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Optimal planning of retrofitting interventions on bridges in a highway network

Giuliano Augusti and Marcello Ciampoli

Dipartimento di Ingegneria Strutturale e Geotecnica, Università di Roma La Sapienza, I-00184 Roma, Italy

Dan M. Frangopol

Department of Civil, Environmental and Architectural Engineering, University of Colorado, Boulder, CO 80309-0428, USA

The aim of the co-ordinated research effort initiated by the Authors consists in developing life-cycle reliability-based methodologies for the management and retrofitting of deteriorating structures and lifelines. As a first step, network systems with vulnerable nodes are considered. The object of this paper is the optimal planning of retrofitting interventions on bridges included in a highway network, taking into account their deterioration and the limitation of available economic resources. The procedure is illustrated with reference to a 10-node network. It is assumed that the resources available for retrofitting are not sufficient to guarantee the required structural reliability for all bridges throughout the design service life: thence the set of retrofitting interventions is sought that maximizes the network reliability (defined as the probability of maintaining connectivity) under a constraint on the total expenditure. The allocation is performed by means of a dynamic programming procedure. © 1998 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Many civil engineering structures and constructed facilities throughout the world are in a condition of serious deterioration, that is, are subject to changes in their mechanical properties that occur over time and can hinder their functionality and even lead to ruin and collapse. Even ordinary service of a structure contributes to such deterioration, that can be accelerated by exposure to an aggressive environment and to accidental actions like earthquakes or fires, as well as by improper use and maintenance.

Because of deterioration, the reliability of a structure is actually time-dependent, and generally decreases with time, thus causing an increase in the probability of failure P_f. Therefore, structural reliability must be referred to a *service life*, defined as the period during which the structure should be able to withstand all loads safely. To this aim, a programme of well-timed periodic inspections is essential, followed by appropriate interventions, such as repair, ugrading, and replacement (demolition and reconstruction).

Decision makers must decide *if*, *when* and *how* to repair, rehabilitate, replace and/or shut-down the deteriorating facilities: in other words, must elaborate *retrofitting strategies*. It has been widely recognized that these decisions should be made on the basis of a Life-Cycle Reliability-based System Analysis (LRSA)[1,2], taking into account of the most relevant action scenarios and of all the consequences of structural failure.

Often, structures in such conditions are essential elements of lifetime systems, like transport or communication networks, whose functionality would be affected by structural failure. When the concerned structure is included as an essential element in a lifeline system (e.g., this is the case of a bridge or a viaduct in an highway network), its loss of functionality may impair the functionality of the whole network: it is essential that the retrofitting strategy takes into account this *system effect*. Such a *system* approach, inherently multidisciplinary, has been seldom dealt with, and is one of the key points of current investigations[3,4].

On the other hand, decision makers must face the fact that the economic resources available to implement retrofitting strategies are limited. This is especially true for public works, where lack of funds is quite a common situation throughout the world: therefore, it is essential that they are exploited in a rational, that is, an *optimal* way[3–6].

On the basis of these considerations, a research effort has been started in order to develop rational methodologies for LRSA multicriteria evaluation and to design appropriate retrofitting strategies for deteriorating structural systems and networks[7,8].

More specifically, the final aim of this research programme will be the development of an operative procedure for the optimal allocation of available economic resources in order to minimize the losses expected throughout the service life of a lifeline network.

In this procedure, the *costs* of inspections and of possible retrofitting interventions on each vulnerable facility of the network and the *benefits* (that is, the loss reductions) they can produce must be evaluated. The action scenario must be considered, including in its definition ordinary service loads (e.g., codified occupany loads on buildings, truck loads on bridges, etc.), aggressive environment and accidental actions, like earthquakes, explosions, vehicles and vessel collisions. Many of these actions are highly uncertain, and therefore can be defined only in probabilistic terms. Consequently, also the losses due to deterioration and their reduction are uncertain: reference can be made to *expected* values in the given service life of the concerned facility.

If the total loss reduction is made as large as possible (in terms of an appropriate *objective function*) during the design service life of the network under the constraint of a given amount of resources employed, it can be said that the resources have been *optimally allocated*: in other words, an *optimal life-cycle reliability-based management strategy* under limited resources has been implemented.

