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A model for earthquake risk management based on the life-cycle performance of structures

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Over 50 years of design life, buildings are exposed to different magnitudes and frequencies of earthquakes that require consideration of life-cycle cost (LCC). The LCC entails quantifying the building performance under seismic hazard and investments throughout the life of the structures. Traditional LCC utilises probabilities of being in different damage states. However, for buildings with inherent irregularities (e.g. vertical irregularity and plan irregularity), these probabilities are not readily available. In this paper, a system-based approach, utilising fuzzy set theory, is used to quantify the possibility of being in different damage states. The analysis is limited to study the effect of seismic exposure on the building LCC. The proposed method is illustrated with two case studies, a six-storey reinforced concrete (RC) building located in Vancouver, Canada, and vulnerability of an urban centre with 1000 RC buildings. Furthermore, sensitivity analysis is carried out to highlight the impact of different building performance modifiers on the LCC.

Keywords: life cycle; fragility; cost; reliability; irregularities; structures

1. Introduction

Although structural design codes are calibrated for fixed time periods, for example, 50 years for commercial buildings (Bartlett \textit{et al}. 2003) and 75 years for infrastructure components, it is well known that useful life is much longer. Under this circumstance, decisions about design specifications and operation of public owned buildings should be made considering their life cycle and expected investments during that period. The life cycle is determined as the time window required to achieve the intended functional or economic objectives of the project, whereas the life-cycle cost (LCC) of a project is defined as the distribution of total cost that is incurred, or may be incurred, in all stages of the project life. The LCC analysis provides a framework to support decisions about resource allocation related to the design, construction and operation of infrastructure systems at minimum cost (Sánchez-Silva \textit{et al}. 2011). Within this context, key infrastructure and structures located in seismic regions should be studied using the LCC analysis.

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The LCC model consists of computing the expected cost of both investments in interventions and losses in operation efficiency, structural capacity or structural remaining life. Interventions include inspection, maintenance and reconstruction after failure. Every intervention has an associated cost, which can include physical interventions or loss of business opportunity. In earthquake engineering, structural performance is commonly modelled by a renewal process in which shocks (earthquakes) may or may not cause the system failure. Depending upon the complexity of the model, the uncertainties about shock sizes, shock occurrence times, the threshold value that defines damage, the condition after the structure has been repaired, etc. may be included. In a classic life-cycle approach, the expected cost of losses requires computing failure probability distributions that can be quantified using a fragility curve. Fragility theory is a generalised branch of structural reliability which assesses the vulnerability of a structure conditioned upon some other input parameter. A fragility curve can be generated through empirical (Shinozuka et al. 2000, Rossetto and Elnashai 2003), analytical (Rossetto and Elnashai 2005, Ellingwood et al. 2007) and heuristic (ATC 1985)-based methods.

The contribution of vertical or plan irregularities, for example, has been shown to be critical for seismic performance of buildings (Sánchez-Silva and García 2001, Tesfamariam and Saatcioglu 2008); however, for the most part, their contribution is not readily included in existing fragility curves. Consequently, the existing fragility curves will underestimate the level of damage to be sustained and, consequently, the LCC. The main reason is that the impact of these factors (e.g. topology, ground motion characteristics and construction specifications) is very difficult to capture and include in traditional models, because they differ in nature significantly. Furthermore, some of these factors are quantified linguistically (e.g. construction quality). In large cities and building inventories, developing a complex mathematical formulation of each building in the LCC assessment is not feasible. Thus, the building vulnerability model should be versatile for incorporating the different irregularities. It has been suggested that the complexity of building vulnerability assessment can be better handled through a system-based approach. The system-based approach can be used as an initial screening tool to aid decision-makers in resource allocation. Once the critical buildings are identified, a rigorous analytically based method can be used to generate the appropriate fragility curves (e.g. Ellingwood et al. 2007).

The major considerations in the LCC analysis are the proper treatment of uncertainties in external demand and structural capacity and cost incurred due to unsatisfactory performance (Wen 2001, Wen et al. 2003). Several formulations of the life-cycle performance of buildings and infrastructure systems are reported in the literature (e.g. Rackwitz 2000, Wen 2001, Frangopol et al. 2004, Sánchez-Silva et al. 2011). They all describe a stochastic representation of the structural performance linked with the costs associated to any intervention (maintenance or reconstruction). However, nature of the decision variables and uncertainties in such open problems requires incorporation of various other uncertainties. Blockley (1995) classified the sources of uncertainty into the lack of a pattern (randomness), incompleteness (what is unknown) and fuzziness (difficulty in defining boundaries between categories). The latter is particularly relevant for damage assessment mainly because there is an inherent uncertainty in the quantification of structural damage and parameters that contribute to building vulnerability.

This paper presents a model that incorporates, in the LCC of a structure, concepts of fuzzy logic to evaluate information coming from different sources and building irregularities. The information is arranged hierarchically to better represent the processes leading to building damageability. Based on these considerations, the objectives of the paper are as follows:

(1) to propose a life-cycle model of structures based on a systems approach and
(2) to extend the existing approaches to LCC analysis to include a detailed methodology of damage assessment and quantification.
This paper is organised as follows: Section 2 describes the LCC analysis. Section 3 focuses on the structural performance model, and Section 4 discusses the fuzzy model. Section 5 describes the fuzzy LCC evaluation procedure and Section 6 presents an illustrative example.

