Supply and Demand System Approach to Development of Bridge Management Strategies

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Abstract: A supply and demand system approach is presented to deal with the inability of existing bridge management systems to determine optimal management strategies when multiple bridges may be adversely affected simultaneously. The supply and demand system approach alleviates this limitation because the optimization problem is formulated to minimize overall costs on the transportation network. The optimization problem is formulated focusing on the ability of the transportation network as a whole (system) to provide an adequate level of service, taking into consideration the role and performance of the bridges in the network (supply) and the consequences if an adequate level of service is not provided (demand). The supply and demand system approach is illustrated by determining the optimal management strategies for five bridges in a real transportation network subjected to two hazard scenarios: overloading due to traffic and scouring due to flooding. The main conclusion is that the supply and demand system approach is a rational approach to the development of optimal management strategies when bridges are adversely affected and may become nonoperational simultaneously.

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Introduction

In the past 2 decades, under the pressure of deteriorating infrastructure and constrained budgets in North America and Europe, computer aided bridge management systems (BMS) have been developed, such as Pontis (Cambridge Systematics 1997), Bridgit (National Engineering Technology Corporation 1998) and KUBA-MS (Ludescher and Hajdin 1995). These management systems allow decision makers to prioritize bridges with respect to their need of intervention as a precursor to a more in-depth analysis by an engineer at the individual bridge level. The prioritization of these bridges allows decision makers to analyze numerous management strategies for their bridge network in the search for the optimal allocation of resource budgets that ensures an adequate level of service for the users, i.e., the optimal management strategy (OMS).

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State of the Art

The current approach to bridge management in computer aided BMS is principally to keep the existing bridges between their original as-built condition states and certain minimum acceptable condition states (this is usually called the maintenance repair and rehabilitation optimization module), although there are provisions for incorporating possible improvements to bridges, such as widening, raising of a bridge, seismic retrofits, and scour mitigation (this is usually called the Improvement Optimization module). In the maintenance repair and rehabilitation module of BMS, the present condition states of bridge elements are determined by visual inspections. The future condition states are predicted based on the present condition state and knowledge of the behavior of similar bridges under similar conditions, via Markov transition probabilities (Cambridge Systematics 1997; Ludescher and Hajdin 1995), although recent work has shown that they can also be determined directly by taking into consideration the deterioration phenomena at work (Roelfstra 2001). It is assumed that an adequate level of service is provided to the users of the bridge as long as the bridge condition is equal to or better than the minimum acceptable condition state (except during an intervention). In the improvement module of BMS, it is assumed that an intervention will change the functional characteristics of the bridge and that once the intervention is performed the functional characteristics of the bridge remain constant. In this module, the user costs incurred on the unmodified bridge are compared with those that are incurred on the modified bridge to decide whether or not an intervention is warranted.

The optimal management strategy in existing BMS for the maintenance repair and rehabilitation module has the lowest net present value of overall intervention cost while ensuring that the probability of falling below the minimum acceptable condition state is negligible. The optimal management strategy in existing BMS, for the improvement module, has the most favorable cost/benefit ratio. The combined optimal management strategy is determined by combining the prioritized lists produced from the maintenance repair and rehabilitation module and the improvement module.

Neither the maintenance repair and rehabilitation module nor the improvement module in existing BMS can be used to determine OMS when multiple bridges may be adversely affected and may become nonoperational simultaneously, due to the individual bridge approach used. An individual bridge approach is defined here as an approach where the decision to intervene on a bridge depends solely on that bridge and how it ranks against other bridges, including the attributing of user costs to that bridge. There is no consideration that the multiple bridges may be nonoperational simultaneously. If bridges are nonoperational simultaneously, which is sometimes the result of natural hazards, the user costs are often very large (Cooper et al. 1994; McCown et al. 1999). Because an individual bridge approach neglects these costs, it cannot be used to find the OMS if bridges are adversely affected and may be nonoperational simultaneously. The supply and demand system approach overcomes this limitation.

Supply and Demand System Approach

A supply and demand system (SDS) approach to bridge management focuses on the ability of the transportation network as a whole (system) to provide an adequate level of service, i.e., meet user demands. This is done by taking into consideration the role and performance of all of the bridges in the network (supply) and the consequences if an adequate level of service is not provided (demand). The OMS determined using the SDS approach are found by balancing the costs of providing an adequate level of service to the users of the network with the costs if an adequate level of service is not provided. In general, this can be represented as the minimization of overall costs for the network

$$\text{Minimize:}\quad \lambda = C_A + W_U \cdot C_U \tag{1}$$

The costs of providing an adequate level of service are those incurred by the owner of the transportation network (e.g., public authorities), agency costs C_A. The costs if an adequate level of service is not provided are those incurred by the users of the network, user costs C_U. The user costs are multiplied by a weighting factor W_U to illustrate the possible unequal importance of user costs and agency costs in the decision-making process.

An inadequate level of service results from a network deficiency that makes it more difficult for the users of the network to travel, e.g., increased congestion, longer routes, or higher accident rates. It can be quantified in terms of costs. The probability that an adequate level of service will be provided by a transportation network depends on the reliability of the components in the transportation network, i.e., the roadways and structures and the network connectivity and functionality. The reliability of the roadways and structures depends on the actions to which they are subjected and their ability to resist the effects induced by these actions. It can be used to determine the probability that the individual links in the network will perform adequately. The probability of an inadequate level of service on the network as a whole and the costs if there is an inadequate level of service depend on both the network connectivity and functionality.

Network connectivity describes the way that bridges in the network are connected. The network connectivity determines the number of alternate routes available if a link is not fully operational. The availability of alternate routes affects the probability of having an adequate level of service at the network level. For example, the closure of a road in a redundant network forces users to take an alternate route but does not stop them from travelling. However, the closure of a road in a nonredundant network means that travel by road between the two cities can no longer occur or becomes extremely difficult. Even if the ability to travel is not lost, the connectivity of the network can affect the length and quality, and therefore cost, of alternate routes.

Network functionality describes the capacity of the links of the network as well as the volume of traffic on these links. The network functionality determines the effect on the users if a link is not fully operational. For example, the closure of a road that is travelled by a small number of vehicles in a redundant network may result in a detour in traffic that results in only small increases in travel time or wear on the vehicles and has little impact on the original traffic on the roads used for the detour. The closure of a road that is travelled by a large number of vehicles in a redundant network may result in a detour in traffic that results in a significant increase in travel time and wear on vehicles and causes severe congestion on the roads used for the detour, affecting both the detoured vehicles and the original vehicles on the detour link.

The costs if there is an inadequate level of service are those incurred either by the users who still can travel although not along the most efficient routes or by the users who are not able to travel. When users cannot travel as desired but travel is still possible, the user costs depend on road characteristics such as the condition and length of the detour links and the traffic volume on these links. Both road characteristics and traffic volume affect travel time, vehicle operating costs, and the possibility of accidents. When users cannot travel as desired and travel is not possible, the user costs are associated with the lost benefit of travel. Because transportation networks are used for economic benefit, among other things, a loss of the ability of the network to meet the users' demands means there is a loss of this economic gain. An economic analysis of the region to be analyzed is required to determine the user costs if travel is not possible.

Supply Side

To determine the supply side of the network in the SDS approach, the ability of the network to perform adequately during a certain period of time must be evaluated. This requires first the evaluation of the performance of the individual structures and then that of the network.

Individual Structures

The performance of a structure is based on its ability to adequately resist the actions to which it is subjected, such as traffic loads, wind loads, floods, and earthquakes. The ability of structures to resist these actions depends on the structural system, the structural dimensions, material properties, and how these change with time when subjected to deterioration phenomena. In the SDS approach, probabilistic methods are used to quantify the probability of adequate structural performance. It is assumed that as soon as set performance criteria are exceeded for a bridge, such as the yield stress in the tensile reinforcement, the performance is inadequate and the bridge becomes nonoperational. The criteria, of course, can be set as desired by the engineer, to whatever it is thought will require immediate action.

A probabilistic approach is convenient when evaluating structural performance in the presence of uncertainties involved in estimating the actions and their effects (such as the uncertainty in the variation in truck loads or wind velocities) and the resistance of structures to these effects (such as variation in concrete strength and abutment depth). Good guides to the use of probabilistic methods in the evaluation of structures are Schneider (1997), Thoft-Christensen and Baker (1982), and Nowak and Collins (2000).

