Methodology to determine optimal intervention strategies for structures adversely affected by latent processes

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ABSTRACT

Determination of optimal intervention strategies depends on predictions of the future, with which there is uncertainty. The degree of uncertainty varies significantly depending on whether the processes that can result in the structure providing an inadequate level of performance are manifest or latent under normal inspection regimes. In this paper a methodology is presented that can be used to evaluate the effectiveness of intervention strategies for structures adversely affected by latent processes. The steps of the methodology include the determination of the most effective intervention strategy and the verification that it satisfies all absolute constraints, e.g. constraints on the allowable probability of failure, and relative constraints, e.g. marginal cost constraints for saving lives. The methodology is not dependent on the level of detail required and can be used for single structures as well as entire road networks.

Keywords: inadequate structural performance, infrastructure, latent processes, structure failure, structure management, optimal intervention strategies, risk management

INTRODUCTION

The goal of infrastructure managers can be seen as the minimization of their costs while providing an adequate level of service, where an adequate level of service is defined through requirements to be satisfied, such as those given in codes of practice. Since infrastructure deteriorates over time, eventually resulting in an inadequate level of service, if no intervention is performed and financial resources are limited, achievement of this goal requires the determination of the most effective intervention strategies[1].

Determination of these strategies depends on predictions of the future, with which there is uncertainty. The degree of uncertainty varies significantly depending on the processes at work that can result in the structure providing an in adequate level of service. These processes can be classified as either manifest or latent, depending on whether they are regularly and easily observed in such a way that future performance can be predicted with respect to these processes with relative little uncertainty[2].

There are well documented and agreed upon methodologies to be used to determine the most effective strategies for structures adversely affected by manifest processes. Many of which are implemented in the state-of-the-art structures management systems, including KUBA in Switzerland (Hajdin et al., 2009) and the Q-BMS in Quebec Canada (Ellis et al., 2008). There are not yet, however, well documented and agreed upon methodologies to be used in these systems to determine the most effective strategies for structures adversely affected by latent processes. As the optimal strategy for a structure depends on all of the processes that affect it, both types need to be considered in the evaluation of strategies.

To fill this need, a general methodology was developed for the evaluation of the effectiveness of strategies for maintaining structures adversely affected by latent processes. The steps of the methodology are presented in this paper, including the determination of the most effective strategy and the verification that it satisfies all absolute constraints, e.g. constraints on the probability of failure, and relative constraints, e.g. marginal cost constraints for saving lives. The methodology is not dependent on the level of detail required and can be used for single structures as well as entire road networks.

The research conducted to produce this methodology (Adey et al., 2009) was conducted within the research package "Safety of highways and their structures" in Switzerland and has built on ideas from the other research projects within this package. The three projects of particular importance are:

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[1] Herein intervention strategies are referred to simply as strategies.
[2] Herein manifest and latent processes that might result in failure are referred to simply as a manifest and latent processes.

- "*Methodological basis for comparative risk assessment*" (Faber et al., 2009) which was focused on how to compare risks in general on the highway system.
- "*Risk assessment for highway* structures" (Fermaud et al., 2009), which was focused on extending this methodological basis developed by (Faber et al., 2009) to structures
- "*Effectiveness and efficiency of interventions"* (Van Linn et al., 2009), which was focused on how to compare strategies in general on the highway system.

STATE-OF-THE-ART

Although there is very little work on the evaluation of the effectiveness of strategies for structures adversely affected by latent processes, there is a substantial amount of work focused on the assessment of the risks due to latent processes. This work is, or can be, used to determine effective strategies. Four of the most significant on-going projects are:

- The development of HAZUS-MH in the United States of America (FEMA, 2004) to estimate building and infrastructure losses from natural hazards, specifically earthquake, flood, and wind. HAZUS-MH includes consideration of the hazard intensity, geographic coincidence analysis between infrastructure location and the effects of hazards, and the estimation of loss if the hazard effect occurs.
- The vulnerability assessment approach developed by the New York State department of transport (NYDOT, 2008) to provide an assessment of the likelihood of sudden failure and a quantification of the resulting consequences. A similar methodology is to be included in the upcoming version of Pontis (Patidar et al., 2007).
- The risk maps being developed in Germany to enable large scale quantification of natural hazards, including earthquake, flood and wind, and man-made hazards (Wenzell et al., 2008). For public infrastructure, it focuses on the identification of critical transportation links and estimating the potential consequences due to their failure.
- The Riskscape software being developed in New Zealand to model losses due to natural hazards including earthquake, flood, wind, tsunami, and volcano (Reese et al., 2007).The software includes the assessment of hazard intensity, identification of exposed objects, assessment of damage states and assessment of consequences.

