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PROBABILISTIC BASED ECONOMIC FEASIBILITY ASSESSMENT OF SEISMIC RETROFIT METHODS FOR STRUCTURES

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ABSTRACT

One of the main deficiencies of the current seismic rehabilitation codes is ignoring economic criteria in designing retrofit methods for structures. In this study, a novel probabilistic based procedure for the economic assessment of the different designed retrofit methods for a structure is proposed. In this procedure seismic hazard and fragility analysis, are applied in the Cost-Benefit Analysis (CBA) to compute the Economic Feasibility Index (EFI) of a retrofit method. This index is the ratio of the present value of the benefit from a seismic retrofit method to its cost. This benefit is computed by difference of the annualized loss expectancy of the structure before and after the retrofit. A retrofit method is economically feasible only if its EFI is greater than unity. The proposed index is used to economic assessment of the three retrofit methods, including, RC jacketing, steel jacketing and CFRP wrapping for a pre-code RC building located in Tehran. According to the obtained results in addition to the seismic performance of the retrofitted building and its cost of retrofit, site seismic hazard, Investment Return Period (IRP) and interest rate are also important parameters in economic feasibility assessment of a retrofit method. Increasing IRP will increase EFI but decrease the rate of its increase. Consequently, considering return periods more than 50 years has a negligible effect on increasing EFI. This Index is highly site dependent i.e., a retrofit method for a building may be economically beneficial but for a similar building, in another site become non-beneficial.

Keywords: seismic retrofit, fragility curve, economic feasibility index, RC frame, incremental dynamic analysis, annualized loss expectancy, damage factor, cost-benefit analysis.

INTRODUCTION

One of the main challenges in earthquake-prone countries is seismic retrofitting of buildings that are not designed or constructed according to the modern building codes in order to reduce loss of life and property. In this regard in many countries including Iran, numbers of seismic assessment and rehabilitation codes are published. A common problem in these codes, in designing retrofit methods for a structure, is neglecting economic criteria, which have the most importance in stakeholders' points of view. The best retrofit method, among different designed methods is the most economical one, although in some cases none of the designed retrofit methods are economically feasible. In order to select the most economical and feasible retrofit method, the cost of work isn't unique predominant criterion whereas, the benefit from a seismic retrofit method is also an important criterion, in which, losses of the structure in probable future earthquake, seismic hazard at the location of the structure, interest rate and investment return periods are incorporated. Here, the Cost-Benefit Analysis (CBA) is used to assess the economic aspects of the retrofit methods. CBA usually tries to put all relevant costs and benefits of a project using the time value of money. This is often done by converting the future expected streams of costs and benefits into a present value amount using an interest rate [1]. Some researchers have used CBA to select the preferred retrofit methods for structure and infrastructure [2, 3], but a new probabilistic approach proposed in this study to compute the benefit of a retrofit method in CBA.

Although the maximum reduction in the life risk is highly intended in seismic rehabilitation of buildings, due to ambiguities in the number of residents, duration of their presence in the building, the time of earthquake occurrence and the monetary losses associated with the many severity levels of injuries and casualties, risk of life is ignored in this study. On the other hand results of this study can be used as a criterion among different criteria, i.e., risk of life, architectural, social and political concerns, importance of building and its residents and available workmanship, etc. in selecting the best retrofit method using the common multi-criteria decision making analysis [4]. In this study, a novel probabilistic based procedure for the economic feasibility assessment of different retrofit methods for a structure using CBA is proposed.

PROPOSED FRAMEWORK

To investigate the economic feasibility assessment of a seismic retrofit method and computing proposed index the following procedure should be used.

Hazard Curve Determination

Seismic hazard curve is plotted using return periods versus the magnitudes of the spectral accelerations at the fundamental structural period [Sa (T1)], considered here as the earthquake intensity measure (IM). Seismic hazard curve can be approximated as a linear function on a log-log scale for a relatively wide range of intensities as follows [5, 6]:

$$\lambda(Sa(T1)) = k_0 [Sa(T1)]^{-k} \tag{1}$$

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where, $\lambda(Sa(T1))$ is the mean annual exceedance frequency of Sa(T1), k and k_0 are the constant coefficients.