It must be noted that the proposed procedure is a combined development of two previous procedures, respectively relevant (a) to optimal allocation among the bridges of a highway network in respect of the expected effects of an exceptional event (e.g., an earthquake)[3–6], and (b) to the life-cycle reliability-based management of single structures[1,2,9].

Thus, the object of the present paper is the optimal planning of retrofitting interventions on bridges included in a highway network, taking into account their deterioration and the limitation of available economic resources.

It is evident that the development of procedures for implementing such strategies is far from simple. The whole process can be further complicated by the fact that not only several types of losses can be relevant, but they can be of a quite different nature, and therefore cannot be summed or combined, not even by attributing to them appropriate weights. For instance, some losses can be expressed in monetary values (these can be grouped under the term *economic*), but some other cannot, like human casualties, or the loss of artistic and historic heritage (we shall call these *intangibles*). In this case, different optimizations must be performed and the final decision taken on non quantifiable basis.

2. General procedures for life-cycle management of bridge networks

The procedure is developed with specific reference to highway networks, and the bridges located in the network are considered to be the only elements with a non-zero probability of failure P_f: hence, they constitute the *critical elements* of the network. In the allocation procedure, the highway network is described by a *graph*, whose *branches* represent functional connections between *nodes*. As usual in graph theory, only the nodes are vulnerable and constitute possible weak points of the network: this type of approach makes it possible to consider the whole network as a single system and to take correctly into account the role played by each element in its functional logic.

Besides normal traffic loads (like codified truck loads), the bridges can be exposed to aggressive environment and/or accidental actions, like earthquakes, explosions, vehicle and vessel collisions. In this study, the action scenario is assumed to be given, and the bridge failures to be stochastically independent events.

With regard to the economic resources, they can be made (i) globally available at a certain time (that is, the time in which the optimal allocation is decided), or (ii) available in successive tranches at different times. In the latter case, the time sequence of expenditures can be defined *a priori*, or be the subject of an optimization process by itself. Also, the cost of the inspection programme should be included in the optimization, but in this paper it will be considered as a given constant.

The available amount of resources may be sufficient to retrofit the whole set of vulnerable elements, or only some of them. In the former case, it is possible to guarantee that the reliability of every vulnerable element remains larger than a fixed threshold value at all times during the projected lifetime, for instance by the procedure developed by Estes and Frangopol[9]. In the latter case, it is likely that retrofitting will preferentially concern the elements that are the most critical in the functional logic of the network, and not necessarily the most vulnerable by themselves; therefore, careful attention must be paid to recognize dangerous situations that cannot be solved for economic reasons, and to suggest appropriate measures to satisfy safety requirements (e.g., by limiting or forbidding the use of some bridges starting from a certain time).

In the following, the allocation of resources is optimized with respect to a single *objective function*, namely the *network reliability*, defined as the probability of maintaining active at least one connection between the source (S) and destination (D) nodes of the network. In follow-up studies, other objective functions will be considered, e.g. the *expected traffic capacity* of the network, i.e. the quantity of traffic that can run between source and destination[10].

Differently from the quoted previous studies by Augusti *et al*.[3–6], in which the cause of structural damage was assumed to be a future earthquake of given (design) intensity, in the present approach, explicit reference is made to a service life or a *design lifetime* LT: in fact, the reliability $R_i(t)$ of each vulnerable element decreases monotonically with time t, because of the effects of repeated normal loads and of possible exposure to an aggressive environment that adds to the expected effects of accidental actions. Consequently, also the reliability of the whole network $R_{sys}(t)$, which is related to the reliabilities $R_i(t)$ of the vulnerable elements by the functional logic of the network, is a non-increasing function of time t.

To develop the optimal allocation procedure, it is first necessary to assess the expected reliability $R_i(t)$ of each vulnerable element as a function of time. In the following, it is assumed that — without retrofitting interventions — $R_i(t)$ is a continuous function, depending on the deterioration due to the continuous effects of aggressive agents (chemical and/or physial), to regular operation, and to expected accidental events, such as thermal shocks or earthquakes[11]. It is also assumed — as already hinted — that the cost of inspections is fixed, and that the inspections are sufficient to check the estimated reliability $R_i(t)$.

