is for one of two reasons: (1) the influence of the probability of concrete deck deterioration and the probability of bearing malfunction; (2) the probability of concrete deck deterioration and the probability of expansion joint malfunction. These reasons can thus be formulated as the probability of deck deterioration ("Deck deterioration (T1)") = "Concrete deck deterioration (X1)" AND ("Bearing malfunction (X2)" OR "Expansion joint malfunction (X3)". Based on equations (2) and (3), the probability of deck deterioration (Fig. 3) can be computed as follows:

"Deck deterioration (T1)" = "Concrete deck deterioration (X1)" * ("Bearing malfunction (X2)" + "Expansion joint malfunction (X3)" - ("Bearing malfunction (X2)" * "Expansion joint malfunction (X3)")).

For the variables of accelerated girder and abutment/pier deterioration there is a similar calculation to that for the accelerated deck deterioration variable.

"Girder deterioration (T2)" = "Concrete girder deterioration (Y1)" * ("Bearing malfunction (Y2)" + "Expansion joint malfunction (Y3)" - ("Bearing malfunction (Y2)" * "Expansion joint malfunction (Y3)")).

"Abutment/pier deterioration (T3)" = "Concrete abutment/pier deterioration (Z1)" * ("Bearing malfunction (Z2)" + "Scour countermeasure (Z3)" - ("Bearing malfunction (Z2)" * "Scour countermeasure (Z3)")).

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. That is why, in order to see if the model has worked properly or not, the simulation models must be run.

The SD simulation model was performed by using a preliminary data input, and it was predicted that the output of running the program would validate the result. 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 Equations (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)). This was clear as the result of this study (Table 2). To validate this model, we can use previous findings [20] in which the probability of deck deterioration is 0.40. So, this model can be developed to calculate the girder and abutment/pier deterioration.

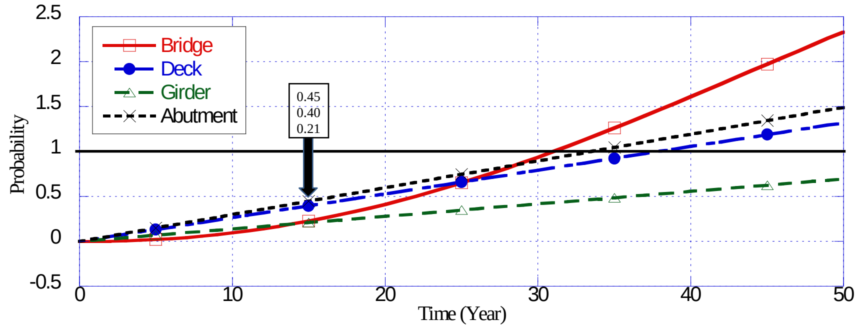
Table 2 Simulation and verification model of SD

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	

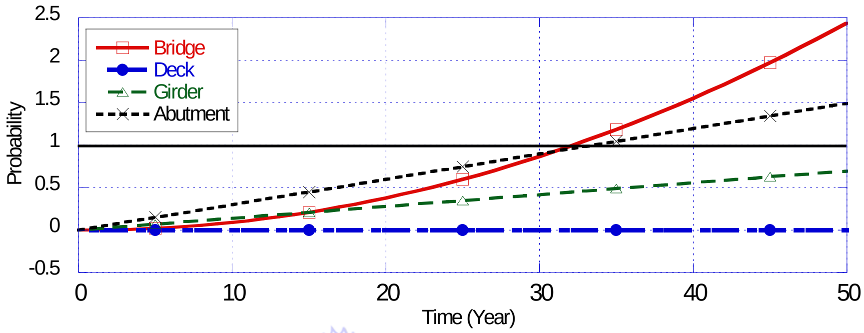
3.4. Scenario of SD model

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 the percentage of repair needed annually to prevent bridge collapse. The percentage of repair depended on the annual rate of deterioration probability.

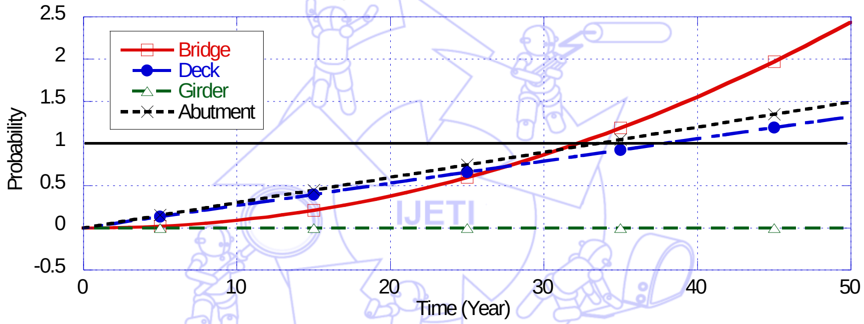
Furthermore, it can be explained that for the first scenario, the probabilities for the parameters of the bridge components were changed. This model produced four types of outputs: (i) the values of preliminary probability were given to all components; (ii) the bridge deck did not collapse (the value of the probability for the deck [P(d)] = 0); (iii) the girder bridge too was considered not to collapse (hence the probability value for the girder [P(g)] = 0); and (iv) the abutment/pier bridge was assumed not to 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.