Ground Motions Selection

Regarding the site specifications, a set of ground motions should be selected which their response spectra match a site-specific target response spectrum. According to Shome and Cornell [7], for mid-rise buildings only 10–20 records can usually provide sufficient accuracy of the seismic demand estimation. In this regard, a relatively efficient IM, such as spectral acceleration at the fundamental period of the structure [Sa (T1), $\eta = 5\%$], should be selected.

Incremental Dynamic Analysis

Structural damage is simulated based on the Incremental Dynamic Analysis (IDA) [8]. IDA is a parametric nonlinear analysis through which the structural model is subjected to several ground motion time histories, each scaled into several intensity levels, until that record causes the structural collapse, identified by runaway inter-story drift. IDA can describe the evolution of structural response in whole investigated range of seismic intensities and synthetically explain the record-to-record variability effects. IDA curve is generally a plot of maximum inter-story drift ratios versus earthquake intensity measures (IM). In this step, IDAs are performed for the structure before and after the retrofit.

Definition of the Damage Limit States

In this study four damage states i.e., Insignificant (I), Moderate (M), Heavy (H) and Complete (C) are applied. A damage factor is assigned to each damage state. The damage factors are the cost of structural repairs for a given damage state, as a fraction of the replacement cost of building [10]. Damage states and damage factors in this paper are similar to that of Bai *et al*. [9]. Three performance levels from FEMA 356, [10] i.e., Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP), are used for the fragility analysis. In Table-1 relation between damage states, damage factors and performance levels are shown.

Table-1. Relation between damage states, damage factors and performance levels and of the structure [10].

Damage State	Damage Factor (%)	Performance Level
Insignificant (I)	0.5	IO
Moderate (M)	15.5	LS
Heavy (H)	55	CP
Complete (C)	90	

Fragility Curve Determination

The relationship between the probability of the structural damage and earthquake intensity measure (IM) is graphically illustrated by fragility curves [11, 12]. Fragility curves are generally modeled by a lognormal cumulative distribution function [13, 14] and express the probability of reaching or exceeding a particular damage state, for a given earthquake intensity. In this study, fragility curves are constructed in terms of the spectral acceleration at the average fundamental periods of the structures [15] and expressed in the form of two-parameter lognormal distribution functions. The conditional probability of being or exceeding, a particular damage state DSi, given the spectral acceleration [Sa (T1)] is defined by the following relationship:

$$P\,(DS \geq DSi\,|Sa\,(T1)) = \Phi\left(\frac{\ln X - \lambda}{\zeta}\right) \qquad (2)$$

where $\Phi(.)$ is Cumulative Distribution Function (CDF) of the standard normal distribution; X is the lognormal distributed spectral acceleration; and λ and ζ are the mean and standard deviation of Ln(X). In Figure-1 relation between fragility curves and damage limit states are shown.

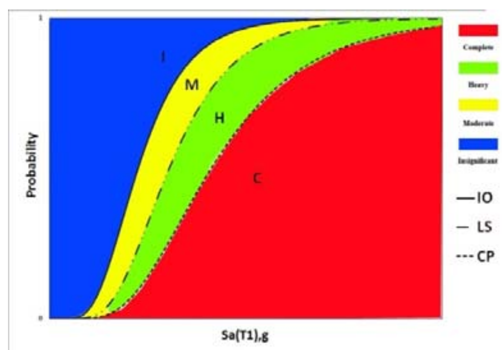

Figure-1. Illustrative relation between fragility curves and damage limit states.

Total Damage Factor

Damage states are assumed to be bonded by the fragility curves, as illustrated in Figure-1 thus; the probability of being in each damage state for a given Sa (T1) can be computed by the difference between the conditional probabilities of the bounding fragility curves at this Sa (T1), shown in Figure-2. The Total Damage Factor (TDF) which is the repair cost of a building as a fraction of its replacement cost (R) is computed by summing the multiplication of the probability of each damage state and its relevant damage factor as follows:

$$TDF\,(Sa(T1)) = \sum_{1}^{4} DF_i \times P(DS_i\,|Sa(T1)) \qquad (3)$$

where TDF(Sa(T1)) is the total damage factor at a given Sa(T1), DF_i is the damage factor of i-th damage state and $P(DS_i\,|Sa(T1))$ is the probability of i-th damage state at a given Sa(T1).