Let R_i^* be an allowable threshold for the reliability of element i. If the reliability $R_i(t)$ downcrosses R_i^* at any time during the design lifetime, possible retrofitting strategies must be considered.

A *retrofitting strategy* is defined as a well specified sequence of retrofitting works, usually executed at different times, which guarantee that the element reliability is always above the threshold R_i^* during its lifetime. In general, for each vulnerable element, a set of m different retrofitting strategies can be recognized, and compared with respect to their actual costs and to their efficiencies[9]; these strategies comprise the possibility of replacing the structure, at least at some time during its projected lifetime.

In what follows, the term *intervention* on a vulnerable element will indicate either a retrofitting strategy, or the choice of no intervention at all during the whole lifetime: therefore, for each element (bridge), $n = m + 1$ different *interventions* can be considered.

The optimization problem under limited resources can be formulated in at least three ways, depending on the total amount of available resources:

(1) if the available amount of economic resoures is smaller than the amount necessary to guarantee the above mentioned condition $R_i(t) > R_i^*$ at all times for all vulnerable elements, optimize the distribution of interventions that maximizes the expected reliability of the network throughout the design lifetime;
(2) if the available amount of economic resources is larger than the amount needed to guarantee the above mentioned condition $R_i(t) > R_i^*$ at all times for all elements, select the distribution of retrofitting strategies which not only satisfies — always — the condition $R_i(t) > R_i^*$, but also maximizes the expected reliability of the network R_{sys} in the design lifetime;
(3) if the total amount of economic resources (assumed larger than the amount defined in alternative 2) is made available at different times, select the distribution of strategies that maximizes the expected reliability of the network in the design lifetime, under the constraint that $R_{sys}(t) > R_{sys}^*$ at all times during the projected lifteime, R_{sys}^* being a threshold value of the network reliability.

Alternative 1) implies that not all the vulnerable elements can be retrofitted: therefore, it must be aimed at maximizing the reliability of the network $R_{sys}(t)$. Once the optimal allocation procedure is completed, it will be possible to *control* whether $R_{sys}(t)$ is larger than the threshold value R_{sys}^* throughout the projected lifetime, and to *identify* the elements for which the threshold R_i^* is violated. For these elements, special expedients must be adopted, like forbidding the use of the bridge to all traffic or to heavy vehicles only.

Alternative 2) can be regarded as a special case of alternative 1). The surplus over the amount of resources employed in retrofitting works able to guarantee that always $R_i(t) > R_i^*$, can be utilized to optimize the reliability of the network $R_{sys}(t)$.

Alternative 3) poses peculiar and cumbersome problems, especially if also the times of the expenditures can be chosen and optimized. Under the simplifying assumption that the distribution of these times is defined, every stage of the procedure corresponds to a problem as in alternative 1), but operates on a network that is modified every time.

In the developments that follow, only alternative 1) is explicitly considered.

Finally, it is worth noting again that calibration of inspection programmes is not considered in this paper, although it is well known that planning of inspections on vulnerable elements constitute an essential part of an optimal life-cycle management strategy, and can be optimized according to well defined procedures[12]. Here, however, the inspections are assumed to be performed at pre-defined times, with defined costs; their main aim would be therefore to check the evolution of the element reliability over time, and calibrate the model parameters, also in order to update the procedure[13], if some amount of economic resource is still available (alternative 3).

3. Formulation of the problem

In the examples so far developed[3–10], the (vulnerable) nodes are bridges, but other vulnerable elements could be included, like embankments, landfills, tunnels, etc.

To develop the optimal allocation procedure, it is first necessary to assess the expected reliability $R_j(t)$ of each bridge as a function of time[14].

Let R_j^* be the admissible threshold for the reliability of element j. If the reliability $R_j(t)$ downcrosses R_j^* at any time during the design lifetime, and if the available amount of economic resources is smaller than the amount necessary to guarantee the above mentioned condition $R_j(t) > R_j^*$ at all times for all bridges, obviously not all bridges can be adequately retrofitted (alternative 1 in section 2). Therefore, the purpose of the retrofitting strategy must rather be aimed towards the reliability of the network $R_{sys}(t)$: here it has been assumed that the optimal strategy consists in the distribution of interventions that maximizes the expected reliability of the network, either at the end of or averaged over the design lifetime LT.

