An Intelligent Approach to Optimal Predictive Maintenance Strategy Defining

Ivan Mustakerov
Dept. Information Processes and Decision Support Systems
Institute of Information and Communication Technologies – BAS
Sofia-1113, Bulgaria
mustakerov@iit.bas.bg

Daniela Borissova
Dept. Information Processes and Decision Support Systems
Institute of Information and Communication Technologies – BAS
Sofia-1113, Bulgaria
dborissova@iit.bas.bg

***Abstract*—The rapid growth of industries has complicated the systems functioning and has intensified the maintenance process. This emphasizes the need for effective maintenance planning. The improvement in maintenance technology relies on predictive maintenance, which is based on the determination of a machine condition while in operation. Maintenance planning is complex problem involving condition monitoring and expert knowledge. In the paper, an intelligent approach to optimal predictive maintenance strategy defining is proposed. It is based on methodology for predictive maintenance that increases reliability by determining the optimal maintenance strategy. For the goal, an algorithm based on cost-benefit analysis and optimization tasks solution is developed. The proposed approach to optimal predictive maintenance is demonstrated on the example of real vibrating feeder data. The results of numerical illustration show the applicability of intelligent decision making for optimal predictive maintenance strategy defining.**

Keywords—component predictive maintenance strategy; optimization; intelligent decision making; cost-benefit evaluations.

I. INTRODUCTION

Technological development resulted in increased complexity in both industrial machinery and production systems. The modern industry is constantly demanding for work at high reliability, low environmental risks, and human safety while operating their processes at maximum yield. Therefore, prevention of failures and early detection of incipient machine and systems problems increase the useful operating life of plant machinery. Fault detection and diagnosis in the early stages of damage is necessary to prevent their malfunctioning and failure during operation. This will reflect in substantial benefits achieved through the use of optimization techniques in plant operations by improving the resource utilization at different levels of decision-making process. The premise of condition based maintenance is that regular monitoring of the actual mechanical condition of equipment and operating efficiency of process systems will ensure the maximum interval between repairs; minimize the number and cost of unscheduled outages created by machines failures and improve the overall availability of operating plants [1]. One of the most cost effective maintenance techniques is condition based maintenance.

Condition based maintenance in a plant management program provides the ability to optimize the availability of process machinery and greatly reduce the cost of maintenance. Major improvements can be achieved in: maintenance costs, unscheduled machine failures, repair downtime, spare parts inventory, and both direct and in-direct overtime premiums. A side benefit of condition based maintenance is the automatic ability to monitor the mean-time-between-failures. This data provides the means to determine the most cost effective time to replace machinery rather than continue to absorb high maintenance costs.

Many efforts have been made to develop methods and tools to diagnose failures for predictive maintenance goal [2]-[5]. The essence of prognostics is the estimation of remaining life in meaningful terms that would lead to a profound and intelligent maintenance decision process. This in turn, would lead to proactive maintenance processes minimizing downtime of machinery and production and increasing of manufacturing efficiency [6]. Prognostics are viewed as an add on capabilities to diagnosis. They assess the current health of a system and predict its remaining life, based on features that capture the gradual degradation in the operational capabilities of a system [7]. Prognostics are critical to improve safety, plan successful missions, schedule maintenance, and reduce maintenance cost and downtime [8].

Condition based maintenance techniques provide an assessment of the system's condition, based on data collected from the system by continuous monitoring. The goal is to determine the required maintenance plan prior to any predicted failure. Therefore, the maintenance strategies aim to minimize the cost by improvement of the operational safety and reduce the severity and number of in-service system failures. Accordingly to the ISO 13381-1:2004 standard, the activities start with monitoring, followed by diagnostic, prediction and posterior actions [9].

Various decision making approaches have been proposed for maintenance strategy selection such as analytic hierarchy process, fuzzy set theory, genetic algorithm, mathematical programming, factor analysis, simple multi-attribute rating technique, multi-criteria optimization, etc. [10]-[14].

978-1-4799-0661-1/13/$31.00 ©2013 IEEE

The current paper aims to define the optimal maintenance strategy by solution of optimization tasks. Cost-benefit analysis is used to quantify the particular estimation for each maintenance alternative. The problem of optimal maintenance strategy is used to outline a generalized algorithm for predictive maintenance. In particular, this problem is dependable on the processes related with monitoring, collecting and processing of actual data. All of these are summarized in a generalized structural diagram for developing of decision support system.

