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Long-term sustainability and resilience enhancement of building portfolios

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A R T I C L E I N F O

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A B S T R A C T

The role of community building portfolios in socioeconomic development and the growth of the built environment cannot be overstated. Damage to these structures can have far-reaching consequences on socioeconomic and environmental aspects, requiring a long-term perspective for recovery. As communities aim to enhance their resilience and sustainability, there is a cost burden that needs to be considered. To address this issue, this paper proposes a community-level performance enhancement approach that focuses on optimizing the long-term resilience and sustainability of community building portfolios, taking into account recurrent seismic hazards. A Gaussian process surrogate-based multi-objective optimization framework is utilized to optimize the cost objective while considering performance indicators for resilience and sustainability. The proposed framework involves using performance-based assessment methods to evaluate the socioeconomic and environmental consequences under stochastic and recurrent seismic hazard scenarios. These evaluated indicators are then used to efficiently optimize the community resilience and sustainability, taking into account the retrofit costs. Finally, approximate Pareto-optimal solutions are extracted and utilized for decision-making. In summary, this paper presents a novel approach for optimizing the long-term resilience and sustainability of community building portfolios by considering recurrent seismic hazards. The proposed framework incorporates performance-based assessment methods and multi-objective optimization techniques to achieve an optimal balance between cost, resilience, and sustainability, with the ultimate goal of enhancing community well-being and decision-making in the face of seismic hazards.

1. Introduction

The design service life of residential buildings is 50 years on average based on various design codes [1–3]. Nonetheless, residential buildings remain serviceable beyond the design service life due to financial constraints, lack of regulatory enforcement, and among others [4,5]. These buildings share common attributes within a specific geographical area and exhibit shared services and are referred to herein as community building portfolios. Furthermore, most of the building communities in developing countries consist of deficient structures vulnerable to extreme events [6]. Also, many of the buildings fall under the category of pre-code and low-code buildings, burdened by low-quality construction materials, and lack of quality control, among others [7]. During their extended service life, these community building portfolios are subjected to recurrent extreme events. Such settings make the communities in the developing world at increased vulnerability to extreme events and can cause huge social, economic, and environmental consequences [8,9]. Additionally, the socioeconomic development and growth of communities depend on the normal functioning of the built environment [10]. The normal functioning of the built environment during the investigated time can be compromised due to these recurrent extreme events [11,12]. Hence, it is essential to assess the social, economic, and environmental consequences of these recurrent extreme events along with the functionality of the community building portfolios [13].

The intensity measures and the occurrence time of these recurrent extreme events such as earthquakes are uncertain and hence a stochastic occurrence model could be utilized to model the occurrence of seismic hazard scenarios [14,15]. A homogenous Poisson process is a stochastic process that has been widely utilized to model the occurrence of seismic hazards [16]. In this process, the inter-arrival time of seismic hazard follows an exponential distribution having a constant mean annual frequency of exceedance i.e., occurrence rate [17]. The homogenous Poisson process is considered to be a time-independent process and seismic hazard scenarios could be considered as time-dependent stochastic processes since the seismic hazards are linked to certain threshold levels of energy accumulations in the interlocked tectonic fault plates [18]. After a seismic hazard has taken place, the accumulated energy is released and the energy accumulation process is repeated. This time-dependent stochastic process can be modeled by utilizing the Brownian passage-time (BPT) renewal process [19]. The BPT renewal process is a nonsta-

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tionary arrival process in which the inter-arrival times of the considered seismic hazard follow a BPT distribution function having a mean equal to the return period of an earthquake scenario with some coefficient of variation [20]. The intensity measures of the seismic hazard scenarios can be investigated by utilizing probabilistic seismic hazard assessment techniques, hazard curves, codes, and among others [21–24].

The consequences and functioning of the building environment could be assessed by utilizing the sustainability and resilience performance indicators on a community level [25–28]. Sustainability in the context of earthquakes may include social, economic, and environmental consequences arising from a seismic hazard including casualties, repair costs, carbon emissions, and among others [29,30]. The resilience may include the functionality of community building portfolios during the investigated time and may be determined from downtime and building damage and recovery profiles, among others [31,32]. Nonetheless, the sustainability and resilience assessment of community building portfolios given seismic hazards provides meaningful information to the community stakeholders and decision-makers to assess the performance and possibly enhance the performance given the mitigation alternatives [33].

The performance of community building portfolios could be enhanced by pre-hazard mitigation alternatives and implementing post-hazard recovery management strategies [34,35]. In this paper, the pre-hazard mitigation alternatives are explored to investigate the performance enhancement of community building portfolios considering retrofitting the individual buildings with various conventional retrofit alternatives practiced in developing countries including reinforced concrete jacketing, steel jacketing, reinforces concrete polymers, and among others [36,37]. However, a community building portfolio consists of numerous buildings having different structural configurations, design codes, and building archetypes and one single fit for all buildings is not feasible [38,39]. Additionally, different retrofit alternatives provide a varying degree of strength, stiffness, and ductility enhancement properties and also at varying retrofit costs [40]. Hence, a numerical optimization approach is required to extract the optimal solutions on a community level.

