# A Decision Tree for a Cost-Benefit Analysis on Flood Risk Management with Uncertain Funding

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**Abstract.** River floods generated relevant disasters worldwide and motivated the need to set up Flood Risk Management plans. According to the European Directive 2007/60/CE, the flood-risk evaluation should include a cost–benefit analysis on a long-term planning horizon. However, the cost-benefit analysis is typically made under the deterministic assumption to know which uncertain events will be observed in the planning horizon and a priori establishes which actions will be taken throughout this long time interval. Clearly, this myopic policy is not adequate in the domain of Flood Risk Management, in which most of the data are uncertain when the cost-benefit analysis is made and decisions should dynamically respond to the observation of uncertain parameters. In order to face the former challenges, this paper shows how the cost-benefit analysis can be supported by a decision tree for structuring and analyzing decisions in the face of uncertainty on the available funding. Finally, the paper reports some outcomes in the experimentation on the Coghinas Basin (Sardinia, Italy).

**Keywords:** Flood mitigation · Cost-benefit analysis · Decision trees · Decision analysis

## 1 Introduction

Climate change and current urbanization trends increase the occurrences of flood events. Hence, Flood Risk Management plans are needed for preparation, mitigation and reconstruction when natural disasters occur [1]. The European Commission Flood Directive 2007/60 [2] requires a preliminary damage assessment to estimate flood impact and recommends policy-makers to decide upon flood mitigation strategies implementation via a Cost-Benefit approach.

The Directive draws attention to the assessment and management of flood mitigation measures. Flood damage and loss estimation analyses are essential for planning flood mitigation structural works, since decisions on scenarios mitigation achievements should

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be based on a Cost-Benefit Analysis (CBA). As a matter of fact, article 7 in Chapter IV of the Directive states that the "Flood Risk Management plans has to take into account relevant aspects such as costs and benefits". Benefits can be evaluated as the reduction in the expected damages, which are avoided by the realization of scenario mitigation works, the management of river systems and the consideration of flood flows resulting from hydrological analysis [3]. The expected flood flows frequently refer to a set of time return periods (expressed in years), which are denoted by $T_r$. Therefore, the expected damages are evaluated both in the current scenario and after the conclusions of works [4, 5].

Water flow depth and velocity in potential floodplain areas are, in addition, an essential information given from hydraulic simulation models of flood flows. Damage estimation functions (e.g., the European JRC "Flood Damages Functions") can be subsequently applied to express a relationship between the flood inundation and potential losses in flood scenarios [6]. Damages can be divided into two categories: tangible (i.e., physical damages due to contact with water and loss of production and income) and intangible damages (i.e., loss of life and trauma); the former damages are direct or indirect [7]. In this study, direct tangible and indirect tangible damages are considered to estimate benefits, which are evaluated as damages reduction avoided by the realization of mitigation works [8, 9].

Generally speaking, CBA is a systematic approach for estimating the strengths and weaknesses of several alternatives. It aims to select the best alternative for achieving benefits while preserving savings [10]. However, CBA typically concerns a long-term planning horizon under a deterministic setting. This means that one assumes to know the data observed and the decisions taken throughout the planning horizon. All in all, CBA is used by organizations to appraise the desirability of a given policy and the most important outcome is the year in which benefits start overcoming costs.

The former drawback does not match with the requirements of Flood Risk Management, which must be made in a highly uncertain climatic environment. Clearly, it is also impractical to make a CBA for all possible policies (i.e., all realizations of uncertain parameters and all possible decisions for each realization). Since CBA is based on a single objective criterion (the net benefit), it is of interest to build a decision tree with this criterion. Generally speaking, decision trees are logical and systematic ways to address a variety of problems involving decision making with a single criterion in an uncertain environment. To the best of our knowledge, they have never been adopted in the domain of Flood-Risk-Management.

In this paper we enhance the analysis of CBA for a flood-mitigation problem by a decision tree. We show which management insights can be obtained in the real case study of the Coghinas Basin in the Sardinia region (Italy). Three possible actions (or mitigation works configurations) are investigated to minimize the net benefit in the case of uncertain funding.

