Multi-objective optimization approach to define risk layer for seismic mitigation

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**ABSTRACT**
Earthquakes have caused more than 50,000 lives and $4,000 million economic losses over a period of 20 years in Iran. Having accurate risk assessment and effective future plans can significantly reduce these losses. In this paper, two key parameters, which are effective in both human and economic loss reduction, have been defined, one of which is the number of saved lives before and after taking mitigation measures and the other one is the household expense ratio related to the cost of earthquake mitigation measures. For this reason, Shiraz city, located in the southwest of Iran, has been selected for evaluation. Detailed building taxonomy is performed, and for seismic vulnerability evaluation, vulnerability curves exclusively derived for Iranian buildings are used. Multi-objective genetic algorithm optimization method is conducted to find a balance between the costs of seismic mitigation measures and number of casualties. This balance proposes the extent of mitigation actions which is representative of a specific layer of risk and is identified as a set of Pareto Front for all types of buildings. The optimal risk layer can play a vital role in shaping management policies for decision-makers in order to reduce the inherent risk of country.

**1. Introduction**
Earthquakes have made huge human and economic losses in most parts of Iran, especially in vulnerable and populated areas which have highlighted the high risk of this country. A better understanding of this risk and the use of an effective action to mitigate them can significantly reduce the losses. Mitigation is any action taking to minimize the extent of a disaster or potential disaster and can take place before, during or after a disaster (Benson & Twigg 2004). Having the mitigation measures accessible and affordable is the key concern of government’s policy, as well as households'. Another issue would be minimizing the casualties during and after the earthquakes. Risk management involves three major steps: risk identification, financing and reduction. Risk financing and identification have been studied earlier (Pakdel-Lahiji et al. 2014a, 2014b) by evaluation of possible earthquake scheme and assessing the affordability and financial vulnerability of households. The aforementioned study shows that earthquake insurance premiums are high for most of the buildings due to their structural vulnerability and in many cases unaffordable for households in Iran. Therefore, risk reduction efforts by taking mitigation actions seem crucial to reduce the risk which will lower the economic and human losses. The objective of this paper is to propose the optimal extent
of mitigation actions to decision-makers in order to achieve this goal. This issue is addressed by calculating an earthquake return period within a specific layer of risk.

Most of the optimization problems in the real world contain more than one objective function which are essential to be considered simultaneously. Multi-objective optimization techniques with a set of possible solutions play a vital role in several engineering fields (Reddy & Kumar 2007). Here, the genetic algorithm (GA) that can be used for discrete optimization problems is selected. The concept of GAs has been developed by Holland and his colleagues in 1960s and 1970s (Holland 1975). The distinction of GA is to search several regions of decision space to find a diverse set of solutions. Moreover, most of multi-objective GAs do not require to scale, prioritize or weight objectives and, therefore, the GA has been the most popular approach to multi-objective design and optimization problems (Jones et al. 2002). The evolutionary optimization algorithms are being used in several complex and nonlinear functions because these algorithms have several positive aspects such as few input information about the problem and easy implementation and initial details of the objective functions might be enough. Several researches have been conducted on the evaluation of optimization methods and benefit—cost estimation for mitigation measures.

In the context of optimization, Shah et al. (1992) introduced the concept of capital budgeting for implementation of seismic risk management program by analyzing benefit—cost of mitigation program via optimizing four objective functions which were formulated based on minimum loss, minimum cost, maximum return period and maximum profit. Dodo et al. (2004) have described the challenges and benefits of regional mitigation planning analysis and presented two linear programs and one stochastic program as alternative optimization model formulations. Dodo et al. (2007) studied the application of regional earthquake mitigation optimization by focusing on two efficient algorithms to solve the model; a Dantzig—Wolfe decomposition algorithm and a greedy heuristic algorithm. Motamed et al. (2012) have described the development of an automated model for Tehran which uses the output of existing earthquake estimation to optimize the budget allocation in order to mitigate losses of earthquakes in urban settlement. This paper performs multi-objective optimization to optimize both human and economic losses under mitigation actions for Iranian buildings by defining two key parameters representing household’s expenses and number of saved lives (NSL).