Optimization on a community level considering multi-objective resilience and sustainability indicators could be challenging since formulating an analytical objective function may not be feasible and a numerical optimization may be computationally expensive [41]. This could be solved by establishing surrogates from the fewer outputs of the performance objectives from the expensive black box [42,43]. The sequential sampling technique could be utilized to improve the surrogate at each iteration and utilize as an inexpensive alternative to the black box to extract approximate Pareto-optimal solutions [44]. The approximate Pareto-optimal solutions could provide optimized retrofit costs on a community level and corresponding sustainability and resilience performance indicators. The approximate Pareto-optimal solutions considering expected annual consequences have been investigated but the long-term perspective on sustainability and resilience considering recurrent seismic hazards and stochastic occurrences have not been previously explored [45]. According to the best of the authors' knowledge, a computationally inexpensive community performance enhancement framework for building portfolios considering resilience and sustainability-related multi-objectives in a long-term perspective under stochastic seismic hazards have not been investigated.

Hence, this paper aims to investigate the time-dependent long-term sustainability and resilience of community building portfolios by utilizing a stochastic hazard arrival process. The proposed methodology enhances long-term sustainability and resilience at the community level by utilizing Gaussian process-based multi-objective genetic optimization approach. To make the process computationally efficient, the expensive performance-based assessment tool is replaced with a computationally inexpensive Gaussian process surrogate, which determines the performance enhancements considering retrofit costs on a community level. The proposed framework is then illustrated on a community building portfolio under a stochastic hazard arrival process to demonstrate the methodology. This paper is organized into 6 sections: section (1) provides the introduction of the paper, section (2) outlines the proposed methodology for the long-term sustainability and resilience enhancement framework, section (3) provides the performance-based and long-term sustainability and resilience assessment segment of the methodology, section (4) outlines the surrogate-based optimization segment of the methodology, section (5) illustrates the proposed methodology on community building portfolios, and section (6) provides conclusions and discussions of the paper.

2. Framework for long-term sustainability and resilience enhancement

Long-term sustainability is referred to herein as meeting present needs while preserving resources and minimizing socioeconomic and environmental consequences for future generations. While, long-term resilience involves systems to withstand and recover from shocks, maintain functionality during and after disruptive events, and aim to recover rapidly. The proposed long-term sustainability and resilience assessment and enhancement framework for community building portfolios under seismic hazards is shown in Fig. 1. The framework has three main segments including (1) performance assessment segment acting as a computationally expensive black box, (2) surrogate-based optimization segment, and (3) long-term sustainability and resilience enhancement segment. The performance-based assessment segment consists of two parts including extreme event modeling and damage and consequence assessment.

The extreme event modeling part is utilized to identify the extreme event scenarios and consequently determine their occurrences and intensity measures. After the hazard scenarios are identified and the stochastic hazard arrival process is established, the damage, consequences, and downtimes for all the buildings in the community building portfolios could be determined. The damage, consequences, and downtime assessment requires identifying the fragility and consequence functions for all the buildings in a community building portfolio. The fragility functions are lognormal cumulative distribution functions providing the probability of exceedance of considered damage states of individual buildings depending upon the building archetype and code configurations and can be empirically developed from historical records, numerically computed, or based on expert opinions or judgments [46–49]. The consequence functions are normal or lognormal cumulative distribution functions and are utilized to assess the social, economic, and environmental consequences for the sustainability assessment and downtime for the resilience assessment. These consequences are assessed for all the buildings in a community building portfolio given the damage states of individual buildings. Then, the consequences and downtimes for individual buildings are summed into community-level performance indicators i.e., sustainability and resilience.

The process has to be repeated for all the buildings in a community given hazard arrival time samples and the investigated time horizon. Furthermore, performance enhancement requires decisions including retrofitting individual buildings with various retrofit alternatives to determine optimal performance enhancements on a community level [50]. This requires a numerical optimization technique that requires performing damage and consequence assessments iteratively and for numerous community scenarios of different retrofit alternative settings on a community level depending upon the number of individuals selected in the genetic optimization. Hence, considering these complexities a conventional genetic optimization approach could not be utilized considering the computational aspect [51].

Hence, the second segment of the proposed framework is utilized for retrofit optimization by utilizing Gaussian process-based surrogates. In this segment, a Gaussian-process-based optimization tool assigns retrofit alternatives to all the individual buildings randomly referred to herein as individual. Similarly, a finite number of individuals are established ran-