Once the optimal allocation procedure is completed, it is possible to *control* whether $R_{sys}(t)$ remains larger than a set threshold value R_{sys}^* throughout LT, and to *identify* the bridges for which the threshold R_j^* has been violated, at least at some times.

Summing up, in the case and under the assumptions considered, the optimization procedure consists of the following steps:

(1) examine the relevant road network, identify its vulnerable elements, schematize the network into a graph whose nodes coincide with the vulnerable elements, and choose a design lifetime LT;
(2) define the action scenario (expected "codified" loads, aggressive environment, possible exceptional loads like collisions, earthquakes, etc.) in relation with ultimate

and service limit conditions of the structure (assumed as *performance criteria*);

(3) identify the functional logic of the network (described, as usual, by minimal path set or minimal cut set representations) in relation to the performance criteria;

(4) choose threshold levels (R_{sys}* and R_j* respectively) of the system and element reliabilities, $R_{sys}(t)$ and $R_j(t)$;

(5) for each vulnerable element *j*, assess the reliability R_{j0} in the present state; then evaluate, according to a suitable degradation model and the assumed hazard scenario, the evolution of the expected reliability $R_j(t)$ during the projected lifetime;

(6) on the basis of (3) and (5), evaluate $R_{sys}(t)$ as a function of $R_j(t)$;

(7) for each vulnerable element *j*:
  - identify possible retrofitting operations; evaluate their efficiencies and costs;
  - identify alternative sequences of retrofitting operations (referred to as *interventions* in the present paper) able to keep $R_j(t) > R_j$*, and evaluate their actual costs.

(8) for the network:
  - evaluate the distribution of interventions that maximizes the network reliability, under the constraint of a limited global amount of available resources, by comparing the possible combinations of interventions on each vulnerable element according to the functional logic of the network.

4. Case example

The considered network is represented in *Figure 1*; the vulnerable elements are the ten bridges a–k, all equal to the three-span, four-lane steel girder bridge described by Estes and Frangopol[9] and Estes[14]. The deck is reinforced concrete and the steel girders are standard rolled shapes with simple-span supports. The interior span supports are reinforced concrete pier columns, with a pier cap, four supporting square tapered columns, and individual column footings. The bridge length is 42.1 m, and the roadway width is 12.2 m. The pier height is approximately equal to 7.60 m.

The probability of failure P_{fj} of the bridge has been assessed by considering 16 different failure modes, that include flexural failure of the slab, flexural and shear failure of the girders, and multiple failure modes of the pier cap, column and footings[9,14]. The random variables considered have been material strengths, dimensions, service loads, weight and model uncertainties. P_{fj} increases with the time interval considered because the expected live load increases and the structure deteriorates. Two different sources of deterioration have been considered: the slab and the pier cap are exposed to the aggressive action of de-icing salts, so that chlorides penetrate the concrete and cause the steel reinforcement to corrode after threshold concentration is reached; the steel girders are also corroding, so that the web area and the section modulus reduce over time. The deterioration process introduces new random variables: diffusion rate, chloride surface concentration, and rate and depth of corrosion.

A minimum allowable bridge lifetime reliability index $\beta = 2$ (corresponding to $P_{fj} \cong 0.023$) has been chosen. The bridge is inspected every two years, and anytime the bridge reliability falls below the prescribed minimum, some type of retrofitting or replacement must be made.

Different retrofitting/replacement options have been considered, and their 1996 costs carefully evaluated, with the results shown below:

(1) *replace slab* (US$ 225,600)
(2) *repair exterior two girders* (US$ 229,200)
(3) *replace exterior two girders and slab* (US$ 341,800)
(4) *replace entire superstructure* (US$ 487,100)
(5) *replace entire bridge* (US$ 659,900)

Accounting for all feasible and useable combinations of options, the possible interventions which guarantee that the bridge reliability never falls below the prescribed minimum have been selected. They are reported in *Table 1* and in *Figure 2*, together with their 1996 value costs (derived by considering a discount rate of two percent). In *Table 1*, an intervention 0 (i.e. the chance of not performing any retrofitting) has been added for completeness.