2. The LCC analysis

The structural LCC model can be described as

$$Z(X) = B(X) - C(X) - D(X),$$

where \( B(X) \) is the benefit, \( C(X) \) is the construction cost and \( D(X) \) is the cost of losses. The vector parameter \( X \) describes resistance (capacity) of the building. It might also include building performance modifiers, such as vertical irregularities, year of construction and construction quality. According to classic decision theory, the LCC should be evaluated in terms of the expected cost. In most cases, estimating the benefits is a difficult task, and therefore, the analysis becomes a cost-minimisation problem. The model presented in this paper is based on Wen’s (2001) LCC model, but any other model can be used as the basis for the LCC analysis. The expected total cost which the owner will incur during the project life \( t \) can then be expressed as a function of time (Wen 2001):

$$E[C(t, X)] = C_o + E\left[\sum_{i=1}^{N(t)} \sum_{j=1}^{k} C_j e^{-\lambda t_i} P_{ij}(X, t_i) + \int_{0}^{t} C_m(X)e^{-\lambda t} d\tau\right], \quad (1)$$

where \( E[\cdot] \) is the expected value; \( C_o \) is the initial cost for new construction or retrofitting; \( X \) is a vector depicting building performance modifiers; \( i \) is the number of severe loading occurrences (e.g. live, wind and seismic loads); \( t_i \) is the loading occurrence time, a random variable; \( N(t) \) is the total number of severe loading occurrences in \( t \); \( C_j \) is the cost in present dollar value of \( j \)-th limit state being reached at time of the loading occurrence, which include costs of damage, repair, loss of service, and deaths and injuries; \( e^{-\lambda t} \) is the discounted factor over time; \( \lambda \) is the constant discount rate per year; \( P_{ij} \) is the probability of \( j \)-th limit states being exceeded given \( i \)-th occurrence of a single hazard or joint occurrence of different hazards; \( k \) is the total number of limit states under consideration and \( C_m \) is the operation and maintenance cost per year.

With the assumption of the Poisson frequency of hazard occurrence \( \nu \) and for a single hazard, Equation (1) can be simplified to (Wen 2001)

$$E[C(t, X)] = C_o + \left[ C_1 P_1(X) + C_2 P_2(X) + \cdots + C_k P_k(X) \right] \frac{\nu}{\lambda} (1 - e^{-\lambda t}) + \frac{C_m}{\lambda} (1 - e^{-\lambda t}). \quad (2)$$

Computing the probability \( P_j \) of \( j \)-th limit states being exceeded is a daunting task, which becomes more difficult if a set of building performance variables need to be included in the assessment. Moreover, damage estimation models cannot be easily incorporated due to the complexity of damage evaluation process. These considerations support the need for Equation (1) using a systems approach that uses a hierarchical representation of the structural performance leading to a robust damage assessment and Equation (2) including assessment aspects that are usually not taken into account in the structural LCC evaluations.

3. Structural performance model

Quantifying the performance of a building, when exposed to seismic events, is of importance in the LCC analysis. The characteristics of a building define the possibility of incurring structural damage, which will, in turn, lead to an intervention, and consequently to some investment, during
its life. Estimations of the performance of the structure are commonly referred to as vulnerability assessments or damageability analysis. Many techniques are available in the literature and have been developed for building vulnerability assessment and loss estimation: empirical, heuristic and analytical methods (FEMA-249 1994). In this paper, the focus is on a systems approach, which can be used for a broader view of the structural performance problem.

3.1. Systems approach

A systems approach to any problem is built on the idea that a system cannot be modelled as a collection of separate elements, rather as a dynamic structured functional unit (i.e. whole). A system is defined as a set of interacting components (subsystems) called holons, which are organised hierarchically. A holon is a process which is both a whole and a part at the same time (Blockley and Godfrey 2000). Holons are obtained by desegregation of the subsystem in the upper level of the hierarchy. A hierarchical structure of a system is a dynamic form of organising information. It is not the same as a fault tree nor should it be interpreted as a rigid structure (Blockley and Godfrey 2000). A hierarchical representation of a system requires a logical and structured way of identifying subsystems and their relationships at every level. A hierarchy is used to describe different levels of description of the system. In the upper level, holons are more general, have greater scope and are less precisely defined. In the lower level, they have less scope and are more precisely defined. A systems approach helps to describe complex systems simply by providing a better representation of the problem. It provides the means to identify processes, properties and characteristics of a system at different scales (levels of precision). This is useful for supporting decisions at different levels and to make a more efficient assignment of resources.

3.2. Hierarchical representation of a structure

A complex problem incorporating different building irregularities can be handled through a hierarchical structure. The hierarchical structure follows a logical order where the causal relationship for each supporting argument is further subdivided into specific contributors. Miyasato et al. (1986) have proposed a hierarchical building vulnerability model and performed aggregation through prospect theory. Salvaneschi et al. (1997) have used a causal framework and Petri nets to model building vulnerability. Sánchez-Silva and García (2001) have incorporated the different building performance modifiers through a hierarchical model and quantified uncertainty through a fuzzy logic and neural network. Tesfamariam and Saatcioglu (2008, 2010) have proposed a heuristic-based hierarchical structure and performed aggregation through fuzzy logic.