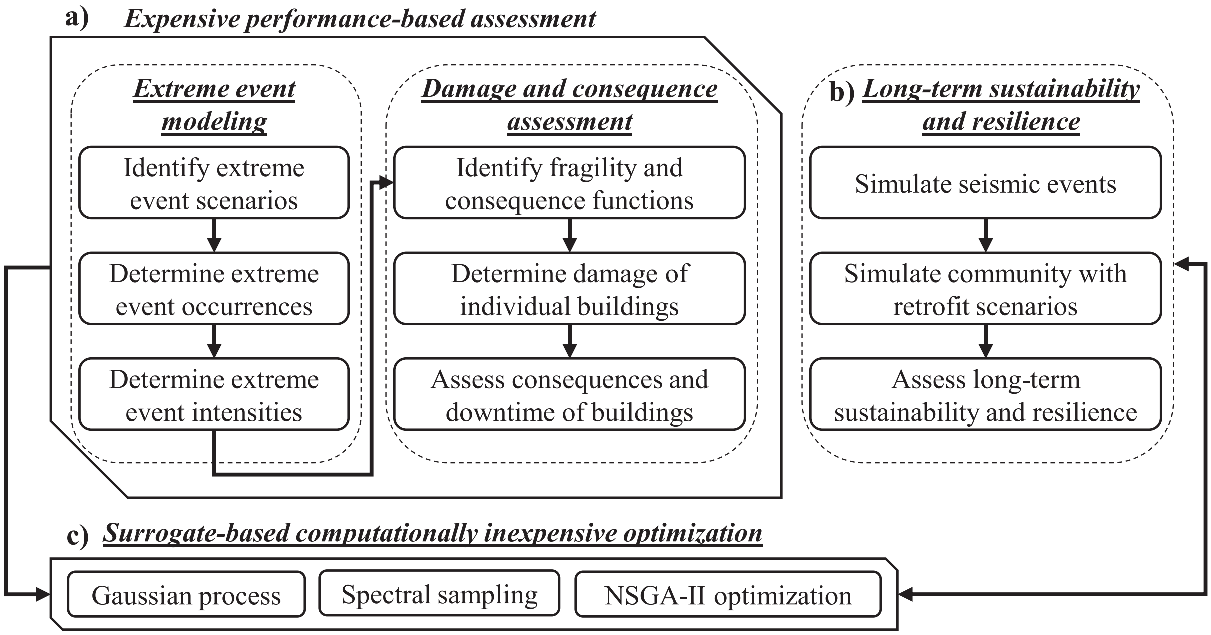

Fig. 1. Proposed surrogate-based long-term sustainability and resilience enhancement framework for community building portfolios.

domly, and expensive performance-based assessment black box is utilized to extract the social, economic, and environmental consequences and downtime of individual buildings. These responses including consequences and downtimes are utilized to build Gaussian process models given the retrofit costs of individual buildings for the entire community building portfolio. The established Gaussian process models are then utilized as computationally inexpensive surrogates for the retrofit optimization given the consequences, downtimes, and retrofit costs. The retrofit optimization can be performed by utilizing any numerical optimization technique and subsequently, approximate Pareto-optimal solutions can be extracted [52]. The approximate Pareto-optimal solutions are improved at each iteration of Gaussian process-based optimization by extracting another individual from the expensive black box by utilizing a hyper improvement indicator.

The third segment utilizes the information related to the consequences and downtimes given retrofit costs for individual buildings during the investigated time and for given hazard arrival samples. The social, economic, and environmental consequences for individual buildings are utilized to evaluate the time-dependent sustainability on a community level and the downtimes for individual buildings given hazard arrival samples during the investigated time are utilized to evaluate the long-term resilience on a community level. The individual segments of the proposed methodology are discussed in detail in the subsequent sections.

3. Long-term sustainability and resilience

This section discusses the expensive performance-based assessment segment and the subsequent long-term sustainability and resilience assessment segment of the proposed framework. The performance-based assessment methodology outlined herein consists of two main parts (1) extreme event modeling and (2) damage and consequence assessment. Extreme event modeling is utilized to simulate the inter-arrival time samples during the investigated time based on the stochastic hazard arrival process. Then, the hazard arrivals are utilized to assess the damage states for all the individual buildings in considered community building portfolios. Finally, the damage states are utilized to assess the consequences and downtimes for the time-dependent long-term sustainability and resilience assessment. The subsequent subsections discuss the performance-based assessment and subsequent long-term sustainability and resilience assessment methodology.

3.1. Expensive performance-based assessment

The seismic hazard is modeled herein by utilizing a stochastic process including the Poisson renewal process and BPT renewal process [53]. The renewal process is also referred to as a counting process in which the inter-arrival times of the counting process are non-negative and are independent and identically distributed (IID). For instance, let $\{X_n,\ n = 1, 2, 3, \ldots\}$ is a sequence of non-negative IID random variables having a distribution f_X and a mean μ. The sequence $\{T_n,\ n \geq 0\}$ can then be defined as follows:

$$T_0 = 0,\ T_n = T_{n-1} +\ X_n = X_1 + X_2 + X_3 + \ldots + X_n,\ n \geq 1 \tag{1}$$

where T_n is a random variable referred to as the n*th* renewal time, while the inter-arrival time X_n is referred to as the n*th* renewal interval. Further, the random variable is defined for the number of renewals during the investigated time t as:

$$N(t) = \sup\left\{n :\ T_n \leq t\right\} \tag{2}$$

where $N(t)$ is the continuous time process called renewal process having distribution f_X given $N(t),\ t \geq 0\}$. In the case of the Poisson renewal process, the inter-arrival times follow an exponential distribution and for the BPT renewal process, the inter-arrival times follow a BPT distribution. The probability density function of the exponential distribution function is expressed as:

$$f_X(x) = \lambda \exp(-\lambda x) \tag{3}$$

where λ is the mean annual frequency of exceedance of a recurrent seismic hazard scenario. The probability density function of the BPT distribution function is expressed as:

$$f_X(x) = \sqrt{\frac{\mu}{2\mu\alpha^2 x^3}} \exp\left\{-\frac{(x-\mu)^2}{2\mu\alpha^2 x}\right\} \tag{4}$$

where μ is the mean return period of the seismic hazard scenario and α represents the coefficient of variation. These probability density functions provide the inter-arrival times of the recurrent hazard events and the intensity measures of the hazard events can be determined by utilizing ground motion prediction models developed from historical records, among others [54].

