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# A framework for quantifying the impact of target retrofitting on risk reduction in urban areas

**Ante Pilipović[1], Mario Uroš[1], Marta Šavor Novak[1]**
**1- University of Zagreb Faculty of Civil Engineering, Fra Andrije Kačića Miošića 26, 10000 Zagreb**
⋮
ante.pilipovic@grad.unizg.hr

**Abstract**

Post-earthquake reconstructions involve complex decision-making processes which are often limited to one-time solutions based on seismic design codes after each devastating event, without developing a long-term strategy for earthquake resilience. Within that framework, each building is often approached individually and a decision whether to retrofit the building or not is reached on a post-event building-by-building basis. Instead of reactive planning, a proactive risk-targeted retrofitting strategy can be a better option. Within a risk framework, losses gain precedence as a primary driver of seismic design, which in turn becomes only a means to reduce losses to an acceptable level. For example, instead of full-scale retrofitting, a target retrofit typology may be proposed for a building type, where only critical elements of the building are retrofitted, contributing optimally to improve the seismic performance of the building at a minimum cost. Urban areas often comprise of classes of very similar or identical buildings, with similar contribution to seismic risk. By applying a typical target retrofit solution to all such buildings, an optimal reduction in seismic risk may be achieved. This study proposes a probabilistic framework for assessing the impact of target retrofit solutions applied to typical buildings on seismic risk reduction in urban areas. A novel decision-making tool Target retrofit index (TRI) is proposed, which compares different target retrofit solutions as applied to a building within the performance-based earthquake engineering framework (PBEE), with respect to a target behavior, which may be risk-based or design-based. It also serves as a tool to decide if a retrofit is required at all, with respect to the target behavior. TRI is applied to a common unreinforced masonry residential building type found in Zagreb, Croatia, as a case study. As-built and target retrofitted configurations are considered. A vulnerability model is produced using incremental dynamic analysis for the considered building type by including a deterministic damage-to-loss model. A single-building probabilistic seismic risk assessment is performed using the ESHM20 seismic hazard model. Loss curves and expected annual losses are computed for the as-built and retrofitted configurations. Cost-to-benefit analysis is performed with respect to a service life of 50 years. The results show that cost-to-benefit ratios may be higher for cheaper and less impactful target retrofit options, which may make them viable instead of more expensive and higher performance options, giving target retrofitting an advantage over traditional full-scale retrofit strategies. However, TRI serves as a safeguard, ruling out any retrofit options that do not meet the target. The cost-to-benefit ratio and TRI combined serve as a powerful tool for designing target retrofit campaigns in urban areas to proactively and efficiently reduce seismic risk.

**Keywords: Target retrofit index, physical vulnerability, cost-to-benefit ratio, seismic risk mitigation**

## 1- INTRODUCTION

Post-earthquake reconstructions involve complex decision making which aims to rebuild urban areas using limited resources. In many cases, a case-by-case approach is adopted, where each damaged building is approached individually post-event and a reconstruction project is proposed according to relevant seismic codes [1], often resulting in extremely high reconstruction costs, which are not manageable by the local authorities. For example, after the Croatia 2020 earthquakes, such an approach was necessary because no earthquake mitigation strategy was in place prior to the earthquake event [2]. The high costs of reconstruction were partly covered by the EU solidarity fund for some public buildings, critical infrastructure and heritage buildings, but residential buildings could not be covered.

An alternative strategy was proposed within the recently completed 2BESAFE project of the Croatian Science Foundation ("New vulnerability models of typical buildings in urban areas: Applications to seismic

risk assessment and target retrofitting methodology") where the concept of pre-emptive target retrofitting was introduced [3]. A target retrofit solution is a local intervention which strengthens only critical elements of a building, those that are the most likely to be damaged during an earthquake, resulting in a maximum contribution to the reduction of building vulnerability at a minimum cost of intervention. Instead of expensive post-event reconstruction, a pre-event target retrofit solution may prevent reaching higher damage states and drastically reduce reconstruction costs.

In this study, a new probabilistic framework is proposed for quantifying the impact of target retrofit solutions on reduction of vulnerability and risk for residential buildings in urban areas, and new criteria are proposed for evaluating the effectiveness and cost-efficiency of proposed target retrofit solutions to support the decision-making process. This framework is embedded within the broader performance-based earthquake engineering (PBEE) framework which connects the decision-making to design alternatives through seismic hazard, demand, damage, vulnerability and loss analyses. Two key criteria are identified for evaluating the effectiveness of a proposed target retrofit solution: physical vulnerability reduction [4], and economic benefit [5]. Sometimes a designed target retrofit solution can be very effective in reducing the vulnerability component of risk, but the overall risk is not significantly impacted due to the influence of seismic hazard and exposure components, e..g when a retrofit solution effectively prevents collapse, but not light and widespread damage which may still be expensive to repair due to frequent low-intensity earthquakes. This is why both vulnerability and risk criteria should be considered separately.