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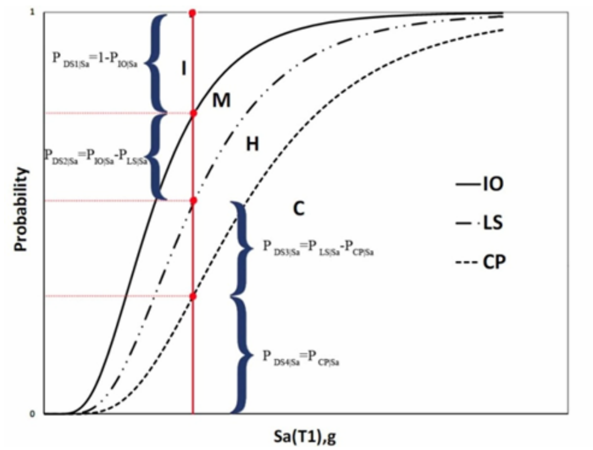

Figure-2. Illustrative computing of the probability of being in each damage state.

Annual Loss Expectancy (ALE)

Annual loss expectancy is computed by integrating the TDF of the structure with the hazard curve as follows:

$$ALE = R\int_{Sa(T1)=0}^{\infty} TDF\big(Sa(T1)\big)\nu\big(Sa(T1)\big) \quad (4)$$

where ALE is Annual Loss Expectancy, R is the replacement cost of the building and ν (Sa(T1)) is the average annual frequency of experiencing Sa(T1), which is defined as:

$$\nu(Sa) = -\frac{d\lambda(Sa)}{dSa} \quad (5)$$

Economic Feasibility Index (EFI)

The EFI is the ratio of the present value of the annual benefit from a seismic retrofit method to its cost obtained from Eq. (6). This benefit is computed by difference of the annualized loss expectancy of a structure before and after the retrofit, using the interest rate.

$$EFI = \frac{(ALE - ALE_R)(1 - e^{-rT})}{rC} \quad (6)$$

where ALE and ALE_R are the mean annual losses of the building before and after the earthquake respectively, r is the interest rate, T is the predicted remained lifetime of the structure or investment return period and C is the cost of the retrofit method. The higher the value of EFI, the greater economic benefits. If the EFI is less than unity, the retrofit method is economically non feasible. According to the Eq. (6) increasing investment return period (T) or decreasing interest rate (r) will increase EFI and leads to more economical and feasible retrofit practice.

CASE STUDY

In this section, three retrofit methods including, RC Jacketing, steel Jacketing and CFRP wrapping are economically assessed for a pre-code residential RC building in Tehran. These methods satisfy Basic Safety Objective (BSO) requirements of the Iranian seismic rehabilitation code [16].

Structural Model of the Original Building

A 5-story RC frame which is the typical residential building stock in the central region of Tehran used in this work. The structure has been designed according to the primitive version of the Iranian seismic design standard [17]. The regularity in plan and in elevation of the structural system allows the analysis of the planar model instead of the 3D model. The typical 2D frame and the sections of beams and columns are shown in Figure-3. The details of reinforcements of the building are illustrated in this Figure as well. The floors are one way concrete joist system. The concrete adopted for the frame has the mean cylinder compressive strength of 18MPa, and the reinforcement steels have the mean yield strength of 300MPa. The beam's loads are evaluated by considering the floor's tributary length equal to the frames spacing (5 m); the floor's loads are 6kN/m^2 dead and 2kN/m^2 live. The finite-element program SeismoStruct [18] is applied here in all analyses. Structural members are modelled using distributed-plasticity fibre elements, which use member cross-section properties and material constitutive behaviour to explicitly define element hysteretic behaviour (Figure-4).

Structural Model of the Retrofitted Buildings

Three retrofit methods are studied in this work as follows:

1- RC jacketing of the columns (denoted by R1): A jacket, consists of a 10-cm thick layer of reinforced concrete, cast around each column.