This paper is organized as follows. In Sect. 2, we briefly describe CBA with a focus on flood risk management. In Sect. 3, decision trees are briefly introduced. In Sect. 4, the case study of Coghinas river basin is presented and the outcomes are described. Conclusions are reported in Sect. 5.

## 2 The Cost-Benefit Analysis

The effectiveness (or suitability) of public structural works on flood risk mitigation could be evaluated through economic criteria, motivating the choice among different alternatives [3, 11]. In this research, the integration of cost-benefit analysis (CBA) and decision tree is introduced, to present an interesting decision-support system for the optimal planning on flood mitigation measures.

The CBA is widely used in economic and engineering fields to evaluate different projects or alternatives [12]. In CBA benefits and costs should be expressed in monetary terms and should be adjusted according to the time value of money.

Economic comparisons will be hereafter made by the Net Present Value (NPV). Alternative projects may be also evaluated using different indicators such as the Internal Rate of Return (IRR), the Benefit-Cost Ratio (BCR) and the payback period (PBP). In this study, all streams of benefits and costs over time must be expressed on a common basis in terms of their present values, regardless of whether they are incurred at different times. Therefore, one should evaluate the Present Value (PV) of future costs or benefit values, to perform a correct comparison between them. The PV represents the result of today's value of a future stream of payments. In a simple way, the PV can be evaluated as:

$$PV = \sum_{t=1}^{T} \frac{R_t}{(1+r)^t} \tag{1}$$

where:
$R_t$: net cash inflow/outflows during a period $t$;
$r$: discount rate;
$T$: number of time periods.

The PV in Eq. 1 allows to put all costs and benefits in a common temporal step, using time and money-values (cost/benefit) occurrence estimations. The expected Net Present Value (NPV) of Benefits can be obtained by the subtraction of the future expected streams of awaited benefits (B) and costs (C), as expressed in Eq. 2:

$$NPV = \sum_{t=1}^{T} \frac{B_t - C_t}{(1+r)^t} \tag{2}$$

In a CBA, the NPV should be maximized. This optimization allows the comparison for ranking alternative mitigation policies in terms of NPV.

### 2.1 CBA in Flood Risk Management Problem

In a flood risk management problem, a fixed time horizon should be considered to compute a correct and effective economical comparison between costs and benefits. Each alternative of infrastructures (or infrastructure configuration) can be considered as a flood mitigation solution [13]. These infrastructure configurations are characterized by different cost and benefit functions.