Residential buildings are the main beneficiaries of the proposed framework, as many nearly identical buildings often exist in many urban areas, and they may be classified under one building type [6]. An effective target retrofit solution designed for one of these buildings could then be applied to all buildings of that type within the urban area, with the potential benefits stacking. In this way, the proposed framework also supports evaluating strategies of preemptive target retrofitting campaigns, where the residential building types with the most expected and quantified benefits could be retrofitted, and appropriate cost subsidizing for building owners may be determined, or at least priority building types identified.

A novel concept of target retrofit index (TRI) is introduced, which evaluates the effectiveness of target retrofit solutions to reduce physical vulnerability at varying intensity levels of ground shaking. It is based on normalization of seismic demand at specified risk-based or code-based target performance thresholds, which can be tailored to specific user needs. For the risk criterion, the existing concepts of cost-to-benefit ratio (CBR) and breakeven analysis are used [5], which rely on the results of a probabilistic seismic risk assessment (PSRA), specifically loss metrics such as loss curves and expected annual losses (EAL). Jointly, these metrics form a reliable framework for determining whether or not a proposed target retrofit solution is feasible for real-world application for a given class of typical residential buildings.

In this study, the proposed framework (Figure 1) is first described in more detail in the Methodology section, and then it is applied to a case study building, a typical unreinforced masonry (URM) building located in Zagreb, Croatia, where a potential target retrofit solution was evaluated using the proposed criteria. The results are then discussed considering the decision-making process and finally conclusions are given.

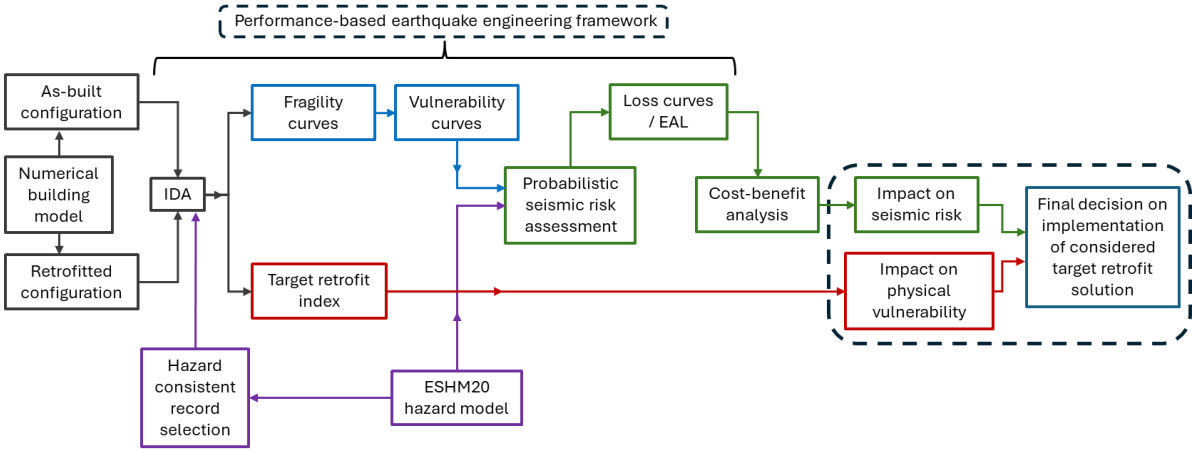



**Figure 1- Flowchart of the proposed framework for quantifying the impact of target retrofit solutions on reduction of seismic risk**

## 2- METHODOLOGY

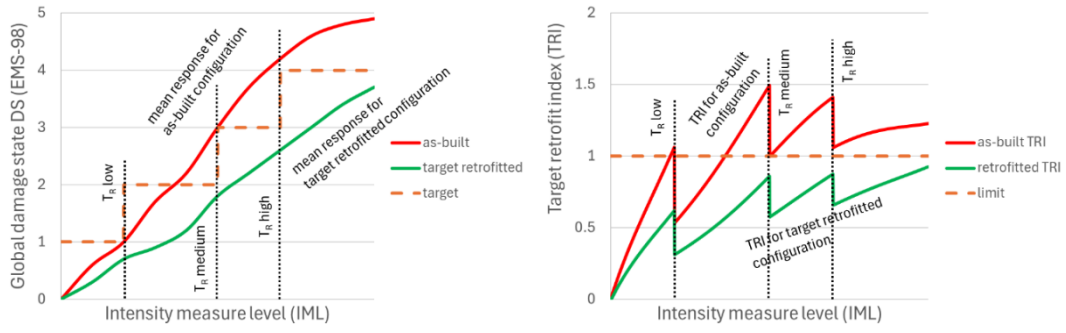
In this section the methodology applied in this study is presented in more detail. First, the novel concept of Target retrofit index is introduced as the physical vulnerability-based criterion, and then the cost-to-benefit ratio is briefly explained as the risk-based criterion. Both criteria are instrumental for the final decision regarding a potential target retrofit solution for a specific residential building type.