The methodology presented in this paper goes further than the methodologies currently used in these research projects in that it focuses on the entire process from formulation of goals and constraints to the verification of the relative constraints in the determination of the most effective strategy. It also gives guidelines on the representation of the system that should be used in the estimation of risks due to latent processes and the evaluation of strategies to ensure an adequate level of service.

METHODOLOGY

General

The evaluation of a strategy is based on comparison with a reference strategy. The reference strategy consists of the maintenance interventions[3] performed to ensure that there are negligible risks[4], and to restore the structure so that it provides an adequate level of service following (an improbable) failure, due to manifest processes and the loads to which the structure is subjected under normal use. The methodology is appropriate once it has been determined that there are unacceptable risks due to latent processes. The steps of the methodology are shown in Figure 1.

Definition of the problem

Formulation of constraints

The goal of the decision maker is to find the most effective strategy that satisfies all of the constraints. Constraints may be placed on strategies with respect to the whole period being investigated or for time intervals within the investigated time period. A summary of the constraints that are often placed on strategies are presented in Table 1.

There are absolute constraints that are not dependent on other strategies and there are relative constraints that are dependent on other strategies. The most discussed relative constraint is on the amount of money to be spent to reduce death risks, i.e. the limit on the marginal increase in cost between strategies per additional saved human life. If constraints are set with respect to individual benefit types, it is necessary to determine, the portion of strategy costs attributed to the appropriate benefit type. This is in practice often difficult.

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[3] An example of a reference intervention strategy is routine maintenance every 5 years, the repair of a bridge when it is condition state 4 (out of a possible 5) and the reconstruction of a bridge if it fails.
[4] These risks can be assumed to be negligible during normal use as they are relatively small per unit time. They can also be assumed to be negligible during interventions, even though they can be large per unit time, as the time period in which the intervention is performed is normally short in comparison with the investigated time period.

Determination of the possible strategies

The strategies to be investigated can include interventions from the entire spectrum of technical and administrative possibilities and can include interventions that reduce risks due to multiple hazards. The potential strategies need to be identified before they can be evaluated and the optimal among them determined.

System representation

The system representation is a model of the relevant part of reality used for the evaluation and consists of all possible realizations of stochastic processes within the investigated time period. It includes sufficiently good representations of the structures, hazards, and consequences, as well as the interaction between them so that it can be reasonably certain that there is an appropriate understanding of the system and that the risks and the effectiveness of the strategies can be determined. A system representation consists of all possible scenarios, including those that may occur due to the system changes caused by following strategies. These can be shown in the form of event trees where a scenario is represented by a path in the event tree. The paths are divided in ways that can be used to describe the hazards and consequences, e.g. an event, an effect, a direct consequence or an indirect consequence. An example for a bridge exposed to flooding and avalanches is shown in Figure 2, assuming that flood and avalanche events are mutually exclusive. In this event tree the hazard consists of the event and the effects on the structure that are considered to have consequences. The effects on the structure are represented by two levels of the key parameters, water depth $>= a$ and water depth $< a$, where a is the bridge clearance, and snow depth $>= b$ and snow depth $< b$, where b is the depth of snow on the bridge.

The consequence portion of the event tree is composed of the non-monetarisable and monetarisable direct and indirect consequences. For each level of the key parameter(s) assumptions are made with respect to the non-monetarisable direct consequences that can occur, e.g. the physical behavior of the structure when the specified level of the key parameter(s) occurs. The effect on the structure should be described with the fewest possible parameters. Assumptions are made with respect to the monetarisable direct consequences that can occur for each non-monetarisable direct consequence, e.g. the fatalities related to the collapse of a structure. Assumptions are made with respect to the monetarisable indirect consequences that can occur for each monetarisable direct consequence, e.g. the additional user traffic time due to a deviation. The monetarisable consequences can be attributed to those that will carry the consequences if failure occurs and can be grouped by consequences type.

In the example event tree (Figure 2), each effect has two possible non-monetarisable direct consequences ($nmIC_1$, $nmIC_2$). For example, when the water depth during a flood is >= *a*, than the two possible failure modes are the wash out of the abutments ($nmDC_1$) and the wash out of the columns ($nmDC_2$). The monetarisable direct consequences deterministically follow the non monetarisable direct consequences ($nmDC_1$). The monetarisable indirect consequences are branched into the monetarisable indirect consequences that would occur if the abutments were washed out during winter with low traffic volumes (mIC_1) and those that would occur if the abutments were washed out during summer with high traffic volumes (mIC_2).

Due to the almost infinite number of ways to represent reality and the almost infinite number of ways that intervention strategies can affect reality, an appropriate system representation needs to be developed. A good starting point is often the system representation used to determine that there was a problem. It needs, however, to be verified that this representation is adequate for the evaluation of the candidate strategies. The necessary detail to be used depends on the specific question, the strategies to be evaluated and the level of detail desired.