In the context of loss estimation and benefit—cost analysis, in 2004, Smyth et al. have established realistic cost estimates of the retrofitting schemes for buildings in Turkey. In the mentioned study, analysis implies that even with considering only direct losses, mitigation measures are very desirable for all Istanbul buildings, but within very short time horizons (Smyth et al. 2004). Rose et al. (2007) report on a study that applied benefit—cost analysis methodologies to a statistical sample of nearly 5,500 Federal Emergency Management Agency (FEMA) mitigation grants between 1993 and 2003 for earthquake, flood, and wind hazards. Their results indicate that overall benefit—cost ratio for FEMA mitigation grants is about 4:1. Hochrainer-Stigler et al. (2011) have examined benefits and costs of improving or retrofitting residential structures in highly exposed as well as low- and middle-income households in developing countries. They illustrated the bounds of the benefit—cost analysis, and demonstrated a systematic and probabilistic approach for evaluating alternative risk-reducing measures. Pomonis and Gaspari (2013) estimated the vulnerability of the post-retrofit buildings in order to assess the potential reduction in economic and human losses. While effect of mitigation measures on economic and human losses for Shiraz city has been studied separately in the previous research (see Sadeghi 2013; Sadeghi et al. 2015a), the essential need for combining these two important parameters to find the optimal layer of risk for mitigation practices seems essential. On the other hand, making a trade-off between these two parameters is one of the challenging issues for the government as it requires considering all aspects of society such as social, political and economic, at the same time. Multi-objective optimization can provide all optimized options in which the decision-makers can easily choose the best one by looking at the economic and human losses at the same time for their society’s interest. Therefore, in this paper, multi-objective optimization is applied on structural mitigation measures and human losses to define optimized extent for mitigation.
The paper is organized as follows. Section 2 introduces the specifications of Shiraz city and its building taxonomy. Section 3 presents the vulnerability functions used in this study and their concepts. In Section 4, the overview of multi-objective optimization methodology and how to select and calculate the objective functions are described. In Section 5, Pareto Fronts and graphs of optimal results for selected types of buildings are presented and results for all types of buildings are tabulated. Finally, Section 6 ends with a discussion and concludes with an outlook to the future.

2. Shiraz city building stock

Shiraz city, capital of Fars province, is the sixth most populous city in Iran, which is located in the southwest of Iran (29.6167°N – 52.5333°E). Shiraz has characteristics of a traditional-historic city, with a strong potential of tourism sightseeing. There are different building structures in this city for which the classification is essential. Referring to the date of construction of buildings, three classes of building codes have been defined: pre-code, moderate code and high code, which refer to the buildings constructed before 1990, between 1990 and 2000 and after 2000, respectively (see Figure 1).

In this study, buildings are classified based on the type of earthquake-resistant system, year of construction, height, and building material. Three different categories of building height, which are low-rise, mid-rise and high-rise for three and below stories, four to seven stories and eight and above stories, respectively, are defined for two building types of steel and concrete structures. For masonry buildings, only two classes, low-rise and mid-rise, are selected which are referred to the buildings with one and two stories and three and above stories building as shown in Figure 2. In terms of structural system, steel structures are broken down into moment-resistant frame (Steel-MRF) and braced frame (Steel-BF) and concrete structures have been broken down into moment-resistant frame (Concrete-MRF) and shear-wall (Concrete-SW) and no category has been defined for masonry structures (Masonry-ALL) (Sadeghi et al. 2015b).

Shiraz city has nine municipal districts and, in this paper, district one is selected because of the variety of the building distribution. Based on the municipal year book of Shiraz, the built residential area of district one is 4,235 hectares with the total number of families of 66,553 containing a total

![Figure 1](image1.png)

**Figure 1.** Basis for seismic design levels’ definition.

![Figure 2](image2.png)

**Figure 2.** Shiraz building taxonomy.
population of 226,952 people, including 110,644 men and 116,308 women (Shiraz Municipal Yearbook 2013). Figure 3 shows the general view of the building distribution in district one, and Figure 4 shows the building distribution by the construction code and building type.

Among 25,687 residential buildings in district one, 12,934 (50%) are pre-code masonry, 4,424 (17%) are high-code steel structures, 3,175 (12%) are moderate-code masonry, 1,662 (6%) are high-code concrete, 1,780 (7%) are moderate-code concrete and the others include 8% of total buildings. Figure 5 shows the distribution of the building heights in the district one of Shiraz.