In this paper, the heuristic model proposed by Tesfamariam and Saatcioglu (2008) is further modified to model the building damageability. A four-level hierarchical structure is proposed to model the building damageability (Figure 1). Level 1 of the hierarchy is the overall goal of the analysis, that is, building damageability. The building damageability is computed by integrating the parameters at level 2, site seismic hazard and building vulnerability. Levels 3 and 4 of the hierarchy are the five building performance modifiers. In this paper, the building performance modifiers considered are in congruence with FEMA 154 (ATC 2002): (i) building type, (ii) vertical irregularity, (iii) plan irregularity, (iv) year of construction and (v) construction quality. Level 3 of the hierarchy is topology, structural system and construction features. The topology is quantified through aggregation of vertical and plan irregularities (level 4). Furthermore, at level 4, the construction features are modelled through construction quality and year of construction. The year of construction is used to infer the type of building code considered and the corresponding seismic design consideration.
4. Fuzzy rule-based modelling

The building performance modifiers (Figure 1) are obtained through a walk down survey. In any walk down survey, however, the evaluation is performed by an expert and the information is provided in linguistic terms (strongly compliant, compliant, non-compliant, strongly non-compliant, etc.). As a result, the assessment is prone to subjective/qualitative judgements (Hadipriono and Ross 1991). Consequently, the evaluation process is dominated by vagueness uncertainty that can be handled through the fuzzy set theory (Zadeh 1965).

The basic theory of fuzzy sets was first introduced by Zadeh (1965) to deal with the difficulties in quantifying uncertainty where human intervention was significant. A fuzzy set describes the relationship between an uncertain quantity $x$ and a membership function $\mu_x$, which ranges between 0 and 1. A fuzzy set is an extension of the traditional set theory (in which $x$ is either a member of set $A$ or not) in that an $x$ can be a member of set $A$ with a certain degree of membership $\mu_x$. Fuzzy logic has been used extensively to handle the difficulties in defining limits. Fuzzy logic maps qualitative judgement into numerical reasoning. The strength of fuzzy logic is that it can integrate descriptive (linguistic) judgement and numerical data and use approximate reasoning algorithms to propagate the uncertainties (Zadeh 1973). The proposed fuzzy inference system (FIS) entails the following: (i) linguistic representation of hierarchical concepts; (ii) structural performance description and (iii) inference mechanisms.

4.1. Membership functions – fuzzification (linguistic representation of hierarchical concepts)

The basic input parameters must be mapped to the same measure scale; in this case, all linguistic representations will be mapped to the interval $[0, 1]$ (universe of discourse). The mapping process consists of capturing the expert’s opinion by using linguistic variables, which are later assigned to a set within $[0, 1]$. Linguistic variables (quantifiers) are, for instance, low (L), medium (M) and high (H). The process of assigning these linguistic values can be viewed as a form of data compression, which is known as granulation (Zadeh 1994). The fuzzification process converts the input values into a homogeneous scale by assigning corresponding memberships $\mu_x$ with respect to their specified granularities (e.g. $\mu_L$, $\mu_M$ and $\mu_H$). Membership function essentially embodies knowledge base in the fuzzy system and is a crucial part of the fuzzy rule-based modelling. Three-tuple membership values are used at levels 3 and 4 of the hierarchy (Figure 1), whereas at levels 1 and 2, five-tuple membership values are used to coincide with five damage levels. Different methods of assigning membership values or functions to a fuzzy variable are available (Ross 2004), and in this paper, the heuristic-based method is utilised (Figure 2).
Figure 2. Transformation and granulation of the year of construction.

Table 1. Transformation and fuzzification of building performance modifiers.

<table>
<thead>
<tr>
<th>Building performance modifiers</th>
<th>Linguistic parameter</th>
<th>C1 a</th>
<th>C2 b</th>
<th>C3 c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical irregularity (VI)</td>
<td>Yes</td>
<td>(0, 0.25, 0.75)</td>
<td>(0, 0.63, 0.38)</td>
<td>(0, 0.50, 0.50)</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>(0.75, 0.25, 0)</td>
<td>(0.75, 0.25, 0)</td>
<td>(0.75, 0.25, 0)</td>
</tr>
<tr>
<td>Plan irregularity (PI)</td>
<td>Yes</td>
<td>(0, 0.67, 0.33)</td>
<td>(0.20, 0.80, 0)</td>
<td>(0, 1.0)</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>(0.80, 0.20, 0)</td>
<td>(0.80, 0.20, 0)</td>
<td>(0.80, 0.20, 0)</td>
</tr>
<tr>
<td>Construction quality (CQ)</td>
<td>Poor</td>
<td>(0, 0, 1)</td>
<td>(0, 0, 1)</td>
<td>(0, 0, 1)</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>(0, 0.50, 0.50)</td>
<td>(0, 0.50, 0.50)</td>
<td>(0.50, 0.50)</td>
</tr>
<tr>
<td></td>
<td>Good</td>
<td>(0.75, 0.25, 0)</td>
<td>(0.75, 0.25, 0)</td>
<td>(0.75, 0.25, 0)</td>
</tr>
<tr>
<td>Building type (BT)</td>
<td>–</td>
<td>(0.08, 0.92, 0)</td>
<td>(0.67, 0.33, 0)</td>
<td>(0.42, 0.58, 0)</td>
</tr>
</tbody>
</table>

* aC1 = Moment resisting frame building.
* bC2 = Shear wall building.
* cC3 = Masonry wall building.