Since the impact of interventions within a strategy depend on the condition of the structures, the actions on the structure and the use of the structure, which change over time due to deterioration, other interventions and changes in use, the system representation must allow the consideration of changes over time and must be adequate for the time period of investigation. Ideally, the time period to be investigated is selected so that the impact of all strategies at the end of the period can be assumed to be the same.

System representations can be grouped by problem class:

- a structure problem, where a single structure is represented alone and the correlations with other structures with respect to hazards and consequences are not taken into consideration,
- a type of structure problem, where a typical structure is represented alone with representative hazards and consequences, and the correlations with other structures problems are not taken into consideration, and
- a network problem, where part or all of a network, with all structures together, is represented with all correlations between the structures with respect to hazards and consequences taken into consideration.

Estimation of costs and benefits of strategies

The estimation of the costs and benefits of strategies is done using the present worth method and the time intervals within the investigated time periods are chosen so that the cost and benefit streams can be adequately approximated, normally 1 year intervals. The costs of a strategy are the financial costs to the owner due to the following of a strategy, including all costs incurred due to the maintenance of new structures and the costs associated with failure. The benefits of a strategy are the advantageous impacts on the user and general public. Benefits can occur through the normal use of the road, e.g. due to noise reduction, and through exceptional events, e.g. reduction of fatalities due to a failure.

The determination of the optimal strategies only requires the determination of the difference between the costs and the benefits of the investigated strategies and the reference strategy. These are referred to as relative costs and relative benefits.

The estimation of the costs and benefits of intervention strategies requires the estimation of the probability of occurrence (or occurrence rate) of the scenarios. These are determined using the probability of occurrence (or occurrence rate) of the event and the conditional probabilities of occurrence of the effects, the non-monetarisable direct consequences, and the monetarisable direct and indirect consequences. The choice as to whether the probability of occurrence of the event or the occurrence rate is used depends on the strategies being investigated. If the strategy stipulates that the structure is to be restored following a failure, then the occurrence rate is most likely appropriate. If the strategy stipulates that the structure is not to be replaced or is to be replaced with a different structure, then the probability of occurrence is more applicable.

Evaluation of strategies

Verification of the absolute constraints

Each strategy is verified with respect to the absolute constraints (Table 1), so that fundamentally unacceptable strategies are no longer considered. For the verification of the cost limits that are targeted to a specific benefit, only the part of the total cost that was used to achieve this benefit should be used (e.g. the reduction of fatality risks). The division is often difficult to achieve.

Maximization of the objective function without relative constraints

Without relative constraints, the determination of the strategy with maximum effectiveness can be formulated as an optimization problem as follows:

$$\sum_{i \in M} \lambda_i \cdot (N_i - C_i) = max!\,, \qquad \sum_{i \in M} \lambda_i = 1$$

Equation 1

where

N_i = relative benefit of strategy i
C_i = relative cost of strategy i
M = number of strategies

Graphically, when all strategies are plotted on a benefit – cost diagram as points, the optimal strategy is the one with the largest vertical distance from the efficiency limit. For example, assume that the five strategies shown in Table 2 (listed by increasing total costs) are being investigated. Costs are divided into those for planned interventions and those for restoration of the structure following failure. Benefits are divided into the reduction of material damage risks and the reduction of fatality risks due to a failure. It can be seen that strategy 3 is optimal (Figure 3).

Maximization of the objective function with relative constraints

When there are relative constraints, the determination of the optimal strategy is an iterative process, because once the optimal strategy is found it must be verified that it satisfies the relative constraints. The most important relative constraint is the marginal cost criterion for reducing the number of fatalities. It states that one needs to continue to select increasingly expensive intervention strategies that increasingly reduce the number of fatalities until the increase in cost per saved human life is more than the specified cost limit. It depends on the comparison of two intervention strategies, i.e. the changes in costs and fatality risks associated with each.

With relative constraints, the determination of the strategy with maximum effectiveness can be formulated as an optimization problem as follows:

$$\sum_{i \in A} z_i \cdot y_i \cdot \left(N_i - C_i\right) = \max!$$
$$\sum_{i \in A} y_i = 1$$
$$z_i, y_i, w_i \text{ binary}$$
$$w_i = D_{ijl} \cdot z_{jl}$$
$$\frac{C_{f,k} - C_{f,j}}{\delta_{f,k} - \delta_{f,j}} \cdot z_j \cdot w_j \geq G_k \quad \forall j,k \in A \wedge C_{f,k} > C_{f,j}$$

Equation 2

where:

i = strategy
A = number of strategies
z_i = binary variable that defines the strategies that should comprise the convex

hull

y_i = binary variable that ensures only one strategy is selected
w_i = binary variable that indicates that a strategy is at the limit of the convex hull.
D_{ijl} = convex operator for any combination of z_i values
δ_f = number of fatalities
K_f = portion of costs of intervention strategies for the reduction of number of fatalities

Although the verification for a large number of strategies is mathematically complex, the solution can be found relatively easily graphically for a small number of strategies. For example, using the strategies shown in Table 2, and assuming the marginal cost criterion is 5 x 10^6 CHF, the verification is shown graphically in Figure 4.