Figure 3. General view of the district 1 of Shiraz [© Vogel G, May 2013].

Figure 4. Number of buildings in district one of Shiraz.
Among 31,589 building blocks existing in district one, 28,901 buildings have three and below stories, 2,539 buildings have four to seven stories, and 149 buildings have eight and above stories.

3. Vulnerability assessment and loss estimation

For many types of structures, damageability may be defined in terms of vulnerability parameters. The vulnerability parameters of Iranian buildings, which have been recently developed by Sadeghi et al. (2015b), are used in this paper to evaluate Shiraz buildings’ behaviour. In the aforementioned study, more than 300 fragility/vulnerability curves are collected from Iran and other countries and the logic-tree method is used to combine these curves by weighting in accordance with the building construction, seismic code and engineering judgement. Figure 6 shows an example of these vulnerability curves for masonry buildings.

Figure 5. Building’s height distribution of district one of Shiraz.

Figure 6. Vulnerability curves for masonry buildings (Source: own calculations).
According to the vulnerability curves shown in Figure 6, pre-code, mid-rise and high-code, low-rise masonry buildings are the most and least vulnerable buildings, respectively. The other parameter needed for loss estimation is seismic hazard curve of the city. For this reason, the seismic hazard curve developed by Sadeghi et al. (2014) is used. As the aforementioned curve is based on Peak Ground Acceleration (PGA) and vulnerability parameters are presented based on $S_a$, the Graizer and Kalkan method is used to obtain spectral acceleration ($S_a$) from the PGA. In this method, PGA is calculated for 5% damped pseudo-spectral acceleration of free-field horizontal component of ground motion (Graizer & Kalkan 2009). It is notable that $S_a$-based vulnerability curves are more reliable than PGA-based ones, as $S_a$ is a better parameter to represent the building’s behaviour.

Figure 7 depicts the selected Shiraz hazard curves for pre-code steel structures.

4. GA-based multi-objective optimization procedure

A GA-based multi-objective optimization considers more than one objective function to be optimized simultaneously. In other words, single objective optimization might have a unique solution, but the multi-objective optimization has a range of possible solutions. The optimal solutions in the decision space $X$ are represented as a Pareto set $X_i \subseteq X$, which also represents the objective space as Pareto Front $Y_i = f(X_i) \subseteq Y$. The set of Pareto Front can help most of the decision-makers to choose the best solution among all other optimal ones (Zitzler et al. 2004). Figure 8 shows the general procedure of multi-objective optimization.

Given the fact that objective functions should be selected in order to satisfy several criteria, household expense ratio (HER) and NSL are selected as two objective functions. HER is the annual expense of households with consideration of mandatory earthquake insurance and mitigation costs and NSL is the difference between human casualties in earthquake before and after taking mitigation measures. HER is selected in order to consider the financial aspect of risk mitigation measures and is related to the household’s affordability, awareness and willingness to protect their houses against earthquake. This parameter is selected as one of the most important issues affecting people’s decisions on allocating budget for their protection against earthquake impacts. Moreover, according to Sadeghi et al. (2015a), mitigation measures can play a vital role in reducing household losses.

Cost-effectiveness and applicability are two reasons for selecting these parameters as they can be seen as a measure for the extent to which a policy can achieve an objective of reducing human and
economic loss, simultaneously. Like the cost-effectiveness counterpart, also adaptation policy has to be correctly addressed, but the real challenge lies in the determination of effectiveness part, for two reasons. The first one in assessing cost-effectiveness is that, uncertainty prevails in the extent of different methods of mitigation and their cost, which can vary based on inflation. This means that policy-makers should often update their indexes. The second reason is that the human loss indicator may affect the final decisions while this can be seen as one of the important issues for the governments and decision-makers.

