Economic Risk Evaluation in Road Pavement Management

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Abstract. Pavement maintenance is essential to prevent the deterioration of asset value and satisfy all stakeholders' expectations. However, the budgets are often insufficient to keep the road pavement at optimum levels. Therefore, a decision-making process ought to be used to prioritize different maintenance activities to optimize the fulfillment of the pre-defined goals. At the same time, there is a growing need to integrate risk management into asset management, and therefore into the Pavement Management System. It is the best way to understand risk in decision-making at the program and organizational levels. This paper examines how risk-based pavement management practices can be implemented. The idea is to identify the best combination of maintenance actions given budget constraints, also considering budget risk reduction within a multiobjective optimization process. As far as economic risk assessment is concerned, probabilistic LCCA with Monte Carlo Simulation was used to investigate the risk of budget exceeding in Pavement Management Systems as a secondary criterion for choosing the optimal maintenance strategy on a road network. The method allows assessing epistemic uncertainties regarding discount rate and materials, man-power, transportation, and equipment rental costs. Outputs were able to show the possible variability of maintenance strategies costs. Moreover, probability density functions provide for establishing the most economically advantageous solutions (lower mean value) and for the riskiest ones (greater standard deviation). The optimal strategy might be selected by minimizing the probability of budget exceeding. The innovation of this research is in the introduction of the quantitative economic risk analyses into pavement management, with the aim to integrate epistemic and aleatory uncertainties in the process.

Keywords: Pavement management · Budget risk management · Multi-criteria decision-making

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1 Introduction

Roads are the core of an integrated transport system and their performance is essential for all citizens in terms of mobility, quality of life, economic competitiveness and sustainable development. Furthermore, road infrastructures are a huge economic public asset in many countries, for example the European road network consists of 5.5 million Km and, according to European Road Federation "ERF" it represents an estimated value of over € 8,000 billion.

Since road networks have an important instrumental function and a significant asset value, it is necessary to maintain them in order to ensure adequate performance and their durability.

Asset management has been widely accepted by road organizations as a means to deliver a more efficient and effective approach to management of highway infrastructure assets through longer term planning, ensuring that standards are defined and achievable for available budgets.

The transportation infrastructure system includes many assets: pavements, signals, lighting, bridges, right-of-way, and all other roadway related structures. Thus, an asset management system can include various individual component management systems such as a pavement management system (PMS), bridge management system (BMS), etc., all coordinated together. Asset management can only be efficient if component management systems are efficient, properly integrated into the process and coordinated. Particularly, road pavements represent one of the most important infrastructure elements, thus needs to be managed in such a way that supports broad asset management approach.

Analyses for prioritization of interventions usually consider average values for the variables. However, the need to evaluate the risk associated with the planning decisions undertaken is becoming increasingly evident, as this can produce variability of used and/or available economic resources and variability of expected performance.

For this reason, systems that support resource allocation decisions should be implemented with a Risk Management (RM) process, in order to ensure the most effective use of limited funds to maintain assets. Today, the leading international transportation organizations, manuals and standards consider risk assessment and management an important components of the asset management process (ISO 2015). Although they pay adequate attention to the definition of risk in asset management, little guidance is given on how risk management can be applied to road asset management.

All activities from management, identification and prioritization of works to the establishment of budgets have risks and opportunities associated with them. The most common use of the term "risk", when applied to transportation infrastructure, refers to the risk of failure of a transportation asset, but there are several different types of risks that can impact the management of pavements in a highway network, such as: funding uncertainty, variability of costs, regulatory changes, improper maintenance treatment selection, inaccurate pavement condition forecasts, severe weather events and evolving technology.

Risks affecting transportation asset management programs can be generally grouped in 4 categories:

• Economic Risks - increasing material prices, rising interest rates, budget uncertainty or shortfall;

• Hazard and external Risks - natural events, such as earthquakes, floods, climate changing, hurricanes;

• Strategic Risks - environmental standards, stakeholder demands, public opinion;

• Operational Risks: weak program management, lack of management support, poor asset inventories, maintenance failures.

The analytical definition of risk, or "Risk Rating", usually adopted is:

$$R = L * C$$

where "L" is the likelihood for an event to occur, and "C" is its consequence.

Approaches managing risk range from qualitative assessments of likelihood and consequence at the enterprise level to quantitative, probabilistic approaches such as scenario analysis, simulation, and other approaches to predictive modelling. Current practices provide for qualitative risk analyses, and most road organizations found in "Risk Register" the perfect tool to integrate the Risk Management in Management Systems at Network Level.

Qualitative risk analysis cannot be integrated in the multi-criteria optimization approaches required in the modern asset management system.