The proposed model can be applied to any type of building construction. Tesfamariam and Saatcioglu (2008) studied the performance of three RC building types: moment-resisting frame (C1), moment-resisting frames with infill masonry wall (C3) and shear wall (C2) buildings. For each building type, the proposed fuzzy representation of the performance modifiers located at the bottom of the hierarchy (Figure 1) is summarised in Table 1. For example, for building types C1 and C2, fuzzification of vertical irregularity = {Yes} is (0, 0.25, 0.75) and (0, 0.63, 0.38), respectively. The expression (0, 0.25, 0.75) should be interpreted such that \( \mu_L = 0 \), \( \mu_M = 0.25 \) and \( \mu_H = 0.75 \).

The process of transformation and fuzzification for the year of construction (YC) and site seismic hazard are discussed in Tesfamariam and Saatcioglu (2008). In general, YC is categorised into three distinct groups with corresponding transformation functions: low code (YC ≤ 1941), moderate code (1941 ≤ YC < 1975) and high code (YC ≥ 1975). The corresponding transformation functions and the membership values defined as low [0, 0, 0.40], medium [0, 0.40, 1] and high [0.40,
1, 1] are shown in Figure 2. The magnitude of seismic hazard for a building is specified through spectral acceleration $S_a$ and fuzzified into five-tuple membership values ($\mu_{VLL}^{SSH}$, $\mu_{L}^{SSH}$, $\mu_{M}^{SSH}$, $\mu_{H}^{SSH}$ and $\mu_{VH}^{SSH}$) using the membership values defined as very low [0, 0.025, 0.068], low [0.025, 0.068, 0.186], medium [0.068, 0.186, 0.508], high [0.186, 0.508, 1.387] and very high [0.508, 1.387, 10] and these are shown in Figure 3.

### 4.2. Fuzzy rule base (structural performance description) and inferencing

For linguistic consequent parameters, Mamdani-type inferencing can be used (Mamdani 1977). Mamdani’s inference mechanism consists of three connectives: the aggregation of antecedents in each rule (AND connectives), implication (i.e. IF–THEN connectives) and aggregation of the rules (ALSO connectives). The IF–THEN rules can be established as follows:

$$R_i : \text{IF } x_1 \text{ is } A_{i1} \text{ AND } x_2 \text{ is } A_{i2} \text{ THEN } y \text{ is } B_i, \quad i = 1, \ldots, n. \quad (3)$$

Thus, for each level of the hierarchy, a rule base has to be established. Given the rule base and corresponding fuzzified values, fuzzy inferencing is performed using Equation (3). Details of the fuzzy rules and aggregation process are provided in Tesfamariam and Saatcioglu (2008). The fuzzy rule-based for the decrease in resistance is provided in Table 2.

At each level of the hierarchy, the fuzzy output is converted into a crisp number through a process of defuzzification. Several techniques are available for defuzzification, for example, centre of area, centre of maxima and mean of maxima (Klir and Yuan 1995). In this paper, the weighted average method is used (Ross 2004):

$$z^* = \frac{\sum_{i=1}^{N} \mu_i(\bar{x}) \cdot \bar{x}}{\sum_{i=1}^{N} \mu_i(\bar{x})}, \quad (4)$$

where $z^*$ is the defuzzified value, $\bar{x}$ is the universe of discourse for the specified input parameter, for example, VI [0, 1], and $\mu_i(\bar{x})$ are the three-tuple fuzzy numbers.
Table 2. Fuzzy rule base for decrease in resistance (Tesfamariam and Saatcioglu, 2008).

<table>
<thead>
<tr>
<th>Rule i</th>
<th>Construction quality</th>
<th>Year of construction</th>
<th>Decrease in resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>L</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>2</td>
<td>L</td>
<td>M</td>
<td>L</td>
</tr>
<tr>
<td>3</td>
<td>L</td>
<td>H</td>
<td>M</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>7</td>
<td>H</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>8</td>
<td>H</td>
<td>M</td>
<td>H</td>
</tr>
<tr>
<td>9</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
</tbody>
</table>

5. Evaluation of the fuzzy LCC

Once the five building performance modifiers (Figure 1) are obtained through a walk down survey and are fuzzified, inferencing is done through the FRB modelling. The building vulnerability coupled with the site seismic hazard is used to quantify the building damageability. The final building damageability is furnished as five-tuple membership values \( \left( \mu_{BD_{N-S}}, \mu_{BD_{L}}, \mu_{BD_{M}}, \mu_{BD_{H}}, \mu_{BD_{M-D}} \right) \). Each membership value, respectively, is associated with five discrete damage states, none–slight (N–S), light (L), moderate (M), heavy (H) and major–destroyed (collapse) (M–D). The building damageability membership functions \( \mu_j \) can be viewed as the possibility of the structure being in \( j \)-th-limit state for the given seismic hazard magnitude and building vulnerability. Furthermore, the building vulnerability is assumed to be time invariant.

The fuzzy membership \( \mu_j \) values can be used to replace the \( P_i \) values given in Equation (2) leading to the following:

\[
E[C(t, X)] = C_o + (C_1 \mu_{BD_{N-S}} + C_2 \mu_{BD_{L}} + \cdots + C_k \mu_{BD_{M-D}}) \frac{\nu}{\lambda} (1 - e^{-\lambda t}) + \frac{C_m}{\lambda} (1 - e^{-\lambda t}), \tag{5}
\]

where ‘\( \lambda \)’ is the discount rate and ‘\( \nu \)’ is the earthquake occurrence rate. \( C_o \) can be used to denote the initial cost for new or retrofitted buildings. The latter is of paramount importance for buildings with inherent irregularities. Similarly, \( C_m \) is the operation and maintenance cost in a year. Each damage state \( (\mu_{BD_{N-S}}, \mu_{BD_{L}}, \mu_{BD_{M}}, \mu_{BD_{H}}, \mu_{BD_{M-D}}) \) has an associated cost \( C_j \) \( (j = 1, \ldots, 5) \). Thus a Monte Carlo simulation (MCS) can be undertaken to capture the variability in the site seismic hazard, and the corresponding expected value \( E[C(t, X)] \) is computed and plotted with the probability of exceedance. This process is discussed further in Section 6.