Given the hazard scenarios, the presented stochastic process could be utilized to model the hazard arrivals during the investigated time, and the ground motion prediction equations or other techniques could be utilized to model the seismic hazard intensity measures. The simulated hazard events are then utilized to assess the damage states of individual buildings by utilizing fragility functions that are lognormal communitive distribution functions providing the probability of exceedance of given damage states as follows:

$$p^i_{DS_k|IM} = \varphi\left[\frac{1}{\beta^i_{DS_k}}\ln\left(\frac{IM^i}{\theta^i_{DS_k|IM}}\right)\right] \tag{5}$$

where $\varphi[.]$ is the lognormal cumulative distribution function, IM^i is the intensity measure at a given building i, $\theta^i_{DS_k|IM}$ is the median fragility function for the k*th* damage state and $\beta^i_{DS_k}$ is the corresponding function dispersion. These damage state exceedance probabilities are utilized to evaluate discrete damage states for all the buildings in a community. The damage states can then be correlated to the amount of material required during the repair of the building that is then correlated with the consequences and downtimes. The social, economic, and environmental consequences and downtimes are estimated by considered consequence functions. More information about estimating the consequences and downtimes can be found in [55–57]. Mathematically the consequences and downtimes for a building can be determined as follows:

$$D^i = \sum_{j=1}^{n}\left[M^i_j * TM^i_j * f\left(C_i\right)\right] \tag{6}$$

where D^i is the socio, economic, and environmental consequence or downtime of building i, M^i_j is the percentage of jth material damage of building i, TM^i_j is the total quantity of building material, and $f(C_i)$ is the consequence function proving the consequence or downtime values for individual buildings.

3.2. Long-term sustainability and resilience

The consequences and downtimes assessed for individual buildings given recurrent seismic hazards are utilized to assess the long-term sustainability and resilience. Sustainability is defined as the ability of a community to meet its needs without compromising the needs of future generations and is considered in terms of social, economic, and environmental consequences [58]. The sustainability-related consequences assessed herein include casualties, repair costs, equivalent carbon emissions, and embodied energy. Resilience is defined as the ability of a community to withstand an extreme event and to recover rapidly from it [59,60]. In this paper, resilience is assessed partially by utilizing the downtimes of individual buildings and determining the percentage of buildings recovered from a seismic hazard during the investigated time. Long-term sustainability and resilience can be mathematically represented as:

$$L_{LT} = \sum_{k=1}^{N(T)} D^I(T) \tag{7}$$

where L_{LT} is the long-term sustainability or resilience, is the considered time horizon, $D^I = \sum_{i=1}^{m} D^i$ is the total consequence or downtime summed for the whole community given a single hazard event considering its probability of occurrence, m is the total number of buildings in a community, and $N(T)$ defines the total number of hazard events during the investigated time considering the probability of occurrences.

During the investigated time, the probability of hazard occurrences varies considering the stochastic hazard arrival process and hence the consequences and downtimes during the investigated time given the probability of occurrences of the utilized earthquake process. The long-term sustainability and resilience can then be determined by adding the consequences and downtimes for all the individual buildings considering the probability of occurrences of the considered hazard scenarios during the investigated time. The subsequent section discusses computationally inexpensive multi-objective optimization segment of the proposed framework.

4. Surrogate-based multi-objective optimization

Extracting Pareto-optimal solutions by utilizing performance-based assessment methodology could be computationally expensive and hence surrogate-based multi-objective optimization is introduced herein as a computationally inexpensive solution. This solution requires establishing a Gaussian process-based surrogate as an alternative to an expensive performance-based assessment tool, spectral sampling technique to extract the sampled functions from the Gaussian process surrogate, acquisition functions to extract the next query point from the performance-based assessment to improve the Gaussian process surrogate, and a numerical optimization technique to converge the multi-objectives for approximating the Pareto-optimal solution. The multi-objective optimization problem is formulated as:

Given:

- The structural archetypes, configurations, retrofit alternatives, and geospatial information of individual buildings in a community building portfolio.
- Intensity measures under considered hazard scenarios, considered materials, and corresponding fragility and consequence functions.

Find:

- Retrofit costs on a community level given consequences and downtimes.

Such that:

- The associated retrofit costs are minimized and the corresponding long-term performance in terms of consequences and downtimes is maximized.

4.1. Dataset for the Gaussian processes

The first step in the surrogate-based optimization is to generate the initial dataset for the considered individuals. The dataset for each individual includes static and dynamic information related to the buildings in a community building portfolio. The static information includes building archetypes, geospatial locations of buildings, stories, number of people present, among others and the dynamic information includes the type of retrofit alternative applied to a building if any. The dataset is then utilized to extract consequences and downtimes for all the buildings by utilizing an expensive performance-based assessment segment. The social, economic, and environmental consequences and the downtimes are then utilized to build the Gaussian process models.