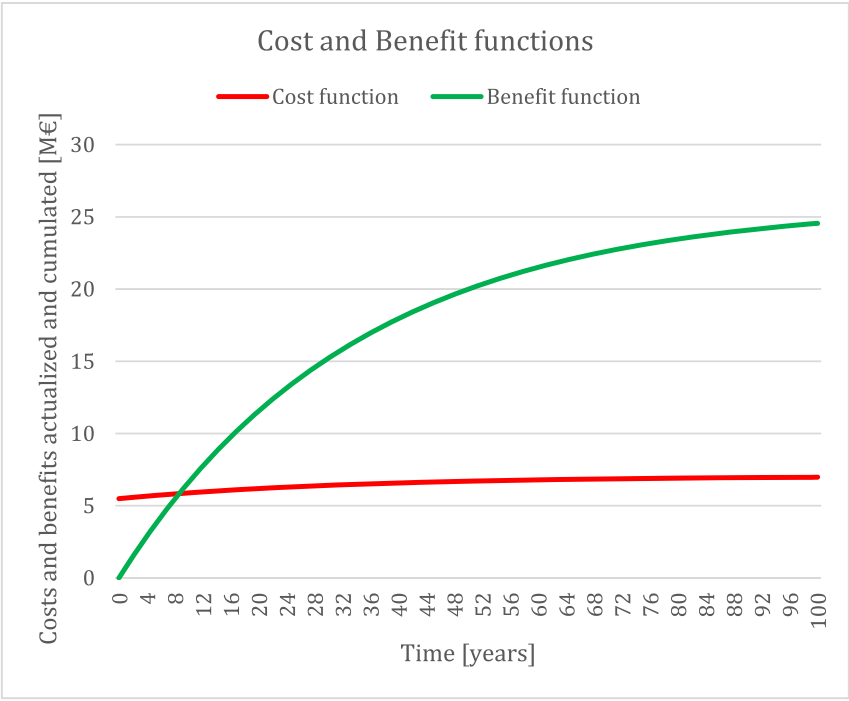


**Fig. 1.** Cost and benefit functions

Costs and Benefits values are actualized and cumulated along this fixed time horizon of analysis, as reported in Fig. 1. For this type of infrastructures, the cost function is usually made by two terms:

$$C_t = C_c + C_{OMR} \tag{3}$$

where:

$C_T$: Total costs;

$C_C$: Construction costs, usually stated in the first year of development of a built asset;

$C_{OMR}$: Operation, maintenance and replacement costs, usually referred to the entire infrastructure life. They start after the construction and are computed year by year.

The benefits are the revenues of a project along the "service life" of the infrastructure. In our problem they can be evaluated starting by the estimation of the expected annual mean value of flood damages. It can be estimated by Eq. 4:

$$E(D) = \int_0^1 D_s \, d(P_s) \tag{4}$$

Herein, $D_S$ is the flood damage evaluated in economic terms which refers to a flood flow expected characterized by an estimated return period $T_r$ and an occurrence probability $P_S$ (where $P_S = \frac{1}{T_r}$).

The effectiveness of each alternative can be evaluated by comparing the mean annual value of flood damages in the configuration of no-intervention (Configuration 0) and the damages in the case of the i-th Configuration.

In Fig. 2 the area between these two functions represents the possible decrease in flood damages due to the adoption of this specific mitigation-works configuration. These damage functions are drawn by varying the occurrence probability $P_S$ (i.e., changing the return periods $T_r$), modelling the water flood flow and considering damage estimation functions, as the European JRC "Flood Damages Functions", to evaluate $D_S$ [15, 16].

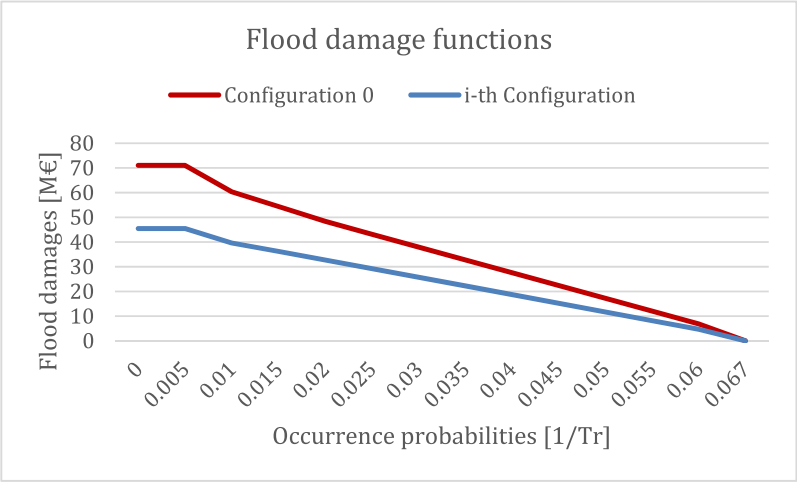


**Fig. 2.** Flood damage comparison: Configuration (0) - Configuration (i)

The horizontality of the curves for very exceptional floods has been adopted to depict the difficulties in these estimations for exceptional events. Expected benefits in each configuration can be evaluated by Eq. 5. It computes, in terms of annual mean value, the expected benefit for a specific configuration ($E(B)_{Conf\,(i)}$) as the difference between the expected damages in Configuration 0 (not-intervention) ($E(D)_{Conf\,(0)}$) and the expected damages in the i-th alternative ($E(D)_{Conf\,(i)}$).

$$E(B)_{Conf\,(i)} = E(D)_{Conf\,(0)} - E(D)_{Conf\,(i)} \tag{5}$$

After the evaluation of costs and benefits in each configuration, CBA procedure actualizes and cumulates their values along the fixed time-horizon. Finally, CBA should be synthesized in a performance index, to choose the configuration maximizing the net benefit among all flood mitigation configurations.