Both criteria are embedded within the probabilistic PBEE framework and are therefore easily evaluated within an incremental dynamic analysis (IDA) or multiple stripe analysis (MSA) calculation using a suite of ground motion records and performing nonlinear dynamic analyses (NLDA). Starting from the results of NLDAs, probabilistic seismic risk assessment (PSRA) can be performed and loss metrics such as loss curves and expected annual losses may be calculated.

### 2-1- TARGET RETROFIT INDEX

The Target Retrofit Index is a target behaviour-based concept where the acceptable performance of a building is specified within the PBEE framework at the seismic demand and damage analysis levels through a particular format of the seismic demand model, as follows. On the horizontal axis is the intensity measure level (IML), while the vertical axis represents the building responses due to all nonlinear dynamic analyses (NLDAs), in the form of global damage states according to a damage classification scale (in this study the EMS-98 classification is used). For example, if the incremental dynamic analysis (IDA) procedure is used [7], the mean responses will be mean IDA curves. This procedure is repeated for the as-built and target retrofitted configurations, especially if multiple target retrofit variants are considered. A target behaviour line is defined in conformity with the EMS-98 damage states, that designates the damage state (DS) thresholds that are considered acceptable for the building at a given intensity level of ground shaking. The target behaviour DS is increasing with increasing IMLs, and discrete target performance return periods $T_R$ are defined, which may be inspired either by a particular seismic code, or by a risk-motivated threshold. The target behaviour changes to higher DSs at these return period limits, reflecting a new category of IML. In general, it is advisable to define low, medium and high intensity level ranges with 3 different $T_R$ limits, but any desirable number is possible. In this study, the return period thresholds and the associated target behaviour DS thresholds are proposed, as shown in Table 1. Such target behaviour for the return periods is in line with Eurocode 8 limits, while the target DS limits are comparable to EC8 requirements for limited damage, significant damage and near collapse limit states. Moreover, the $T_R$=225 years introduces an intermediate additional IML range, to better assess the behaviour of the building in the medium IML range.

At this point the TRI may be introduced as the ratio between the mean demand curve (e.g. a mean IDA curve) and the target behaviour line (orange line in Figure 2b). This ratio is defined for every continuous IML and forms a step-like function as a modification of the mean behaviour curve. This TRI function can have values below or above 1. If the TRI values are above 1, it means that the building does not satisfy the target behaviour at that IML with respect to physical vulnerability, while if it is below 1, the target behaviour is satisfied.




**(a)** **(b)**

**Figure 2- (a) Conceptual performance curves for the as-built and retrofitted configurations. The orange line represents the target behaviour for the building; (b) Target retrofit index (TRI) for the as-built and retrofitted configurations, with the TRI=1 orange line indicating the threshold of acceptable performance (TRI<1) or limit exceeded (TRI>1)**

**Table 1- Proposed global EMS-98 damage level thresholds and the associated return period ranges**

| **Return period range [years]** | 0-95 | 95-225 | 225-475 | 475-2475 |
|---|---|---|---|---|
| **Allowed global EMS-98 damage state** | 1 | 2 | 3 | 4 |

It is important to note that the vertical axis does not necessarily need to be associated with EMS-98 damage states, but it needs to be associated with building responses that can be associated with target building performance. If interstorey drifts are used as global engineering demand parameters (EDPs), they may also be used in the TRI plots, if appropriate thresholds are provided to link their values to target performance. In the context of numerical (analytical) assessment of real buildings and in the interest of preserving comparability with real post-earthquake building inspections, this study uses the EMS-98 descriptive damage states as global performance indicators.

### 2-2- COST-TO-BENEFIT RATIO

Loss curves represent the primary and most important result of probabilistic seismic risk assessment, but expected annual losses (EAL) are often more useful, calculated as:

$$\boldsymbol{EAL = \int_0^\infty E[C|IM = x]|d\lambda(IM > x)| = \int_0^\infty \lambda(C > c)dc,} \quad (1)$$

where E(c) is the expected loss at a given IM level and $\lambda(IM > x)$ is the seismic hazard curve [8]. The EAL describes the losses that can be expected, on average, each year on a very large time scale. EAL is calculated as the area under the loss curve, or the integral of the loss curve, according to Equation (1). It is the sum of all losses in the probability space.

To calculate the impact of target retrofit solutions on reduction of losses, a breakeven analysis can be performed, where the expected benefits are counted on a yearly basis, discounted at a rate $r$ which describes the effects of inflation and value loss over time. Then, the costs of target retrofitting for the single building are estimated. These are the initial costs of investment in a target retrofit campaign. The breakeven analysis is conducted for a planned remaining lifespan of the building. When performing full-scale reconstructions, the seismic design codes require that the retrofitted building performs as a new building, which for Croatia is a building design lifespan of 50 years. This lifespan is adopted also for the case of target retrofitting. The expected benefits as discounted over the remaining lifespan of the building can be expressed in terms of net present value (NPV) of the investment, expressed as:

$$\boldsymbol{NPV = \sum_{t=1}^{T} \frac{\Delta EAL}{(1+r)^t} - C_{TR}.} \quad (2)$$

In this equation, $T$ is the remaining lifespan of the building (assumed as 50yrs). $\Delta EAL$ is the difference between EALs of the as-built and retrofitted buildings and represents the expected annual benefit from reduction of direct structural damage due to target retrofitting. This benefit is summed up for each year during the remaining lifespan of the building, and the benefits are gradually added.

