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Resource allocation in seismic risk mitigation

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ABSTRACT: This paper introduces the concepts of capital budgeting for the implementation of seismic risk management programs. Based on parameters of costs and returns, several practical cost allocation situations are identified and analytically modeled as 0-1 Integer Programming problems. Four objective functions were formulated based on Minimum Loss, Minimum Cost, Maximum Return, and Maximum Profit. Six set of constraints were developed to represent logical relationships and technological and financial considerations that could define actual situations. The cost benefits of a seismic risk mitigation program could be analyzed under any of the four optimization criteria. The analysis produces an optimum schedule of seismic retrofit schemes for the whole portfolio of structures at risk consistent with the constraints of the problem. A methodology for computing an optimum budget (i.e. budget yielding the maximum return) is explained. A case study of 15 buildings under four alternatives is presented and several considerations are illustrated

1 INTRODUCTION

We conceive a seismic risk mitigation program as a three steps program:

Step 1. Understanding of the objectives to be reached;
Step 2. Development of essential seismic risk parameters: ground motion, exposure, and structural deficiencies
Step 3. Study of scenarios to establish a prevention program with a list of buildings to be retrofitted, and related cost and benefits.

A rational development of these three steps clarifies the uncertainties associated with the earthquake risk elements and establishes an action plan that reaches the program goals (Bendimerad, & Shah 1991). The last step in this process is the execution of the plan which consists of the allocation and expenditure of the resources. In this paper, we propose several optimization models for resource allocation considering the available funds, retrofit alternatives, and financial and physical constraints.

2 PROBLEM FORMULATION AND SOLUTION

Given a portfolio of facilities requiring seismic strengthening, the resource allocation problem consists of developing a schedule of retrofit schemes that optimizes the available funds. The problem has also several types of constraints such as resource (funds) availability constraints, feasibility constraints, and logical and technological constraints.

Provided that data describing costs and returns for each scheme and for each facility are quantified, the resource allocation problem can be rationally formulated and solved in an Operations Research (OR) context. Such problems are known as Capital Budgeting (CB) problems. In a typical CB problem, decisions involve the selection of potential investments. Hence, large scale seismic retrofit problems involving several structures, alternatives, and constraints can be formulated as CB problems.

In this study, we modeled the seismic resource allocation CB problem using a Zero-One Integer programming (0-1IP) formulation (See for example Lev & Weiss, 1982). This formulation is simple and efficient because partial investment is not an option among the retrofit schemes. A scheme is either selected or rejected on a basis of its full cost and benefit. IP problems can be solved by the Branch-and-Bound Technique (Balas & Martin, 1980). For binary variables (as in this case) variations of this technique are known as additive algorithms. The Branch-and Bound methods compute a sequence of lower and upper bounds on the optimal objective value of the problem. An optimal solution is found when the lower and the upper bounds coincide. Commercial computer codes that solve 0-1 IP problems are available (Brooke, et al, 1990; Tijms & Kalvelagen, 1990).

The complex relations between the projects and retrofit schemes are represented by the constraints equations of the CB model. The constraints represent the logical technological, operational, and financial considerations. We have identified the following six types of constraints:

1. *Resource availability constraints*: Indicate that the resources expended by the retrofit program (funds, surge space, time) cannot exceed the available resources.

2. *Structural Feasibility Constraints*: Include the required single choice constraint (i.e. only one scheme could be selected per facility); also used to indicate that a scheme is viable only if its achieves a minimum protection goal.

3. *Contingency constraints*: Typically used in the case where the retrofit of a facility is contingent upon retrofit of some other facility.

4. *Alternative constraints*: Used to indicate that not all constraints should be fully enforced but only selected ones.

5. *Conditional constraints*: Used to model a situation where enforcing a constraint implies satisfying another.

6. *Operational constraints*: Used to express time, space, and other operational restrictions

The basic parameters of the model formulation are the cost and the expected total dollar loss associated with the potential damage of each facility under the original condition (i.e. do nothing) and the retrofitted or rebuild condition. Expected losses are related to damage (ATC, 1985). For each facility, several retrofit schemes are available. Generally, the schemes are related to established performance criteria such as achieving protection of life safety, or controlling damage. Do nothing and facility replacement are also realistic options. The expected loss could be evaluated for a target earthquake that is determine from the scenario analyses. This procedure as well as the methodology to evaluate the costs and various types of losses, and basic modeling techniques to convert cost and damage information into logical constraints in OR format are given by the authors in a separate publication (1992). Considerations on costs of retrofit are discussed in the literature (See FEMA 1988, 1989).

3 CB MODELS FOR SEISMIC RETROFIT

The representation of practical problems depends on the adequate formulation of the objective function and the associated constraints. Once the constraints are properly identified and formulated it has been our experience that most practical situations could be solved with an appropriate objective function. This capability is essentially due to the robustness of the 0-1 IP algorithm. In the following we explain the fundamental model formulations.