4.2. Prior of the Gaussian process

The Gaussian process models are built for each consequence and downtime for all the considered individuals. The Gaussian process model can be defined by the mean and a covariance function as follows:

$$m(x) := E[f(x)] \tag{8}$$

$$k\left(x, x'\right) := E\left[(y(x) - m(x))\left(y\left(x'\right) - m\left(x'\right)\right)\right] \tag{9}$$

where $m(\,.)$ is the mean function, $k(\,.)$ is the covariance function, $E[.]$ is the expectation of the function $f(.)$, and $y(\,.)$ includes points distributed as a Gaussian process as follows:

$$y(x) \sim GP\left(m(x), k\left(x, x'\right)\right) \tag{10}$$

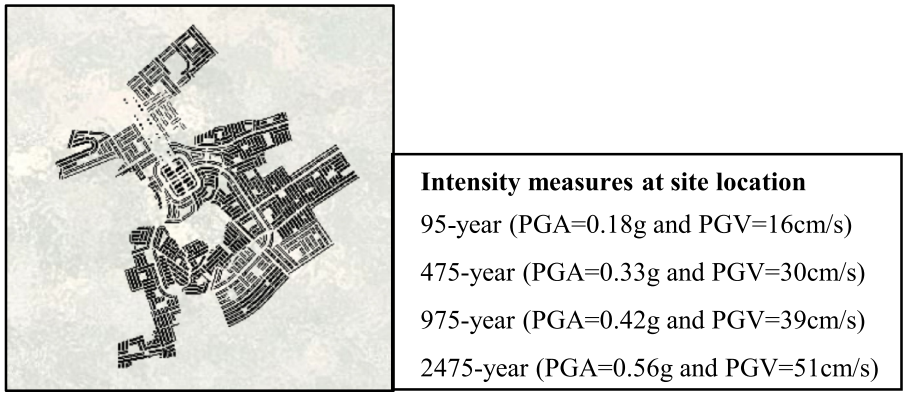

Fig. 2. Spatial distribution of community building structures and considered four hazard scenarios.

where GP (.) represents the Gaussian process with mean $m(x)$ and covariance $k(x, x')$.

4.3. Posterior of the Gaussian process and spectral sampling

The priors of the Gaussian process are updated by utilizing the extracted consequences and downtimes from the initial dataset to develop the posterior based on Bayes' rule as follows:

$$f(x) \sim GP(m(x), k(x, x')|X, Y) \tag{11}$$

where $x, x' \in R^d$ are random input vectors, X, and Y are the input and out of the dataset where the input is related to the dynamic information related to the buildings and output are the consequences and downtimes extracted from the expensive performance-based assessment segment. The next step is to perform spectral sampling to extract functions from the Gaussian process models to inexpensively evaluate the consequences and downtimes given retrofits and a hazard process.

4.4. Multi-objective genetic optimization

The sampled functions are utilized to extract approximate Pareto-optimal suctions by utilizing the genetic optimization approach. For this purpose, the non-dominated sorting and crowding distance genetic optimization technique is utilized and more information can be found in [61,62].

At each iteration, the Gaussian process models are updated and the approximate Pareto-optimal solutions are generated. After a given number of iterations, the converged approximate Pareto-optimal solutions could be extracted. The Gaussian process models are updated by generating a new data point from the expensive performance-based assessment segment by utilizing a hyper-improvement indicator that measures the regions between the non-dominated solutions from a reference point. The next query point is selected such that the maximum hyper-improvement is achieved. The maximum hyper improvement is mathematically presented as follows and more information can be found in [45].

$$x_{n+i+1} \epsilon \arg max \Delta HV\left(y_C, \wp^{\boldsymbol{i}}, \boldsymbol{r}^{\boldsymbol{i}}\right) \tag{12}$$

where y_C is sampled functions from spectral sampling, $\wp^i$ is a converged Pareto-optimal front at a given iteration i and at a reference point r^i, and ΔHV is the change in hypervolume between the two iterations.

5. Illustrative example

The proposed methodology is illustrated on a community building portfolio comprising of residential, commercial, educational, emergency, and healthcare buildings. The community include approximately