II. Problem of Optimum Maintenance Strategy

Manufacturing machinery may have flaws that can cause a significant reduction in efficiency and lifespan, negatively affecting production, equipment operations and maintenance costs. Incorporating continuous monitoring inspections into condition-based maintenance strategy will ensure that equipment is operating as designed. Condition monitoring is a component of predictive maintenance activities. Condition monitoring allows in preventing breakdowns, helps to avoid unplanned shutdowns and enables to optimize maintenance resources by scheduling maintenance as needed based on analysis of asset condition data. All of these activities help to predict potential equipment failures before they occur. Condition based maintenance is a decision-making strategy based on real-time diagnosis of impending failures and prognosis of future equipment health [15]. To provide optimal decision making on when to take equipment down for maintenance should be integrated with overall manufacturing operations. This is why additional information about sensing and data acquisition is needed. The accurate data for available signals from the equipment are to be collected. The signals are captured by using specific sensors. The condition monitoring and establishing of health assessment is a baseline for equipment performance as critical step in enabling predictive maintenance solutions. Standard condition monitoring techniques like statistical process control or advanced process control could be employed primarily in process monitoring. Going forward, health assessment and prognostics is considered as one of the key challenges in enabling predictive/preventive maintenance solutions. The mathematical algorithms complexity to infer impending failure requires artificial intelligence to get the solutions. That is why manufacturing sites create challenges for integrated optimal predictive maintenance solutions. Integration of data from multiple sources is needed to be included in the final decision.

The choice of maintenance alternative is a complex and difficult decision making problem. A maintenance program needs to define different maintenance alternative for different equipments. Therefore, the maintenance problem could be recognizing as a combinatorial optimization problem. When considering a decision making problem it should be noted that in all cases there exists a decision-maker. Another prerequisite is that the optimal solution implies the existence of a function, which should be optimized.

Let **x** be a vector containing p decision variables. An optimization problem can be stated as:

$$\text{Minimize/maximize } f_i(\mathbf{x}) \text{ for } i = (1, 2, \ldots, \text{n}). \quad (1)$$

s.t.

$$g_j(\mathbf{x}) \leq 0 \text{ for } j = (1, 2, \ldots, \text{J}). \quad (2)$$

where $\mathbf{x} = \{x_1, x_2, \ldots, x_p\}$ and each x_i denotes the *i-th* decision variable (*i-th* alternative).

A variety of approaches implemented in efficient mathematical programming software can be used to solve such problems [16].

One widely used in economics and resource management approach to evaluate maintenance alternatives is *cost-benefit* analysis [16], [17]. The cost-benefit analysis is estimation of marginal benefit of increasing investment for a given repair/replace demand, or willingness to pay and it decreases with increasing effort or expenditure on failure prevention.

III. Predictive Maintenance Methodology

Predictive maintenance techniques are recognized as an integral part of instructional decision-making. Condition-based maintenance is a methodology that combines predictive and preventive maintenance with real-time monitoring. The goal of predictive maintenance is to optimize reliability and availability by determining the need for maintenance activities based on equipment condition. Condition monitoring involves fault diagnosis and condition prognosis and looks at the system and all of its assets. Predictive maintenance strives to identify incipient faults before they become critical. Therefore, predictive maintenance could be considered as a decision making strategy enabling real-time diagnosis of impending failures and prognosis of future equipment health, where the decision to perform maintenance is reached by observing the "condition" of the system and its components. This process requires technologies, expert knowledge, and communication to integrate all available equipment condition data, such as: diagnostic and performance data; maintenance histories; operator logs; and design data, to make timely decisions about the maintenance requirements of major/critical equipment.

The management of particular system can be realized by collecting information about the system, defining the objectives of its management, formulating of appropriate task for a decision making, solving this problem, implementation of the decision, assessment of its effectiveness and interactive influence of the decision-maker during various stages. The corresponding methodology is proposed in Fig. 1.

Condition monitoring is an essential part of predictive maintenance where the condition of specific equipment is monitored. This can be done automatically with the use of proper sensors or manually. During the stage 1, phase 1a of the methodology implementation, quantitative information about the investigated system is collected by means of sensors. For example, the frequency of the vibrations can be mapped since certain frequencies will only be present when conditions that indicate an impending defect are present. Equipment can be monitored using sophisticated instrumentation such as vibration analysis equipment or the expert senses. Therefore, phase 1b collects information from professionals serving the system and experts to ensure additional knowledge from human information.