The objectives of this research project is to:

• Introduce a quantitative enhanced technique to evaluate economic risk related to road pavement;

• Develop a procedures for incorporating risk in the multi-objective optimization tools of the PMS;

• Demonstrate the effectiveness of the proposed methodology by applying it to a case study.

The article is structured on 5 sections: after this introduction, Sect. 2 describes the analytical methods to deal with economic risk and uncertainties. Subsequently, Sect. 3 analyses the stochastic modeling to determine life-cycle cost of maintenance strategies and Sect. 4 presents a case study. Finally, Sect. 5 summarizes the features of the proposed methodology and the results obtained.

2 Analytical Methods to Deal with Economic Risk and Uncertainties

Aging infrastructure, increasingly sophisticated stakeholder demands and low funding availability have created a need for increasingly efficient tools to manage road networks and to take wise decisions of investing founds. Net present value (NPV), pay back period (PBP), internal rate of return (IRR) are some of widely used tools to evaluate alternative infrastructure investment options. In this paper, life-cycle cost analysis (LCCA) has been used to evaluate alternative maintenance options, as it considers every cost category throughout the life of the maintenance strategies, and better represents the effective use of funds in its totality.

LCC can be defined as "the sum of the total direct, indirect, recurring, nonrecurring, and other costs estimated to be incurred in the design, development, production, operation, maintenance, support and final disposition of a system over its anticipated useful life span" (U.S. Department of Energy 2011). There are numerous costs associated to

its calculation, such as construction costs, user's costs, maintenance and repair costs, residual value, and replacement costs.

Many methods can be used to analyze life-cycle costs of infrastructure rehabilitation alternatives (Hudson et al. 1997).The AASHTO Guide (AASHTO 1993) recommends the use of the Present Worth Method to evaluate construction/rehabilitation alternatives for infrastructure projects, and particularly pavement and highway projects. It involves discounting all future costs to the present using a specific discount rate. The main advantage of using this method is that it is straightforward and simple.

Using the Present Worth Method, life cycle cost model can be applied through the following equation, that represents the whole life cycle cost for a maintenance strategy:

$$LCC_S = \sum_{x=1}^{N} LCC_{x,s} = \sum_{x=1}^{N} \left[\sum_{t=0}^{T} PWF_t \cdot \rho_{s,i,x,t} \cdot CM_{i,x,s,t} + \sum_{t=0}^{T} PWF_t \cdot CU_{x,s,t} - PWF_T \cdot SV_{x,s} \right] \quad (1)$$

Where:

LCC_s is the total present worth of life-cycle cost for the maintenance strategy s in the analysis period (from year 1 to T),
$LCC_{x,s}$ is the present worth of life-cycle cost for the maintenance strategy s in the road section x,
PWF_t is the present worth factor of future amount at time t at the discount rate r $PWF_t = 1/(1+r)^t$,
$CM_{i,x,s,t} = UCM_i \cdot Q_{x,i,s,t}$ is the cost of maintenance intervent i on the road section x for the maintenance strategy s, in the year t of the analysis period,
UCM_i is the unit cost of maintenance intervent i.
$Q_{x,i,s,t}$ is the estension of intervent i on the road section x at time t for the strategy s.
$\rho_{s,x,i,t}$ is a bolean variabile = 1 if in the maintenance strategy s the intervent "i" is applied on the road section "x" at time t, = 0 otherwise.
$CU_{x,s,t}$ is the user cost on the road section x for the maintenance strategy s in the year t of the analysis period (random variable).
$SV_{x,s} = min\left[1; \frac{TF_{x,s}}{T}\right] \cdot \sum_{t=0}^{T} \rho_{s,i,x,t} \cdot CM_{i,x,s,t}$ is the remaining service life value for maintenance strategy s on the road section x at the end of analysis period (year T).
TF is the time to failure (i.e. the remaing life at the end of period of analysis "T" for the maintenance strategy s on the road section x).

Some of the quantities in the formulation are random variables (i.e. UCM_i, r) so the result obtained is also a random variable. In the evaluation of the life cycle costs of the maintenance strategies, the variations of the costs sustained by the users are often difficult to calculate and they are of less interest for the managers therefore, in order to make simpler the problem, at least in a first approach, they have been neglected.

Therefore the Eq. (1) is simplified as follows:

$$LCC_{x,s} = \sum_{t=0}^{T} PWF_t \cdot \rho_{s,i,x,t} \cdot CM_{i,x,s,t} - PWF_T \cdot SV_{x,s} \quad (2)$$

To estimate the stochastic variability of the LCC parameter on the road section for the maintenance strategy s, the variabilities of the quantities that appear in the Eq. (2) have been analyzed.