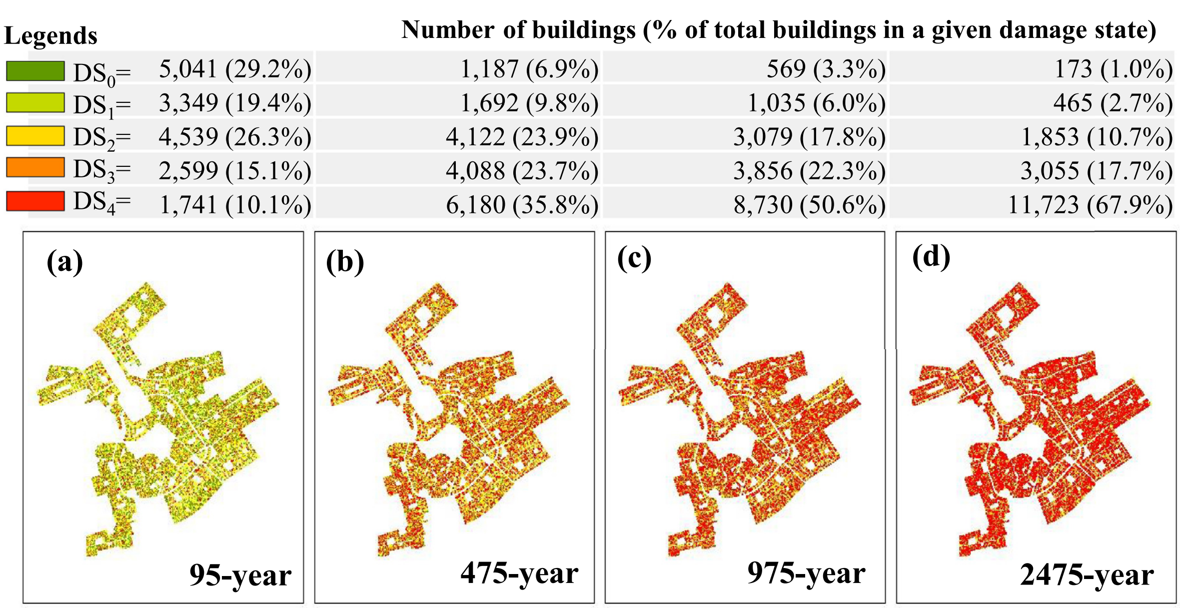

Fig. 3. Damage states of individual buildings under (a) 95-year (b) 475-year (c) 975-year and (d) 2475-year seismic hazard scenarios.

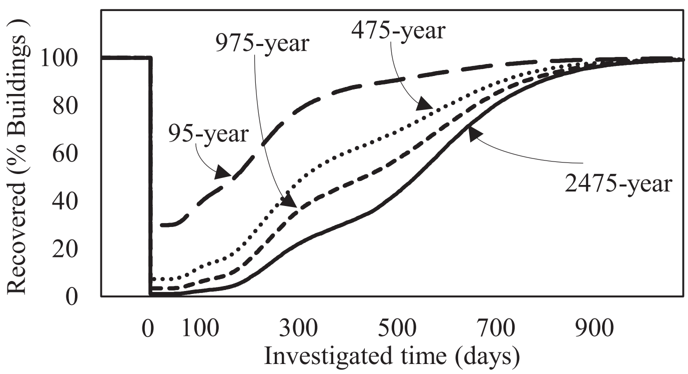

Fig. 4. Resilience in terms of the percentage of buildings recovered during the investigated time under four hazard scenarios.

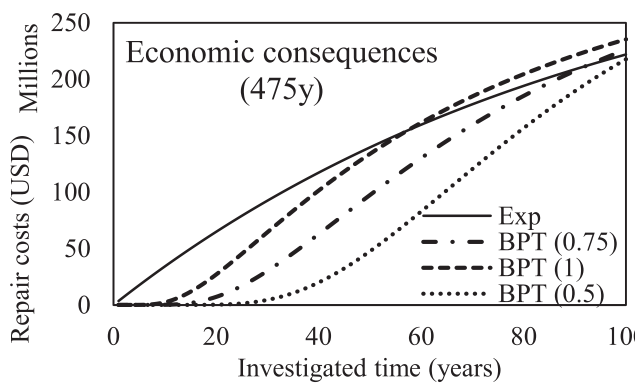

Fig. 5. Long-term economic consequences under design hazard scenario given Poisson and BPT renewal process.

16,653 residential buildings, 591 commercial buildings, and 25 essential facilities, such as educational, emergency, and healthcare facilities. The buildings exhibit a range of structural design code configurations, including pre-code, low-code, moderate code, and high-code, as defined by HAZUS [63]. The community predominantly consists of pre-code to low-code residential buildings with masonry structural configuration and the remaining buildings are reinforced concrete structures with and without the masonry infills. Details concerning the design code configurations, considered retrofits, and building archetypes can be explored from [64–67]. The community building portfolio presented in Fig. 2 along with the considered four hazard scenarios for the illustration of the proposed framework.

The mitigation alternatives considered in this illustrative example include retrofitting individual buildings with different retrofit alternatives. Also, it is important to note that different retrofit alternatives have varying implementation costs and effectiveness in enhancing the resilience and sustainability of individual building structures. Furthermore, the retrofit costs and the subsequent performance enhancement are conflicting in nature i.e., increasing the mitigation costs on a community level may enhance the performance but at a higher retrofit cost. Also, optimizing a community building portfolio having numerous buildings is burdened by huge computational costs, and hence a surrogate-based optimization is introduced herein to enhance the computational efficiency of the approach. The approximate Pareto-optimal solutions are extracted by utilizing this approach that considers performance-based assessment methods along with the surrogate-based optimization technique. The optimized solutions are then investigated for long-term sustainability and resilience investigations. The proposed methodology is illustrated in the subsequent subsections.

5.1. Performance-based damage assessment under seismic hazard scenarios

The performance-based assessment methodology is utilized herein to assess the damage state of individual buildings in the community building portfolio given the intensity measures of seismic hazard scenarios. The selected hazard scenarios include (1) frequent level hazard having 50% probability of occurrence in 50 years of service life of buildings