The optimal intervention for a single bridge and a given lifetime can be easily determined from *Figure 2*[9]. After 106 years, the replacement of the entire bridge becomes mandatory. Note also that option 2 never appears in the possible interventions, because it is not efficient.

In numerical calculations, a network representing schematically a real portion of a highway system has been considered. However, a reliability-based condition assessment taking into account the effects of deterioration was available only for one specific bridge. The network example is therefore unrealistic; nonetheless the developed numerical calculations can be useful to evaluate the efficiency of the procedure, and to understand the kind of results that it can yield.

The optimization has been aimed at minimizing the probability of network failure P_{fsys}, that is given by the relation:

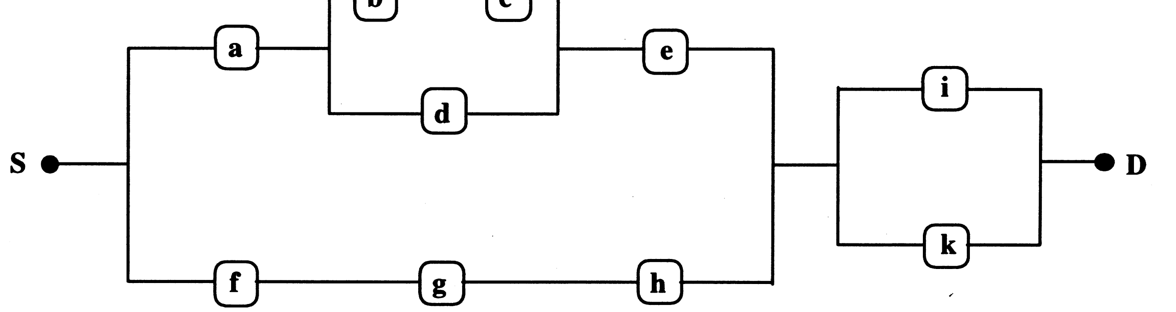

Figure 1 Example network

Table 1 Alternative interventions

- *Intervention 0*: no intervention during the lifetime.
- *Intervention 1*: the slab is replaced at year 50 (option I).
- *Intervention 2*: the slab and two exterior girders are replaced at year 50 (option III); at year 92, some other action is needed to meet the bridge reliability requirement.
- *Intervention 3*: the slab and the entire superstructure are replaced at year 50 (option IV); at year 94, some other action is needed to meet the bridge reliability requirement.
- *Intervention 4*: the bridge is replaced at year 50 (option V).
- *Intervention 5*: the slab is replaced twice at year 50 and year 94 (option I); the slab replacement at year 106 is not sufficient to raise the bridge reliability above the minimum prescribed.
- *Intervention 6*: the slab is replaced at year 50 (option I) and the exterior 2 girders and slab are replaced at year 94 (option III). At year 108, the only option which will meet the bridge reliability requirement is to replace the bridge.
- *Intervention 7*: the slab is replaced at year 50 (option I) and the entire superstructure is replaced at year 94 (option IV). At year 108, the only option which will meet the bridge reliability requirement is to replace the bridge.
- *Intervention 8*: the slab is replaced at year 50 (option I) and the entire structure is replaced at year 94 (option V).
- *Intervention 9*: the slab is replaced twice at year 50 and 94 (option I); at year 106, the only option which will meet the bridge reliability requirement is to replace the bridge (option V).