The Life Cycle Cost (LCC) of the construction and maintenance actions cannot be univocally defined, as it is affected by risk and uncertainties. Therefore, it needs to be treated by a Risk Management process, in order to get useful outputs to the decision-making process.

Usually, the best guessed values for each input variable are selected and then are computed in a single deterministic result. On the other hand, this approach often excludes information that could improve the decision, even if a sensitivity analysis is conducted (FHWA 1998). Monte Carlo Simulation (MCS), as a probabilistic method, can take the haziness of the variables into account and produces a random variable as a finale Net Present Value for LCC, with a probability distribution function (PDF).

Interpretation of risk analysis goes beyond a simple comparison of which alternative on average costs less. In the example of Fig. 1, two NPVs of maintenance strategies, considered as random variables, are represented by their cumulative distribution function (CDF).

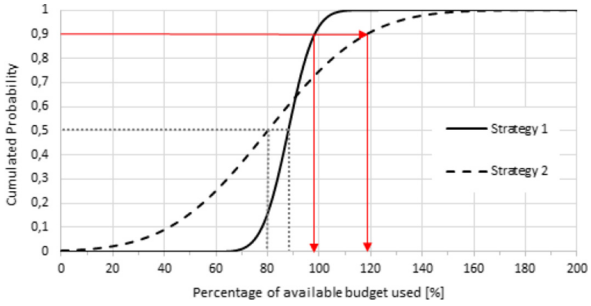

Fig. 1. Cumulative risk profiles of two maintenance strategies

Considering the budget that not be exceed with a probability of 90%, from the cumulative distribution curves clearly emerges that the best solution for a risk-based approach is strategy 1 although strategy 2 has an average budget used lower than strategy 1. This because the chances of funding overrun for strategy 2 are lower than strategy 1.

It have to be highlight that LCCAs have been rarely implemented in practice (Wu, et al, 2015) because they are usually a large-scale problem involving many input parameters with a high-level uncertainty. Besides, the time-horizon of the analysis plays a fundamental role and its increasing could leads to unreliable output. While it is possible to represent through the described process the variability of the parameters, it is difficult to fully represent the vagueness of the long-term forecasts (e.g. investigate the whole life-cycle cost of a pavement can still lead to unreliable results). Therefore, it is advisable to restrict the use of probabilistic LCCA to time-horizon of 4/5 years. However, this does not represent a limit for the application in PMS, as the time analysis for maintenance program is usually 3 to 5 years. In the next section a methodology to determine LCC of the maintenance strategies by a stochastic approach is presented.

3 Stochastic Modeling to Determine LCC of Maintenance Strategies

The LCC accuracy of strategies is strongly conditioned by the unit cost of the interventions. A deterministic approach obscures risk associated with road pavement treatment selection and inhibits the capability of the agency or administration to mitigate the budget risk. Preservation costs are often unpredictable, as they are affected by uncertainties and should be treated probabilistically. An attempt to assess risk on unit costs have to be made for each of the considered interventions. To perform a probabilistic analysis, it is necessary to apply some variations to the factor affecting LCCs, attributing to them a theoretical probability distribution. It is possible to do this by two ways:

1. Defining probabilistic variations on the basis of a large data sample gathered e.g. historical data, data from bid tabulations or management systems (Pittenger et al. 2012);

2. Choosing a priori the most suitable probability distribution and calibrating it based on a small amount of data or qualitative information.

The framework of the proposed methodology is reported in Fig. 2 and it is explained in detail in the following subsections.

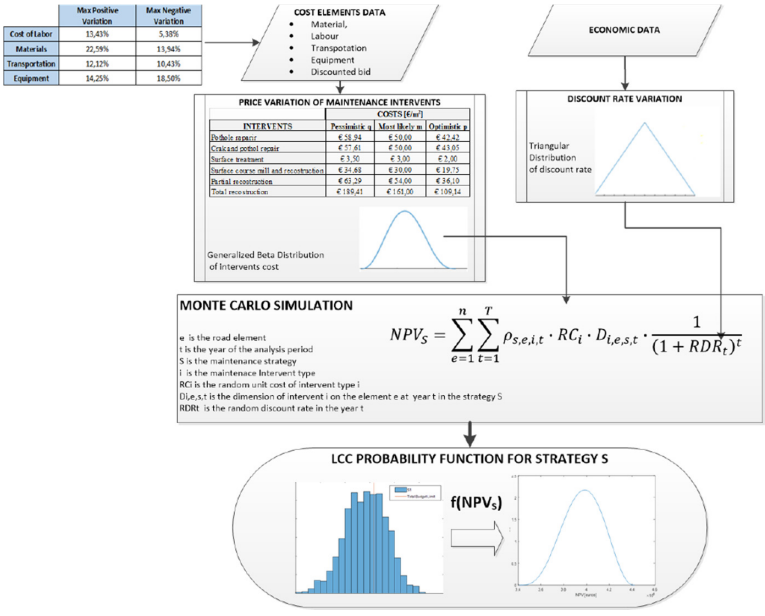

Fig. 2. Framework of proposed methodology

3.1 Probabilistic representations of the Factors Influencing the Cost of Interventions

The normal distribution is commonly assumed to be the appropriate distribution for data and is further justified by the central limit theorem. However, selection of normal