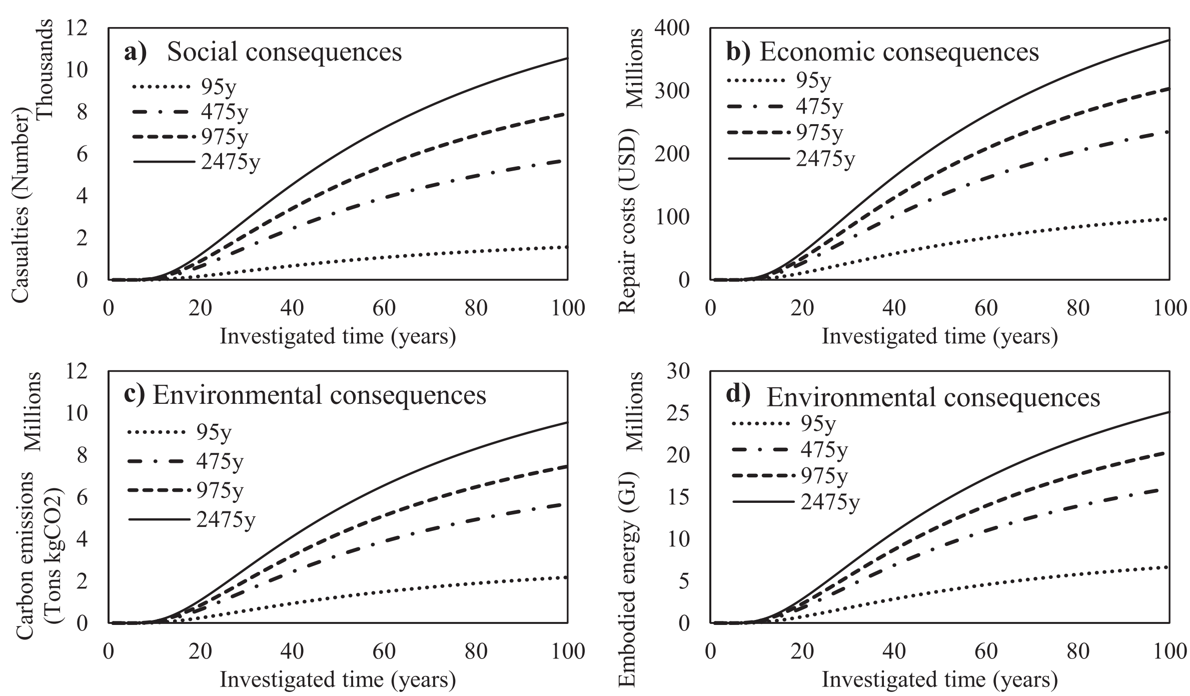

Fig. 6. Time-dependent long-term sustainability under considered hazard scenarios following the BPT renewal process in terms of (a) social consequence (casualties), (b) economic consequence (repair costs), (c) environmental consequence (carbon emissions), and (d) environmental consequence (embodied energy).

i.e., seismic hazard with a return period of 95 years, (2) design hazard scenario having 10% probability of occurrence in 50 years service life (3) rare hazard scenario with 975 years return period, and (4) maximum considered hazard scenario with 2475 years of the return period.

The determined Peak Ground Acceleration (PGA) values in this illustrative example for frequent, design, rare, and maximum considered earthquakes include 0.18 g, 0.33 g, 0.42 g, and 0.56 g accordingly. The five distinct damage states are probabilistically assessed for all the buildings in a community building portfolio under considered hazard scenarios and are illustratively shown in Fig. 3. As shown, with increasing intensity measures, the number of damaged buildings and the damage states increases. For instance, under frequent level seismic hazard, the number of un-damaged buildings are 5041 reduced to 1187, 569, and 173 for design, rare, and maximum considered seismic hazard scenarios. Similarly, the buildings suffering complete damage under frequent level seismic hazard scenarios are 1741 and increased to 6180, 8730, and 11,723 for design, rare, and maximum considered seismic hazard scenarios.

The damage states can then be correlated to evaluate the socioeconomic and environmental consequences and the downtimes for all the buildings in a community building portfolio. These consequences are assessed by utilizing consequence functions. The fragility and consequence functions utilized herein are extracted from multiple sources including HAZUS [63], among others [46,56]. The consequences are assessed in terms of injuries, repair costs, downtimes, carbon emissions, and embodied energy. Sustainability is assessed herein in terms of social, economic, and environmental consequences, and resilience is assessed herein as the percentage of buildings repaired on a community level during the investigated time and the total downtime days on a community level. The social consequences are assessed in terms of the total number of in-