The top diagram (iteration 1), where the relative costs and relative benefits are plotted, shows that strategy 3 is the optimal strategy before verification of the relative constraint. The lower diagram (iteration 1), where the relative costs and relative number of fatalities are plotted, shows, however, that strategy 3 does not satisfy the marginal cost criterion because there is at least one straight line connecting the optimal strategy to a more expensive strategy that is steeper than the marginal cost line, in this case to strategy 4. In other words, there exists a more expensive strategy than strategy 3 where the additional relative costs per saved human life are less than the marginal cost limit. This is also shown in Table 3 where the Δ Relative costs/Δ Relative number of fatalities (CHF) of strategy 4 are less than 5 million CHF. The strategies in Table 3 are ordered by increasing relative costs for reduction of number of fatalities.

Since strategy 3 does not satisfy the relative constraint, it is removed from the analysis and a new optimal strategy is found (top diagram iteration 2). This optimal strategy does satisfy the marginal cost criterion (bottom diagram iteration 2), in this case because there are no more expensive strategies, and therefore should be followed.

IMPLEMENTATION IN MANAGEMENT SYSTEMS

The implementation of such a methodology in a management system requires further precision with respect to some of the above explained steps. Some first thoughts in this direction are that the problem would become the determination of the optimal strategy types for types of structure problems, i.e. the combinations of structures and hazards that are of interest, e.g. continuous concrete box girder bridges exposed to floods. This information could be determined with the help of a geographic coincidence analysis using the location of infrastructure objects and hazard maps. Constraints would only be used for the representative structure and the representative hazards.

The time period to be investigated would need to be unlimited, as it currently is for the evaluation of strategies with respect to manifest processes. This is because the most reasonable default assumption is that it will always be desired to have the structures providing an adequate level of service.

The representations of the system (structure and surroundings, or links and surroundings) will be determined once the desired level of detail is assessed. The level of detail will depend on the amount of available or soon to be available data. Assuming information on hazards is available in the form of hazard maps, system representations could be built as binary event trees where the only branching takes place at the effect on the structure (Figure 5).

Of course, the assumption that all consequences follow directly from the effect is approximate, but with the use of expected values of each consequence branch could give a good approximation of risks and, therefore, a good idea of the most effective strategies to reduce these risks. The probability of occurrence of each scenario can be estimated through the probability of occurrence of the event and the condition probabilities of occurrence of the effects of the event. The time intervals that should be used are the ones where it can be assumed that only one event can occur per year. In most cases a time interval of one year is expected to be appropriate.

The probabilities of each branch and the expected values would change when different strategies are followed. For example, if it is assumed that there are three types of strategies for a concrete bridge exposed to floods 1) do nothing, 2) increase the height of the superstructure and 3) anchoring the superstructure, the expected consequences can be illustrated as shown in Figure 6.

Following strategy type 1, the raising of the superstructure lowers the probability that the water depth will be greater than or equal to *a* (the clearance of the superstructure). The consequences if *a* is reached are not changed. Following strategy type 2, the anchoring of the superstructure does not affect the probability that the water depth being greater than or equal to *a* but it alters the consequences in the case that it is, i.e. it is no longer expected that the superstructure will be washed away.

The determination of suitable threshold values for the effects on the structures and the estimation of the expected consequences should be based on a representative structure. To demonstrate that this structure is sufficiently representative of all structures included in this structure type to support management decisions, it should be compared with a number of structures over the spectrum of structures that it is intended to represent. Codes of practice could be helpful in the determination of potential failure modes.

The implementation of such a methodology in a specific management system requires significant work, including the determination of:

- the rate of occurrence of the scenarios, with respect to the use of the information from hazard maps and geographic information systems
- suitable key parameters from which failure modes can be identified
- the intervention strategy types to be investigated
- suitable event trees.
- models for:
  - the threshold values of the effects, which define the branching in the event tree and the corresponding failure modes,
  - the distribution functions of the direct consequences, and
  - the distribution functions of the indirect consequences.
- tests and procedures to verify the suitability of the representative models.
- appropriate algorithms to find optimal strategies when many structures are simultaneously taken into consideration.

CONCLUSIONS

The presented methodology can be used to determine optimal intervention strategies for structures affected by latent processes. With additional work, it is possible to implement this methodology into management systems. The work required depends, among other things, on the management system into which it is desired to implement the methodology and the availability of information.