The general methodology to evaluate the probability of inadequate structural performance is as follows:

1. Identify the relevant hazard scenarios, such as traffic loading, flooding, and earthquakes. Because it is not possible to consider all hazard scenarios, the ones most likely to occur must be evaluated. These are determined based on visual inspection of the bridge and engineering judgment.
2. Identify the relevant modes of inadequate performance for each hazard scenario, such as excessive flexural cracks in a concrete beam or bearing failure of a support for the traffic hazard scenario. There may be multiple modes of inadequate structural performance for each hazard scenario. The relevant modes are determined based on visual inspection of the bridge and engineering judgment.
3. Determine general limit state equations for each mode of inadequate performance. The general limit-state equations take into consideration structural behavior and the definition of inadequate structural performance. The general limit-state equations for the specific modes are developed based on the actions to which the structure is subjected, how these actions affect the structure, how the structure resists these action effects, and the definition of inadequate structural performance. How each of these parameters change with time (e.g., the structural resistance to traffic loads can be diminished when the structure is subjected to chloride attack) must also be included in the limit-states equation. The general form of a limit state equation (G) is given in Eq. (2).
$$G=R\cdot g_R(t)-S\cdot g_S(t) \tag{2}$$
where G = the difference between the initial structural resistance (such as the moment capacity), R, that deteriorates with time based on the type and rate of deterioration, $g_R(t)$, and the action effects on the structure (such as the maximum applied moment), S, that change with respect to time according to $g_s(t)$.
4. Develop resistance models based on how the structure behaves and how this behavior may change with respect to time. The resistance of a structure depends on the type of structural system, redundancy, dimensions, material properties, and their rates of change. Changes in structural dimensions or material properties affect structural resistance and should be incorporated in the limit-state equations.
5. Develop action and action effect models. The modelling of actions that affect bridges (such as the heaviest annual truck or strongest annual winds) are based on observed data. The models should include, when, where, and the magnitude of the actions when required. The action-effects side of the limit-state equation is determined based on the actions to which the structure is subjected and how these actions create effects in the structure. The action-effects model depends on the structural system, the dimensions and material properties of the structure, and how they change with time.

   The most severe actions to which structures are subjected, within the time period to be investigated, must be estimated to determine the maximum action effects in the structures. The time period must be divided into smaller time periods where it can be assumed that the structural resistance and maximum action effects that the structure will experience can be represented by constant probability distributions (Kameda and Koike 1975; Stewart and Val 1998). The original time period must be divided into smaller ones because the resistance of the structure as well as the action change with time. Normally, it is sufficiently accurate in the priorization of bridge interventions to assume that this period of time corresponds to the time between inspection periods (1–2 years).
6. Determine appropriate distributions to model the random variables in the limit state-equations, such as the strength of the tensile reinforcement in a concrete beam or the stone size of riverbed material and find their parameters (e.g., mean and standard deviation for the normal distribution). Nondestructive and destructive tests can be used to help determine the appropriate distributions and parameters.
7. Evaluate probability of inadequate performance. Because only the most likely hazard scenarios and the most likely modes of inadequate performance within each hazard scenario are selected, it will not be possible to obtain an exact probability of inadequate structural performance. If the likely hazard scenarios and modes of inadequate performance are selected appropriately, however, the estimation will be sufficient for comparisons of structural performance (Ressler and Daniels 1990).

To determine the probability of inadequate performance due to a hazard scenario, it is necessary to combine the probabilities of inadequate performance due to each mode of inadequate structural performance that may be caused by a hazard scenario [Eq. (3)]. In Eq. (3), it is assumed for simplicity that all modes of inadequate structural performance are statistically independent for one bridge within a hazard scenario. In reality, the different modes are generally not independent because they tend to be functions of one or more common random variables, e.g., the same truck loads or positions. The correlation between variables can be minimized by defining the modes so that there are a minimum number of common variables. If there is any correlation between modes, the probability of inadequate structural performance predicted by Eq. (3) will be too high. If they are perfectly correlated, the probability predicted by Eq. (3) will be equal to the largest probability of inadequate performance due to a single mode.

$$P_{FH}=1-P_{SH}=1-\prod_{i=1}^{n_F}(P_{SFi}) \tag{3}$$

where P_F = probability of inadequate performance; P_{FH} = probability of performing inadequately due to a hazard scenario; P_{SH} = probability of not performing inadequately due to a hazard scenario; and P_{SFi} = probability of not performing inadequately due to a mode i of inadequate performance.

The assumption of independent modes is expected to give reasonable approximations for P_{FH} that are consistent with the level of accuracy needed to assess the probability of inadequate structural performance (i.e. an order of magnitude) (Ressler and Daniels 1990) and therefore the planning of OMS.

Transportation Networks

The ability of a network to provide an adequate level of service to its users depends on its connectivity and functionality, as well as the performance of its individual structures. The performance of a transportation network is how well it meets user demands. The methodology to evaluate the ability of the network to provide an adequate level of service in the proposed SDS approach is as follows:

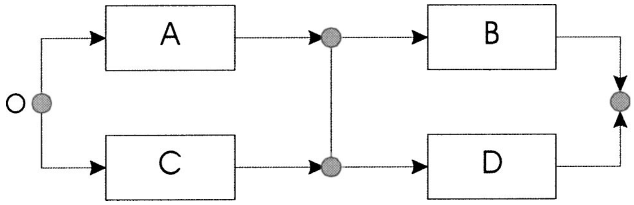

Fig. 1. Example of a four-bridge network

1. Determine the objective function to be used in network evaluation, such as target network reliability or user costs. An objective function defines how a network is to be evaluated, as a limit-state equation defines how an individual structure is to be evaluated. To evaluate the objective function it is necessary to determine the probability of the network condition states (NCS) in which the undesired conditions occur and by multiplying these probabilities by the weight attributed to each NCS (the weight attributed to the lack of adequate service). The description of a NCS requires knowledge of the condition states (i.e., fully operational, partially operational, and nonoperational) of all structures in the network. The probability of occurrence of a NCS is based on the probabilities that each of the structures in the network will be in a certain condition state. For example, assuming the only possible structural conditions are operational or nonoperational, the probability of occurrence of NCS-A ($P_{\text{NCS-A}}$) in the four-bridge network shown in Fig. 1 (i.e., bridge A nonoperational and bridges B, C, and D operational) is
$$P_{\text{NCS-A}} = P(A_F)\cdot P(B_S|A_F)\cdot P(C_S|A_FB_S)\cdot P(D_S|A_FB_SC_S) \tag{4}$$
where $P(A_F)$ = the probability that bridge A is not operational in the investigated time period; $P(B_S|A_F)$ = the probability that bridge B is operational at the same time that bridge A is nonoperational; $P(C_S|A_FB_S)$ = the probability that bridge C is operational at the same time as bridge A is not operational and bridge B is operational; and $P(D_S|A_FB_SC_S)$ = the probability that bridge D is operational at the same time that bridge B and C are operational and bridge A is nonoperational.
2. Estimate the probability of inadequate performance of individual structures. Actions affect networks by affecting the structures within the network. The effect on the network of these actions depends not only on where the structures are located within the network but also on when the structures are affected. For example, assume both bridges A and C in Fig. 1 perform inadequately in a 15-year period and must be closed for an intervention. If bridge A is nonoperational but is repaired before bridge C is nonoperational there is no connection loss. If bridges A and C are nonoperational at the same time, however, there will be connection loss. The user costs associated with these different NCS are different.

   When evaluating network performance, the correlation in time of the effects of actions on the structures within the network must be considered. To determine the probability of having a simultaneous inadequate performance by structures, conditional probabilities are required. A conditional probability is the probability of one event (the inadequate performance of bridge C) knowing that another event (the inadequate performance of bridge A) has taken place, $P = (C|A)$.
3. Evaluate the network performance. Once the appropriate probabilities of inadequate performance of the individual structures have been estimated, the ability of the transportation network to meet the needs of the users can be evaluated. To evaluate network performance, the network resistance, defined in terms of expected additional users costs (the difference between the user costs incurred on the fully operational network and the partially operational network), must be determined. If the expected additional user costs are high, then the network has a low resistance, and if the expected additional user costs are low, then the network has a high resistance.

This methodology gives the supply side of the transportation network. This alone, however, is not sufficient to plan OMS using the SDS approach; it is also necessary to evaluate the demand side of the transportation network.

