An Integrated BIM-Based Life Cycle-Oriented Framework for Seismic Design of High-Rise Steel Structures

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ABSTRACT

In general, the dominant strategy in the design of structures is to reduce the initial weight of the structure. Of course, the possible future costs such as damages caused by earthquakes are generally ignored. Considering the variety of urban buildings from the point of view of regularity and irregularity, it is important to examine their life cycle cost (LCC); this issue has not yet been fully explored in previous research. On the one hand, the lack of utilization of building information modeling (BIM) in previous structural design-based LCC research is evident. This research aims to highlight the impact of irregularity on the LCC of structures by providing an integrated framework based on the seismic design optimization of structures by using LCC and BIM capacities. For this, a shared environment is created in MATLAB software, information is exchanged between Revit, Etabs, and Excel software, and optimization is done using NSGA-II for establishing a trade-off between initial cost and LCC. BIM tools can greatly reduce the limitations of LCC analysis, such as information exchange time, and increase the accuracy and speed of calculations. By modeling six models in two regular and irregular types, the framework of the research and the difference in the behavior of the structures are examined. The results showed that the indirect costs of irregular structures are more than the regular ones. In addition, the findings show that reducing the LCC of irregular structures compared to regular ones requires a higher initial cost percentage. For example, for regular and irregular 13-story structures, a 17% increase in the initial cost leads to a 48% and 40% reduction in their LCC, respectively.

KEYWORDS

Irregular structures, building information modeling, life cycle cost, performance-based design, multi-objective optimization.

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Introduction

In the construction industry, most engineers often reduce the building weight to optimize the structure design [1]. However, this kind of optimization may not be efficient from a life-cycle view, especially in the face of natural disasters. Previous experiences demonstrated that human and financial losses resulting from natural disasters can be much more than the initial construction costs. Therefore, a different approach should be adopted to optimize the life cycle costs (LCC) of structures instead of solely reducing initial costs (IC) to increase human safety while preserving financial resources in the long term [2].

The complexities of LCC-based design, and its time consuming, hinder its application as a common design practice. One of the solutions that can reduce these complexities is the integration of LCC methods with Building Information Modeling (BIM) [3].

On the other hand, it can be argued that it is rare to find regular buildings in cities. Attention to irregular structures (IRS) is important because studies show that seismic vulnerability in IRS is generally higher than in regular structures (RS), Particularly in high-rise structures [4]. Nonetheless, very few studies have compared LCC-based designs of IRS and RS.

So the primary goal of this paper is to create a framework for LCC-based optimizing seismic design using BIM capacities. The second goal is to highlight the difference in seismic damage costs that may be incurred by the IRS compared to RS from a performance-based perspective. For this purpose, the optimization of 6 steel structure models with 7, 10, and 13 floors in two regular and setback irregular scenarios is addressed through the use of metaheuristic algorithms.

Methodology

The research method is illustrated in Figure 1. Once the building is modeled, the required data for LCC estimation is extracted from the database and the BIM model. These datasets are integrated through MATLAB acting as a shared space. Subsequently, an optimization method within this shared space is utilized to optimize the structure based on LCC. In a defined cycle, structural elements undergo modifications using NSGA-II while their performance levels are assessed by ETABS, and the required performance level is obtained. Considering that, the expected failure, the indirect costs (C_{ID}) associated with it, and the LCC are obtained. By creating the Pareto Front at the end of the optimization cycle, the optimized structure replaces the initial structure as the output of the BIM model.

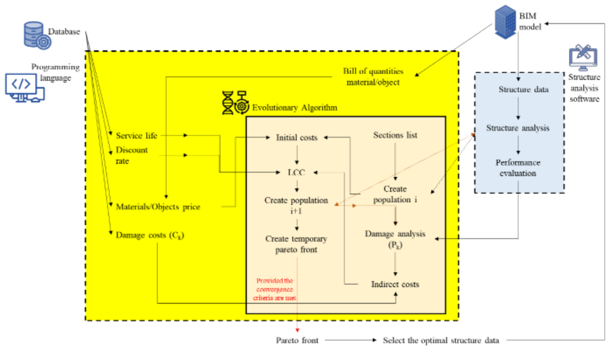

Figure 1. Research method

The LCC objective functions are IC and C_{ID}. C_{ID} includes fatality costs (C_f), injury costs (C_{inj}), economic losses (C_e), relocation costs (C_r), property losses (C_p), and repair costs (C_{re}). For calculating LCC based on probabilistic methods, Eq. 1 is adopted [5].

$$E\left[C(t.X)\right]=C_0+(C_1P_1+C_2P_2+...+C_kP_k)\frac{v}{\lambda}(1-e^{-\lambda t}) \quad (1)$$

Where t denotes the useful lifespan of the examined structure, which is set at 50 years for residential purposes. v represents the annual rate of significant earthquakes modeled through the Poisson process. P_k is equal to the kth damage state probability considering the earthquake occurrence (Eqs.2 and 3), and C_k represents the corresponding cost. To convert all future values of C_{ID} into time values, a 5% annual discount rate (λ) is applied.

$$P_k=P_k(\Delta>\Delta_k)-P_{k+1}(\Delta>\Delta_{k+1}) \quad (2)$$

$$P_k(\Delta>\Delta_k)=(\frac{-1}{t})\ln\left[1-\overline{P_k}(\Delta>\Delta_k)\right] \quad (3)$$

The items obtained in the calculation of the secondary cost of the life cycle are briefly stated according to Table 1.