6. Illustrative examples

In order to illustrate the applicability of the model, two case studies are used. The first case assesses the damage of a single building using the HAZUS (FEMA 2003) and the proposed method. The second case discusses the extension of the methodology to a set of buildings located in a town that is assumed to have 1000 buildings.


A six-storey RC moment-resisting frame building subject to the seismic hazard of Vancouver, Canada, is used to illustrate the proposed method. This building is classified as building
Table 3. Scenarios for the LCC illustrative example.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>VI</th>
<th>PI</th>
<th>CQ</th>
<th>YC</th>
<th>$p(D &gt; 20)$a</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>No</td>
<td>Good</td>
<td>2004</td>
<td>0.16</td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>Yes</td>
<td>Good</td>
<td>2004</td>
<td>0.29</td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
<td>No</td>
<td>Good</td>
<td>2004</td>
<td>0.28</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>Yes</td>
<td>Good</td>
<td>2004</td>
<td>0.30</td>
</tr>
<tr>
<td>5</td>
<td>No</td>
<td>No</td>
<td>Poor</td>
<td>2004</td>
<td>0.63</td>
</tr>
<tr>
<td>6</td>
<td>No</td>
<td>Yes</td>
<td>Poor</td>
<td>2004</td>
<td>0.65</td>
</tr>
<tr>
<td>7</td>
<td>Yes</td>
<td>No</td>
<td>Poor</td>
<td>2004</td>
<td>0.63</td>
</tr>
<tr>
<td>8</td>
<td>Yes</td>
<td>Yes</td>
<td>Poor</td>
<td>2004</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Notes: VI, Vertical irregularity; PI, plan irregularity; CQ, construction quality; and YC, Year of construction.

*Probability that the LCC exceeds 20 million.

The height of the six-storey building considered in this study is 21.9 m, and the corresponding fundamental period can be estimated to be $T_1 = 0.76$ s. The building was constructed in 2004.

The first objective of this analysis is to highlight the impact of different performance modifiers on the building LCC. The performance modifiers and the linguistic parameters are (Table 3) vertical irregularity (VI) {yes, no}, plan irregularity (PI) {yes, no} and construction quality (CQ) {poor, good}. Based on the possible combination of these parameters, eight possible walk down evaluations (scenarios) are computed (Table 3, columns 1–5).

The parameters considered in the calculation of the fuzzy LCC given in Equation (5) are as follows:

- yearly rate of earthquake occurrence $\nu = 3$/year,
- discount rate $\lambda = 2\%$ and
- simulation time window $t = 50$ years.

6.1.1. Earthquake hazard

The building damageability (Figure 1) requires quantifying seismicity at a given site. For the RC building situated in Vancouver, in agreement with the current Canadian building code (Adams and Halchuk 2003; Atkinson 2004), the spectral acceleration is calculated as a function of earthquake magnitude $M$ and epicentral distance $R$. The attenuation law relating the peak spectral acceleration (PSA) with the earthquake magnitude and the epicentral distance is (Adams and Halchuk 2003) as follows:

$$\ln S_A(T_n, \xi) = b_1 + b_2(M - 6) + b_3(M - 6)^2 + b_5 \log_{10} r + b_6 + \varepsilon \ln(10), \quad (6)$$

where $S_A(T_n, \xi)$ represents the PSA in centimetres per second squared of a linear elastic single degree of freedom system on firm soil sites with the natural vibration period $T_n$ and damping ratio $\xi = 5\%; b_i$ $(i = 1, \ldots, 6)$ are the model parameters that depend on $T_n$ and $\xi; M$ is the moment magnitude of the earthquake; $r = (r_{epi}^2 + h^2)^{0.5}$, $r_{epi}$ (km) is the epicentral distance; $h$ (km) represents a fictitious depth and $\varepsilon$ is the uncertain error term that is modelled as a normal variable with zero mean and standard deviation represented by $\sigma_\varepsilon$.

The parameters for Equation (6) are provided in Table 4, and the conditions considered for deriving these parameters are magnitude $M$, ranging from 5.0 to 7.7, and $r_{epi}$, which is less than or equal to 100 km (Hong and Goda 2006). In Adams and Halchuk (2003), $b_1$ is provided as [lower, best, upper] values with each value having corresponding probabilities of [0.30, 0.40,
Table 4. Model parameters for the attenuation relations provided in Equation 6 (adapted from Adams and Halchuk 2003).