## 3 Building and Solving a Decision Tree

Decision trees are analytical models to systematically structure and analyze decision problems in an uncertain environment with a single criterion [14]. In what follows, we briefly list the steps to build a decision tree.

The first step in decision trees is the definition of the criterion. In this paper, we assume that the only criterion on which to differentiate between policies is the *NPV* of benefits and one obviously prefers a higher net benefit to a lower net benefit. This means that all other policies would offer a similar impact w.r.t. all parameters neglected in the criterion.

The second step is the construction of the decision tree from the list of possible decisions and the list of possible outcomes. Each decision is represented by a decision node and each possible choice is represented as a branch emanating from the decision node. Each uncertain event is represented by an event node and each possible outcome of an event is represented as a branch emanating from the event node. Note that in a decision node the decision-maker selects which branch to opt for according to the criterion, whereas this is not possible at event nodes, because one cannot decide which outcome will be observed. The outcomes in an event node are requested to be mutually exclusive and collectively exhaustive. The first property means that no two outcomes could ever be observed at the same time. The second property means that all possible outcomes are considered and any non-represented outcome cannot occur.

The third step is the assignment or determination of probabilities to each branch emanating from event nodes, to report the possibility to observe the associated random outcome. The sum of probabilities of each branch emanating from a given node must be 1, owing to the former assumptions of mutual exclusivity and collective exhaustivity. The next step is to assign the numerical value of the decision criterion to the final branches in the decision tree.

The procedure for solving a decision tree is called backwards induction or folding back. It starts from the final branches of the decision tree and moves toward the starting node. When an event node is visited, compute the average value of criterion from all possible outcomes. In a CBA analysis, this means to convert the distribution of possible net benefits to a single numerical value using the average, which weights all possible outcomes by their probability. When a decision node is visited, choose the branch emanating from this node with the best value of the criterion. In a CBA analysis, this means to cross off the branches emanating from a node with worse value of the *NPV* of benefits. The decision tree is solved after the evaluation of all nodes.

Finally, the sensitivity analysis must be performed to make a critical evaluation of the impact of key data on the optimal decision. This is particularly important when the decision-maker lacks confidence in some data. They are considered one at a time to test how the optimal decision strategy will change owing to a change in a data value.

## 4 Experimentation

### 4.1 The Coghinas Flood-Plain

The Coghinas river basin is located in the northern part of Sardinia region (Italy) and it is characterized by a drainage basin of 2551 $km^2$. It is the third longest river of the region and flows in the Mediterranean sea into the Asinara Gulf (Fig. 3).

In the lowland floodplain area urban settlements and some towns are located: Viddalba, Santa Maria Coghinas and Valledoria. Moreover, the Coghinas lowland valley has a strategic relevance for agricultural uses.