distributions can introduce, in some cases, bias into the LCCA (Tighe 2009) for various reasons. Firstly, normal distribution has not the capability to model distribution with a finite range, as it is defined from (−"∞") to (+"∞"); secondly, most of the costs would tend to yield an asymmetric shape with a positive skew, so normal distribution is not suitable. For the second reason, the lognormal distribution should be more appropriate. The compromise between the two distributions, which also makes it possible to define the probability distribution in a finite interval, is the Generalized Beta Distribution (GBD).

Therefore, in this study, a generalized beta random variable for the stochastic representation of factors that influence the cost of interventions (i.e., materials, equipment, labor, and contractor profit) was used. The actual costs of the administration are also affected by the discount applied by construction companies for maintenance activities (tender discount). This discount can obviously be at most equal to the profit of the construction company, which is normally 10%, so it is plausible to imagine that the discount can fluctuate between 10% and 0%. The unit cost is:

$$UCM_i = (LC_i + MC_i + TC_i + EC_i) \cdot d \tag{3}$$

Where:

LCi is the labor cost for the maintenance intervent i,
MCi is the material cost for the maintenance intervent i,
TCi is the transport cost for the maintenance intervent i,
ECi is the equipment cost for the maintenance intervent i,
d is the tender discount.

It can be assumed that unit cost can be represented through a Generalized Beta Distribution (GBD) with the following probability density function (PDF):

$$f(z) = \frac{1}{B(a,b)} \cdot \frac{(z-p)^{a-1} \cdot (q-z)^{b-1}}{(q-p)^{a+b-2}} \tag{4}$$

$$B(a,b) = \int_p^q \left(\frac{z-p}{q-p}\right)^{a-1} \cdot \left(\frac{q-z}{q-p}\right)^{b-1} dz \tag{5}$$

where "a" and "b" are shape parameters and "p" and "q" are respectively the minimum and maximum value, as f(p) = 0 and f(q) = 0.

The availability of data allows to obtain the probability density functions in rigorous way, by applying the method of moments for estimating all the parameters of GBD (Zaven et al. 2000).

However if only limited data are available but, the parameters of the distribution can be equally estimated (Johnson and Kotz 1970). As matter of fact, starting from the estimate of "optimistic cost" p, "most likely" m, "pessimistic" q values, the mean and variance of the distribution can be calculated as follow (Hendirckson 2008):

$$a = \frac{(\mu - p)^2 \cdot (q - \mu) - \sigma^2 \cdot (\mu - p)}{\sigma^2 \cdot (q - p)} \tag{6}$$

$$\sigma^2 = \frac{1}{36} \cdot (q-p)^2 \tag{7}$$

If mean, variance and extreme values "p" and "q" are known, the shape parameters of GBD can be obtained as follows (D'Apuzzo and Nicolosi 2010):

$$\boldsymbol{a} = \frac{(\boldsymbol{\mu}-\boldsymbol{p})^2 \cdot \cdot(\boldsymbol{q}-\boldsymbol{\mu}) - \boldsymbol{\sigma}^2 \cdot (\boldsymbol{\mu}-\boldsymbol{p})}{\boldsymbol{\sigma}^2 \cdot (\boldsymbol{q}-\boldsymbol{p})} \tag{8}$$

$$b = \frac{(\mu-p)^2 \cdot (q-\mu) - \sigma^2 \cdot (q-\mu)}{\sigma^2 \cdot (q-p)} \tag{9}$$

So, considering the unit cost of each type of maintenance work as a generalized beta random variable and estimating the most probable value, the optimistic one and the pessimistic one, the probability function of unit costs can be obtained, applying the relations represented above. Then, multiplying the random variable "discounted unit cost" of the intervention by the extent of the intervention on each section "x" (i.e. the surface of the pavement on which to carry out the intervention) the random variable cost of the intervention i on section x can be achieved as:

$$f\left(CM_{i,x,s,t}\right) = f\left(UCM_i\right) \cdot Q_{x,i,s,t} \tag{10}$$

3.2 Probabilistic Representations of the Discount Rate

The discount rate in analyses is normally assumed to be constant throughout the analysis period, although the historical data indicate that it is not particularly stable. Since it is difficult to predict the average value of the discount rate during the analysis period, it is appropriate to consider this parameter as a random variable in the risk analysis. In this study, a symmetric triangular probability distribution was used to describe the discount rate random variable, as suggested by FHWA (FHWA 1998). Thus, the probability distribution can be uniquely determined once the minimum and maximum values are estimated during the analysis period.