3.1 Unrestricted and Restricted Models

We divided the resource allocation problem into two models, namely: *Unrestricted* and *Restricted*. The unrestricted CB model generates a solution that optimizes the available funds but may result in doing no strengthening in the structures for which none of the retrofit schemes is economically "profitable". On the other hand, the restricted CB model mandates that all buildings in the risk mitigation program be retrofitted. This implies that a minimum level of fund is available. The two models generally result in different solutions. Restrictions are imposed through the proper formulation of the structural feasibility constraints.

3.2 Optimality Criteria

We developed the analytical formulations of both the restricted and unrestricted models along four optimality criteria, namely: Minimum cost, minimum loss, maximum return, and maximum profit.

In the *minimum cost criterion*, the objective is to minimize the overall portfolio retrofit costs. The main constraint is that portfolio loss does not exceed a pre-established threshold level. The threshold value could be related either to a mandatory (i.e. code) requirement or voluntary requirement.

The *minimum loss criterion* interchanges the objective function and the resource availability constraint. The objective is to minimize the expected loss to the portfolio while the overall retrofit cost remains within the available funds (budget).

The *maximum return criterion* is a variation of the minimum loss criterion. The objective is to maximize the portfolio return (damage reduction) within the available funds

The *maximum profit criterion* considers the retrofit costs as a potential investment. We define "Profit" as the difference between the expected loss reduction and the portfolio retrofit cost. The objective is to maximize the profit within the available funds. Profit as defined here indicates a level of the cost-effectiveness of the retrofit program. However, profit is generally not a predominant deciding factor in seismic risk mitigation.

4 GLOBAL CB PROBLEM VERSUS LOCAL CB PROBLEM

The solution of CB resource allocation problem determines a schedule of the retrofit options that optimizes the particular objective function either globally or locally. The "Global" problem consists of the general case where one seeks an optimum solution for the whole portfolio of facilities at risk. In this case, both the objective function and the constraints of the problem are formulated to solve for a cost-benefit of the entire risk mitigation program. In some cases, however, a phasing approach to the execution of the seismic mitigation program is desired. We developed an analytical formulation that provides an optimum solution per phase. We referred to this case as "Local" problem. The local resource allocation problem is resolved by appropriate sequential implementation of the CB models. In this case every time the model is implemented, its size and constraints change, because not only the facilities upgraded in previous phases are excluded from the new phase, but also, the cost and return values change. For this reason the model is called *Dynamic CB model.*

5 OPTIMUM BUDGET

Of interest in any CB problem is the determination of an optimum budget, i.e. the budget that yields the maximum return from the investment. This budget level is defined as "Critical" budget. We developed a methodology to determine the critical budget by performing iterative solutions of the maximum profit model from which a graphical representation of profit versus funds is generated. The critical budget corresponds to the point where an increase in funds results in no profit (i.e point of horizontal tangent in the graph).

6 CASE STUDY

In the following, we illustrate the concepts discussed above by considering a portfolio of fifteen buildings taken from Stanford University's seismic risk mitigation program. Following the general framework for risk mitigation (definition of objectives, determination of the seismic risk parameters, earthquake scenario analyses) it was determined that MMI IX should be the base for developing an optimum risk mitigation strategy (Bendimerad, & Shah 1991). The portfolio represents a typical university mix of buildings with different structural types, use, and importance. Under consideration for retrofit are unreinforced masonry (URM) buildings, non-ductile (N.D.) reinforced concrete (RC) buildings, and tilt up structures.

6.1 Costs and Returns

For each building, we considered the following retrofit alternatives:

Alternative 0: do nothing
Alternative 1: life safety level retrofit
Alternative 2: damage control level retrofit
Alternative 3: building replacement

The University has developed costs for each of alternatives 1, 2, and 3. These costs as well as the expected damage (in $ value) from MMI IX are reproduced in Table 1.

Table 1. Expected Eq. loss and cost for retrofit (in $millions)

Bldg ID	Expected EQ.Loss	Cost ($Millions) Altern. 1	Altern. 2	Altern.3
1	11.35	5.62	19.37	N/A
2	9.15	2.73	17.02	N/A
3	9.15	2.53	16.63	N/A
4	28.24	8.52	19.94	14.00
5	35.45	22.80	32.60	39.00
6	7.65	5.11	6.93	16.06
7	3.75	2.82	15.64	N/A
8	5.25	3.30	16.72	N/A
9	11.30	4.00	8.50	N/A
10	4.35	1.71	3.13	N/A
11	7.95	0.75	2.00	N/A
12	4.80	0.92	2.14	N/A
13	2.20	0.48	0.96	N/A
14	3.25	0.76	11.70	N/A
15	1.75	0.51	89	N/A

N/A: Not Applicable

We computed the return values as the sum of the dollar loss reductions from physical damage and business interuption. The return values represent the benefit from the mitigation program. As we explain in a separate publication (1992), the computations of the return values is a tedious and rather judgmental process. The results are summarized in Table 2.