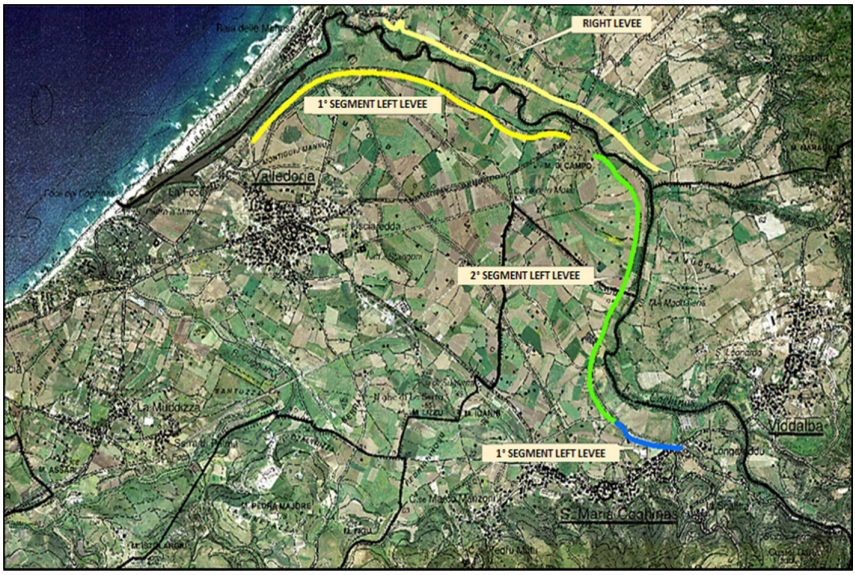


**Fig. 3.** Coghinas river with original levees configuration

Unfortunately, the valley has a long history of floods causing significant damages to civil properties, crops, infrastructures and environment. Therefore, to reduce the impact of flood damages, the Sardinia Region Administration defined some strategic solutions such as critical bridges demolition, levees and channel improvements and new constructions [15].

The possible flood damage reduction actions in the Coghinas floodplain area according to the Regional Plan for Flood Mitigation [15] are reported in Table 1 with the related construction costs.

**Table 1.** Flood-risk mitigation actions

| Work code | Work description | $C_C$[M€] |
|---|---|---|
| A | New levee on the right bank to protect Viddalba town | 2.38 |
| B | Adjustment of the levee on the left bank | 2.59 |
| C | New levee to protect Santa Maria Coghinas town | 1.81 |
| D | Hydraulic arrangement of the hydrographic network upstream of the levee which protect Santa Maria Coghinas town | 0.33 |
| F | Demolition of the old bridge along the provincial road n° 146 over the Coghinas river near Viddalba town | 0.09 |
| G | Demolition of the bridge along the provincial road n° 90 over the Coghinas river near Valledoria town | 0.32 |
| O | Demolition of the bridge over the Badu Crabile river along the provincial road n° 35 | 0.19 |

The flood risk mitigation actions can be clustered into three main configurations.

**Table 2.** Cluster of works related to each project configuration

| | Project configuration | | |
|---|---|---|---|
| | Configuration 0 | Configuration 1 | Configuration 2 |
| Work Code | F | A | B |
| | G | O | C |
| | | F | D |
| | | G | F |
| | | | G |

As illustrated in Table 2 each configuration is made by clustering different works and aims to protect different areas from upstream to downstream along the Coghinas river [15]. Each configuration gathers different actions, which could be planned and financed in the Regional Plan for Flood Mitigation.

The Configuration 0 represents the non-intervention option. Nevertheless, it concerns the demolition of two existing bridges and these actions are also included in the other two possible configurations. The Configuration 1 and Configuration 2 aim to safeguard the two towns of Viddalba and Santa Maria Coghinas, respectively.

The benefits in each configuration are estimated from the expected damages referred to 12 categories of land use. Land uses are listed in Table 3 with their related values of maximum damage for surface unit [3]. As shown in the following table, economic maximum flood damage cannot be always defined in univocal way, such as for labels 9–12.

**Table 3.** Land-use classes and maximum damage values

| Label | Land-use class | Max damage value [€/m$^2$] |
|---|---|---|
| 1 | Residential buildings | 618 |
| 2 | Commercial | 511 |
| 3 | Industry | 440 |
| 4 | Agriculture | 0.63 |
| 5 | Council roads | 10 |
| 6 | Provincial roads | 20 |
| 7 | Other roads | 40 |
| 8 | Infrastructural (areas with water supply network, electricity grid and similar systems) | 40 |
| 9 | Dams, rivers and similar areas | – |
| 10 | Environmental heritage areas | – |
| 11 | Historical and archeological heritage areas | – |
| 12 | Area subjected of other intangible damages | – |

The definition of the damage function was made for each land-use according to the evaluation of water depths in the flood-plain area by hydraulic simulation models [3, 5]. To predict the expected damages, three flood peaks of flood return periods are considered: $T_r = 50$, 100 and 200 years.

As described in Sect. 2.1, the expected benefit of each alternative is evaluated using Eq. 5 by the comparison of each Configuration to the quantity of expected damages in Configuration 0.