3.3 Probabilistic representations of the Life Cycle Cost

Life-cycle cost assessment contains complex functions of random variables so it is not possible to estimate the final probability distribution a priori. Therefore, a Monte Carlo simulation (MCS) has been employed to obtain the final distribution of the cost on the life cycle.

After the probability distribution of the unit costs of the single interventions has been determined a vector of m = 1000 random numbers that follow the wanted distribution is generated through MCS for each maintenance intervention. For the generic intervention "I", the cost matrix [UCM_I] can be, for example:

$$[UCM_I] = \begin{pmatrix} UCM_{I1,1} & \cdots & UCM_{I1,m} \\ \vdots & \ddots & \vdots \\ UCM_{IN,1} & \cdots & UCM_{IN,m} \end{pmatrix}_{Nxm} \tag{11}$$

Similarly, from the known probability distribution of the discount rate, it is possible to generate, through a random sampling, 1000 values of r (discount rate) and then a matrix of values of the Present Worth Factor (PWF) for each year of the analysis period:

$$[PWF] = \begin{pmatrix} PWF_{m=1,t=1} & \cdots & PWF_{m=1,t=5} \\ \vdots & \ddots & \vdots \\ PWF_{\mathrm{m=1000,t=1}} & \cdots & PWF_{1000,t=5} \end{pmatrix}_{mxt} \tag{12}$$

Replacing these data in the Eq. (2) it is possible to obtain, for every strategy of maintenance "s", 1000 values of the LCC of which it is possible to calculate the average and the statistical variance. Therefore applying the theorem of the central limit it is reasonable to assume that the distribution of the total LCC is a normal random variable whose parameters are known using the statistical estimates of the average and the variance carried out on the base of the data obtained from the Monte Carlo simulation.

Thereafter, they are combined with working areas for each section, obtaining in the end the Net Present Value (NPV) of the strategy.

The risk analysis lets to different outcomes such as total NPV of the solutions and Yearly NPV for each year of analysis. As the probabilistic LCCA does not provide a single result, every parameter can be useful to the decision-making process, in order to select the best strategy selection. Consequently, a method based on the probability of exceeding the budget limits is proposed, with the aim to consider whether the probabilistic LCCA can be regarded as the most suitable tool to investigate the financial risk.

In the following section, a case study will be analyzed with the aim to show how the budget risk minimization can be introduced in the probabilistic calculation of LCC at Network Level.

4 Case Study: Choice of M&R Strategy with Budget Risk Reduction

The methodology was adopted to test the effectiveness and the incidence of probabilistic Life Cycle Cost Calculation, overall decision-making process; risk is assessed through the evaluation of Epistemic Uncertainties regarding M&R unit costs interventions for the Italian context.

The study consisted in the identification of the optimal maintenance strategies for the main road network of IX Municipality in Rome that involved 46 road sections with a total length of 23 km.

The time period of the analysis is 5 years and three strategies are considered for the sections maintenance:

- Strategy 1: Do Nothing;
- Strategy 2: Functional and Preservation Maintenance;
- Strategy 3: Structural Maintenance.

Decision trees express the trigger values of their realization. The evolution of pavement performance and the calculation of work quantities, are obtained by Highway Development and Management Software "HDM-4".

A multiobjective optimization method has been used for prioritizing different maintenance activities in order to achieve pre-defined goals, optimizing the use of the available budget. One of the biggest difficulties in multiobjective optimization method is the large number of the feasible solutions (Pareto optimal set or its approximation), which makes it hard for the Decision Maker to select the best solution. To support interaction with the decision maker for identifying the best combination of maintenance actions, this paper refers to a new methodology named "Interactive Multiobjective Optimization-Dominance Rough Set Approach" (IMO-DRSA), already used in a previous research. For more details about the method see (Augeri et al. 2019).

In order to select the most suitable solution starting from the feasible solutions of the multi-objective optimization, in this paper a new element is introduced, in fact additional information comes from minimizing the risk of exceeding the budget was added.

For the analytical formulation of the problem, the following variables was considered:

- $x_{i,u}$ is decision variable, and it is equal to 1 if the strategy u is applied to the section, 0 otherwise;
- S is the set of all the possible strategies to be applied on road section i;
- $C_{i,u}$ is the cost of maintenance strategy u on section i;
- C_{TOT} is the total budget constraint in the planning period;
- C_{YEAR} is the yearly budget constraint in the planning period;
- $c_{i,u,y}$ is the cost of maintenance strategy u, applied on section i, in the year y, as a discount rate will be considered;
- l_i is the length of section i;
- $L = \sum_i^n l_i$ is the total length of the network;
- $t = 5 years$ is the planning period.