<table>
<thead>
<tr>
<th>$T_n$ (s)</th>
<th>$b_1$</th>
<th>$b_2$</th>
<th>$b_3$</th>
<th>$b_4$</th>
<th>$b_5$</th>
<th>$b_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>3.451</td>
<td>0.327</td>
<td>-0.098</td>
<td>-0.00395</td>
<td>-0.934</td>
<td>0.046</td>
</tr>
<tr>
<td>0.15</td>
<td>3.514</td>
<td>0.305</td>
<td>-0.099</td>
<td>-0.00309</td>
<td>-0.937</td>
<td>0.140</td>
</tr>
<tr>
<td>0.2</td>
<td>3.464</td>
<td>0.309</td>
<td>-0.090</td>
<td>-0.00259</td>
<td>-0.924</td>
<td>0.190</td>
</tr>
<tr>
<td>0.3</td>
<td>3.295</td>
<td>0.334</td>
<td>-0.070</td>
<td>-0.00202</td>
<td>-0.893</td>
<td>0.239</td>
</tr>
<tr>
<td>0.4</td>
<td>3.126</td>
<td>0.361</td>
<td>-0.052</td>
<td>-0.00170</td>
<td>-0.867</td>
<td>0.264</td>
</tr>
<tr>
<td>0.5</td>
<td>2.980</td>
<td>0.384</td>
<td>-0.039</td>
<td>-0.00148</td>
<td>-0.846</td>
<td>0.279</td>
</tr>
<tr>
<td>1.0</td>
<td>2.522</td>
<td>0.450</td>
<td>-0.014</td>
<td>-0.00097</td>
<td>-0.798</td>
<td>0.314</td>
</tr>
<tr>
<td>2.0</td>
<td>2.234</td>
<td>0.471</td>
<td>-0.037</td>
<td>-0.00064</td>
<td>-0.812</td>
<td>0.360</td>
</tr>
</tbody>
</table>

For $T_1 = 0.76$ s, values of $b_i$ ($i = 1, \ldots, 6$) are interpolated from Table 3 and results of the probability of exceedance magnitudes (Equation 7) and PSA (Equation 6) for distance = 100 km are calculated and plotted in Figure 4(a) and (b), respectively.

6.1.2. Cost estimation

For the LCC calculation (Equation 5), the regular maintenance cost $C_m$ and initial cost $C_o$ are set to zero. This will not have a bearing on the overall LCC, since the objective of this example is to highlight the relative sensitivity of the building performance modifiers. The costs of the
The fragilities in HAZUS are modelled by log-normal distributions, defined by the median building capacity and a logarithmic standard deviation, $\beta$, in which the aleatoric and epistemic uncertainties are combined. The fragility curves are described by the condition probabilities of being in, or exceeding, a damage state $ds$ and expressed analytically as

$$P[ds / S_d] = \Phi \left[ \frac{1}{\beta_{ds}} \ln \left( \frac{S_d}{S_{d,ds}} \right) \right].$$

where $S_d$ is the spectral displacement; $\bar{S}_{d,ds}$ is the median value of spectral displacement at which the building reaches the threshold of damage state $ds$; $S_{d,ds}$ is the standard deviation of the natural logarithm of spectral displacement for damage state $ds$ and $\Phi$ is the standard normal cumulative distribution function. The damage states in HAZUS are classified as \{slight, moderate, extensive, complete\}. The parameters pertinent to Equation 8 are summarised in Table 6, which are obtained from the HAZUS manual (Table 5.9c) for building type = \{C1M\} and moderate-code seismic design level.

The spectral acceleration $S_a$ obtained from the seismic hazard is converted into $S_d = S_a/\omega^2 (\omega = 2\pi/T = 8.27 \text{ cps})$. The cost associated with each damage state (Table 4) is considered to be valid for this example also.

<table>
<thead>
<tr>
<th>Damage level</th>
<th>Cost ($C_i$)</th>
<th>$c_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>$C_1 = (c_1 \times C_R) + (0 \times \text{ICAF})$</td>
<td>$c_1 = 0$</td>
</tr>
<tr>
<td>Light</td>
<td>$C_2 = (c_2 \times C_R) + (0 \times \text{ICAF})$</td>
<td>$c_2 = 10%$</td>
</tr>
<tr>
<td>Moderate</td>
<td>$C_3 = (c_3 \times C_R) + (0 \times \text{ICAF})$</td>
<td>$c_3 = 20%$</td>
</tr>
<tr>
<td>Major</td>
<td>$C_4 = (c_4 \times C_R) + (0 \times \text{ICAF}) + \text{Demo}$</td>
<td>$c_4 = 50%$</td>
</tr>
<tr>
<td>Collapse</td>
<td>$C_5 = (c_5 \times C_R) + (N_L \times \text{ICAF}) + \text{Demo}$</td>
<td>$c_5 = 100%$</td>
</tr>
</tbody>
</table>

Notes: $N_L$, number of lives lost; $C_R$, replacement building cost; ICAF, implied cost of averting a fatality; $c_i (i = 1, \ldots, 5)$, percentage of damage cost; Demo, demolition and debris removal cost (assumed to be 15% of $C_R$).
6.1.4. Calculation of the expected LCC

The algorithm used to compute the expected LCC of the building is shown in Figure 5. For example, let us consider that the following building performance modifiers are obtained from a walk down survey: vertical irregularity (VI) = {No}, plan irregularity (PI) = {No}, construction quality (CQ) = {Good}, year of construction (YC) = {2004} and building type (BT) = {C1}. The corresponding fuzzified values are provided in Table 6. Following the hierarchy shown in Figure 1, and FIS outlined in the previous sections, the building vulnerability \( (\mu_{BV}^N, \mu_{BV}^V, \mu_{BV}^M, \mu_{BV}^H, \mu_{BV}^{M-D}) \) is computed to be \((0.96, 0.04, 0, 0, 0)\). Note that the building damageability is considered to be time invariant, and it is computed only once.