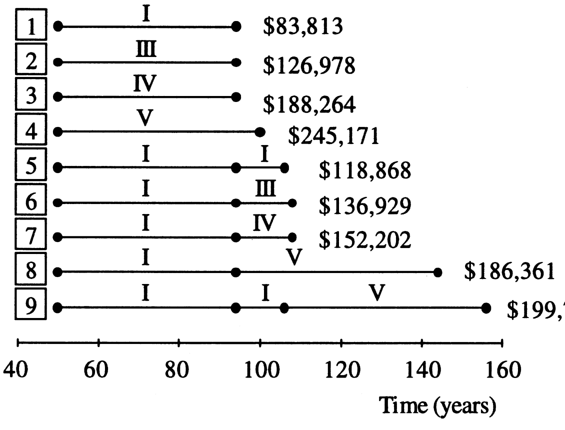

Figure 2 Possible interventions and 1996 costs

$$
\begin{aligned}
P_{\text{fsys}} = 1 - \{1 - \{1 - (1 - P_{\text{fa}}) \\
\cdot\{1 - [1 - (1 - P_{\text{fb}})\cdot(1 - P_{\text{fc}})]\cdot P_{\text{fd}}\} \\
\cdot(1 - P_{\text{fe}})\}\cdot\{1 - (1 - P_{\text{ff}})\cdot(1 - P_{\text{fg}}) \\
\cdot(1 - P_{\text{fh}})\}\}\cdot(1 - P_{\text{fi}}P_{\text{fk}})\}
\end{aligned}
$$

where P_{fj}'s are the probabilities of the individual bridge failures, assumed to be stochastically independent events.

The system reliability varies throughout the lifetime due to the considered degradation mechanisms. Therefore its value at the end of LT might not be the most significant decisional parameter: for instance, the average value may also be of interest. Both measures have been considered in the numerical calculations, by introducing the alternative corresponding values of the probability of failure P_{fj} of each bridge, namely: the value at the end of the design lifetime; the mean value during the lifetime.

In finding the optimal distributions of interventions between the vulnerable elements of the network represented in *Figure 1*, two alternative values of the design lifetime LT have been considered, namely 80 and 100 years: interventions 1, 2, 3, 4 have not been taken into account in the latter case.

Also, alternative amounts of available resources have been considered, comprised in the range between US$ 60 000 and US$ 420 000 (note that the cost of replacing all ten bridges according to the most expensive intervention 4-option V-is equal to US$ 2 451 710–1996 value costs).

The optimization has been performed by means of dynamic programming[15]. The implemented dynamic programming technique is very powerful in solving this type of discrete nonlinear optimization problems. In this example, an exhaustive search was also tried, but it was extremely time-consuming, although the number of vulnerable elements was not so large.

The optimized distributions of interventions are shown in *Table 2,* for different amounts of available resources C_{ava}, indicated in thousands of US$.

Figure 3 shows the coresponding values of P_{fsys} for the four cases considered.

As already indicated, the vulnerable elements are all equal to each other. Therefore the results reflect only the structure of the network: the optimal distribution of interventions tends to create a preferential path a–d–e–i. Note also that bridges a and e and, respectively, i and k are identically located in the graph of the network (see *Figure 1*): therefore, interventions on either of them are interchangeable.

It is to be noted again that, due to the limited amount of available resources, the optimization procedure does not check the reliability of the single bridges. In particular, the reliability of bridges b and c, or f, g and h may become critical; if no intervention is possible, some measures must be planned, like forbidding the use of these bridges to all traffic or to heaviest vehicles from a certain time onwards.

5. Concluding remarks and further developments

Although there are many public constructed facilities in Europe and in the United States that are in a condition of serious deterioration, the economic resources available for their management are usually limited, and therefore must be employed in the wisest possible way. It is the engineers' task to provide rational bases to the decision makers who must decide if, when and how to repair, rehabilitate, replace and/or shut-down the deteriorating individual structures and networks.

A specific case has been tackled in this paper, namely deteriorating bridges inserted as essential elements in a highway network; it has been assumed that the bridges can be retrofitted but the layout of the network cannot be modified, and that the main scope of the network is its connectivity. Previously developed ideas on (i) life-cycle management of single structures and (ii) optimal resource allocation among the elements of a network to reduce the expected consequences of exceptional events, are combined into a novel procedure for the optimal allocation among gradually deteriorating bridges.

Table 2 Optimized distributions of interventions among the vulnerable elements, considering respectively: the failure probabilities at the end of the lifetime, for a lifetime of 80 (case A) or 100 years (case B); the average probabilities during the lifetime, for a lifetime of 80 (case C) or 100 years (case D)

case A: LT = 80 years C_{ava} (1000 $)	60	90	120	150	180	210	240	270	300	330	360	390	420
a	1	1	1	1	1	1	1	1	1	1	1	1	1
b–c–d	–	–	–	–	–	–	–	–	–	–	–	–	–
e	–	–	1	1	1	1	1	1	1	1	1	1	1
f	–	–	–	–	–	–	1	1	–	–	1	1	1
g	–	–	–	–	–	–	–	–	1	1	1	1	1
h	–	–	–	–	–	–	–	–	1	1	1	1	1
i	–	–	–	–	1	1	1	1	1	1	1	1	1
k	–	–	–	–	–	–	–	–	–	–	–	–	1