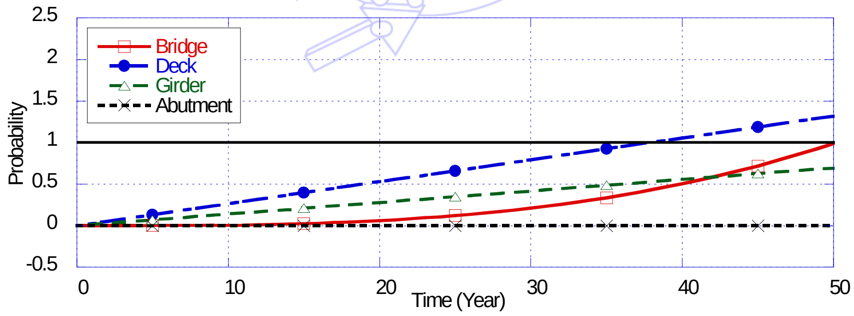
(a) Accelerated bridge and components deterioration [P(d), P(g), P(a) = preliminary probabilities]



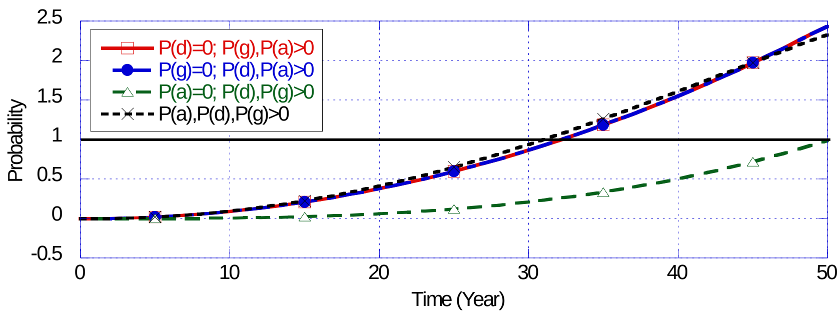
(b) Accelerated bridge and components deterioration [P(d) = 0, P(g), P(a) = preliminary probabilities]



(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

It was found that the bridge deterioration (probability = 1) occurred over different time periods. The minimum failure happened if the bridge abutment/pier construction was assumed to be very strong (value of the abutment/pier deterioration probability = 0), in which the bridge would sustain damage in the 50th year (Fig. 4d). If all components used the values of preliminary probability, the bridge deterioration would take place in the 31st year (Fig. 4a). Fig. 4b and 4c indicate that the bridge would collapse in the 33rd year, if each element of the bridge deck or girder was considered to have no damage (the probability of deck and girder deterioration was respectively = 0). Comparison of these models in the first scenario showed that the bridge had the smallest deterioration with one condition, i.e. no damage in the abutment/pier construction (Fig. 4e). Compared with the preliminary probabilities (Fig. 4e), the period of the bridge construction could be extended by up to 19 years or 61.29% of bridge deterioration of all components by using the preliminary probability values.

The second scenario was developed to find the percentage of repair needed to decrease the annual rate of bridge deterioration, so that the bridge would not collapse. This scenario gave the annual treatment as the rate of bridge repair based on the annual rate of the bridge deterioration probabilities. 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. 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 had not yet been developed to heal concrete, to replace failed elements, arrange traffic regulation etc., and thus to influence the bridge deterioration. The results scenario is shown in Fig. 5.

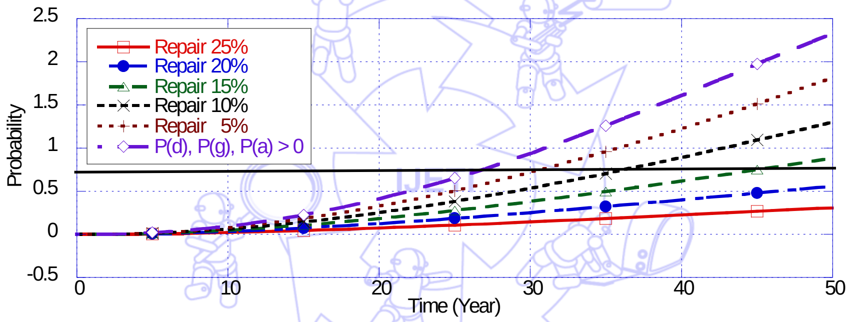


Fig. 5 The second scenario SD model, varying the bridge repair.

The probabilities of bridge deterioration of ≤ 0.75 would be 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 $\geq$ 20% of the annual rate of deterioration).

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 fault tree analysis. The SD models yielded the following results: (1) the longest deterioration if the abutment/pier probability value = 0 would 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 repairing $\geq$ 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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