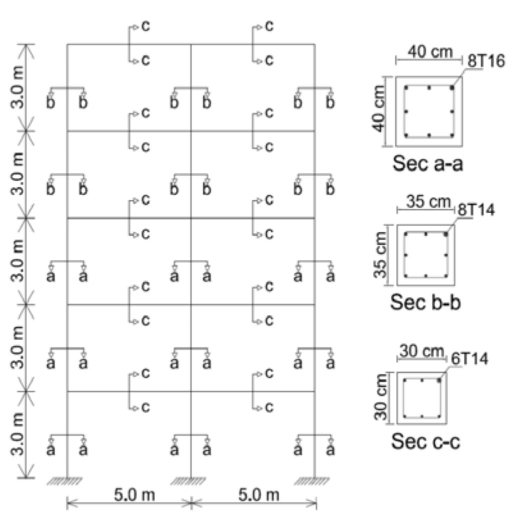

Figure-3. Typical 5-story RC frame and the sections of beams and columns.

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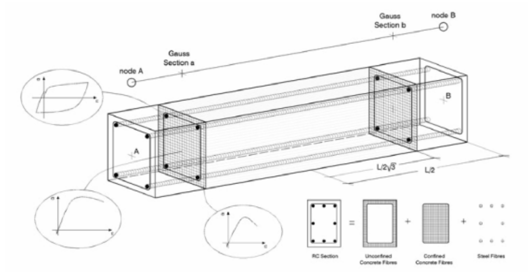

Figure-4. Discretization of typical RC cross section in Seismostruct.

Extensive longitudinal and transverse reinforcement is added in the new layer of concrete. Reinforcement steel with the mean value of yield strength of 400MPa and concrete with the mean value of 28-days cylinder compressive strength of 24MPa are adopted (Figure-5a).

2- Steel jacketing of columns and attaching steel plates to the bottom of beams (denoted by R2): The thickness of the steel plates is 2-cm and the mean value of yield strength of steel is 240 MPa (Figures 5b and 5c).
3- Wrapping of the columns with the CFRP sheets and bonding the CFRP laminates under the beams (denoted by R3): The mechanical properties of the CFRP sheets and laminates are listed in Table-2. The CFRP behavior is modeled using the Tri-linear FRP material in SeismoStruct.

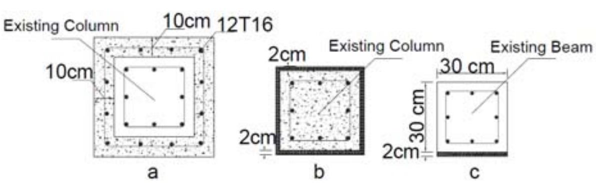

Figure-5. Three retrofit methods used in this study
a- Reinforced concrete column jacketing
b- Steel jacketing of RC columns
c- Bolted steel plate under beams.

Table-2. CFRP Mechanical Property.

	Module of Elasticity (GPa)	Tensile Strength (MPa)	Thickness (mm)
CFRP Sheet	240	3900	0.117
CFRP Laminate	165	2500	1.4

Ground Motion Time Histories

Twenty records, used in this study, are retrieved from FEMA 440 [19] for site class C, having response spectra relatively similar to that of soil type II in Iranian seismic code [20]. These ground motion records are listed in Table-3.

Table-3. Ground motions selected for soil type II of Iranian seismic code.

NO	Earthquake Name	Station Number	Magnitude	PGA(g)
1	Imperial Valley	5051	6.8	0.204
2	San Fernando	80055	6.5	0.11
3	San Fernando	269	6.5	0.136
4	Landers	12149	7.5	0.171
5	Loma Prieta	58378	7.1	0.156
6	Loma Prieta	57373	7.1	0.17
7	Loma Prieta	58065	7.1	0.504
8	Loma Prieta	47006	7.1	0.56
9	Loma Prieta	58135	7.1	0.441
10	Loma Prieta	58130	7.1	0.113
11	Loma Prieta	576064	7.1	0.124
12	Loma Prieta	47377	7.1	0.073
13	Loma Prieta	58163	7.1	0.068
14	Loma Prieta	1652	7.1	0.244
15	Morgan Hill	47006	6.1	0.097
16	Morgan Hill	57383	6.1	0.286
17	Palmspring	5069	6	0.131
18	Northridge	23595	6.8	0.072
19	Northridge	24278	6.8	0.514
20	Northridge	24271	6.8	0.204