All in all, Configuration 0 is cheap and leads to reduced benefits; Configuration 2 is the most expensive and leads to the largest benefits, whereas Configuration 1 is a trade-off between them in terms of costs and benefits.

### 4.2 Using a Decision Tree for the CBA on the Coghinas Floodplain

We investigate a CBA for mitigation measures in the Coghinas floodplain with a planning horizon of 100 years. The objective is to determine which of the three configurations should be selected and when this selection should be made. At the beginning of the planning horizon, there is a sufficient budget for Configuration 0 and Configuration 1, but it is uncertain in the future. More precisely, a budget change could be observed in the $10^{\text{th}}$ and $20^{\text{th}}$ year: in both cases it could increase with probability 0.5 and allow the realization of the most expensive configuration (i.e., Configuration 2) or it could be lower with probability 0.5 and allow to keep the current configuration only.

The criterion of the decision tree is the net benefit, which is computed as the difference between benefits and costs, which account for construction costs, operation, maintenance and replacement costs, as well as additional penalties. These penalties are paid if the budget for a more expensive configuration is available and the configuration is not made. More formally, if one denotes by $I$ the number of configurations and $T$ the number of years in the planning horizon, the criterion can be formalized as follows:

$$\sum_{i=1}^{I} \sum_{t=t_c+1}^{T} B_{i,t} - \sum_{i=1}^{I} C_{ci,t_c} - \sum_{i=1}^{I} \sum_{t=t_c+1}^{T} (C_{OMRi,t} - p_{NCi,t_{NC}}) \qquad (6)$$

where

- $B_{i,t}$ is the benefit of the construction of configuration $i \in I$ at year $t \in T$;
- $C_{Ci,t_c}$ is the construction cost of configuration $i$ actualized at the building year $t_c$;
- $C_{OMRi,t}$ are Operation, Maintenance and Replacement costs in configuration $i$ at year $t$;
- $p_{NCi,t_{NC}}$ is the penalty for not constructing configuration $i$ and actualized at year $t_{NC}$, when the choice has been done. More precisely, it is assumed to amount to 10% of construction costs.

At the beginning of the planning horizon, there is a sufficient budget only for Configuration 0 or Configuration 1 and only one of them can be selected. In Fig. 4 this choice is modeled by a decision node, which is represented by a small box with label A at year t = 0. Each possible choice is represented by a branch emanating from node A: the branch in red shows the selection of Configuration 0; the branch in green represents the choice of Configuration 1.

If Configuration 0 is selected, one must face the uncertainty of whether the budget will increase or decrease at year t = 10. Since it may decrease with probability 0.5 or increase with probability 0.5, in Fig. 4 this uncertain event is modeled by an event node, which is represented by a small cycle with label B at year t = 10. Each possible outcome of this event is represented by a branch emanating from B. More precisely, if the budget decreases, one joins node E from node B; if the budget increases, one joins node D from B.