The constraints of the optimization problem are:

$$\sum_{i=1}^{n} \sum_{u=1}^{s} \sum_{y=1}^{t} c_{i,u,y} \cdot x_{i,u} \leq C_{TOT}, \; C_{TOT} = 4.034.300 \text{ €} \tag{13}$$

$$\sum_{i=1}^{n} \sum_{u=1}^{s} c_{i,u,y} \cdot x_{i,u} \leq C_{YEAR}, \qquad C_{YEAR} = 1.049.000 \text{ €} \tag{14}$$

The yearly budget is obtained from the total one, divided by the years of planning period and increased of its 30%.

The objectives are mathematically formulated by the objective functions described in Table 1. These have to be maximized.

Where:

li is the length of the road section i and is the total length of the road network;

$\overline{PCI}_{i,u,y}$ is the annual average value of pavement condition index (ASTM D5340 standard) on the road section i, in the year y of the analysis period obtained applying treatment provided by strategy u;

$\overline{PSI}_{i,u,y}$ is the annual average value of the Present serviceability Index on section i, in the year y of the analysis period obtained applying treatment provided by strategy u;

Table 1. Objective functions

Pavement structural condition during the planning time-span	User comfort during the planning time-span:
$F_1(x_{i,u}) = E = \frac{\sum_{i=1}^{n}\sum_{u=1}^{s}\sum_{y=1}^{t}(\overline{PCI}_{i,u,y}\cdot l_i\cdot x_{i,u})}{L}$	$F_2(x_{i,u}) = C = \frac{\sum_{i=1}^{n}\sum_{u=1}^{s}\sum_{y=1}^{t}(\overline{PSI}_{i,u,y}\cdot TI_i\cdot l_i\cdot x_{i,u})}{L}$
Average safety improvement during the planning time-span:	percentage of road network in sufficient serviceability condition during the planning time-span:
$F_3(x_{i,u}) = \Delta AC = \frac{\sum_{i=1}^{n}\sum_{u=1}^{s}\left[\left(\sum_{y=1}^{t}\overline{AC}_i\cdot CMF_{i,u,y}\right)\cdot x_{i,u}\right]}{L\cdot t}$	$F_4(x_{i,u}) = PSIS = \frac{\sum_{i=1}^{n}\sum_{u=1}^{s}\left(l_i\cdot x_{i,u}\cdot\sum_{y=1}^{t}PSIS_{i,u,y}\right)}{L\cdot t}$
percentage of road network in good serviceability condition during the planning time-span	percentage of road network in sufficient structural condition during the planning time-span:
$F_5(x_{i,u}) = SIG = \frac{\sum_{i=1}^{n}\sum_{u=1}^{s}\left(l_i\cdot x_{i,u}\cdot\sum_{y=1}^{t}PSIG_{i,u,y}\right)}{L\cdot t}$	$F_6(x_{i,u}) = PCIA = \frac{\sum_{i=1}^{n}\sum_{u=1}^{s}\left(l_i\cdot x_{i,u}\cdot\sum_{y=1}^{t}PCIS_{i,u,y}\right)}{L\cdot t}$
percentage of road network in good structural condition during the planning time-span:	
$F_7(x_{i,u}) = \mathrm{PCIG} = \frac{\sum_{i=1}^{n}\sum_{u=1}^{s}\left(l_i\cdot x_{i,u}\cdot\sum_{y=1}^{t}PCIG_{i,u,y}\right)}{L\cdot t}$	

TI is the traffic impact factor (TI = 1 if AADT ≤ 10000 veic/day TI = 2 if 10000 < AADT ≤ 20000 a nd TI = 3 if AADT > 20000).

ΔACi is the expected number of accidents on site i without maintenance activity implementation.

As mentioned earlier, three strategies were considered for the maintenance of the road sections. Each of them includes different interventions that can be applied, with different costs associated (Table 2).

The fluctuation of the unit costs was assessed and for each of the considered interventions the impact of the four factors that make up the final cost was evaluated. These factors are: cost of labor, materials, transportation, equipment rental.

Starting from ISTAT (Italian Institute of Statistic) data, positive and negative maximum variation of costs for a period of 5 years were evaluated obtaining percentages in Table 3.