Demand Side

The demand side in the SDS approach is the evaluation of the consequences to the users if an adequate level of service is not provided. These are expressed in terms of costs to the users and are taken into consideration directly. Each negative impact is given a monetary value, including the loss of network reliability (Augusti et al. 1995; Kameda 1997; Pardi et al. 1997; Minami 2000), restriction in traffic flow capacities (Augusti and Ciampoli 1997), and injuries and deaths (Blanchard and Systermans 1983). Of course there is a philosophical question of whether or not it is possible to assign a monetary value to each one of these items, especially the value of human life. Although it may be argued that a value cannot be put on a human life it is often necessary to do so in the evaluation of the allocation of resources. The estimation of the value of human life is normally determined using one or a combination of the four following factors: loss of production, implicit value derived from community choices in the allocation of resources, surveys on the populations' willingness to pay, and the implicit value derived from the behavior of individuals as regards to expenditure on protection against road accidents and their consequences (Blanchard and Systermans 1983). If it is completely undesirable to put a value on human life, even as a way to prioritize bridge interventions, then it is possible to structure the problem as a multiobjective optimization problem treating economic costs and human life separately. It will still, however, at some point be required to decide how these are balanced. For the remainder of this work, the costs used to determine the optimal management strategies are economic. The costs are divided into categories: those incurred when travel is possible, i.e., there is no loss of connectivity in the network, travel time costs, vehicle operating costs, and accident costs, and those incurred when travel is not possible, i.e., there is a loss of connectivity in the network and the loss of economic benefit if travel is not possible.

User Costs When Travel Is Possible

User costs, when all desired travel on the network is possible, are comprised of travel time costs, vehicle operating costs, and accident costs. The magnitude of these costs is affected by the interrelation between the traffic flow (number of vehicles travelling), the road condition on which the vehicles are traveling, and vehicle speed.

Traffic flow depends on the route choices made by drivers. These choices are based on road condition and vehicle speed and depend on the characteristics of each driver, such as type of vehicle and desired destination. Qualitative choice models derived from utility theory, such as logit and probit models, can be used to approximate these route choices (Train 1993).

Road conditions deteriorate due to a combination of parameters including traffic volume, traffic loads, amount of rainfall, moisture levels in the road, material strength properties and thickness, and the variability of material behavior and construction quality (Watanatada et al. 1987). Road conditions can be predicted with respect to the distress mechanisms occurring. The degree of road improvement depends on the type and quality of the maintenance intervention.

Vehicle speeds are limited by road characteristics and traffic volume. In the absence of other vehicles (no congestion), a single vehicle will have a limiting speed based on road characteristics. The greater the number of vehicles simultaneously on a link (congestion), the more this speed is reduced. Vehicle speeds, assuming no congestion, are dependent on surface type, average roughness, horizontal curvature, and vertical gradient of the roads, as well as vehicle characteristics, such as braking capacity and engine power. When there are many vehicles on the road, traffic flow becomes constrained or congested, and this affects vehicle speeds. The severity of road congestion depends on traffic flow, road capacity, and speed of travel (Hoban et al. 1994).

Vehicle operating costs depend on the speed at which the vehicles travel and the condition of the roads on which they travel. To estimate vehicle operating costs, the quantities of resources consumed such as liters of fuel, numbers of tires, man-hours of labor, etc, must be determined as a function of traffic flow, vehicle speed, and road condition. They may also include depreciation, interest, and overhead costs.

Travel time costs depend on the value of time for passengers and cargo as well as the amount of time spent travelling. The value of travel time depends on the average total travel time of each vehicle, the fraction of time each vehicle spends in congested conditions, the income of the driver of the vehicle, and the monetary cost of the trip (Small et al. 1999). The estimation of travel time costs is further complicated by the fact that time spent in congested travel is not necessarily unproductive and that not all travel time is equal. For example, making a large number of people wait a short period of time is not necessarily equivalent to making a few people wait a long period of time even if the monetary figure of the time wasted is equivalent (Blanchard and Systerman 1983). Most recent research has suggested that the value of time for work trips is about 50% of the wage rate on average (Small et al. 1999; Waters 1992).

Accident costs depend on the value of human life, the cost of injury, and the frequency of accidents. The costs are related to the victim's medical and rehabilitation costs (or funeral expenses), the loss of productive capacity due to the victim's inability to work, and the physical and mental pain of the victims and their families, loss of free time, and diminished life expectancy (Blanchard and Systerman 1983). Once the value to be attached to accidents is determined, this value and the accident rate are used to determine the overall accident costs.

User Costs When Travel is Not Possible

The costs of not traveling are the losses of the benefits of traveling minus the savings in travel costs. The maximum yearly monetary benefit from traveling on the transportation network can be thought of as the gross domestic product (GDP). GDP is a measure of a country's domestic production of goods and services over the course of a year but not directly including unreported activities, such as unpaid housework or unreported activities. Because not all of the GDP relies on the use of the transportation network, it is reasonable to assume that the loss of not being able to use the network can be expressed as a percentage of GDP. An economic analysis, which is beyond the scope of this paper, is required to determine the percentage loss of GDP for different NCS.

Temporal Variation of User Costs

User costs that are incurred when the network is in a NCS depend on when the NCS occurs during the investigated time period. For example, if a vehicle is detoured onto a newly graded unpaved road, the vehicle operating costs are lower than if it is detoured onto an unpaved road 15 years after it was graded. To consider the change in user costs with respect to road deterioration as well as the change in the value of money with time (the discount rate) the probability and cost of nonoperational bridges in each month must be explicitly considered [Eq. (5)].

$$UC=\sum_{i=1}^{m}\sum_{j=1}^{n}\left(P(\mathrm{NCS}_i)_j\cdot\frac{UC_{ij}}{(1+r)^j}\right) \tag{5}$$

where $P(\mathrm{NCS}_i)$ = probability of having network condition state i, in interval j; UC_{ij} = the user costs that would be NCS i occurred in interval j; and r = discount rate.

Estimation of User Costs

The user costs, if there is an inadequate level of service on a transportation network, are the difference between the user costs incurred when there is an inadequate level of service and the user costs incurred when an adequate level of service is provided. In the SDS approach, these additional user costs are estimated by simulating the traffic flow on both the fully operational and partially operational network for each NCS and using established relationships between vehicle operating, travel time, accident costs, traffic flow, road condition, and vehicle speed, as well as determining lost benefits if not all desired travel is possible.

Optimal Management Strategies

The optimal management strategy in the SDS approach is the one that has the lowest overall costs where unattained benefits are treated as costs. To determine the OMS, the costs and benefits of all strategies to be considered must be evaluated. This requires the selection of an analysis method and a methodical evaluation and comparison of each of the candidate strategies. Four methods that can be used to compare these candidate strategies are (1) present value method; (2) equivalent uniform cost method; (3) incremental rate of return method; and (4) incremental benefit-cost ratio method (Hudson et al. 1997). In the present worth method, all costs and benefits are calculated and transformed into present day values using discount rates. In the equivalent uniform annual cost method, all of the costs and benefits are transformed into equal annual costs over the investigated time period. The rate of return method involves the estimation of the discount rate at which costs and benefits and the rate of return are calculated with respect to a base strategy. The incremental benefit-cost ratio method involves expressing the ratio of the benefits of a strategy to the costs. By evaluating the supply and demand side of the network as de-

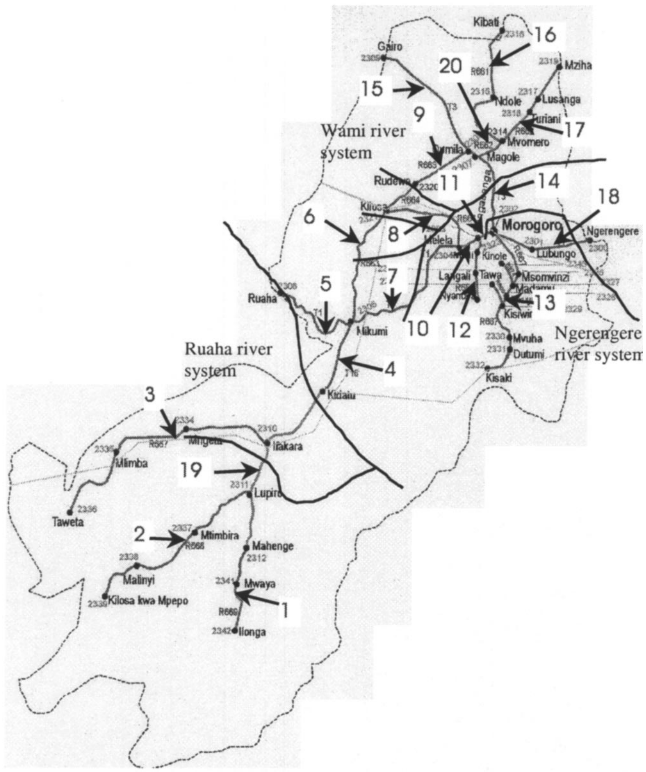

Fig. 2. The Morogoro road network

scribed and balancing their costs using one of the above mentioned analysis methods, the OMS for a group of bridges can be determined.