case B: LT = 100 years C_{ava} (1000 $)	60	90	120	150	180	210	240	270	300	330	360	390	420
a	–	5	–	–	5	6	8	5	8	8	8	8	8
b–c	–	–	–	–	–	–	–	–	–	–	–	–	–
d	–	–	–	–	–	–	–	–	–	–	–	5	–
e	–	–	7	8	6	7	7	6	5	7	8	5	8
f–g–h	–	–	–	–	–	–	–	–	–	–	–	–	–
i	–	–	–	–	–	–	–	5	5	5	6	5	8
k	–	–	–	–	–	–	–	–	–	–	–	–	–

case C: LT = 80 years C_{ava} (1000 $)	60	90	120	150	180	210	240	270	300	330	360	390	420
a	1	2	1	2	1	2	1	2	1	2	1	2	1
b–c–d	–	–	–	–	–	–	–	–	–	–	–	–	–
e	–	–	1	1	1	1	1	1	1	1	1	1	1
f	–	–	–	–	–	–	1	1	1	1	1	1	1
g	–	–	–	–	–	–	–	–	1	1	1	1	1
h	–	–	–	–	–	–	–	–	–	–	1	1	1
i	–	–	–	–	1	1	1	1	1	1	1	1	1
k	–	–	–	–	–	–	–	–	–	–	–	–	1

case D: LT = 100 years C_{ava} (1000 $)	60	90	120	150	180	210	240	270	300	330	360	390	420
a	–	–	7	8	5	7	8	5	5	8	5	5	5
b–c–d	–	–	–	–	–	–	–	–	–	–	–	–	–
e	–	5	–	–	6	6	7	6	8	7	7	8	5
f	–	–	–	–	–	–	–	–	–	–	–	–	5
g	–	–	–	–	–	–	–	–	–	–	–	–	5
h	–	–	–	–	–	–	–	–	–	–	5	5	–
i	–	–	–	–	–	–	–	5	5	5	5	5	5
k	–	–	–	–	–	–	–	–	–	–	–	–	–

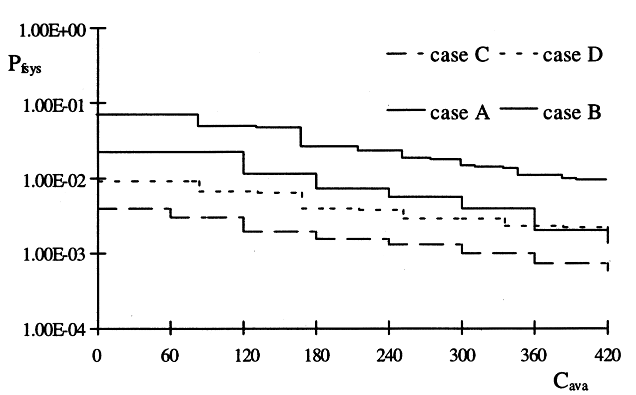

Figure 3 Optimized probabilities of network failure vs. total amount of available economic resources

An application to a realistic example network has confirmed the effectiveness of the procedure, but underlined that an exhaustive search involves too much computer time, while an allocation procedure based on dynamic programming is feasible.

Further studies will try and tackle additional aspects of the problem, with regard to: (a) the numerical optimization procedures; (b) the vulnerable elements taken into consideration (bridges and viaducts, but also embankments, landfills, tunnels, ...); (c) the objective functions of the optimization (e.g., the *expected traffic capacity* of the network, i.e. the quantity of traffic that can run between the source and destination nodes and that is as important as simple connectivity); (d) the several ways in which funds can be made available; (e) the causes of structural deterioration (in patricular, the combination of slow actions and sudden man-made or environmental accidents); (f) the practical applicability to real examples with much more complicated network topologies; and (i) the removal of the condition of independence, of failures of vulnerable elements.

It is hoped that the relevance of the question and the feasibility of the procedures will raise the general interest and allow their application to real examples.

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