The method used in this study for considering mitigation measures is based on the fact that strengthening buildings can improve the structural performance of lower quality to higher quality for selected typologies. NSL is selected to include the effects of risk mitigation measures on human losses in this risk management study. Although the aforementioned parameters have no direct correlation in definition, they are correlated in case of earthquake impacts and can play a vital role in the macroeconomic decision-making in every society. Finally, with GA algorithm, Pareto Fronts for two defined objective functions are generated. The objective of this model is to maximize HER and NSL, simultaneously (as shown in equation (1)).

$$\text{Max} \sum_i \sum_j \sum_k (\text{HER})_{i,j,k}(\text{NSL})_{i,j,k},$$

where $\text{HER}_{i,j,k}$ is the household expense ratio and $\text{NSL}_{i,j,k}$ is the number of saved lives of people living in building class $i$, building code $j$ and building height $k$. The mathematical expression of these functions and their constraints on earthquake return period $t$ are presented in equation (2).

$$\begin{cases} f_1 (t) = \text{Max}(\text{NSL}) \\ f_2 (t) = \text{Max}(\text{HER}) \end{cases} \quad 100 \leq \text{EQ return periods} \quad (t) \leq 500.$$  

As shown in equation (2), the earthquake return period, which is the inverse of expected frequency of an earthquake occurrence, is set between two frequent and rare earthquakes with 100 and

![Figure 8. General procedure of multi-objective optimization (Zitzler et al. 2004).](image-url)
500 year-events, respectively. These two values have been selected, based on Iranian building code, which are consistent with Iran’s seismicity and building performances. Additionally, some other constraints are involved in the decision-making process of using the results of these optimization models such as household’s affordability which has been studied in the author’s previous research (see Pakdel-Lahiji et al. 2014a); another important parameter would be the extent of government financial support for households, specially the high-risk groups and the poor. Meanwhile, the collaboration between the banks or other financial institutions with the government with regard to loans and related issues would be essential as well.

4.1. Household expense ratios (HER)

In order to define parameters to show the household expenses, two important parameters are considered, insurance premium and mitigation cost. This ratio is illustrated in equation (3).

$$\text{Household Expense Ratio (HER)} = \frac{IP_b}{IP_a + MC},$$

where $IP_b$ and $IP_a$ are insurance premiums calculated for each household before and after taking mitigation measures, respectively. $MC$ is the cost of mitigation which will vary based on the type of structure, location and level of mitigation. The mitigation costs are considered as a percentage of damage as shown in Table 1. These values are presented based on engineering judgement and regular mitigation measures in Iran. Some assumptions which have been made here are based on the authors’ previous research (Sadeghi et al. 2015a) in which cost—benefit analysis for different mitigation strategies and sensitivity analysis are performed. These assumptions are:

1. mitigation costs which can be offered by government, banks, or any financial institution via a loan with 4% interest rate over 15-year payback,
2. the structural vulnerability more than 50% is considered as the total reconstruction cost and
3. 100 m$^2$ is considered as a household average living area as a basic unit for expense calculation.

Insurance premiums are calculated based on the average annual loss (AAL) via equation (4), and regarding the lack of pre-defined insurance loading factors in Iran, the loading factors are not considered in earthquake insurance premium calculations. It is notable that, AAL is representative of building’s potential losses relating to each building category identified in Figure 2 which would be paid by each household.

$$\text{AAL} = \sum_{i=1}^{n} P_i L_c,$$

where $P_c$ is the annual probability of occurrence and $L_c$ is associated loss and $n$ is the number of events per year (Grossi & Kunreuther 2005). Given the definition presented in equation (4), AAL is the area under the loss distribution curve, the so-called exceedance probability (EP) curve. Figure 9

| Building vulnerability (%) | Mitigation cost (% of reconstruction cost) |
|----------------------------|------------------------------------------|
| Less than 10               | No cost                                  |
| 10–20                      | 10                                       |
| 20–30                      | 15                                       |
| 30–40                      | 20                                       |
| 40–50                      | 30                                       |
| More than 50               | 100                                      |
illustrates the part of the EP curve considered as a mitigation risk layer with an earthquake return period of 500 or equivalent to 0.002 exceedance probability.

In other words, Figure 9 shows that, by taking mitigation actions, the household’s probable maximum losses would be decreased from $L_1$ to $L_2$, which lowers the premiums significantly.