Example

To illustrate the SDS approach, the OMS for five bridges within a transportation network are determined. The OMS are determined

Table 1. Link Characteristics

Link	Road class	Length (km)	Road width (m)	Rise and fall (m/km)	Curvature (degrees/km)
1	Unpaved	99	3	50	300
2	Unpaved	152	3	50	300
3	Unpaved	210	3	50	300
4	Unpaved	109	3	20	150
5	Paved	73	7	10	50
6	Unpaved	78	3	10	50
7	Paved	79	7	10	50
8	Unpaved	78	3	0	0
9	Unpaved	66	3	10	50
10	Paved	23	7	10	50
11	Paved	23	7	10	50
12	Unpaved	32	3	50	300
13	Unpaved	144	7	20	150
14	Paved	66	7	0	0
15	Paved	73	7	0	0
16	Unpaved	80	3	20	150
17	Unpaved	73	3	0	0
18	Paved	48	7	10	50
19	Unpaved	30	3	20	150
20	Unpaved	14	3	0	0

Table 2. Average Daily Traffic

Link	Car	Pick-up	Bus	Light truck	Medium truck	Articulated truck	Total volume
1	4	5	3	3	1	3	19
2	4	5	3	3	1	3	19
3	8	9	6	5	2	6	36
4	27	30	19	15	7	18	116
5	23	99	73	23	50	63	241
6	9	18	11	34	23	5	100
7	17	128	128	55	51	47	426
8	4	44	18	6	13	6	91
9	32	37	75	22	28	4	198
10	239	239	94	58	73	22	725
11	239	239	94	58	73	22	725
12	0	22	12	29	14	0	77
13	419	419	165	101	127	38	1,269
14	323	135	246	32	48	8	792
15	10	103	113	23	60	23	332
16	1	1	1	1	0	0	5
17	14	20	78	29	12	0	153
18	162	270	972	648	351	297	2,700
19	19	20	13	10	5	13	80
20	12	17	66	25	10	0	130

with respect to the traffic hazard scenario—excessive structural demands due to traffic loading (THS) and the flood hazard scenario—excessive scour depth due to flooding (FHS). Two intervention options for each bridge are considered: complete rehabilitation with respect to the THS or complete rehabilitation with respect to the FHS. Complete rehabilitation is defined as rehabilitating the bridge so that there is a negligible probability that the bridge will be nonoperational during the 15-year investigated time period due to the respective hazard scenario. A 15-year time period is a reasonable time period with which to expect that there is a negligible probability of having to perform an intervention on a bridge after it is newly rehabilitated.

The OMS are defined as the order in which interventions are to be performed to minimize the expected additional user costs for given amounts of resources. The OMS are found for single interventions (if only one intervention is to be performed) and multiple interventions (if multiple interventions are to be performed in succession). It is assumed, in the determination of the OMS, that the agency costs of each intervention are the same. By making this assumption, the OMS are determined based solely on the

Table 3. Description of Five Investigated Bridges

Bridge	Type	Lanes	Length of bridge (m)	Number of spans
6	Reinforced concrete on steel girders	1	4.2	1
8	Reinforced concrete on steel girders	1	23.7	3
9	Reinforced concrete on steel girders	1	65.0	5
14	Concrete T-beam bridge with a drop in composite center span	2	60.2	3
20	Reinforced concrete on steel girders	1	5.2	1

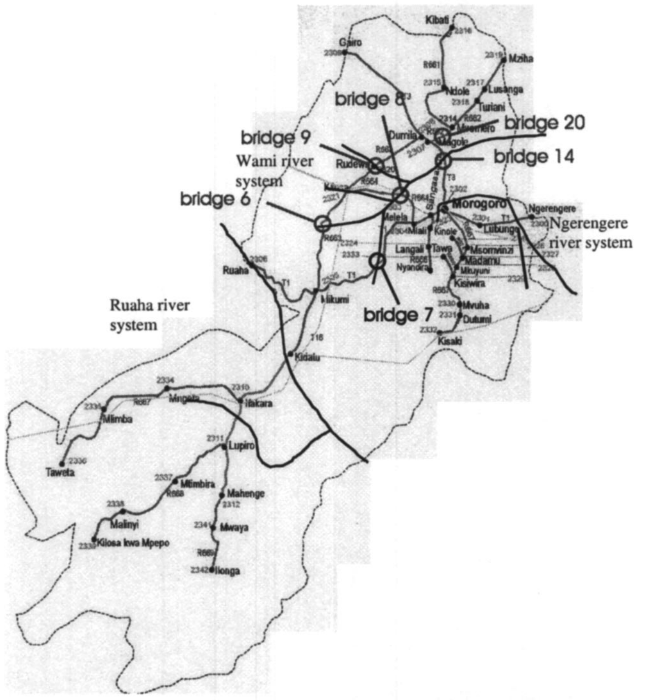

Fig. 3. The location of the five investigated bridges (6, 8, 9, 14, and 20)

possible reduction in expected additional user costs, which emphasizes the differences between the OMS with respect to the different hazard scenarios using the SDS approach. Interventions are to be performed immediately. Each intervention is assumed to take only 1 month, and only one intervention at a time can be performed. Even though this is not always the case, these assumptions are adequate to illustrate the SDS approach.

Morogoro Road Network

The five investigated bridges are located in the road network of the Morogoro region of Tanzania. The Morogoro road network (Fig. 2) consists of 4,000 km of road (400 km paved; 3,600 km gravel/earth). The main roads are the Tanzam highway (links 5, 7, 10, 11, 18), the Morogoro–Dodoma highway (links 14 and 15), and the Mikumi–Mahenge road (links 1, 19, 4). The Tanzam highway and the Morogoro–Dodoma roads are paved two-lane roads. The section from Mikumi to Kidatu on the Mikumi–Ifakara road is a paved two-lane road, the section from Kidatu to Ifakara is a good well-maintained single-lane dirt road, and the section from Ifakara to Mahenge is a smaller less maintained

Table 4. Bridge 6

Hazard scenario	Traffic hazard scenario	Flood hazard scenario
Failure criterion	Stresses in steel I-beam	Depth of abutment scour
General limit-states equation	$M_R(1-g_R(t))-M_S$	y_a-y_{asc}
Deteriorating element	Width and thickness of bottom flange	Riverbed
Deterioration rate (mm/year)	Thickness, 0.034; width, 0.281	0

one-lane dirt road. The remainder of the roads are less maintained single-lane dirt roads. There are three river systems in the Morogoro region: the Wami river system (crossed by links 6, 7, 8, 9, and 14), the Ruaha river system (crossed by links 4, 5, and 19), and the Ngerengere river system (crossed by links 11 and 18). In this example, the flows in the three river systems are treated as statistically independent. The general link characteristics are given in Table 1. The specific characteristics of the links are assumed to be similar to typical roads in developing equatorial countries (Watanatada et al. 1987). The traffic composition on each link is estimated based on a survey done by the Morogoro regional engineer's office in 1998 (Table 2).

The five investigated bridges consist of a concrete T-beam bridge with a drop in composite center span and four steel I-beam bridges having different span numbers and lengths (Table 3). Their locations in the Morogoro road network are shown in Fig. 3. Specific details on each of the bridges can be found in the work of Adey (2002). They are omitted here because the exact details have little importance on the illustration of the SDS approach. Because only one bridge per link is investigated, the bridges are labeled after the link on which they are located, for example, the bridge investigated on link 14 is referred to as bridge 14.

Supply Side

Individual Bridges

Inadequate bridge performance in this example is most likely to occur due to either traffic loads or flood scour. The structural resistance of the bridges with respect to the traffic load deteriorates with time due to corrosion of the steel reinforcement. The resistance of the bridges to scour depth is constant, as if the riverbeds had reached equilibrium. It is assumed that the bridges are closed for intervention immediately once the set performance criterion for each bridge has been exceeded.