Hazard Curve

The average fundamental periods of the frames in this study, is about 1 second. Therefore, the spectral acceleration at this period is used as the earthquake intensity measure [15]. The seismic hazard curve, shown in Figure-6, is plotted using the data available in the seismic hazard analysis research conducted by engineering faculty of Tehran university [21], for greater Tehran region. The parameters k_0 and k in Eq. (1), obtained by a regression in the logarithmic plane, are 0.00031 and 2.101 for the central region of Tehran, respectively.

$$\lambda\left(Sa(T1 = 1s)\right) = 0.00031\ \left(Sa(T1 = 1s)\right)^{-2.101} \qquad (7)$$

Damage Analysis and Fragility Curves

According to FEMA 356, IO, LS and CP performance levels for RC frames are corresponding to the maximum inter-story drift ratio of 1%, 2% and 4% respectively, considering these values, fragility curves for three performance levels of RC frames (an original and three retrofitted frames) are shown in Figures 7 to 10.

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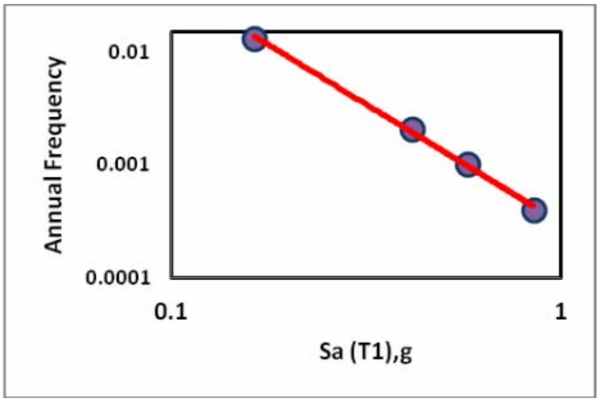

Figure-6. Seismic hazard curve for the central region of Tehran in the logarithmic scale.

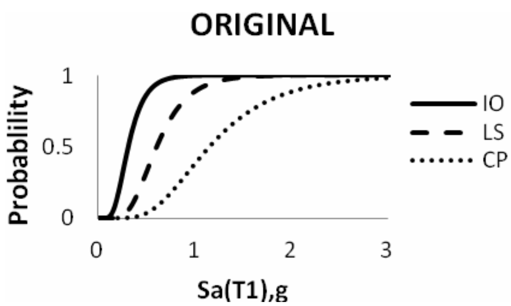

Figure-7. Fragility curves of the original structure.

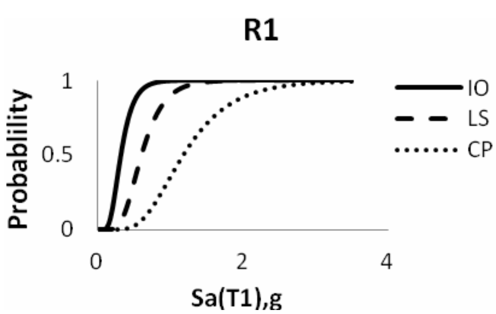

Figure-8. Fragility curves of the structure retrofitted by RC jacketing.

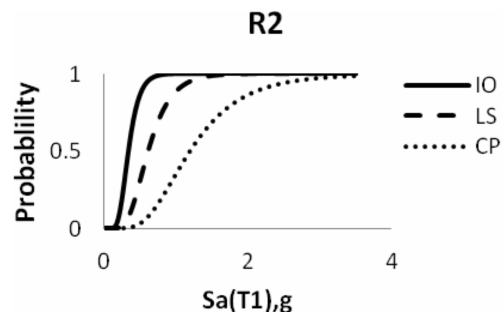

Figure-9. Fragility curves of the structure retrofitted by steel jacketing.

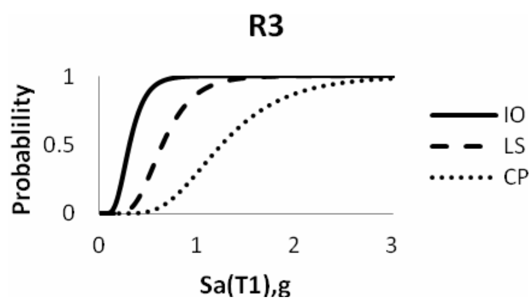

Figure-10. Fragility curve of the structure retrofitted by CFRP Wrapping.