In order to compute the earthquake demand, appropriate earthquake model parameters \( b_i (i = 1, \ldots, 6) \), have to be extracted from Table 3 and be used in Equation 6. These parameters are computed for the fundamental period of the structure \( T_n = 0.76 \) by interpolating between \( T_n = 0.5 \)

Table 6. Structural fragility curve parameters – moderate-code seismic design level.

<table>
<thead>
<tr>
<th>Damage level</th>
<th>( \bar{S}_{d,ds} )</th>
<th>( \beta_{ds} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>1.5</td>
<td>0.66</td>
</tr>
<tr>
<td>Moderate</td>
<td>3</td>
<td>0.64</td>
</tr>
<tr>
<td>Major</td>
<td>9</td>
<td>0.67</td>
</tr>
<tr>
<td>Collapse</td>
<td>24</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Figure 5. Algorithm to compute the life cycle expected cost of a building.
and $T_n = 1.0$:

\[b_1 = 2.74184; b_2 = 0.41832; b_3 = -0.026; b_4 = -0.0012148; b_5 = -0.82104; b_6 = 0.2972.\]

Random earthquake magnitudes are computed from Equation 7 by the inverse transformation method, that is, $m = F^{-1}(u), u [0,1]$, consider $m = 5.31$. Then, using $m$ and $b_i$ values, the $S_A(T_n, \xi) = 0.34$ is computed from Equation 6. Furthermore, this value is fuzzified based on the sets defined in Figure 3 to get $(\mu_{SSN}^{SSH}, \mu_{SL}^{SSH}, \mu_{SM}^{SSH}, \mu_{SH}^{SSH}, \mu_{MD}^{SSH}) = (0, 0, 0.53, 0.47, 0)$.

After the building vulnerability and the earthquake hazard have been evaluated and mapped to the same scale via fuzzification, they are aggregated to get the building damageability $(\mu_{BD_N}^S, \mu_{BD_L}^S, \mu_{BD_M}^S, \mu_{BD_H}^S, \mu_{BD_M-D}^S) = (0.53, 0.47, 0, 0, 0)$. This fuzzy number describes the extent of damage expected as a result of the random earthquake magnitude generated. This value is then used to calculate the life-cycle expected cost $E[C(t, X)]$ (Equation 5) using the building damageability membership values and damage cost (Table 4).

MCS can be utilised to generate $N$ realisations describing potential damage cost scenarios. Then, in every simulation, an earthquake event is generated and the computed spectral acceleration is compared with the building vulnerability, which is fixed during all simulations, that is, it only depends on the building state. The result after $N$ simulations is the distribution of expected costs which the owner of the building will incur during the life cycle of the structure. In this study, a total of 1000 simulations (possible earthquake scenarios) were carried out and the statistics of the data were analysed. Expected costs were arranged in an ascending order and assigned the plotting positions to each iteration using a mean rank formula, $k/(N + 1)$; the results are depicted in Figure 6.

The fuzzy LCC (Equation 5) and probabilistic LCC (Equation 2) are assumed to follow the procedure outlined in Figure 5. In order to show versatility of the proposed model, the fuzzy LCC is computed for the information obtained from a walk down survey (Tables 6 and 7) and the results are shown in Figure 6. Furthermore, the probabilistic LCC, for building information and procedure obtained from HAZUS (summarised in Section 61.2.2), is computed and shown in the same figure. Indeed, the results obtained from the two models follow the same trend and provide a relative comparison for the proposed method.

![Figure 6. Life-cycle cost analysis for the six-storey RC building, results of Scenarios 1 and HAZUS.](image-url)
Table 7. Results from the walk down survey.

<table>
<thead>
<tr>
<th>Building performance modifiers</th>
<th>Linguistic parameter</th>
<th>Membership functions</th>
<th>Fuzzification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical irregularity (VI)</td>
<td>[No]</td>
<td>((\mu^VI_L, \mu^VI_M, \mu^VI_H))</td>
<td>(0.75, 0.25, 0)</td>
</tr>
<tr>
<td>Plan irregularity (PI)</td>
<td>[No]</td>
<td>((\mu^PI_L, \mu^PI_M, \mu^PI_H))</td>
<td>(0.80, 0.20, 0)</td>
</tr>
<tr>
<td>Construction quality (CQ)</td>
<td>[Good]</td>
<td>((\mu^CQ_L, \mu^CQ_M, \mu^CQ_H))</td>
<td>(0.71, 0.29, 0)</td>
</tr>
<tr>
<td>Year of construction (YC)</td>
<td>[2004]</td>
<td>((\mu^YC_L, \mu^YC_M, \mu^YC_H))</td>
<td>(0.75, 0.25, 0)</td>
</tr>
<tr>
<td>Building type (BT)</td>
<td>[C1]</td>
<td>((\mu^BT_L, \mu^BT_M, \mu^BT_H))</td>
<td>(0.08, 0.92, 0)</td>
</tr>
</tbody>
</table>

Figure 7. Life-cycle cost analysis for the six-storey RC building, results of Scenarios 1–8.