The cumulative summation (first term) in Equation (2) represents, for any current $t$, the present value of benefits at that time ($PV_B$), while each term of the summation individually represents the benefits for that year. The benefits are reduced yearly due to the discount rate, and the reduction increases with the passage of years. The NPV may be expressed as:

$$\boldsymbol{NPV = PV_B - C_{TR}.} \quad (3)$$

The cost-benefit ratio (CBR) may now be defined as:

$$\boldsymbol{CBR = \frac{PV_B}{C_{TR}},} \quad (4)$$

which represents the ratio between the total benefits expected during the lifespan of the building and the investments made. If the CBR is greater than 1, the benefits outweigh the investment, and vice versa if CBR is less than 1. There is a point in time $t_{BR}$ for which the current cumulative benefits $PV_B$ match the investment $C_{TR}$ exactly. This is known as the payback time (or the breakeven time) which is required for the initial investment to pay off. The payback time $t_{BR}$ may be closer to the final lifetime of the building (50yrs) for CBRs close to and exceeding 1, which means the investment is paid back in terms of risk very late. On the

other hand, for CBRs exceeding 1 greatly, the payback time is going to be low, and the initial investment is returned during the earlier part of the investment period.

## 3- CASE STUDY: AN UNREINFORCED MASONRY RESIDENTIAL BUILDING IN ZAGREB, CROATIA

The proposed methodology is applied in this section to a typical unreinforced masonry residential building in Zagreb, Croatia, to evaluate the effectiveness of a proposed target retrofit solution for that building type. The building is commonly found in Zagreb in multiple neighbourhoods, was built in the 1960-s before the modern seismic codes were implemented. It consists of 5 URM shear wall levels with an additional RC shear wall basement. It is regular in plan and elevation, and has a rectangular shape, as shown in Figure 3. In this section the equivalent frame model developed for this building type is first described both for the as-built and retrofitted configurations, and then the proposed two criteria for evaluating the proposed target retrofit solution are evaluated for the building.

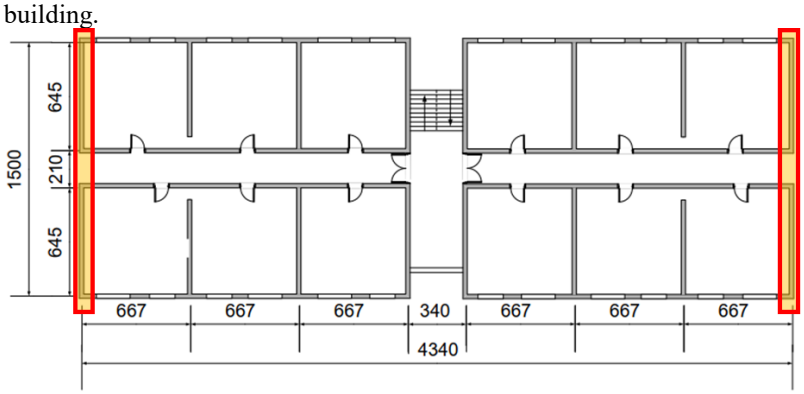
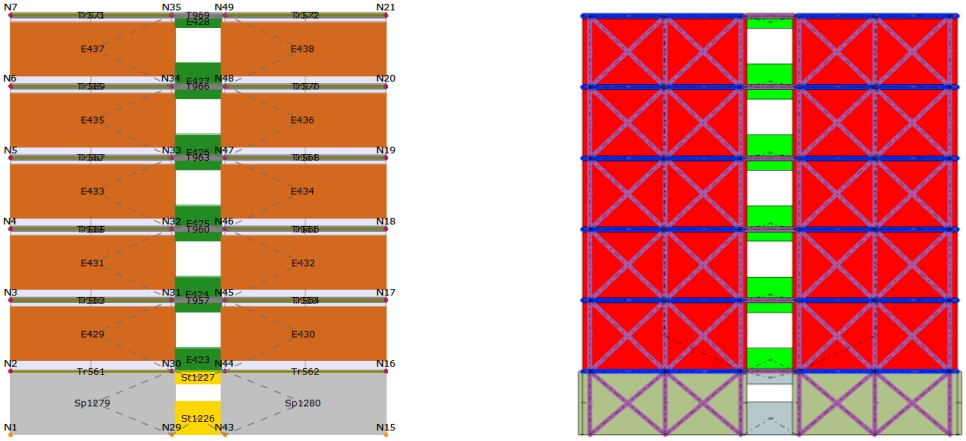



**Figure 3- Characteristic floor layout of the selected case study building with marked locations of the target retrofit solution**

### 3-1- EQUIVALENT FRAME MODEL – AS-BUILT AND RETROFITTED CONFIGURATIONS

The numerical model for the case study URM building was created using the equivalent frame modelling approach within the research version of the Tremuri software [9], utilizing the built-in nonlinear beam model for the masonry elements, which features a phenomenological multilinear constitutive law which captures the post-elastic phase of masonry behaviour up to collapse.