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Table 1. Constraints

Target	Description	Limit criteria
Costs	Cost limits (for one or more cost bearers, and for one or more cost types)	$K_t^a \geq KG_t^a$, $K_t^r \geq GK_t$, $K_t^a \leq KG_t^a$, $K_t^r \leq GK_t$, $K_T^a \geq KG_T^a$, $K_T^r \geq GK_T$, $K_T^a \leq KG_T^a$, $K_T^r \leq GK_T$, where K_t^a, K_t^r, K_T^a, K_T^r = absolute and relative costs of intervention strategy in year *t* and over the entire investigated time period T KG_t^a, GK_t KG_T^a, GK_T = absolute and relative cost limits in year t and over the entire time period T
Time	Time limits (when it is possible to perform interventions)	$y_t \leq Gy_t$, where y_t = binary variable that shows if an intervention in year t will be performed Gy_t = binary variable that shows if an intervention in year t is allowed.
Probability	Probability limits. (consideration of societal preferences.)	$W_t^a \geq WG_t^a$, $W_t^a \leq WG_t^a$, $W_T^a \geq WG_T^a$, $W_T^a \leq WG_T^a$, where W_t^a, W_T^a, = absolute probability in year t and over the entire investigated time period T WG_t^a, WG_T^a, = absolute probability limit in year t and over the entire investigated time period T
Risk	Risk limits. (for one or more cost bearers, and for one or more cost types)	$R_t^a \geq RG_t^a$, $R_t^a \leq RG_t^a$, $R_T^a \geq RG_T^a$, $R_T^a \leq RG_T^a$, where R_t^a, R_T^a, = absolute risks in year t and over the entire investigated period T RG_t^a, RG_T^a, = absolute risk limit in year t, over the entire investigated time period T

Target	Description	Limit criteria
Costs	Cost limits (for one or more cost bearers, and for one or more cost types)	$K_t^a \geq KG_t^a$, $K_t^r \geq GK_t$, $K_t^a \leq KG_t^a$, $K_t^r \leq GK_t$, $K_T^a \geq KG_T^a$, $K_T^r \geq GK_T$, $K_T^a \leq KG_T^a$, $K_T^r \leq GK_T$, where K_t^a, K_t^r, K_T^a, K_T^r = absolute and relative costs of intervention strategy in year *t* and over the entire investigated time period T KG_t^a, GK_t KG_T^a, GK_T = absolute and relative cost limits in year t and over the entire time period T
Time	Time limits (when it is possible to perform interventions)	$y_t \leq Gy_t$, where y_t = binary variable that shows if an intervention in year t will be performed Gy_t = binary variable that shows if an intervention in year t is allowed.
Probability	Probability limits. (consideration of societal preferences.)	$W_t^a \geq WG_t^a$, $W_t^a \leq WG_t^a$, $W_T^a \geq WG_T^a$, $W_T^a \leq WG_T^a$, where W_t^a, W_T^a, = absolute probability in year t and over the entire investigated time period T WG_t^a, WG_T^a, = absolute probability limit in year t and over the entire investigated time period T
Risk	Risk limits. (for one or more cost bearers, and for one or	$R_t^a \geq RG_t^a$, $R_t^a \leq RG_t^a$, $R_T^a \geq RG_T^a$, $R_T^a \leq RG_T^a$, where R_t^a, R_T^a, = absolute risks in year t and over the entire investigated period T

Table 2. Costs, benefits and effectiveness

Strategy	Relative costs (10^6 CHF)			Relative benefits (10^6 CHF)			Effectiveness (B-C)
	Planned interventions	Restoration following failure	Total	Reduction of material damage risks	Reduction of failure risks	Total	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	4.00	-1.00	3.00	2.00	3.00	5.00	2.00
2	11.25	-2.00	9.25	4.00	6.00	10.00	0.75
3	13.00	-3.00	10.00	6.00	9.00	15.00	5.00
4	20.00	-4.00	16.00	8.00	12.00	20.00	4.00

Table 3. Verification of the marginal costs for the reduction in number of fatalities

IS	Iteration 1				Iteration 2			
	Relative costs for reduction of fatalities (mio. CHF)	Δ Relative costs for reduction of fatalities (mio. CHF)	Δ Relative number of fatalities	Δ Relative costs/ Δ Relative number of fatalities (mio. CHF)	Relative costs for reduction of fatalities (mio. CHF)	Δ Relative costs for reduction of fatalities (mio. CHF)	Δ Relative number of fatalities	Δ Relative costs/ Δ Relative number of fatalities (mio. CHF)
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	1.80	1.80	-0.83	-2.16	1.80	1.80	-0.83	-2.16
2	5.55	3.75	-0.83	-4.50	5.55	3.75	-0.83	-4.50
3	6.00	0.45	-0.83	-0.54	[redacted]			
4	9.60	3.60	-0.83	-4.32	9.60	4.05	-1.67	-2.43