Table 2. Unit cost of maintenance intervention

Interventions	Unit Cost €/m^2	Strategies
Pothole repair	50	Do Nothing
Surface patching	50	Do Nothing
Crack and pothole repair	50	Preservation/Structural Maintenance
Chip seal	2,97	Preservation/Structural Maintenance
Surface course reconstruction	29,57	Preservation/Structural Maintenance
Surface course reconstr. and reprofi	38,08	Preservation/Structural Maintenance
Partial reconstruction	53,61	Structural Maintenance
Total reconstruction	160,5	Structural Maintenance

Table 3. Maximum variations of unit cost factors for a 5-year period of analysis

	Max positive variation	Max negative variation
Cost of labor	13,43%	5,38%
Materials	22,59%	13,94%
Transportation	12,12%	10,43%
Equipment rental	14,25%	18,50%

Subsequently, the variations were applied to the cost factors that determine the interventions final price, in order to obtain the extreme values. Results are reported in Table 4 for only one intervention to show how the final price is obtained. Instead, in Table 5 there is an overview of the final prices for all interventions.

Table 4. Variation applied to cost factors for "partial reconstruction"

Partial reconstruction	Price (€/m^2)	Percentage	Maximum value (€/m2)	Minimum value (€/m2)
Cost of Labor	12	23%	14,03	11,72
Materials	27	50%	32,63	22,91
Transportation	4	7%	4,06	3,24
Equipment Rental	11	21%	12,57	8,97
Final price	**54**		**63,29**	**36,10**

To perform the probabilistic analysis, it is necessary to attribute to these costs a theoretical probability distribution. So, using a distribution function that is better suited

to the variability of the cost, the variation of price index of road construction in Italy was analyzed.

Table 5. Price Variation of the interventions

Interventions	Price (€/m^2)	Maximum value (€/m2)	Minimum value (€/m2)
Pothole repair	50	58,94	42,42
Surface patching	50	58,85	42,50
Crack and pothole repair	50	57,61	43,05
Chip seal	2,97	3,50	2
Surface course reconstruction	29,57	34,66	19,75
Surface course reconstr.and reprofil	38,08	44,61	25,42
Partial reconstruction	53,61	63,29	36,10
Total reconstruction	160,5	189,41	109,14

Following the framework illustrated in Sect. 3.1, the probability density functions of unit costs for all the considered interventions were calculated. Results are shown in Table 6.

Table 6. Parameters of GBD for unit costs of maintenance work.

Intervention	Mean [€/m^2]	Std Dev	a	b
Pothole repair	50,23	2,75	3,77	4,20
Surface patching	50,23	2,72	3,77	4,21
Crack and pothole repair	50,11	2,43	3,88	4,12
Chip seal	2,92	0,25	4,62	2,93
Surface course reconstruction	28,79	2,49	4,60	3,00
Surface course reconstruction and reprofiling	37,06	3,20	4,60	2,99
Partial reconstruction	52,31	4,53	4,57	3,10
Total reconstruction	156,76	13,38	4,56	3,13

To carry out the risk analysis, for each solution (strategy) obtained by multi-objective optimization problem, 1000 scenarios have been generated by Monte Carlo Simulation (MCS). To this purpose, a Matlab code was developed and fitted to the case study.

For explanatory purpose, the obtained outputs are showed for one of the strategies obtained by optimization process, named S1. The first output is the histogram of the

scenarios, from which a normal probability distribution has been obtained by means of a statistical inference, and then the cumulative distribution function has been determined (Fig. 3).

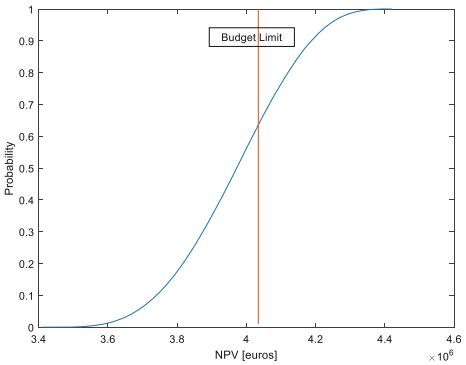

Fig. 3. NPV Cumulative Distribution Function of Strategy S1

The result achievable from these representations is the probability that, for the strategy considered, the budget limit is not exceeded. For the case in analysis, this turns out to be 63%.

The second constraint considered in the multi-objective optimization problem takes the limitation on the Annual Budget into account. Thus, the annual budget risk was investigated for each year of analysis: the functions related to the Yearly NPV were derived in the same way as done for the Total NPV. So, for each strategy, the probability of not exceeding the annual budget was evaluated as shown in Fig. 4 for strategy S1.