4.2. Number of saved lives (NSL)

Defining an index to illustrate the number of lives saved in a specific earthquake is a challenging issue as it needs to have several parameters available such as (1) occupants trapped in the building, (2) injury distribution at collapse, and (3) post-collapse mortality (Coburn & Spence 2002) which are not classified and defined for Iran. Therefore, in this paper, NSL is defined in accordance with building damage before and after mitigation based on HAZUS (2003):

\[
ND_i = D_i \times N_i \times A
\]

\[
NSL_i = \langle ND_i \rangle_{After\ mitigation} - \langle ND_i \rangle_{Before\ mitigation},
\]

where $ND_i$ is the number of deaths in building class $i$, $D_i$ is the damage of building class $i$ derived from vulnerability curves, $N_i$ is the number of families living in building class $i$ which is calculated based on the total floor area for that building class divided by 100 m$^2$ (as an assumption for average living area for each household). $A$ is the average number of people living in each family. Based on the statistical data from Statistical Centre of Iran (2014), the average number of people living in each family in district one of Shiraz is 3.41.

5. Results

Figures 10–12 show all optimal solutions (set of Pareto Fronts) generated as a result of GA-based multi-objective optimization for selected building types. Although all the star points in the figures are optimal, the best proposed strategy can be derived by decision-makers by considering every aspect, such as social and political issues. The numbers beside star points (see Figures 10–12) indicate the corresponding earthquake return periods.

Based on the mathematical expression, the best result would be the one closest to the ideal point (as shown in Figures 10–12). For instance, based on Figure 10, the best optimal HER and NSL corresponding to 300 year-event for low-rise, pre-code masonry buildings are 0.66 and 17,453,
respectively. Figure 11 indicates that the best HER and NSL values are 1.4 and 221 in 204 year-event for steel braced frame, pre-code, low-rise buildings, respectively. These values for concrete moment-resistant frame, moderate-code, low-rise buildings are 0.46 and 165 in 316 year-event, respectively (see Figure 12). Note that, NSL has the direct relationship with population and building’s vulnerability; therefore, the wide range for NSL would be expected in the above figures. Tables 2—4 illustrate all optimal risk layers (shown by their respective earthquake return periods) with corresponding HER and NSL for all building types.

All the results shown in Tables 2—4 have no priority over others, while all are optimal, selecting the best option is up to decision-makers. For instance, if the government offers the mitigation loan for strengthening masonry, pre-code and mid-rise buildings to withstand the earthquake with 500 return period, the HER and NSL would be 0.2 and 1,377, respectively; however, if the government

Figure 10. Pareto Front for masonry, pre-code and low-rise buildings.

Figure 11. Pareto Front for steel braced frame, pre-code and low-rise buildings.
Figure 12. Pareto Front for concrete moment-resistant frame, moderate-code and low-rise buildings.

Table 2. Optimal risk layers for masonry buildings.

| Structural type | Pre-code | Moderate code |
|-----------------|----------|---------------|
|                 | Low-rise | Mid-rise      | Low-rise | Mid-rise      |
|                 | Eq. return period | HER | NSL | Eq. return period | HER | NSL | Eq. return period | HER | NSL | Eq. return period | HER | NSL |
| Masonry ALL     |          |              |          |              |      |      |          |              |      |      |          |              |
|                 | 499      | 0.28 | 18,886      | 500      | 0.2  | 1,377 | 491      | 0.53 | 2,015 | 500      | 0.42 | 478 |
|                 | 460      | 0.33 | 18,699      | 446      | 0.25 | 1,358 | 250      | 0.6  | 1,693 | 446      | 0.43 | 469 |
|                 | 420      | 0.39 | 18,476      | 393      | 0.32 | 1,334 | 126      | 0.62 | 1,337 | 409      | 0.44 | 462 |
|                 | 381      | 0.46 | 18,216      | 331      | 0.43 | 1,297 | 100      | 0.68 | 1,194 | 309      | 0.47 | 434 |
|                 | 352      | 0.52 | 17,980      | 247      | 0.53 | 1,217 |          |      |        | 274      | 0.48 | 420 |
|                 | 328      | 0.58 | 17,753      | 218      | 0.54 | 1,182 |          |      |        | 227      | 0.49 | 399 |
|                 | 317      | 0.61 | 17,645      | 188      | 0.55 | 1,133 |          |      |        | 195      | 0.5  | 381 |
|                 | 300      | 0.66 | 17,453      | 161      | 0.57 | 1,074 |          |      |        | 171      | 0.52 | 363 |
|                 | 217      | 0.71 | 16,301      | 124      | 0.62 | 970   |          |      |        | 159      | 0.53 | 352 |
|                 | 181      | 0.73 | 15,581      | 117      | 0.63 | 947   |          |      |        | 145      | 0.54 | 339 |
|                 | 124      | 0.78 | 13,826      | 103      | 0.66 | 889   |          |      |        | 138      | 0.54 | 333 |
|                 | 107      | 0.8  | 13,068      | 100      | 0.67 | 872   |          |      |        | 129      | 0.55 | 324 |
|                 | 100      | 0.81 | 12,668      |          |      |      |          |      |        | 109      | 0.57 | 298 |
|                 |          |      |              |          |      |      |          |      |        | 100      | 0.58 | 284 |