*all differences are with respect to the next less expensive strategy

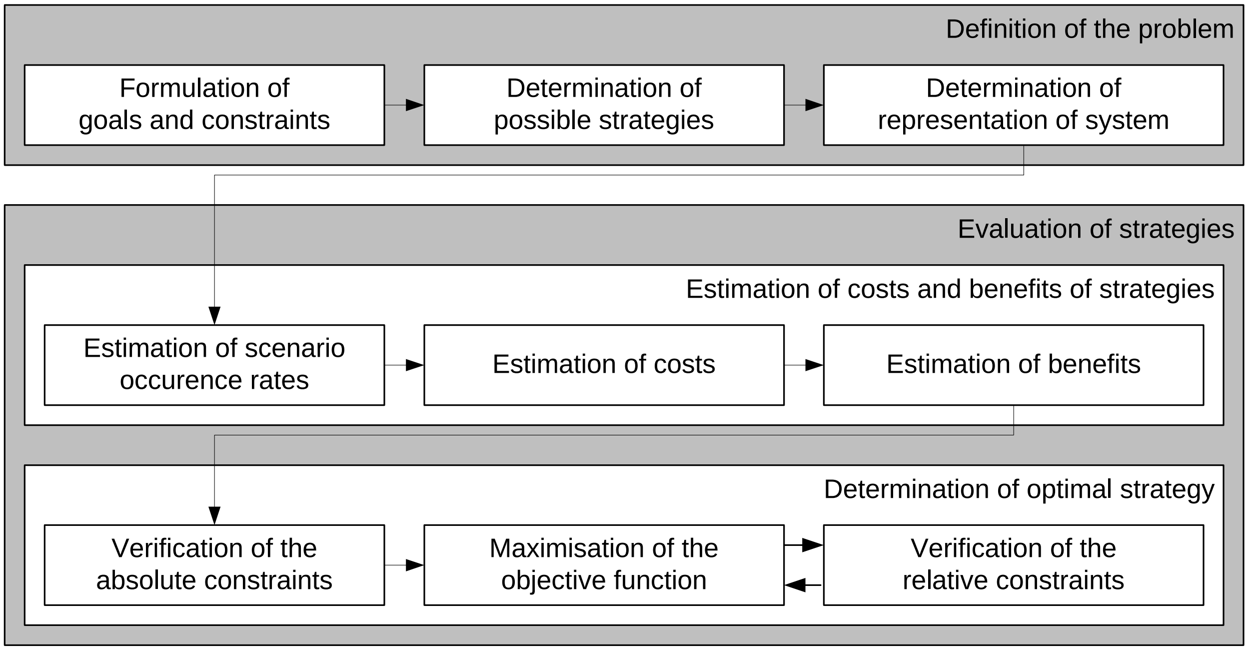


Figure 1 Steps of the methodology