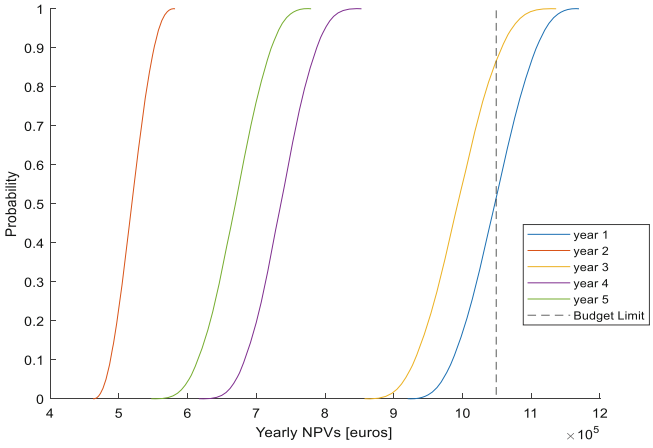

Fig. 4. Yearly NPVs Cumulative Distribution Functions

The parameter Annual Risk Rating (ARR) can be introduced, in order to establish an annual risk factor. It can be evaluated by the following expression:

$$ARR = \frac{1}{t} \cdot \sum_{y=1}^{t} \left(P\left(Yearly_{NPV\,y} \geq Annual_{Budget} \right) \right) \tag{15}$$

All the information and parameters obtained for each strategy have to be compared to identify a risk-based solution.

Once the variable "cost of intervention I" on section l at time t is known, it is possible to associate to each maintenance strategy, besides the performance indicators, also a random total cost (sum of the variable cost of the various interventions chosen). For the theorem of the central limit, the sum of the variable costs of the interventions of the program p will tend to a normal aleatory variable, with average equal to the sum of the average costs and variance equal to the sum of the variances, having hypothesized that the costs are between them independent. This hypothesis is not entirely true but can be considered acceptable.

All the information and parameters obtained for each strategy can be compared to identify a risk-based solution.

The criterion for the optimal strategy selection is:

$$\min(P_i, ARR_i) \tag{16}$$

The choice can be supported by the comparison of cumulative distribution functions of the strategies, as reported in Fig. 5 for some of the obtained strategies, as example.

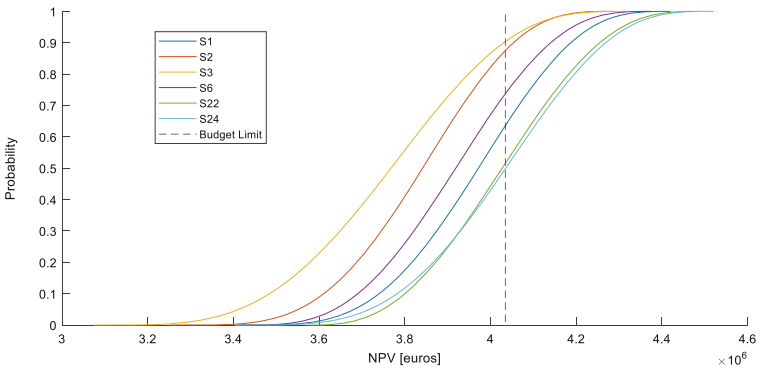

Fig. 5. NPV cumulative distribution functions of some analyzed strategies

The analysis of these curves can be useful to the decision.

The widest curve, which corresponds to Strategy 3, is the one with the greatest amplitude (standard deviation) and therefore representative of the riskiest solution. The worst-case scenario of strategy 3 is not remarkably different from the worst-case scenario of strategy 2; on the other hand, strategy 3 best-case scenario is considerably lower than the strategy 2 one.

Consequently, the riskiest solution appears to be the most economically advantageous, as the most optimistic scenarios belong to it. Finally, the choice of strategy 3

offers the possibility to "take advantage of the risk": despite the solution presents the greatest uncertainty and variability on the final cost, it is the one that minimizes the budget risk.

5 Conclusion

An efficient Asset Management System has to include risk analyses to ensure more informed and transparent choices in resource allocation. Qualitative analyses can surely improve the knowledge of the risk levels involved in maintenance planning; however, they are not sufficiently detailed to improve the decision-making process. Instead, quantitative risk analyses provide more comprehensive results, as the probability theory can assimilate epistemic and aleatory uncertainties.

This paper aims to examine how budget risk reduction can be considered to identify the best combination of maintenance actions given budget constraints within a multiobjective optimization process.

Probabilistic LCCA with Monte Carlo Simulation was used to investigate the risk of budget exceeding in Pavement Management Systems as a secondary criterion for choosing the optimal maintenance strategy on a road network. The method allowed to assess epistemic uncertainties regarding costs and discount rate. Outputs were able to show the possible variability of maintenance strategies costs. Moreover, probability density functions provided for establishing the most economically advantageous solutions (lower mean value) and the riskiest ones (greater standard deviation). Thus, the optimal strategy might be selected by minimizing the probability of budget exceeding. The proposed framework can be used within any multi-objective optimization method.

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