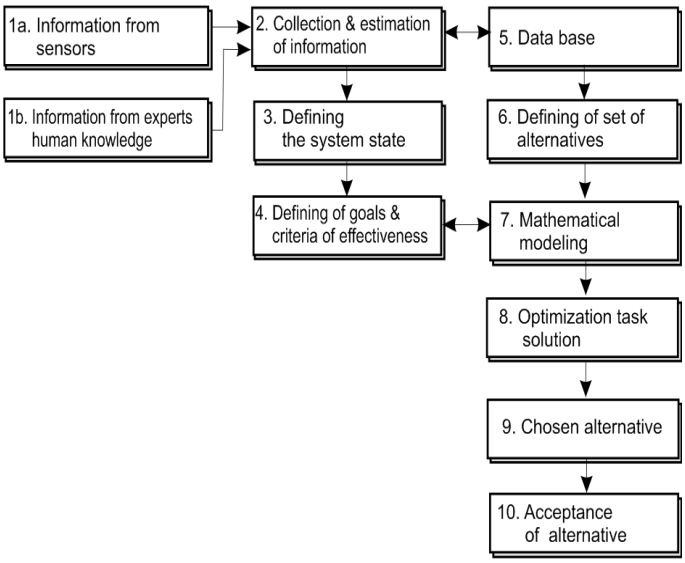

Fig. 1. Generalized methodology for predictive maintenance

The goal of condition monitoring of an item is to collect condition data to make it possible to detect incipient failure so that maintenance tasks can be planned at a proper time. Another goal is to increase the knowledge about failure cause and effect and deterioration pattern.

The stage 2 is carrying out by processing and summarizing the obtained information for the goals of the implementation of stage 3 and 4 aiming to establishing a system description and definition of objectives and criteria effectiveness. Aggregated and processed data from stage 2 is used in stage 5 to establish a database of investigated system. On stage 6 through interactive engagement of experts a set of alternatives is determined. The results of stage 4, 5 and 6 are used to define a mathematical model of the investigated system and to formulate an appropriate optimization task (stage 7). On stage 8 the optimal solution is determined. At stage 9 the defined by the solution alternative is applied. On the stage 10 the alternative application is verified against the goals. If the results differ from the expected, the corresponding correction is setting in the system' mathematical model, the optimization task for decision making is redefined on step 7 and steps 8, 9 and 10 are repeated. In some cases, because of incompleteness of a priori information about the investigated system, a redefinition of the objectives and criteria on stage 4 is required to achieve the desired objectives for management of the system. The implementation of stages 6, 7, 8, 9 and 10 are visualized by structural diagram shown in Fig. 2. As a result of optimization tasks solutions a group or single alternative is chosen and evaluated against all the objectives. Finally, the selected alternative should be approved by the expert.

Since the predictive maintenance is a well-proven strategy that can significantly reduce maintenance costs, the cost-benefit estimation can be used to define the most appropriate decision making strategy. In the current paper two types of costs-benefit estimations are proposed:

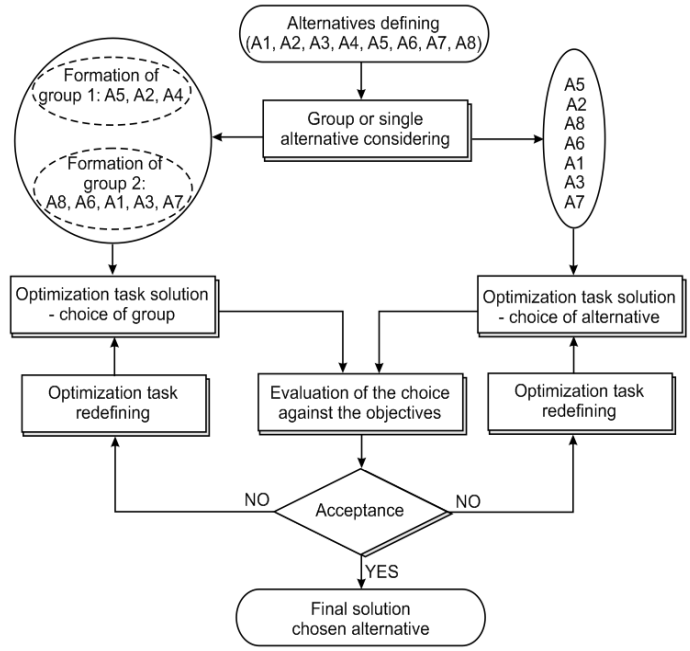

Fig. 2. A generalized structural diagram for decision making

$$CBE^{repair} = \frac{\alpha C_{repair\_component}}{\beta P_{remaining}} \tag{3}$$