Table 5. Bridge 8

Hazard scenario	Traffic hazard scenario 1	Traffic hazard scenario 2	Flood hazard scenario 1	Flood hazard scenario 2
Failure criterion	Stresses in steel I-beam 1	Stresses in steel I-beam 2	Depth of abutment scour	Depth of pier scour
General limit-states equation	$M_R(1-g_R(t))-M_S$	$M_R(1-g_R(t))-M_S$	y_a-y_{asc}	y_p-y_{pc}
Deteriorating element	Width and thickness of bottom flanges	Width and thickness of bottom flanges	River bed	River bed
Deterioration rate (mm/year)	Thickness, 0.00469; width, 0.0563	Thickness, 0.003; width, 0.043	0	0

Table 6. Bridge 9

Hazard scenario	Traffic hazard scenario	Flood hazard scenario
Failure criterion	Stresses in steel I-beam 2	Depth of pier scour
General limit-states equation	$M_R(1-g_R(t))-M_S$	y_p-y_{psc}
Deteriorating element	Width and thickness of bottom flange	Riverbed
Deterioration rate (mm/year)	Thickness, 0.00938; width, 0.106	0

Table 8. Bridge 20

Hazard scenario	Traffic hazard scenario	Flood hazard scenario
Failure criterion	Stresses in steel I-beam	N/A
General limit-states equation	$M_R(1-g_R(t))-M_S$	N/A
Deteriorating element	Width and thickness of bottom flange	N/A
Deterioration rate (mm/year)	Thickness, 0.00714; width, 0.0821	N/A

General Limit-States Equations

The general limit-states equations for each of the investigated modes of inadequate performance for the five bridges are given in Tables 4–8. Deterioration of the resistance of the bridges to the THS occurs due to corrosion of the steel sections and concrete carbonation induced corrosion. It is assumed that there is no deterioration of the resistance of the bridges to the FHS because the riverbeds are assumed to be at equilibrium.

The deterioration of the area of the I-beam tension flanges $A_{t\text{flange}}$, is estimated as a percentage of their initial dimensions [Eq. (6)]. The deterioration of the area of the steel reinforcement A_{rebar} is estimated as a function of the diameter [Eq. (7)]. The deteriorating elements and the rates of deterioration are given in Tables 4–8.

$$A_{t\text{flange}}=(f_t-r_{tcorr}\cdot t)\cdot(f_w-f_{wcorr}\cdot t) \tag{6}$$

$$A_{\text{rebar}}=\sum_{i=1}^{n}(d_{in}-r_{rcorr}\cdot t)^2\cdot\frac{\pi}{4} \tag{7}$$

where d_{in} = initial diameter of one steel reinforcement bar (mm); f_t = thickness of tension flange (mm); f_w = width of tension flange (mm); r_{rcorr} = rate of corrosion of the diameter of the steel reinforcement bar (mm/year); r_{tcorr} = rate of corrosion of the thickness of tension flange (mm/year); r_{wcorr} = rate of corrosion of the width of tension flange (mm/year); and t = time.

Actions

The action effects produced in the THS are the combined effects of the dead and live loads. The dead loads are determined based on the structural and material properties of the bridges. The live loads are approximated using combinations of two trucks typical to the region (Fig. 4). The V1-22 truck is used for bridges on unpaved roads, and the V1-22-22 truck is used for bridges on paved roads. The V1-22 truck has three axles with one wheel on each side for the front axle and two wheels on each side for the rear axles. The V1-22-22 truck has five axles with one wheel on each side for the front axle and two wheels on each side for the other four axles.

The dead loads are treated deterministically; live loads are treated probabilistically. Distributions are selected to represent the heaviest axle loads of the evaluation trucks. All other axle loads are assumed to be perfectly correlated. The 1-year evaluation truck, i.e., the heaviest truck to occur in 1 year, is selected so that the bridges can be analyzed at successive 1-year intervals throughout the investigated time period. The distributions are not varied as a function of the number of vehicles because it is assumed that the worst-case load effects occurred. The truck loads are treated as statistically independent. The same normal distribution with a mean of 150 kN and a standard deviation of 15 kN is used to represent axle loads of both evaluation trucks (axle three for the V1-22 truck and axle five for the V1-22-22 truck). It is assumed that the load is uniformly distributed between axles within the same axle group. The distributions are assumed to include all dynamic amplification effects.

The action effect produced in the FHS is scour, which is a result of the amount of water flowing in the rivers during the flood events. The river flows are treated probabilistically. Normal distributions with the parameters given in Table 9 are used.

Effects

The effects in the bridges produced by the truck loads are functions of the structural dimensions and material properties of the bridges such as the distances between the girders, the deck stiffness, and the lengths of the spans of the bridges. The exact relations used in this example can be found in the work of Adey (2002). The effects produced by the discharge during a flood event are functions of riverbed characteristics and river geometry. The scour depths caused by contraction and local scour are estimated by using empirical equations (Richardson and Davis 1995). The total scour depth is the sum of both.

Table 7. Bridge 14

Hazard scenario	Traffic hazard scenario 1	Traffic hazard scenario 2	Traffic hazard scenario 3	Flood hazard scenario
Failure criterion	Stresses in concrete T-beam rebar	Stresses in stirrups in composite support	Stresses in steel portion of composite beam	Depth of pier scour
General limit-states equation	$M_R(1-g_R(t))-M_S$	$F_R(1-g_R(t))-F_S$	$M_R(1-g_R(t))-M_S$	y_p-y_{pc}
Deteriorating element	Rebar diameter	Rebar diameter	Width and thickness of bottom flange	River bed
Deterioration rate (mm/year)	0.05	0.05	0.075	0

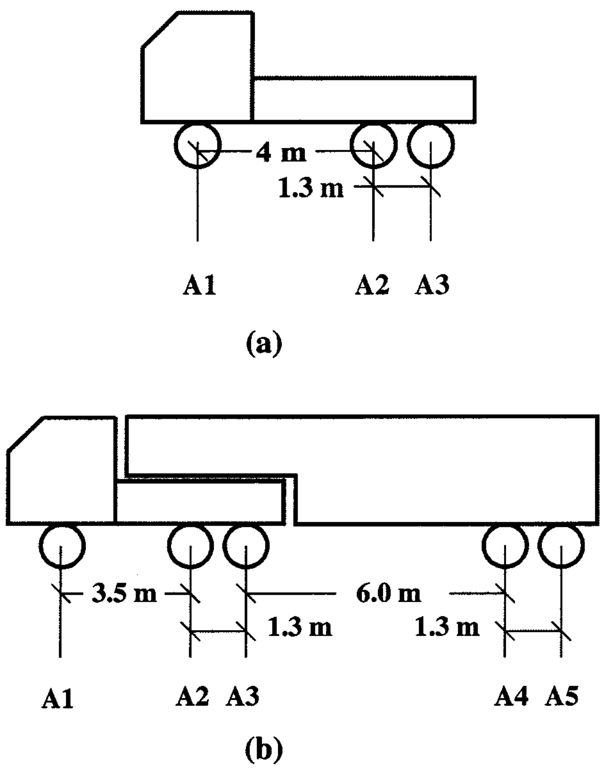

Fig. 4. Evaluation trucks: (a) V1-22; (b) V1-22-22

Analysis

The ability of each bridge to perform adequately during the investigated time period is evaluated probabilistically using the equations for resistance and action effects. The probabilities of performing adequately (expressed as orders of magnitude) due to each investigated mode and each hazard scenario are shown in Table 10.

The probabilities of inadequate structural performance in this example, i.e., exceeding the set performance criterion, are relatively high. This is appropriate when a network is in very poor condition, and it has been decided that it is time to improve essentially the whole network, that is, strict performance criteria are established. If only the THS is considered, there is a probability that the set performance criterion for bridge 14 will be passed during the investigated time period (an order of magnitude of 10^{-1}). It should be kept in mind that the probability of exceeding a set performance criteria depends predominately on the value of the set criteria. For example, if the set performance criteria is determined to be corrosion initiation of the steel rebar and a visual inspection indicates that there is corrosion occurring then the probability of inadequate performance of the bridge this year is one; it is a certainty. The probabilities that the set performance criteria for bridges 8, 9, and 20 will be exceeded are 10^{-2}, 10^{-2}, and 10^{-1}, respectively. There is little probability that the set performance criterion set for bridge 6 will be exceeded, 10^{-14}. Analysis of the five bridges as considering only the FHS indicates that three of the five bridges (bridges 6, 8, and 9) are likely to have the set performance criteria exceeded, 10^{-1}. The two remaining bridges have probabilities of inadequate performance of 10^{-6}. With these probabilities that the set criteria will be exceeded, action must be taken to prevent unplanned closures. With limited resources, the SDS approach can be used to determine the order of intervention to optimally reduce the expected user costs, the optimal management strategy.