ALE of the Buildings

In Table-4 cost of each retrofit method is shown. The mean annual loss of the retrofitted buildings from Eq. (4) and EFI's of the retrofit methods from Eq. (6) are also shown in this Table. The replacement cost of the building is estimated about 400000 US dollars, and the mean annual loss of the original building is computed about 12066 US dollars from Eq. (4). In computing EFI, the investment return periods (predicted remain lifetime of the structure) and the interest rate are assumed 50 years and 15% respectively. As seen in Table-4, RC jacketing is the most economical retrofit method because its EFI value is greater than that of the others and CFRP wrapping is not economically feasible since its cost is greater than its benefit. In Figure-11, EFI 3D-graph of RC jacketing retrofit method versus interest rates and return periods is shown; as seen in this Figure increasing investment return period (T) or decreasing interest rate (r) will increase EFI nevertheless, increasing return period at a constant interest rate, will decrease its rate of increase Consequently, considering return periods more than 50 years has a negligible effect on increasing EFI.

In Figure-12, 3D-graph of the proposed Index (EFI) for RC jacketing retrofit method versus seismic hazard parameters (k_0, k) are shown. As seen in this Figure EFI and accordingly economic feasibility of retrofit methods are highly dependent on the building site.

ARPN Journal of Engineering and Applied Sciences

Table-4. Retrofit cost (US dollar) and their duration (Year).

R3	R2	R1	
63000	42000	23000	Cost (US dollar)
2718	1769	2630	ALER (US dollar)
0.96	1.63	2.73	EFI

CONCLUSIONS

In this study, the Economic Feasibility Index (EFI) of a retrofit method is proposed to determine the most economical and feasible retrofit method for a structure among different code designed retrofit methods. EFI is computed by dividing present value of the benefit from a retrofit method to its cost in CBA. In this regard risk of life is ignored due to ambiguity in its determination. To illustrate the application of the proposed index three retrofit methods including, RC jacketing, steel Jacketing and CFRP wrapping are economically assessed

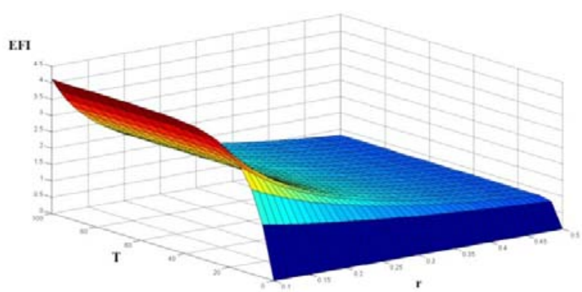

Figure-11. 3D plot of the EFI of the retrofitted frame (R1) vs. interest rates (r) and investment return periods (T).

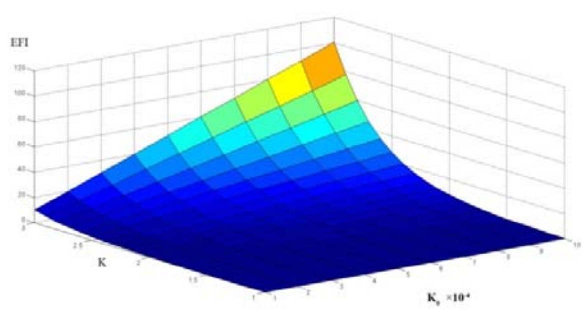

Figure-12. 3D plot of EFI of the retrofitted frame (R1) vs. the hazard curve parameters (k and k_0).

for a pre-code residential RC building in Tehran. Below are some of the obtained results of this study:

a) Among different code designed retrofit methods, the most economical one is a retrofit method with a greater EFI.
b) A retrofit method is economically non-feasible only if its relevant index is less than unity.
c) Increasing investment return periods (T) or decreasing interest rate (r) will both increase EFI.
d) Economic feasibility of a retrofit method is highly dependent to the structure site, on the other hand, a retrofit methods for similar structure in a different site doesn't have the same economic effectiveness.

In selecting the best retrofit methods for a structure in addition to the EFI different criteria such as architectural, social, historical and political concerns are also incorporated to consider all of these criteria multi criteria decision making analysis can be applied, and EFI may be selected as a criterion.

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