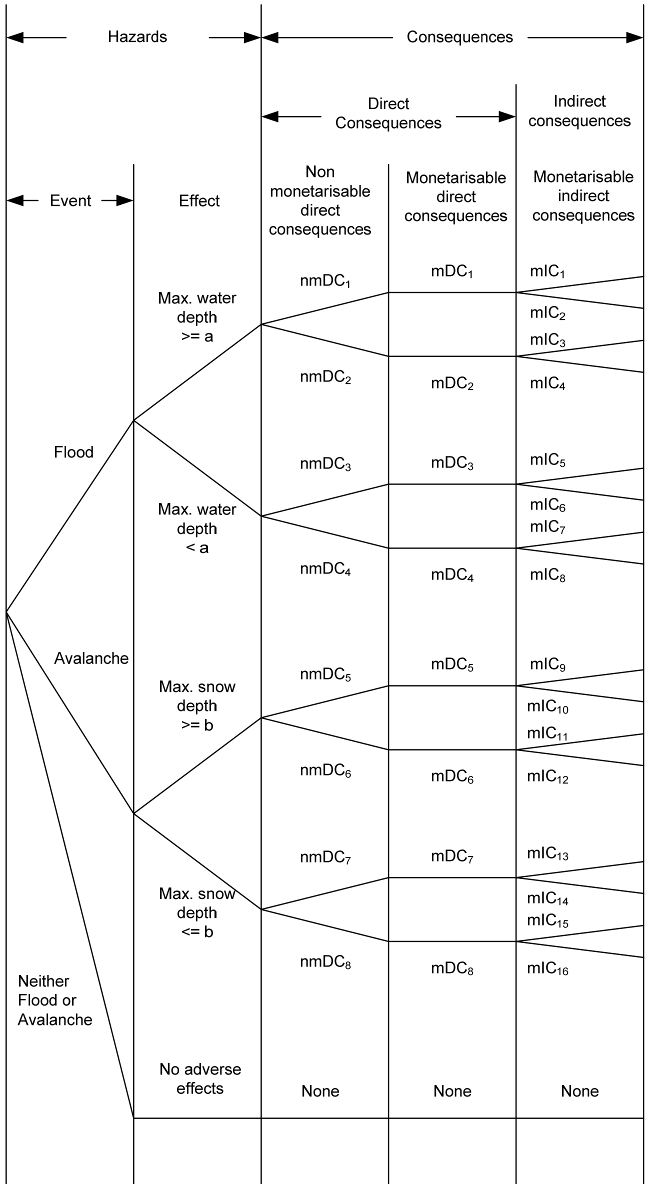


Figure 2. Event tree

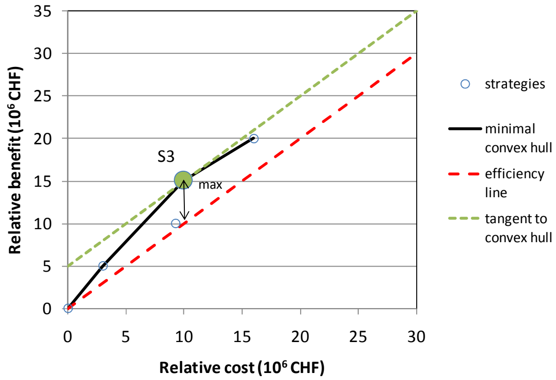
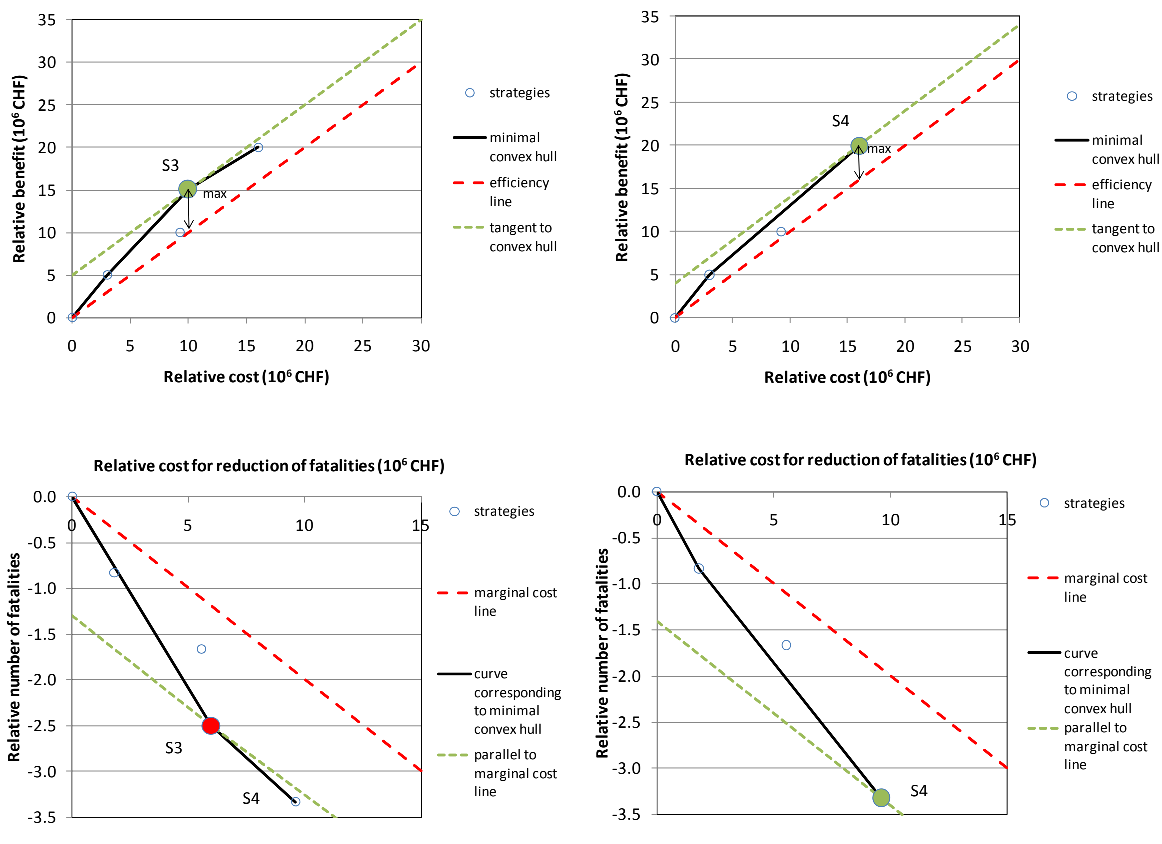
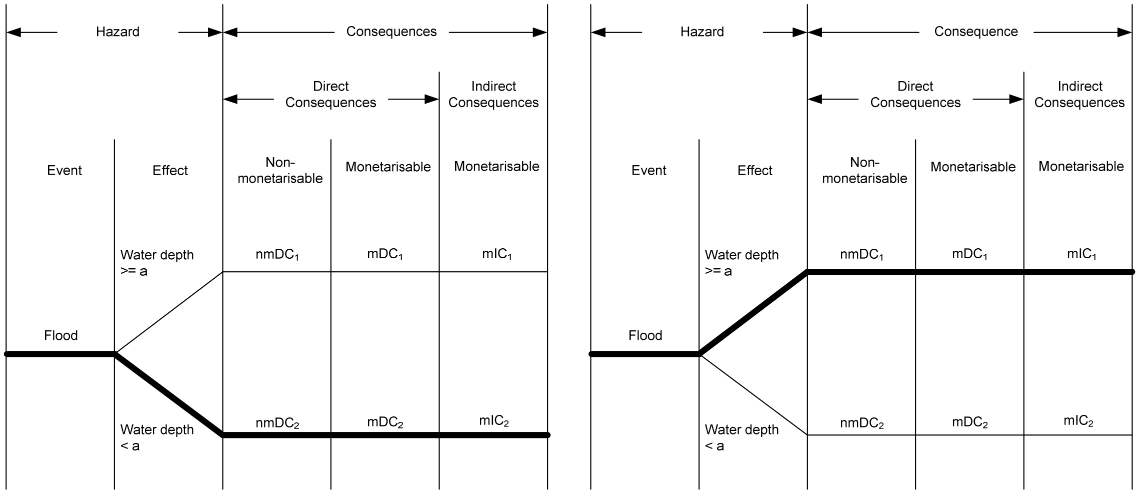