Table 1. Factors of calculating the C_{ID} of the life cycle

Variable	Equation	Basic cost
C_{re}	IC cost*area*damage index	
C_p	Unit contents cost*area* damage index	51,000,000 Rial/m^2
C_r	Relocation cost*area* loss of time	72,000 Rial/day/m^2
C_e	Rental rate*area* loss of function	72,000 Rial/day/m^2
C_{inj}	Injury cost per person* expected injury rate	198,720,000 Rial (minor) 2,094,000,000 Rial (serious)
C_f	Death cost per person* expected death rate	122,400,000,000 Rial /person

Results and Discussion

After generating and analyzing 500 generations of structures, NSGA-II presents the best possible solutions through the Pareto front curve. To compare RS and IRS and the impact of LCC on them, all obtained Pareto front curves are put together in Figure 2.

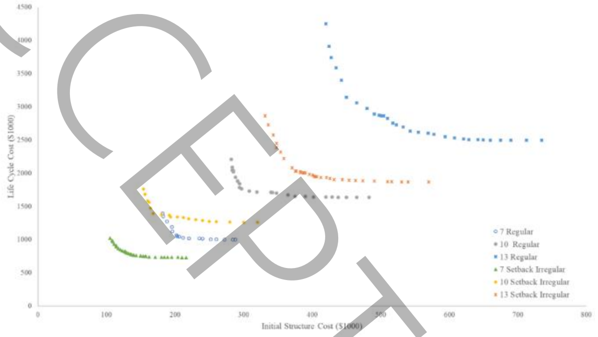

Figure 2. Comparison of Pareto front of RS and IRS

Figure 2 shows that as the IC increases, the LCC decreases. However, beyond a certain point, the increase in the IC has little impact on reducing LCC. For example, at the end of the 10-story RS diagram, with an IC increase of about 3%, the LCC is reduced by 0.5%.

Irregularity can significantly affect the seismic behavior of structures, leading to notable changes in the LCC of structures compared to regular ones. For instance, in the 7-story RS, a 16% increase in IC can reduce around 26% of LCCs. In comparison, a 35% increase in the IC of the 7-story IRS results in about a 37% reduction in LCC. For the 10-story, with a 22% and 27% increase in IC of RS and IRS, respectively, the LCC will decrease 23% for both. For the 13-story, a 17% increase in IC will lead to a 48% and 40% LCC decrease for RS and IRS, respectively.

Conclusions

The costs of a project result from a range of factors that will persist throughout its life cycle. particularly in seismic zones, where even minor alterations during the design phase can either lead to excessive costs or conversely. So the LCC(Life Cycle Cost)-BIM(Building Information Modeling) framework for seismic design optimization of steel structures based on performance was presented by establishing the damage levels of various probable seismic intensities.

Six models were developed within the Revit software, and the required data were generated in an Excel database. Subsequently, the NSGA-II optimization algorithm was implemented on each structure through MATLAB in a mutual environment between Revit, ETABS, and Excel. Ultimately, by comparing the initial cost (IC) and LCC for each structure, a Pareto front was presented as the algorithm output, and the optimal structure became updated as the output of the BIM model.

In summary, the results of numerical analysis can be expressed as follows:

- As the height of a structure increases, LCC becomes more sensitive to IC; In general, the reduction of LCC for irregular structures requires an additional IC compared to regular structures; this cost will increase by height.
- In general, the indirect costs of irregular structures are higher than regular ones, despite the lower surface area. This indicates their higher susceptibility to seismic loads. It may raise doubts whether optimization based on IC reduction is essentially the best design in terms of financial and safety aspects.
- The results showed that 7- and 10-story buildings had minimal differences, but the outcomes for 13-story buildings were markedly different. From an economic and urban perspective, this suggests that the number of floors has little impact on mid-rise buildings compared to high-rise ones. Thus, the ideal number of floors should be determined based on each city's economic and social considerations to achieve greater cost-effectiveness in construction.
- Compared to previous manual research which conducted optimization processes with a limited number of models, using the bi-objective genetic algorithm for optimizing LCC can lead to the capability of examining more LCC structure optimization models and facilitate simultaneous weight reduction.

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