Table 9. Flow Distributions

Bridge	Mean Q (m^3/s)	COV
6	5	0.2
8	84	0.2
9	75	0.2
14	282	0.2
20	N/A	N/A

Network

Supply Side

There are 2^{20} different NCS to consider in the example network if one bridge on each link is to be considered as either operational

Table 10. Probabilities of Exceeding Set Failure Criterion

	THS			FHS		
Bridge	Mode of inadequate performance	Probability of inadequate performance due to mode	Probability of inadequate performance due to hazard scenario	Mode of inadequate performance	Probability of inadequate performance due to mode	Probability of inadequate performance due to hazard scenario
6	Moment steel beam	10^{-14}	10^{-14}	Abutment scour	10^{-1}	10^{-1}
8	Moment steel beam 1	10^{-2}	10^{-2}	Pier scour	10^{-6}	10^{-1}
	Moment steel beam 2	10^{-2}	10^{-2}	Abutment scour	10^{-1}	10^{-1}
9	Moment steel beam	10^{-2}	10^{-2}	Pier scour	10^{-1}	10^{-1}
	Moment composite section	$<10^{-16}$	10^{-1}	Pier scour	10^{-6}	10^{-6}
14	Moment concrete T-beam	10^{-1}	10^{-1}	Pier scour	10^{-6}	10^{-6}
	Shear composite beam support	10^{-1}	10^{-1}	Pier scour	10^{-6}	10^{-6}
20	Moment steel beam	10^{-1}	10^{-1}	Pier scour	10^{-6}	$<10^{-6}$

Note: 10^{-1} indicates that $0.1<$probability of inadequate performance<1. 10^{-2} indicates that $0.01<$probability of inadequate performance<0.1.

Table 11. Probabilities of Inadequate Performance

Bridge	Traffic hazard scenario 6	8	9	14	20	Flood hazard scenario 6	8	9	14	20
6	$\mathbf{10^{-14}}$					$\mathbf{10^{-1}}$	10^{-1}	10^{-1}	10^{-6}	
8		$\mathbf{10^{-2}}$				10^{-1}	$\mathbf{10^{-1}}$	10^{-1}	10^{-6}	
9			$\mathbf{10^{-2}}$			10^{-1}	10^{-1}	$\mathbf{10^{-1}}$	10^{-6}	
14				$\mathbf{10^{-1}}$		10^{-6}	10^{-6}	10^{-6}	$\mathbf{10^{-6}}$	
20					$\mathbf{10^{-1}}$					$\mathbf{10^{-6}}$

Note: Empty cell indicates that the probability of inadequate performance is negligible.

or nonoperational. The number of NCS to be investigated can be reduced by taking into consideration whether or not it is likely that multiple bridges will have to be closed simultaneously due to inadequate performance. If it is possible to neglect simultaneous nonoperational bridges, then the NCS associated with them can also be neglected.

For the determination of the OMS for the five investigated bridges, the probabilities of simultaneous nonoperational bridges due to the THS are neglected. Simultaneous nonoperational bridges due to the FHS, however, are not neglected when they can occur due to a common cause, such as when they are on the same river system. The probabilities of simultaneous nonoperational bridges that are on different river systems are neglected. Because all of the investigated bridges, except bridge 20, are on the Wami river system, the possibility of them performing inadequately at the same time as bridge 7 must be considered, however, it is assumed for this example that bridge 7 has a negligible probability of inadequate performance. Therefore, the NCS considered are

$$\mathrm{NCS}=\left\{\begin{array}{c} 6,8,9,14,20 \\ (6/8),(6/9),(6/14),(6/20),(8/9),(8/14),(8/20),(9/14),(9/20),(14/20) \\ (6/8/9),(6/8/14),(6/8/20),(6/9/14),(6/9/20),(6/14/20) \\ (8/9/14),(8/9/20),(8/14/20) \\ (9/14/20),(6/8/9/14),(6/8/9/20),(6/8/14/20), \\ (6/9/14/20),(8/9/14/20) \\ (6/8/9/14/20) \end{array}\right\} \tag{8}$$

The probabilities of inadequate performance throughout the 15-year period for the five investigated bridges and the conditional probabilities of inadequate performance for the other bridges (the probability of inadequate structural performance at the same time) are shown in Table 11. In this example, the action effects that can result from a common cause are assumed to be perfectly correlated in time, i.e., the actions effects due to flooding for the bridges on the same river system. More research is required to determine the degree of correlation to be used in the analysis of bridge networks. The probabilities of inadequate structural performance are shown diagonally in bold. The conditional probabilities of inadequate structural performance are not bolded. The probabilities of the network being in the NCS due to the THS and the FHS are calculated using Eq. (5). They are shown in Table 12. This gives the supply side of the example.

Demand Side

To evaluate the demand side of the example network the user costs incurred when the network is in NCS and when there is no loss of connectivity are estimated using the Highway Design and Maintenance (HDM) model developed by the World Bank (Watanatada et al. 1987). The user costs incurred when there is a loss of connectivity are estimated using a benefit/cost ratio. It is assumed that the user costs incurred would be the same for every month throughout the investigated time period in each NCS. This simplifies the example. The HDM model was designed to make comparative cost estimates and economic evaluations of different road construction and maintenance options. It first predicts the physical quantities of resources consumed from traveling on roads and then multiplies them by their unit costs. The effect of the road characteristics, vehicle fleet data, and road maintenance strategies are taken into consideration. The effect of nonoperational bridges on network users is determined by estimating the user costs on the roads when the network is fully operational and on the roads when the network is only partially operational for each NCS.

The user costs incurred when the network is in NCS and when there is a loss of connectivity between nodes in the network (an economic analysis of the Morogoro region was beyond the scope of this work) are estimated by using a benefit/cost ratio, B/C, where it is assumed that the value of each trip, B, is directly proportional to the cost of the trip C. In reality, the B/C ratio is not constant, although it is feasible that this ratio has a constant lower bound, 1.0, below which traveling becomes uneconomical and is not done. The B/C ratios used to estimate the cost if there is a loss of connectivity are taken as 1.5 for unpaved links and 15 for paved links, which correspond to the highest observed ratios when the network is in the NCS and where detours are possible and are consistent with the assumption of inelastic traffic demand. The assumption of inelastic traffic demand means that all vehicles traveling on the original link take the detour when travel on the original link is no longer possible. This implies that the economic benefit of traveling on the original link is large enough to warrant incurring the additional cost of traveling on the detour for all

Table 12. Probabilities of Occurrence of NCS

NCS	THS	FHS
6	10^{-14}	
8	10^{-2}	
9	10^{-2}	
14	10^{-1}	10^{-6}
20	10^{-1}	10^{-6}
6/8		
6/9		
6/14		
6/20		
8/9		
8/14		
8/20		
9/14		
9/20		
14/20		
6/8/9		10^{-1}
6/8/14		
6/8/20		
6/9/14		
6/9/20		
6/14/20		
8/9/14		
8/9/20		
8/14/20		
9/14/20		
6/8/9/14		
6/8/9/20		
6/8/14/20		
6/9/14/20		
8/9/14/20		
6/8/9/14/20		

Note: Empty cell means that the probability of occurrence is small enough to be neglected.

vehicles. In reality, some drivers may decide that the trip is no longer worth making. The assumption of inelastic travel demand has been investigated by (Dalziell and Nicholson 2001).

The additional user costs associated with each NCS where the network is not fully operational are estimated by determining the costs incurred on the damaged network and subtracting the costs incurred on the fully operational network for the same time frame. The user costs are determined by modeling the traffic flow on the network and estimating the costs associated with traveling or not traveling, taking into consideration vehicle speeds and road deterioration. It is assumed that all vehicles desire to travel from the beginning of the link to the end.

The NCS, where there is no loss of connectivity, are given in Eq. (9) and the additional user costs that would be incurred when the network is in NCS and where there is no loss of connectivity if each intervention takes 1 month to perform and only one intervention at a time can be performed, are shown in Fig. 5, e.g., the additional user costs for NCS14 is 2.82×10^{6} mu. The costs associated with each NCS are given in monetary units (mu) as only the relative value is important. The smallest additional user costs are associated with NCS6 because it has a relatively small amount of traffic, and detour links 7 and 8 (Fig. 2) are not at capacity before nor after the deviation of the link 6 vehicles. The largest additional user costs are associated with NCS8/14, because link 14 has a relatively large amount of traffic. When link 8 and 14

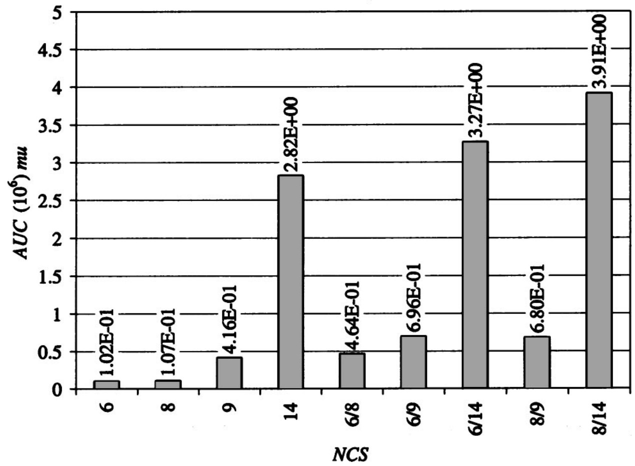

Fig. 5. Additional user costs (AUC) on the partially operational network—no loss in connectivity

fail, all of the traffic along link 14 is detoured along links 10, 11, 7, 6, and 9. This is a long detour with a large number of vehicles detoured onto links that are not designed to carry a large traffic volume (links 6 and 9) resulting in large increases in road deterioration and congestion.