$$CBE^{new} = \frac{C_{new\_component}}{P_{remaining}} \tag{4}$$

where $C_{repair\_component}$ is the cost for component repair, $C_{new\_component}$ is the cost of replacement by new component, α is coefficient indicating how many times the component has failed, $P_{remaining}$ is the profit during the component remaining useful time, β is coefficient that indicates whether the component is repaired ($0 < \beta < 1$) or replaced with a new one ($\beta = 1$).

IV. Mathematical Model Formulation

The question that arises when an alert alarm from the condition monitoring equipment appear is what decision should be taken. The decision process can be realized by two steps. On step I two alternative exist – *to repair or to replace the machine as a whole*. If the decision on the first step is to replace the machine by new one the decision process ends. If the decision on step I is to repair machine, the next question is – *what to do with any particular machine component – to repair or to replace*? The algorithm of this decision making process is shown on Fig. 3.

The mathematical modeling of optimal maintenance strategy (replace or repair) is based on optimization problem formulations taking into account (3) and (4). These formulations are based on maximization of the cost-benefit estimations. This is because maximal cost-benefit values define the worst case scenario requiring proper maintenance reaction.

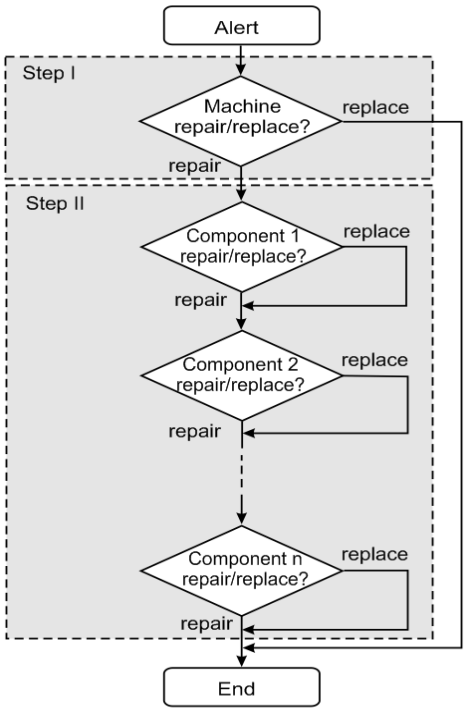

Fig. 3. Predictive maintenance decision making algorithm

Step I: The answer of the question *to repair or to replace the machine as a whole* is result of solution of the following optimization task:

$$\text{maximize}\left(\sum_{i=1}^{n} xCBE_i^{repair} + \sum_{i=1}^{n} yCBE_i^{new}\right) \quad (5)$$

$$\text{s.t.} \quad x + y = 1, \quad x, y \in \{0, 1\}$$

where CBE_i^{repair} represents the cost-benefit evaluations for repairing of *i-th* component, CBE_i^{new} represents the cost-benefit evaluations for replacing of *i-th* component, *x, y* are binary integer variables assigned for each alternative.

Step II: The repair/replace strategy for each particular component is defined by a single run of the following optimization problem:

$$\text{maximize}\left(\sum_{i=1}^{n} x_i CBE_i^{repair} + \sum_{i=1}^{n} y_i CBE_i^{new}\right) \quad (6)$$

$$\text{s.t.} \quad \forall\, i \in \{1,2,\ldots,n\}: \sum_{i=1}^{n} x_i + y_i = 1,\ x_i, y_i \in \{0, 1\}$$

where CBE_i^{repair} represents the cost-benefit evaluation for repairing of *i-th* component, CBE_i^{new} represents the cost-benefit evaluation for replacing of *i-th* component, x_i, y_i are binary integer variables assigned for each machine component alternative.

On this step the maintenance strategy considers each component as independent variable in contrast to the previous step where the machine maintenance is considered as a whole.