Results of the MCS for Scenarios 1–8 are plotted in Figure 7. For example, for Scenario 2, the probability that the damage will exceed 20 million is \(p(D > 20) = 0.29\) (Figure 7). Similarly, for the eight scenarios, \(p(D > 20)\) are calculated and summarised in Table 4. In general, from the results depicted in Figure 7 and \(p(D > 20)\) summary given in Table 4, it can be observed that, as expected, with the presence of irregularities, the probability of damage exceedance increases. Table 4 shows that for the RC building without vertical and plan irregularities (Scenario 1), \(p(D > 20) = 0.16\), and for a building with plan and vertical irregularities and poor quality construction (worst possible case – Scenario 8), \(p(D > 20) = 0.66\). For a building with good construction quality and \(YC = 2004\), the vertical irregularity shows slightly higher impact than the plan irregularity shown as Scenarios 3 and 2, respectively, whereas the presence of both VI and PI showed no marked difference from the presence of VI only, where for both cases, \(p(D > 20) \approx 0.29\). The maximum damages \(D_{\text{max}}\) observed, that is \(p(D > D_{\text{max}}) = 0\), for Scenarios 1–8, respectively, are $30, $60, $22,504, $28,406, $28,415, $40,623, $40,623 and $39,960 million. Results reported in Table 4 and Figure 7 highlight that poor construction quality dominates the value of the building damageability; consequently, incorporation of other building performance modifiers shows no marked difference. The higher maximum damage \(D_{\text{max}}\) is the result of loss of lives.

Sensitivity analysis of the simulation year, discount rate and rate of occurrence was performed, and the results are plotted in Figure 8. The baseline data used are the results of Scenario 2. Indeed,
as expected, as the discount rate increases from 2% to 3%, the LCC decreases. On the other hand, increasing the simulation year and rate of occurrence increases the LCC. The rate of occurrence, however, shows more sensitivity.

6.2. Vulnerability assessment of urban centres

The proposed fuzzy LCC model can also be used for direct prevention and mitigation policies in urban regions. Therefore, the model was used to estimate the impact of several intervention
measures on a fictitious city consisting of 1000 buildings divided into three distinct building height categories. The three categories comprise 334 low-rise ($N = 3$), 333 medium-rise ($N = 6$) and 333 high-rise ($N = 12$) buildings. Furthermore, fundamental periods of each building height ($3, 6, 9$), respectively, are calculated to be 0.44, 0.76 and 1.24, and the corresponding attenuation model parameters $b_i$ ($i = 1, \ldots, 6$) are interpolated from Table 3. The vertical irregularity, plan irregularity, year of construction and construction quality are considered as random variables, where the values vary in the interval of [0, 1]. The building occupancy is assumed to be office buildings, with occupancy of 4 persons/1000 ft$^2$ and fatality of 1 in 5. The replacement costs $C_R$ of each building are considered to be, respectively, $976,498$, $1,627,497$ and $2,712,494$.

Figure 10. Life-cycle cost analysis for a small town – retrofit 1.

Figure 11. Life-cycle analysis for a small town–retrofit 2.
Following the flowchart presented in Figure 5, MCS was performed and results are summarised in Figure 9. Figure 9 shows that, for example, the probability of damage exceedance of $20 trillion is $0.21$, $p(D >$20 trillion) = 0.21$. The probability of damage exceedance shown in Figure 9 can be used as a baseline measurement for retrofit prioritisation. Let us assume that the first decision undertaken is retrofit level 1, where vertical irregularity of every building is eliminated, VI = {No}, and the transformed value of the year of construction is improved to be 0.4. From Figure 9, it can be seen that the probability of damage exceedance of $20 trillion is $0.18$, $p(D >$20 trillion) = 0.18$. The second level of retrofit is used to improve the vertical and plan irregularities, that is, VI = {No} and PI = {No}, and the transformed value of year of construction is 0.1. Similarly, from Figure 9, it can be seen that the probability of damage exceedance of $20 trillion is $0.08$, $p(D >$20 trillion) = 0.08$ (Figures 10 and 11).

7. Conclusions

The LCC of a project is defined as the distribution of total cost that is incurred, or may be incurred, in all stages of the project life. The LCC requires quantification of damage probabilities under each possible earthquake scenario. In this paper, it is highlighted that the damage potential of buildings depends highly on aspects such as construction and topology, which are difficult to quantify. Thus, the damage estimations are prone to vagueness uncertainty that cannot be handled using traditional probabilistic methods. Based on this consideration, in this paper, a life-cycle model of structures based on a systems approach was proposed.

A heuristic-based hierarchical structure was considered to quantify building damageability subject to different performance modifiers. Furthermore, the proposed method was extended to fuzzy LCC analysis to include a detailed methodology of damage assessment and quantification. The fuzzy LCC model was proposed and highlighted with an example. The impact of different performance modifiers on the overall LCC was quantified and illustrated. Sensitivity analysis of the performance modifiers showed that the construction quality and plan irregularity have the most and least impacts on the overall LCC, respectively.

Since the decision to retrofit existing buildings is a complex and expensive undertaking, the proposed method is a tool that be used for retrofitting prioritisation of individual buildings or defining strategies for prevention and mitigation of a large number of buildings. The merits of the proposed approach are that (1) it provides a framework that allows to take into account seismic risk assessments and variables that differ in nature (construction quality, building age and topological characteristics); (2) it is easy to implement and use in practice (individual buildings and urban centres) and (3) it can be used to gather evidence about the proneness to failure of a building or a city, which can be later used for prevention and mitigation purposes.

Finally, this model introduces the concept of LCC analysis to a set of buildings, but it can also include many other aspects of an urban centre. Within this context, LCC is a valuable tool for long-term planning and contributes to decisions regarding urban sustainability. We are currently extending the proposed model for the LCC optimisation of spatially distributed buildings. Also, we are extending this model to incorporate different seismic sources and epistemic uncertainties of the seismic hazard.

References