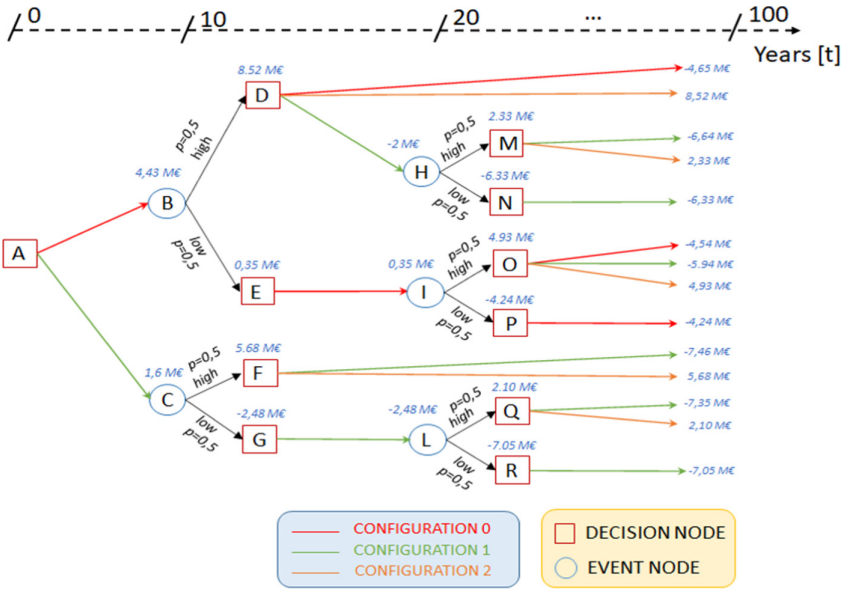


**Fig. 4.** The completed decision tree.

If a lower budget is observed at node B, the only possible decision at year t = 10 is to keep Configuration 0. In Fig. 4 this choice is represented by a red arc emanating from decision node E and joining node I. However, the budget could also change 10 years later (i.e., 20 years after the beginning of the planning horizon). It may be lower with probability 0.5 or higher with probability 0.5. In the first case, one joins node P from event node I and can only decide at this (decision) node to go on with Configuration 0. The value of the criterion at year 100 in path A, B, E, I, P is −4.24 M€. If a budget increase is observed after node I, one moves to decision node 0. Here, one can opt for all the three possible configurations: if Configuration 0 is selected, the final value of the criterion at year 100 is −4.24 M€; if Configuration 1 is selected, the final value of the criterion at year 100 is −5.94 M€; if Configuration 2 is selected, the final value of the criterion at year 100 is 4.93 M€.

If a higher budget is observed at node B at year t = 10, one moves to decision node D, where one can choose all the three possible configurations. More precisely, one can go on with Configuration 0 or switch to Configuration 2 up to the end of the planning horizon. In the first case, the final value of the criterion is −4.65 M€; in the second

case it amounts to 8.52 M€. Note that Configuration 1 cannot be selected up to the end of the planning horizon, but its choice is possible between year t = 10 and year t = 20, when the budget may change at year t = 20: it may become lower with probability 0.5 or higher with probability 0.5. This uncertainty is represented by event node H. If the budget is lower, one moves to decision node N, where it is possible to go on with Configuration 1 only and the final value of the criterion becomes −6.33 M€. If the budget is higher, one moves to decision node M, where two decisions are possible: go on with Configuration 1 or switch to Configuration 2. In the first case, the final value of the criterion is −6.64 M€; in the second case is 2.33 M€.

Consider again decision node A at year t = 0, assume to opt for Configuration 1. At year t = 10 one will observe if the budget is higher or lower. Therefore, one joins an event node from A. In Fig. 4 the event node is denoted by C and has two emanating branches: higher budget with probability 0.5 and lower budget with probability 0.5. If it is higher, one moves to decision node F, where one must decide to go on with Configuration 1 or switch to Configuration 2 up to the end of the planning horizon. In the first case, the final value of the criterion is −7.46 M€; in the second case it is 5.68 M€. Note that the selection of Configuration 0 is neglected at this stage, as the actions in this configuration are also included in configurations 1 and 2. If the budget is lower, one moves to decision node G, where one can only decide to go on with Configuration 1. Ten years later (i.e., 20 years after the beginning of the planning horizon) one will again face the uncertainty of whether the budget is higher with probability 0.5 or lower with probability 0.5. In Fig. 4 this uncertainty is described by event node L. If the budget is higher, one moves to decision node Q, which concerns whether to switch to Configuration 2 or keep Configuration 1. In the first case, the final value of the criterion is 2.10 M€; in the second case it is −7.35 M€. If the budget is lower, one moves to decision node R to decide to go on with Configuration 1 up to the end of the planning horizon. In this case, the final value of the criterion is −7.05 M€.

The solution of this problem is determined by folding back the decision tree. One must start from the final branches, choose that branch emanating from the decision node with the best value of the criterion, write this value above the node and cross off the branches with lower values of the criterion. For example, in Fig. 4 at decision node M we select Configuration 2 and disregard Configuration 1. For each event node, compute the weighted average of the criterion over each branch weighted by its probability and write this number above the event node. For example, in Fig. 4 at decision node H we compute the average between 2.33 M€ and −6.33 M€: $-2.33 * 0.5 + 6.33 * 0.5 = -2$ M€. This algorithm is iterated until all nodes of the decision tree are visited.