$$\mathrm{NCS}=\left\{\begin{matrix}6,8,9,14\\(6/8),(6/9),(6/14),(8/9),(8/14)\end{matrix}\right\} \tag{9}$$

The NCS where there is a loss of connectivity, at least between two nodes in the network, are given in Eq. (10), and the additional user costs that would be incurred when the network is in a NCS, where there is a loss of connectivity, are shown in Fig. 6.

$$\mathrm{NCS}=\left\{\begin{matrix}20\\(6/20),(8/20),(9/14),(9/20),(14/20)\\(6/8/9),(6/8/14),(6/8/20),(6/9/14),(6/9/20),(6/14,20)\\(8/9/14),(8/9/20),(8/14/20)\\(9/14/20),(6/8/9/14),(6/8/9/20),(6/8/14/20)\\(6/9/14/20),(8/9/14/20)\\(6/8/9/14/20)\end{matrix}\right\} \tag{10}$$

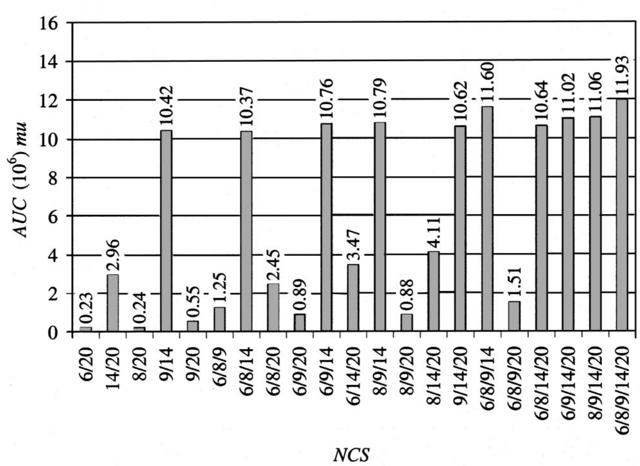

Fig. 6. Additional user costs (AUC) in NCS when there is a loss of connectivity

Table 13. Traffic Hazard Scenario: Optimal Management Strategies

Bridge	Single intervention: Ranking	Single intervention: Reduction in EAC (mu)	Multiple intervention: Sequence	Multiple intervention: Reduction in EAC (mu)
6	5	1.00×10^{-9}	5	1.00×10^{-9}
8	4	1.10×10^{3}	4	1.10×10^{3}
9	3	4.20×10^{3}	3	4.20×10^{3}
14	1	2.82×10^{6}	1	2.82×10^{6}
20	2	7.00×10^{3}	2	7.00×10^{3}

Table 14. Flood Hazard Scenario: Optimal Management Strategies

Bridge	Single intervention: Ranking	Single intervention: Reduction in EAC (mu)	Multiple intervention: Sequence	Multiple intervention: Reduction in EAC (mu)
6	2	570×10^{3}	3	100×10^{3}
8	3	550×10^{3}	2	360×10^{3}
9	1	790×10^{3}	1	790×10^{3}
14	4	2.82×10^{0}	4	2.82×10^{0}
20	5	70.0×10^{-3}	5	70.0×10^{-3}

Optimal Management Strategies

The analysis method used to determine the OMS is the equivalent worth method. As the agency costs are neglected to simplify the illustration of the SDS approach, the costs associated with each NCS are therefore only the user costs that would be incurred [Eq. (11)].

$$C_{i,n}^{EAU}=\sum_{j=1}^{\mathrm{NCS}}\sum_{t=1}^{t_{\mathrm{tot}}} C_{j,t}^{u} \tag{11}$$

where $C_{i,n}^{EAU}$ = equivalent annual user cost for strategy i for an analysis period of n years; and $C_{j,t}^{u}$ = user cost for NCS j for year t.

Traffic Hazard Scenario

The single intervention and multiple intervention OMS and the reduction in expected additional user costs of each intervention are shown in Table 13. The expected additional user costs due to the THS in the investigated time period is 2.83×10^{6} mu. Most of these costs are attributed to the inadequate structural performance of bridge 14 (2.82×10^{6} mu), due to the high probability that its set performance criteria will be exceeded (10^{-1}) and its importance in the network. Bridge 14 is on the main road connecting Morogoro and Dodoma. If it must be closed, all traffic is forced to travel on smaller and longer unpaved roads. By repairing bridge 14 so that there is a negligible probability that it must be closed to the THS in the investigated time period, the expected additional user costs can be reduced by 2.82×10^{6} mu.

By comparing the OMSs shown in Table 13, it can be seen that the possible reductions in expected additional user costs with each intervention do not change depending on the order of intervention, that is, if bridge 8 is repaired as a single intervention, the reduction in expected additional user costs would be 4.2×10^{3} mu, and it would also be 4.2×10^{3} mu if interventions are made on bridge 14 and bridge 20 before bridge 8. This means that the order of intervention does not affect the possible reduction in expected additional user costs of rehabilitating a bridge with a negligible probability of being nonoperational at the same time as another bridge.

Flood Hazard Scenario

The single intervention and multiple intervention OMS for the FHS and the reduction in expected additional user costs of each intervention are shown in Table 14. The expected additional user costs due to the FHS in the investigated time period are 1.25×10^{6} mu. The largest cost is expected to be due to bridges 6, 8, and 9 being nonoperational simultaneously. With these three bridges being simultaneously nonoperational, the town of Kilosa is left isolated with no access until a bridge can be repaired. The most effective way to reduce these expected additional user costs is to repair either bridge 6, 8, or 9 to ensure that all three bridges will not be nonoperational simultaneously. The largest reduction in expected additional user costs would be to reduce the probability of inadequate performance of bridge 9 so that it is negligible.

By comparing the OMSs shown in Table 14, it can be seen that the possible reductions in expected additional user costs of an intervention depend on whether or not there are other interventions performed. For example, if the probability of inadequate performance of bridge 8 is reduced so that it is negligible and no other interventions are performed, the reduction in expected additional user costs would be 550×10^{3} mu. If, however, the probability of inadequate performance of bridge 8 is reduced after the probability of inadequate performance of bridge 9 is negligible, the reduction in expected additional user costs would be only 360×10^{3} mu. This difference is because the estimation of the reduction in expected additional user costs when the probability of simultaneous nonoperational bridges is not negligible depends on the probability of the other bridges being nonoperational at the same time. This means that the order of intervention affects the possible reduction of the expected additional user costs of repairing a bridge with nonnegligible probability of being simultaneously nonoperational with another bridge. For example, on this network if only one intervention is to be performed, the probability of inadequate performance of bridge 6 should be reduced before the probability of inadequate performance of bridge 8. If, however, only two interventions are to be performed, they should be performed on bridges 8 and 9 and not on bridge 6.

Comparison with State-of-the-Art Approaches

To illustrate the difference the SDS approach can have on OMS, the OMS are determined using two state-of-the-art approaches: the supply bridge (SB) approach and the supply and demand bridge (SDB) approach. OMS determined using the SB approach are based solely on the physical condition of the bridge. No consideration is given to user requirements (demand). The SB approach is used in existing BMS, such as Pontis[2], Bridgit[3], and Kuba-MS[4], when only agency costs are considered. When agency costs are the sole decision criteria, the decision to perform an intervention is governed by the condition state of the bridge. (In this paper, the probability of inadequate performance is used to define the condition state of the bridge.) There is no consideration of expected societal costs attributed to lost safety or functionality. The objective function is the minimization of the collective probability of inadequate performance of the structures [Eq. (12)]. Minimize

$$\lambda=\sum_{i=1}^{n} P_i \tag{12}$$

Table 15. Traffic Hazard Scenario: OMSs Supply Bridge Approach

	Single/multiple intervention	
Bridge	Ranking/sequence	Probability of inadequate service
6	5	10^{-14}
8	3	10^{-2}
9	3	10^{-2}
14	1	10^{0}
20	2	10^{-1}

where P_i = probability of inadequate performance of bridge $i = f_i(P_{oi}, res_i)$; P_{oi} = initial probability of inadequate performance of bridge i; res_i = resources allocated to bridge i; and n = number of bridges subject to the following constraint:

$$\sum_{i}^{n} res_i \geqslant res_{\text{tot}} \tag{13}$$

and nonnegativity condition

$$r_i \geqslant 0 \tag{14}$$

$$\overrightarrow{res} \in \overrightarrow{RES}$$

$$\vec{p} \in \vec{P}$$

The OMS determined for the THS and FHS using the SB approach are shown in Tables 15 and 16, respectively. The probabilities of inadequate performance are expressed in orders of magnitude. When two bridges have the same order of magnitude of probability of inadequate performance they are given the same ranking. There is no difference between order of intervention for single intervention and multiple intervention OMS. This is because the SB approach does not consider the condition of the network or how it provides adequate service, as a whole. The improvement of the probability of inadequate performance of one bridge has no effect on the ability of the other bridges to perform adequately.