Table 3. Optimal risk layers for concrete buildings.

| Structural type | Pre-code | Moderate code |
|-----------------|----------|---------------|
|                 | Low-rise | Mid-rise      | Low-rise | Mid-rise      |
|                 | Eq. return period | HER | NSL | Eq. return period | HER | NSL | Eq. return period | HER | NSL | Eq. return period | HER | NSL |
| Concrete MRF    |          |              |          |              |      |      |          |              |      |      |          |              |
|                 | 500      | 0.85 | 103         | 493      | 0.39 | 8    | 458      | 0.38 | 194 | 500      | 0.44 | 11 |
|                 | 258      | 0.98 | 90          | 384      | 0.45 | 8    | 316      | 0.46 | 165 |          |      |    |
|                 | 247      | 1    | 89          | 333      | 0.49 | 8    | 250      | 0.47 | 132 |          |      |    |
|                 | 100      | 1.1  | 68          | 250      | 0.53 | 7    | 100      | 0.57 | 122 |          |      |    |
| Concrete SW     |          |              |          |              |      |      |          |              |      |      |          |              |
|                 | 500      | 0.77 | 466         | 500      | 0.91 | 24   | 498      | 0.68 | 922 | 497      | 0.76 | 42 |
|                 | 249      | 0.85 | 429         | 240      | 0.91 | 18   | 237      | 0.68 | 707 | 278      | 0.87 | 35 |
|                 | 132      | 0.86 | 379         | 168      | 0.99 | 16   | 131      | 0.75 | 535 | 132      | 0.89 | 26 |
|                 | 100      | 0.89 | 351         | 100      | 1.04 | 12   | 100      | 0.76 | 452 | 100      | 0.95 | 23 |

There is no high-rise, pre- and moderate code MRF and SW in district one of Shiraz.
offers the mitigation loan for an event with 100 return period, the HER and NSL are 0.67 and 872, respectively. It is obvious that with the first mentioned loan, more lives would be saved, but the household expenses have less economic justification. Instead, the second mentioned loan will save less lives and has more economic justification for the household; therefore, this method would offer several choices to decision-makers to make the right decision in micro-perspective by considering all aspects.

6. Discussion and conclusion

The main objective of this paper is to propose optimal solutions for taking mitigation measures by considering two important issues: (1) the household annual expenses such as mandatory earthquake insurance premiums and mitigation costs; and (2) the effects of mitigation measures on saving human lives. The proposed model can be distinguished from the similar previously presented models in three ways: (1) it considers the vulnerability curves which were exclusively derived for Iranian buildings, (2) selects spectral acceleration as an earthquake intensity which is more reliable in terms of its involvement to the soil types and building’s natural periods and (3) uses the multi-objective optimization method to optimize both human and economic losses, simultaneously.

The optimal risk layer can be used as a guideline for government or decision-makers to offer the mitigation loans to households in order to strengthen their houses for the optimal earthquake return periods as minimum protection. This approach is
promising for saving lives in future events as people would spend money on strengthening their houses instead of buying more insurance coverage and do nothing against the future losses. Moreover, this process would raise the risk awareness in society and increase people’s attention to earthquake resistance construction which is crucial for high-risk countries such as Iran. In other words, the emphasize here is on the relationship between using mitigation measures and insurance which would result in better building performance and raise risk awareness in the society and will eventually lead to save lives.

Moreover, the proposed risk layers can be very useful for designing insurance schemes. As insurance premiums are really high, and somehow unaffordable, for some Iranian building types due to their vulnerabilities, taking mitigation actions is needed. Therefore, the extent of mitigation defined in this paper is essential for the risk financing by public or private sectors.

Disclosure statement

No potential conflict of interest was reported by the authors.

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