Previous studies have shown using a probabilistic framework and a multi-scale approach [3,10] that the transversal (shorter) direction is critical for the selected building type, and an external steel exoskeleton was designed and applied to the outer façade walls of the building in the critical direction, as shown in Figure 4. The properties of the masonry material, parameters of the constitutive law and characteristics of the exoskeleton and other structural components can be found in [11].




**(a)** **(b)**

**Figure 4- Outer façade wall in the critical transversal direcition for (a) as-built and (b) retrofitted configuration**

### 3-2- TRI CALCULATION FOR THE AS-BUILT AND RETROFITTED CONFIGURATIONS

To calculate TRI a seismic demand model was developed for the selected URM building using the PBEE framework. First, a set of 30 ground motion records was selected using the conditional spectrum approach [12] for $T_R$=225 years and utilizing the ESHM20 hazard model [13] to determine the hazard values at a characteristic site in Zagreb. Average spectral acceleration in the period range 0.2-0.7s was used as the intensity measure. Then, IDA was performed in Tremuri with all 30 records scaled in the range 0.1g-1.0g of $S_{a,avg}$. The global damage states after each NLDA were obtained in post-processing using the multiscale procedure developed by Cattari and Angiolilli [10], which constructs the global damage state according to the EMS-98 classification starting from the damage to individual piers and spandrels at the panel scale, then aggregating to wall scale by taking a weighted average damage of all the elements within each wall, and finally obtaining the global damage state by combining the damage of all the individual walls.

The seismic demand model developed therefore uses global EMS-98 damage states as the engineering demand parameter, and $S_{a,avg}$ as the intensity measure, and is shown in Figure 5 for both as-built and retrofitted configurations, with intensity level thresholds according to Table 1 calculated according to the ESHM20 hazard model.

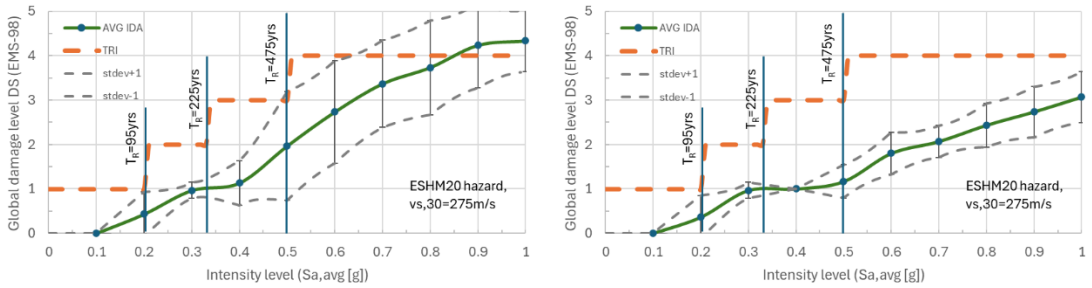



**Figure 5- Mean IDA results and one standard deviation for the (a) as-built and (b) retrofitted configuration. Ddashed orange lines represent the target behaviour according to Table 1**

The TRI values were calculated by normalizing the mean IDA results according to the target behaviour across the different intensity level intervals, obtaining TRI values as in Figure 6 for both configurations of the building. It can be observed that up to TR=225 years the TRI values are similar in both cases, indicating that the steel exoskeleton is not activated for the lower intensity levels of ground shaking. On the other hand, for medium and high intensities, physical vulnerability is decreased considerably, effectively ruling out the possibility of collapse, with TRI values below 1 within one standard deviation. TRI results show that the initial vulnerability of the selected building is not very high with respect to the seismic hazard values that can be expected on site. However, it should be noted that in this study, uncertainty in the hazard values has not been considered explicitly, as other hazard models may yield different results. For example, code-based design spectra produce more conservative results [11], which is important if conformity to the seismic design codes is required.