The OMS determined using the SB and SDS approaches for the THS, where simultaneous probabilities of inadequate performance are neglected, are essentially the same (Tables 13 and 15). The only difference is that when using the SB approach it is not possible to distinguish between bridges 8 and 9. The distinction between bridges using the SDS approach is made clearer. For example, by using the SB approach the difference between bridges 14 and 20 is one order of magnitude, but by using the SDS approach the difference is three orders of magnitude. This statement is valid for both the single intervention and multiple intervention OMS. The OMS determined using the SB and SDS approaches for the FHS, where simultaneous probabilities of inadequate performance cannot be neglected, are also essentially the same (Tables 14 and 16). The only difference is that by using the SB approach it is not possible to distinguish between bridges 6, 8, and 9, nor bridges 14 and 20. Using the SDS approach it is easier to distinguish between bridges. For example, using the SB approach for both the single intervention and multiple intervention OMS, there is no difference between bridges 14 and 20, but by using the SDS approach the difference is two orders of magnitude. Although the ability to distinguish between bridges in this comparison is improved by using the SDS approach, this depends on the order of magnitude of the probabilities of inadequate performance of the bridges and the expected additional user costs associated with each NCS. It is not necessarily a benefit of the SDS approach.

Table 16. Flood Hazard Scenario: OMSs Supply Bridge Approach

	Single/multiple intervention	
Bridge	Ranking/sequence	Probability of inadequate service
6	1	10^{0}
8	1	10^{0}
9	1	10^{0}
14	4	10^{-6}
20	4	10^{-6}

Table 17. Traffic Hazard Scenario: OMS Supply and Demand Bridge Approach

	Single/multiple intervention	
Bridge	Ranking/sequence	Reduction in EAC (mu)
6	5	1.00×10^{-9}
8	4	1.10×10^{3}
9	3	4.20×10^{3}
14	1	2.82×10^{6}
20	2	7.00×10^{3}

OMS determined using the SDB approach are based on the ability of individual bridges to perform adequately and the expected additional user costs if adequate performance is not provided on a bridge-by-bridge basis. The SDB approach does not explicitly take into consideration how the transportation network as a whole provides an adequate level of service. This approach is used in existing BMS[2,3,4] when both agency and user costs are considered. When both agency and user costs are considered, the decision to perform an intervention is governed by the condition state of the bridge (in this paper, the probability of inadequate performance) and the expected reduction of functionality. There is, however, a neglect of the lost functionality due to simultaneous nonoperational bridges. The objective function is to minimize the expected additional user costs [Eq. (15)].

Minimize

$$\lambda = \sum_{i=1}^{n} EAC_i \tag{15}$$

where EAC_i = expected additional costs due to inadequate performance of bridge $i = f_i(P_{oi}, res_i, AC_i)$; and AC_i = the additional costs due to inadequate performance of bridge i subject to the following constraint:

$$\sum_{i}^{n} res_i \leqslant res_{\text{tot}} \tag{16}$$

and nonnegativity condition

$$res_i \geqslant 0 \tag{17}$$

$$\overrightarrow{eac} \in \overrightarrow{EAC}$$

The OMSs determined using the SDB approach for the THS and the FHS are shown in Tables 17 and 18. If no interventions are performed, the expected additional user costs are 2.83×10^6 mu and 630×10^3 mu for the THS and FHS, respectively. There is no difference between the single intervention and multiple intervention OMS.

For the THS, the EAC and the order of intervention in the single intervention and multiple intervention OMS determined using the SDS and the SDB approach are the same (Tables 13–

Table 18. Flood Hazard Scenario: OMSs Supply and Demand Bridge Approach

Bridge	Single/multiple intervention	
	Ranking/sequence	Reduction in EAC (mu)
6	3	100×10^3
8	2	110×10^3
9	1	420×10^3
14	4	2.82×10^0
20	5	70.0×10^{-3}

17). There is no difference because there are negligible probabilities of simultaneous nonoperational bridges in the THS. Because there is a negligible probability of simultaneous nonoperational bridges and the difference between the OMS determined using the two approaches is due to the consideration of the NCS where there are simultaneous nonoperational bridges, the OMS are the same.

For the FHS, there is a difference in the EAC and in the order of intervention in the single intervention and multiple intervention OMS determined using the SDS and the SDB approaches (Tables 14–18). These differences are due to the nonnegligible probability of simultaneous nonoperational bridges in the FHS. A nonnegligible probability of simultaneous nonoperational bridges means that more NCS are considered when the SDS approach is used than when the SDB approach is used. Because there are additional user costs associated with each NCS, the expected additional user costs, and therefore the order of intervention, in the OMS can change.

Conclusions

The supply and demand system approach is a rational approach to the determination of optimal management strategies when multiple bridges may be adversely affected and may be nonoperational simultaneously. The secondary conclusions are the following:

1. The order of intervention in the single intervention optimal management strategies and the multiple intervention optimal management strategies is the same when there is a negligible probability of inadequate structural performance.
2. The order of intervention in the single intervention optimal management strategies and the multiple intervention optimal management strategies may be different when there is a nonnegligible probability of simultaneous inadequate structural performance.
3. The supply bridge approach and the supply and demand bridge approach can result in the determination of different optimal management strategies than those determined using the supply and demand system approach.
4. The supply and demand bridge approach and the supply and demand system approach give the same optimal management strategies for bridges if there is a negligible probability of simultaneous nonoperational bridges and different optimal management strategies for bridges if there is a nonnegligible probability of simultaneous nonoperational bridges.

Unfortunately, the supply and demand system approach is not yet ready to be implemented into bridge management systems, as it is very labor intensive. Some points for future work are as follows:

1. The development of a method with which to quantify the probability of inadequate service of transportation structures with reduced effort.
2. The development of a method with which to approximate user costs with reduced effort.
3. The determination of the probability of success and efficacy of interventions.
4. The determination of the correlation between the probabilities of inadequate bridge performance.

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Notation

The following symbols are used in this paper:

A_F = bridge A is nonoperational;
A_{rebar} = area of steel reinforcement;
$A_{t\text{flange}}$ = area of the I-beam tension flanges;
B_S = bridge B is operational;
$C_{i,n}^{EAU}$ = equivalent annual user cost for strategy i for an analysis period of n years;
$C_{j,t}^{u}$ = user cost for NCS j for year t;
C_A = agency costs, costs incurred by the owner of the transportation network;
C_S = bridge C is operational;
C_U = user costs, costs incurred by the users of the network;
d_{in} = initial diameter of one steel reinforcement bar (mm);
D_S = bridge D is operational;
$EAUC$ = expected additional user costs;
$F_R(r)$ = the probability of the resistance being smaller than r, for each value of r;
f_t = thickness of tension flange (mm);
$f_S(r)$ = probability of the load having a certain value, r;
f_w = width of tension flange (mm);
G = difference between the initial structural resistance and the action effects;
$g_R(t)$ = function describing how initial resistance changes with respect to time;
$g_S(t)$ = function describing how initial action effects change with respect to time;
M_R = moment capacity of beam;
M_S = moment created in beam;
n_F = number of relevant modes of inadequate structural performance in the hazard scenario;
$P(\text{NCS}_i)$ = probability of having network condition state i, in interval j;
P_F = probability of inadequate performance;
P_{FH} = probability of performing inadequately due to a hazard scenario;
P_{SFi} = probability of not performing inadequately due to a mode i of inadequate structural performance;
P_{SH} = probability of not performing inadequately due to a hazard scenario;

R = initial structural resistance;
r = discount rate;
r_{rcorr} = rate of corrosion of the diameter of the steel reinforcement bar (mm/year);
r_{tcorr} = rate of corrosion of the thickness of tension flange (mm/year);
r_{wcorr} = rate of corrosion of the width of tension flange (mm/year);
S = action effects created in the structure;
t = time;
UC = total user costs over the investigated period;
UC_{ij} = the user costs that would be NCS i occurred in interval j;
W_U = user costs weighting factor;
y_a = depth of abutment foundations;
y_{asc} = depth of abutment scour during an evaluation flood event;
y_p = depth of pier foundations; and
y_{psc} = depth of pier scour during evaluation flood event.

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