V. Illustrative Numerical Example

The proposed approach is illustrated by considering a real data example of vibration feeder as object of predictive maintenance. The vibrating feeder consists of the following components: *1 – vibrating frame, 2 – spring, 3 – vibrator, 4 – motor vibrating device* and *5 – motor*.

The cost-benefit analysis calculations are useful, because they allow examining the options and making more informed choices. The vibration feeder cost-benefit evaluations of the component repair/replace alternatives corresponding to the estimations (3) and (4) are shown in Table I.

TABLE I. Matrix of Evaluations of Alternatives

Alter-natives	Costs-Benefit Estimations				
	Component 1	*Component 2*	*Component 3*	*Component 4*	*Component 5*
Repair	0.85	0.70	0.65	0.90	0.80
Replace	0.75	0.80	0.75	0.85	0.70

The optimization problems (5) and (6) are used to formulate corresponding tasks for step I and step II to define the "best" alternative from a set of all available alternatives.

Step I: The optimal strategy *to repair or to replace the machine as a whole* takes into account optimization problem (5) involving the cost-benefit evaluations from Table I:

$$\max\ \{x\,(0.85 + 0.70 + 0.65 + 0.90 + 0.80) + \\ + y\,(0.75 + 0.80 + 0.75 + 0.85 + 0.70)\} \quad (7)$$

$$\text{s.t.} \quad x + y = 1, \quad x, y \in \{0, 1\}$$

The solution results of optimization task (8) are shown in Table II.

TABLE II. Solution Results on Step I

Objective function value	*x (repair)*	*y (replace)*	**Decision**
3.90	1	0	Repair

According solutions results data in Table II the optimal maintenance strategy is to repair the machine. This means step II should be executed.

Step II: The optimization problem (6) is transformed into following optimization task:

$$\max\ \{(0.85\,x_1 + 0.75\,y_1)+(0.70\,x_2 + 0.80\,y_2) + \\ + (0.65\,x_3 + 0.75\,y_3)+(0.90\,x_4 + 0.85\,y_4)+(0.80\,x_5 + 0.70\,y_5)\} \quad (8)$$

$$\text{s.t.} \quad \forall\, i \in \{1,2,\ldots,5\}: \sum_{i=1}^{5} x_i + y_i = 1,\ x_i, y_i \in \{0, 1\},$$

The solution results of optimization task (8) defining the particular strategies for each component are shown in Table III.

TABLE III. OPTIMAL COMPONENT MAINTENANCE STRATEGY

Alter-natives	***Component 1***	***Component 2***	***Component 3***	***Component 4***	***Component 5***
x_i (repair)	**1**	0	0	**1**	**1**
y_i (replace)	0	**1**	**1**	0	0

VI. RESULTS AND DISCUSSION

The results of the first step execution of the proposed algorithm show that the optimal maintenance decision is to repair the machine (Table II). According to the algorithm of predictive maintenance decision making, the step II should be executed too. This is accomplished by a single run of formulated optimization task (8). Its solution results in Table III suggest that component 1, 4 and 5 should be repaired while components 2 and 3 should be replaced by new ones.

The example of vibration feeder is used just for illustration of the proposed approach. In practice, defining of optimal predictive maintenance decision strategy for other machines consisting of much more components will be complex mathematical optimization problem. In such cases the proposed intelligent approach to optimal predictive maintenance strategy defining could be a better alternative to intuitive decision making.

The units in cost-benefit analysis are standard money units thus both costs and benefits can be compared directly. In some cases, where it is difficult to express the benefits into money cost-effectiveness analysis could be used as cost-minimization technique. Other objective functions could be used in estimation of machine components maintenance strategy.

VII. CONCLUSION

The paper describes an intelligent approach to optimal predictive maintenance strategy defining based on optimal decision making algorithm. Different maintenance alternatives – repair or replace, are evaluated using the concept of costs-benefit analysis by means of proper optimization tasks formulations. Two different kinds of optimization problems are formulated: 1) defining of maintenance strategy for machine as a whole; 2) defining of maintenance strategy for each particular machine component. These optimization tasks are used in predictive maintenance decision making algorithm that in turn is included in proposed generalized methodology for optimal predictive maintenance.