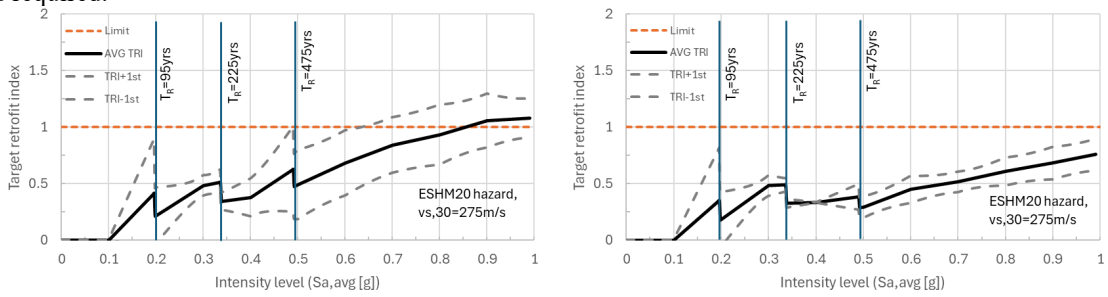



**Figure 6- Target retrofit index (TRI) within one standard deviation for the (a) as-built and (b) retrofitted configuration. Dashed orange lines represents the TRI=1 threshold**

### 3-3- VULNERABILITY AND DAMAGE-TO-LOSS MODELS

The damage-to-loss model (DLM) was defined as a deterministic and discrete function as shown in Figure 7, for EMS-98 damage states 2-5 (assuming no direct losses for DS1), with fixed losses in EUR per $m^2$ of gross

building area assigned to each damage state according to the maximum allowed prices of reconstruction during the post-earthquake reconstruction process in Croatia based on building usability inspections and the prescribed levels of reconstruction (Table 2). The DLM was defined in this way to simulate to some extent the real post-earthquake reconstruction processes in Croatia after the 2020 earthquakes, where DS4 and DS5 building were almost always replaced by new buildings, while DS3 and below were repaired.

**Table 2- Maximum prices of reconstruction for Zagreb and Petrinja areas according to types of intervention and levels of reconstruction**

| Building usage | Usability assessment | Structural intervention (EUR/m$^2$ GBA) | | | | Full-scale reconstruction (EUR/m$^2$ GBA) | | | | Demolition of a collapsed building (EUR/m$^2$ GBA) | Replacement cost for a new building (EUR/m$^2$ GBA) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Reconstruction level | | Level 1 | Level 2 | Level 3 | Level 4 | Level 1 | Level 2 | Level 3 | Level 4 | | |
| Family houses | | | | | | | | | | | |
| | | | 213.54 | 294.43 | | | 269.09 | 355.35 | | | |
| | | | | 345.37 | | | | 405.4 | | | |
| | Collapse | | | | | | | | | 47.64 | 1368.63 |
| Multi-apartment residential buildings, office buildings | | | | | | | | | | | |
| | | | 311.74 | 585.88 | | | 392.83 | 707.1 | | | |
| | | | | 647.03 | | | | 759.48 | | | |
| | Collapse | | | | | | | | | 47.64 | |

The vulnerability model was built by combining the DLM with the EMS-98 fragility curves, derived from IDA results using maximum likelihood estimation. The new vulnerability models for the as-built and retrofitted configurations of the selected URM building are shown in Figure 8. The highest impact is observed for high intensity levels. For example, for $T_R$=475 years the ESHM20 model gives a hazard value $S_{a,avg}$=0.42g where the losses are halved, but for $T_R$=225 years $S_{a,avg}$=0.28g and there is no difference in losses. This reflects well the TRI results, but the impact on seismic risk can be measured only within a probabilistic seismic risk assessment (PSRA) calculation, where all possible earthquake intensities are considered along with physical vulnerability.

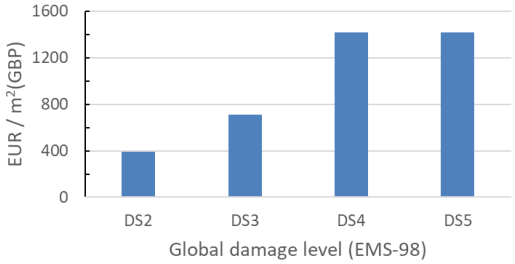



**Figure 7- Deterministic damage-to-loss model adopted for this study, simulating to an extent the post-earthquake reconstruction praxis in Croatia after the 2020 earthquakes**