Table 2. Returns from retrofit schemes (in $Million)

Bldg ID	Scheme 1	Scheme 2	Scheme 3
1	3.80	10.02	N/A
2	4.80	8.79	N/A
3	4.80	8.79	N/A
4	19.28	26.69	27.82
5	21.45	32.72	33.50
6	1.60	6.53	7.17
7	0.45	3.36	N/A
8	3.90	4.62	N/A
9	4.20	10.32	N/A
10	3.45	3.45	N/A
11	3.90	7.86	N/A
12	0.35	3.40	N/A
13	1.20	2.06	N/A
14	1.50	2.80	N/A
15	0.45	1.53	N/A

N/A: Not Applicable

6.2. Budget Scenarios

Table 1 provides the following budget quantities:

1. Life safety scheme budget=$62.56 million
2. Damage control budget=$104.78 million
3. Maximum cost (including replacement of 3 buildings)=$124.37 million

Hence, in a Restricted CB Model, where all building should be retrofitted, a minimum budget of $62.56 is required. Using this model, we computed a critical (optimum) budget of about $78 million representing a profit of about $31 million and a maximum profit budget of $91.6 million representing a profit of about $32.7 million. In this particular case, the seismic mitigation plan could be considered as a highly profitable investment due to the high seismic exposure of the facilities. This is not generally the case for all seismic risk mitigation programs.

6.3 Solution of Global Problem

We developed a solution of the global resource allocation problem using the Restricted CB Model, with total funds of $81 million. This budget is slightly higher than the critical budget identified above. because we accounted for additional costs of surge space during the period of construction. The solution is reproduced in Table 3.

Table 3. Max. Profit Retrofit Program for a Budget of $81 Million

Bldg ID	Retrofit Level	Return	Cost	Profit
1	Damage Control	10.02	9.37	0.65
2	Life Safety	4.80	2.73	2.07
3	Life Safety	4.80	2.53	2.27
4	Damage Control	26.69	9.94	16.75
5	Life Safety	21.45	22.80	-1.35
6	Damage Control	6.53	6.93	-0.40
7	Damage Control	3.36	5.64	-2.28
8	Life Safety	3.90	3.30	0.60
9	Damage Control	10.32	8.50	1.82
10	Life Safety	3.45	1.71	1.74
11	Damage Control	7.86	2.00	5.86
12	Damage Control	3.40	2.14	1.26
13	Damage Control	2.06	0.96	1.10
14	Damage Control	2.80	1.70	1.10
15	Life Safety	0.45	0.51	-0.06
	TOTAL:	111.89	80.76	31.13

Note: Cost, Return, and Profit values are in $Million

6.4. Dynamic CB Model with Surge Space Constraints

We are providing below the solution of the Dynamic CB Model considering three phases, each being two years long, with restriction on availability of surge space and a funding of $27 Million for each phase (3x$27M=$81M). In this case three Restricted CB Model are formulated and solved with the associated funds requirements and surge space requirements. A number of feasibility constraints also need to be developed to express all logical relationships. The optimum phasing schedule is shown in Table 4.

Table 4. Dynamic CB Model Results

Phase Number	Buildings Retrofitted	Cost $Million.	Profit $Million
Phase1	#3, #4, #13	13.77	19.78
Phase2	#1, #2, #9, #10, #11, #14	26.66	12.58
Phase3	#5, #6, #7, #8, #12, #15	40.30	- 3.04
Total:		80.73	29.32

The allocation of funds per individual phase guarantees maximum profit while enforcing all constraints. A conventional phase budget distribution, would probably be more uniform somewhere around $27 million with the aim of using the whole budget for each phase. In such a case, the "profit" would also be evenly distributed amongst individual phases, without "loss" in any of them. However, such solution is not the most efficient one because it will not achieve optimum risk reduction. Should the postulated earthquake take place in the earlier phases of the retrofitting program, the portfolio will be more vulnerable and suffer higher losses.

7 CONCLUSION

The CB resource allocation models for seismic risk mitigation enable the determination of the following elements:

1. The optimum schedule of retrofit schemes consistent with the available funds and the technological and operational constraints,
2. The optimum budget (i.e. budget that provides the maximum benefit of retrofit program), and
3. An optimum phasing strategy for multi-phased programs.

In this paper, we attempted to identify practical considerations and analytically formulate them. We established the general concepts, the mathematical models, and the expressed various objective functions and constraints. We illustrated some of these elements in an actual to demonstrate the applications. We solved the different models by a single solution algorithm based on a 0-1 Integer Programming formulation. This simple, yet powerful formulation is flexible enough to accommodate an analytical solution to complex realistic cases that include a large number of alternatives with several constraints. Of course, the quality of the results depends on the quality of the data (i.e. costs and returns). However, within the uncertainties in the data, the results are rational and consistent.

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