The proposed intelligent approach for optimal maintenance strategy defining is illustrated on the example of real vibration feeder considered as an object of predictive maintenance. The numerical results show the applicability of the developed approach and effectiveness of the described mathematical model formulation toward the optimum maintenance strategy defining. Such optimal maintenance strategy contributes to maximizing process profitability by reducing operating and manufacturing cost. Defining of optimal maintenance strategy based on condition monitoring improve the system reliability levels and reduce unnecessary investment in maintenance.

ACKNOWLEDGMENT

The research work reported in the paper is partly supported by the project AComIn "*Advanced Computing for Innovation*", grant 316087, funded by the FP7 Capacity Programme (Research Potential of Convergence Regions) and project "*Diagnostic and Risk Assessment Predictive Asset Maintenance*" No DVU-10-0267/10.

REFERENCES

[1] K.R. Mobley, An Introduction to Predictive Maintenance. Elsevier Science, 2010.

[2] U.D. Nielsen, Z. Lajic and J.J. Jensen, "Towards fault-tolerant decision support systems for ship operator guidance", Reliab. Eng. & Sys. Safety, vol. 104, pp. 1-14, 2012.

[3] M.L. Mahadevan, S.P. Kumar and R.Vinodh, "Preventive maintenance optimization of critical equipments in process plant using heuristic algorithms", In Proc. of Conf. on Industrial Engineering and Operations Management, Dhaka, Bangladesh, 2010.

[4] R.J.P. Ferreira, A. Teixeira de Almeida and C.A.V. Cavalcante, "A multi-criteria decision model to determine inspection intervals of condition monitoring based on delay time analysis", Reliab. Eng. & Sys. Safety, vol. 94, pp. 905-912, 2009.

[5] K. Bouvard, S. Artus, C. Bérenguer and V. Cocquempot, "Condition-based dynamic maintenance operations planning & grouping. Application to commercial heavy vehicles", Reliab. Eng. & Sys. Safety, vol. 96, pp. 601-610, 2011.

[6] D.C. Swanson, "A general prognostic tracking algorithm for predictive maintenance", In Proc. of Aerospace Conference, IEEE, vol. 6, pp. 2971-2977, 2001.

[7] J. Luo, M. Namburu, K. Pattipati, L. Qiao, M. Kawamoto and S. Chigusa, "Model-based prognostic techniques", In Proc. of IEEE Systems Readiness Technology Conference, pp. 330-340, 2003.

[8] E. Dragomir, R. Gouriveau, F. Dragomir, E. Minca and N. Zerhouni, "Review of prognostic problem in condition-based maintenance". In Proc. of European Control Conference ECC'09, (Budapest, Hungary, 2009), hal-00418761.

[9] D. Borissova, I. Mustakerov and V. Grigorova, "Engineering systems maintenance by optimal decision making strategies under uncertainty conditions", Problems of Eng. Cybernetics & Robotics, vol. 63, pp. 14-21, 2011.

[10] B. Gandhare and M. Akarte, "Maintenance Strategy Selection", In Proc. of Ninth AIMS Int. Conf. on Management, pp. 1330-1336, 2012.

[11] M. Akhshabi, "A new fuzzy multi criteria model for maintenance policy", Middle-East J. of Sci. Res., vol. 10, pp. 33-38, 2011.

[12] C.A.V. Cavalcante, R.J.P. Ferreira and A. Teixeira de Almeida, "A preventive maintenance decision model based on multicriteria method PROMETHEE II integrated with Bayesian approach". IMA J. Mgmt Math, vol. 21, pp. 333-348, 2010.

[13] R. Ginevicius, "A new determining method for the criteria weights in multicriteria evaluation", Int. J. Info. Tech. Dec. Mak., vol. 10, pp. 1067-1095, 2011.

[14] G. Rigopoulos, D. TH. Askounis and K. Metaxiotis, "NeXCLass: A Decision Support System for non-ordered multicriteria classification", Int. J. Info. Tech. Dec. Mak., vol. 9, 53, pp. 53-79, 2010.

[15] Y. Peng, M. Dong and M.J. Zuo, "Current status of machine prognostics in condition-based maintenance: a review", Int. J. of Adv. Manuf. Technol., vol. 50, pp. 297-313, 2010.

[16] C. Park, Natural hazards (1999). http://www.lancs.ac.uk/staff/gyaccp/hazards/chap6.htm

[17] H. F. Campbell and R. P.C. Brown, "A multiple account framework for cost−benefit analysis", Eval. and Program Planning, vol. 28, pp. 23-32, 2005.