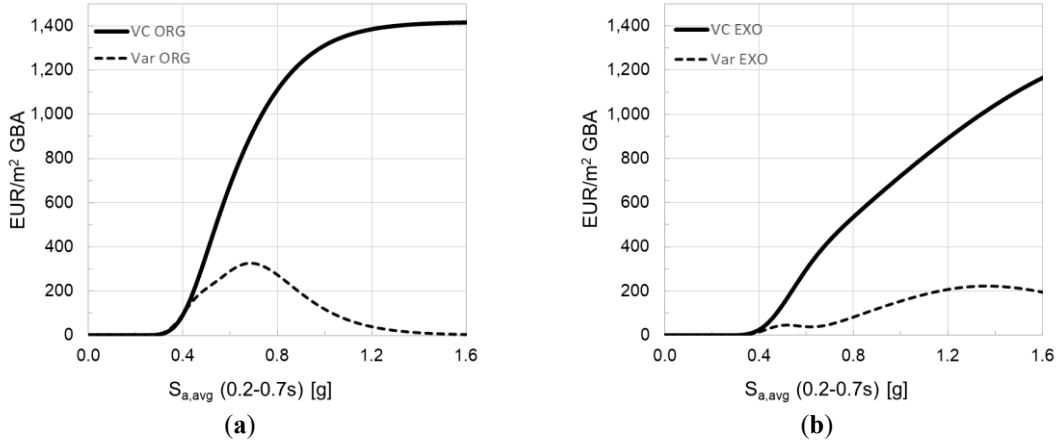



**Figure 8- New vulnerability curves and their variances for the (a) as-built and (b) retrofitted configuration**

## 3-4- COST-BENEFIT ANALYSIS OF THE PROPOSED TARGET RETROFIT SOLUTION

A classical single-building probabilistic seismic risk assessment was conducted by convoluting the site-specific ESHM20 seismic hazard curve with vulnerability curves from Figure 8 to obtain loss curves for both configurations, as shown in Figure 9. By integrating over the loss curve according to Equation (1), expected

annual losses (EALs) were obtained for both configurations, shown in Table 3a. EALs show that the losses are halved after applying the steel exoskeleton, but also that the EAL for the as-built configuration is low in absolute value (0.13% of the replacement value).

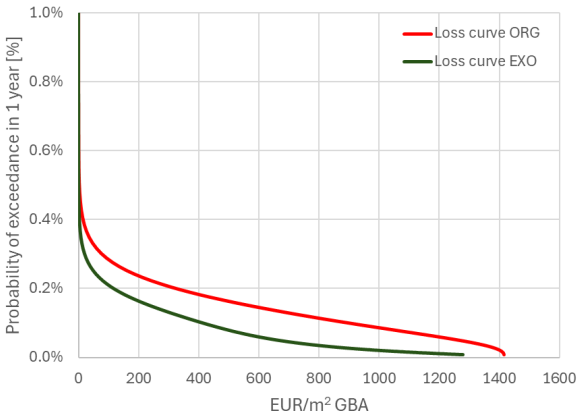



**Figure 9- Loss curves for the (a) as-built and (b) retrofitted configuration**

**Table 3- (a) Expected annual losses for the as-built and retrofitted configurations; (b) Cost-to-benefit ratios of the proposed target retrofit solution for different discount rates r**

| Configuration | EAL [EUR/m² GBA] |
|---|---|
| ORG | 1.97 |
| EXO | 0.98 |
| $\Delta EAL^*$ | 0,99 |

**(a)**

| Discount rate | Cost-to-benefit ratio |
|---|---|
| r=1% | 1.06 |
| r=3% | 0.71 |
| r=5% | 0.51 |

**(b)**

The benefits $\Delta EAL$ were then used in Equation (2) to obtain the Net present values each year during the assumed remaining lifespan of 50 years. The benefits were discounted at a rate $r$ each year, as indicated by the denominator. The discount rate was varied between 1-5% to account for economic uncertainty. The total replacement cost of the building was consulted from Table 2, and a value of 1500 EUR/m² of GBA was adopted. Finally, $C_{TR}$ represents the initial investment costs of implementing the selected target retrofit solution. The cost of the applied external steel exoskeleton was estimated as 2.5% of the total replacement cost of the building. Since the cost is incurred at the start of the new building lifespan, it is not discounted with time, assuming no maintenance costs are required. The NPV results are shown in Figure 10, showing monotonic increases over time. However, for high discount rates (e.g. r=5%) the NPV saturates below the breakeven point, while NPV breaks even only for low r=1%.

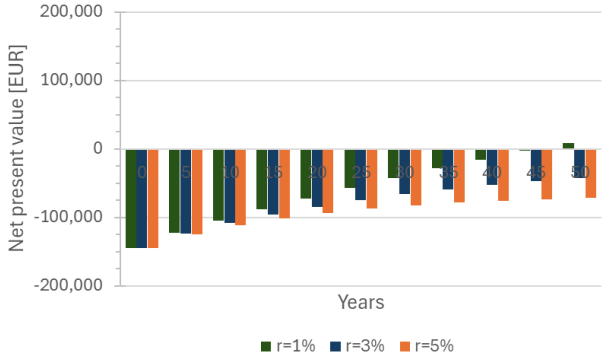



**Figure 10- Net present values for the proposed remaining building lifespan of 50 years for three discount rates r**

The cost-to-benefit ratio was calculated according to Equation (4), as the ratio between NPV at the end of the building lifespan ($PV_B$) and the initial costs of the applied target retrofit solution $C_{TR}$. CBRs are shown in Table 3b. Sensitivity to the discount rate is high, but even at low r, CBR struggles to exceed the breakeven point CBR=1 after 50 years.

It is important to note that these results do not account for the uncertainty in seismic hazard values (which impact both TRI and CBR values), but they do account for record-to-record variability implicitly through IDA. Building geometry and modelling variations are not as relevant since we are interested only in a single common residential building type in this study.