The completed solution of the decision tree is reported in Fig. 5. We now examine the optimal decision strategy under uncertainty. According to the solution, one should select Configuration 0 at the beginning of the planning horizon (move along the branch from A to B). Then, if a higher budget is available after 10 years (move along the branch from B to D), select Configuration 2 up to the end of the planning horizon (this is shown at decision node D). If the budget is lower (move along the branch from B to E), keep Configuration 0 for 10 more years (move along the branch from E to I). If the budget becomes higher (move along the branch from I to O), select Configuration 2, else (move

along the branch from I to P) and keep Configuration 0. The overall value of this decision strategy is the value of the criterion computed in the initial node A.

Finally, it is wise to adopt a sensitivity analysis on the optimal decision strategy. For example, the probability $p$ of a high budget may increase at year 10 and may lead to the selection of Configuration 1 instead of Configuration 0. In this case, the average at node C becomes $5.68p - 2.48(1 - p)$ and, if it is larger than 4.43 M€, one should move to node C instead of node B. The change in the decision occurs when $p$ is larger than the value satisfying equation $5.68p - 2.48(1 - p) = 4.43$ M€, i.e., when $p$ is larger than 0.85. This is reassuring if one is confident that the probability of high budget after the selection of Configuration 1 is not high.

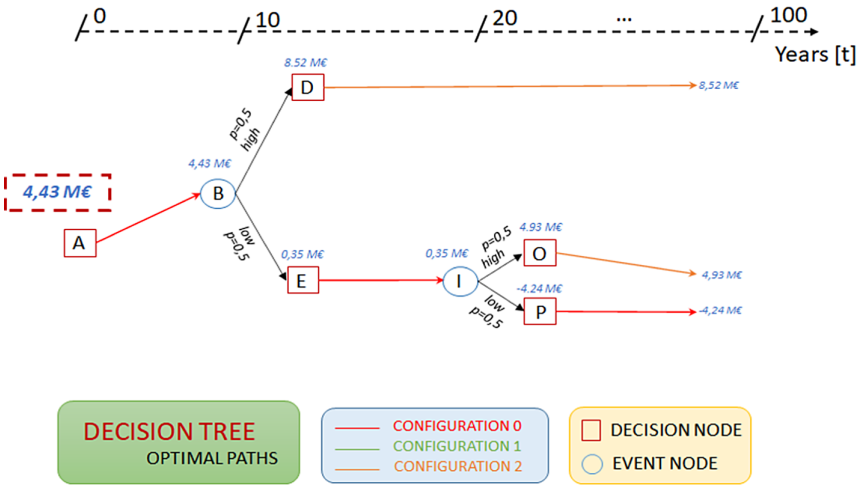


**Fig. 5.** The solution of the decision tree.

## 5 Conclusion

This paper has investigated the introduction of a decision tree in the cost-benefit analysis for planning flood risk mitigation works construction. The analysis starts from the classical CBA for optimizing the net value of expected benefits. Next, a decision tree is developed to make optimal decisions despite data uncertainty. More precisely, we have investigated the possibility to introduce uncertainty on budget availability during the considered life-time by the probability of funding each configuration. The optimization criterion of the decision tree is still the maximization of net benefit weighted by the former probabilities and accounts for construction costs, operation, maintenance and replacement costs. Moreover, additional penalties are considered when constructions are not made, even if the budget is available. Finally, a sensitivity analysis on the optimal decision strategy has been performed.

This approach can be considered suitable in future analysis to evaluate more complex systems even considering different kinds of costs, benefits and penalties. For example, in

the river Coghinas basin, we will investigate the management rules of the higher stream dam of Muzzone by increasing the lamination potentiality in flood-risk evaluations. This extension should include a cost–benefit analysis and an integrated decision-making procedure to optimize operating rules for this multipurpose reservoir, while taking into account the mitigation of flood risks and the priority in water demand supplies.

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