Figure 3. Benefit cost diagram



iteration 1 iteration 2

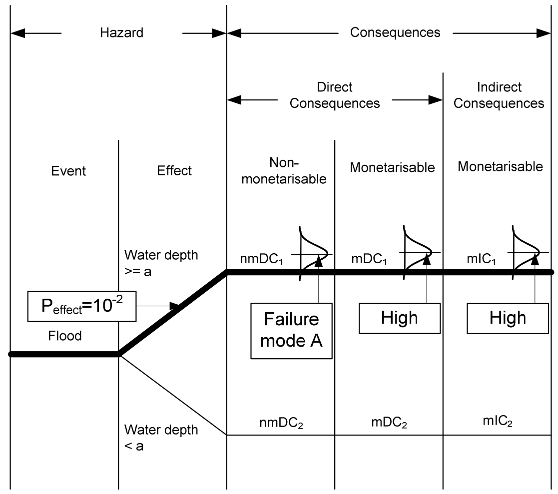
Figure 4. Verification of the marginal costs for reduction of number of fatalities



Branch for water depth < a

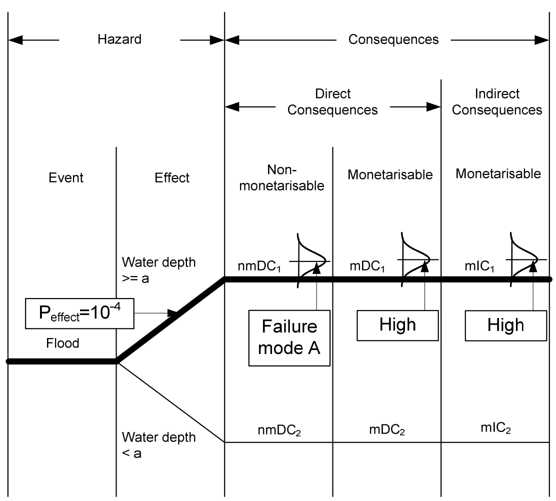
Branch for water depth >= a

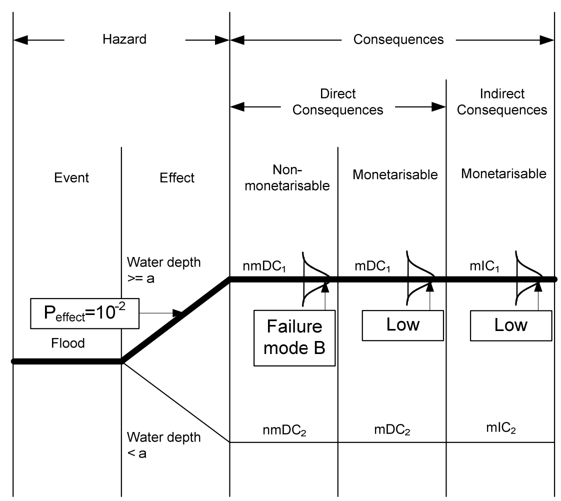
Figure 5. Binary event tree



Path for water depth >= a

Strategy type 0 "Do nothing"





Path for water depth >= a

Path for water depth >= a

Strategy type 1 "Raising"

Strategy type 2 "Anchoring"

Figure 6. Impact of intervention strategy types