## 4- DISCUSSION

There are several key takeaways from the TRI plots that inform the choice of the target retrofit solution from the physical vulnerability perspective. Firstly, the TRI values may be used to decide if there is a need for target retrofitting at all. If the TRI curves for the as-built configuration are consistently below the target TRI=1 line, then no retrofitting is needed. It is especially important to select application-appropriate target behaviour, so that the TRI curves reflect the real needs of the users. The targets chosen in this study reflect the post-earthquake recovery praxis after Zagreb and Petrinja earthquakes of 2020.

The TRI plots are divided by the different return periods into intensity level intervals of low, medium and high intensity events. This is an important feature because different target retrofit solutions may be feasible for affecting the building performance at different intensity levels. For example, to prevent collapse, a more robust intervention to critical walls may be needed, while at low intensities, a light FRCM strengthening may be enough to prevent local cracking. Sometimes, the building will have acceptable performance at some intensity levels, while not at others. This information may prove useful when designing optimal target retrofit interventions, as costs may be reduced and investing in non-impactful solutions may be avoided.

TRI plots may also be used to define a target impact threshold for considered target retrofit options. It can be proposed that a target retrofit solution that modifies building performance below the target TRI=1 line within 1 standard deviation of mean IDA curves should be considered as a "good enough" impact. Out of all considered target retrofit options, those that satisfy the target impact requirements are appropriate solutions, while the others should be discarded. The remaining solutions are then evaluated according to the risk criteria. The TR selection procedure conducted in this way may prove to be an iterative procedure, and also a demanding task since numerous NLDAs need to be performed to arrive at a satisfying seismic demand model for each considered TR option, which presents a limitation to the number of different TR options that can be considered.

Finally, the TRI plots are sensitive to the intensity measure that is used for seismic demand analysis, but even more to the seismic hazard model used. When assigning risk-based target behaviours, an underestimation of seismic hazard may lead to unrealistically low TRI values which may mislead to a conclusion that building performance is satisfactory, when it is in fact above the target. On the other hand, if code-based targets are assigned, the issue is reduced, since all buildings are designed according to that particular code. In that case however, the practicality of IMs is reduced, since seismic hazard maps provided in the seismic design codes are typically given only in terms of PGA or $S_a(T)$.

While NPV is a value expressed in terms of a loss metric, CBR is a unitless ratio. Both represent the same reality, but in different formats. NPV is useful when the absolute value of an investment is of interest and a clear economic interpretation in currency is needed. Also, it is useful when interventions of different scopes and costs are compared. On the other hand, CBR is beneficial for relative comparison of the efficiency of different target retrofit options for the same building, and for prioritization of buildings. CBR in combination with TRI gives a final estimate of the applicability of different target retrofit solutions for a particular building. TRI filters out the solutions with respect to target behaviour and intensity levels, while CBR filters out the remaining options with respect to losses.

If the CBR is greater than 1, the benefits outweigh the investment, and vice versa if CBR is less than 1. There is a point in time $t_{BR}$ for which the current cumulative benefits $PV_B$ match the investment $C_{TR}$ exactly. This is known as the payback time (or the breakeven time) which is required for the initial investment to pay off. The payback time $t_{BR}$ may be closer to the final lifetime of the building (50yrs) for CBRs close to and exceeding 1, which means the investment is paid back in terms of risk very late. On the other hand, for CBRs exceeding 1 greatly, the payback time is going to be low, and the initial investment is returned during the earlier part of the investment period.

TRI is a measure of physical vulnerability reduction due to applying a target retrofit solution, while CBR is a risk-based measure. In the case study considered, TRI indicated high impact of the external steel exoskeleton on reducing physical vulnerability, but CBR was still low as the relevant risk metric. This is because the seismic hazard on location is low in the intensity range where the applied target retrofit solution is most effective. Also, the initial vulnerability of the selected building is not too high according to TRI values for the as-built configuration. Most importantly, both TRI and CBR are quantitative criteria which should be used together to arrive at an informed and cost-effective decision for each considered target retrofit solution. An optimal target retrofit intervention should satisfy both criteria.

## 5- CONCLUSIONS

A novel framework was proposed for quantifying the impact of target retrofit solutions on reduction of seismic risk, using two different metrics. Target retrofit index was introduced as an indicator of physical vulnerability

of the building, capturing the effectiveness of target retrofit solutions at different intensity levels of ground shaking. Cost-to-benefit ratio was used as the seismic risk criterion, calculated using probabilistic seismic risk assessment, to measure the economic feasibility of a target retrofit solution. Both metrics were evaluated in a case study of a common residential mid-rise URM building type in Zagreb, Croatia, using an external steel exoskeleton as the target retrofit solution. TRI results showed high effectiveness of the exoskeleton in reducing vulnerability at medium and high intensities, but CBR remained low due to low seismic hazard on location and low initial vulnerability of the selected building. Both TRI and CBR are important quantitative metrics for effective decision making regarding a particular target retrofit solution. In this case, the exoskeleton was ruled out based on insufficient impact on risk reduction, in spite of high positive impact on vulnerability reduction.

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