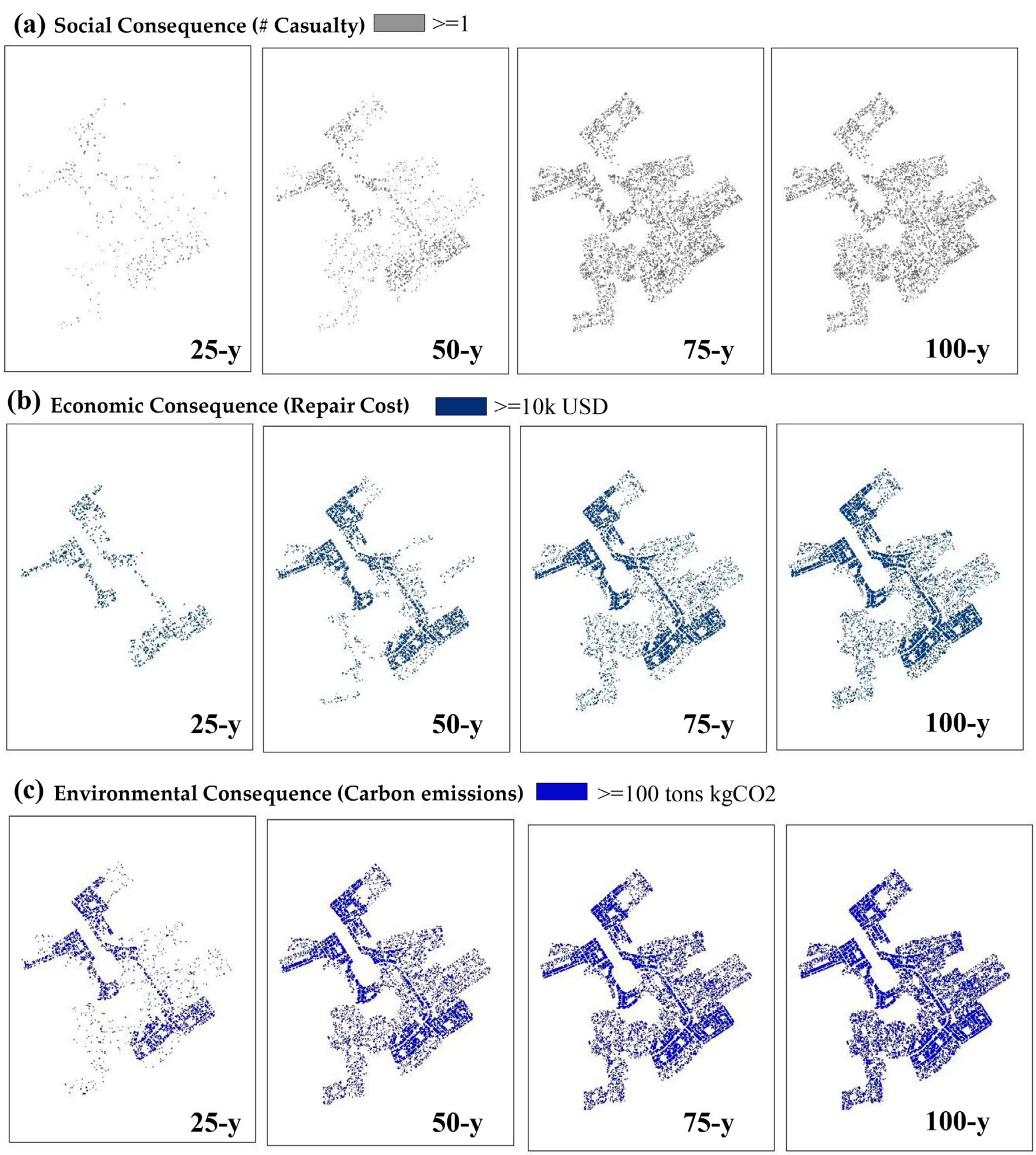

Fig. 7. Social, economic, and environmental consequences during the investigated time: (a) Casualties, (b) repair costs, and (c) equivalent carbon emissions.

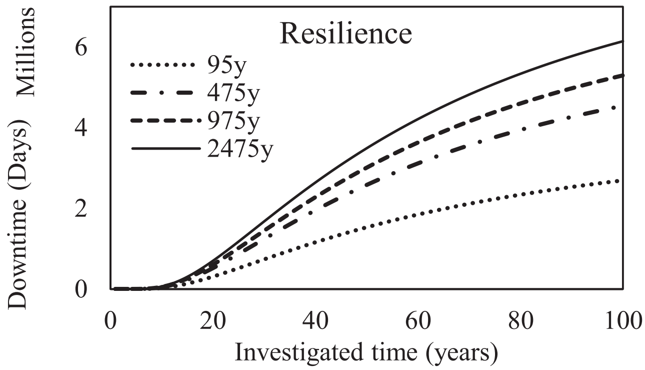

Fig. 8. Time-dependent long-term resilience under considered hazard scenarios following the BPT renewal process in terms of total downtime days.

juries given hazard scenarios, the economic consequences are assessed in terms of total repair costs due to damage to community buildings, and environmental consequences are assessed in terms of total equivalent carbon emissions and embodied energy.

For instance, under four hazard scenarios, the total number of injuries increased from 2261 to 8254, 11,474, and 15,285 given increasing hazard intensities. Similarly, the economic consequences increased from 140 million USD to 341, 440, and 551 million USD under 95-year, 475-year, 975-year, and 2475-year hazard scenarios. The environmental consequences also increased with increasing hazard intensities measured in terms of total equivalent carbon emissions that increased from 3.15 million Tons of kgCO2 to 8.22, 10.8, and 13.8 million Tons of kgCO2. Similarly, the embodied energy increased from 9.66 million GJ to 23.2, 29.5, and 36.4 million GJ under increasing hazard scenarios.

The downtimes are also utilized to evaluate the percentage of buildings being repaired and the percentage of buildings fully recovered from the hazard event during the investigated time. Fig. 4 shows the resilience in terms of the percentage of buildings recovered during the investigated time as a measure of its resilience on a community level and more details about this aspect can be found in [68].

5.2. Long-term sustainability and resilience under seismic hazards

The long-term sustainability and resilience assessment requires modeling the hazard arrival process. In this illustrative example, the Poisson renewal process and BPT renewal process are utilized for comparison purposes and later BPT renewal process is utilized for further illustration of the proposed framework. The considered rate of mean annual frequency of occurrences for the Poisson renewal process for four hazard scenarios is 0.0105, 0.0021, 0.001, and 0.0004 accordingly. The considered return periods for the BPT renewal process for four hazard scenarios include 95-year, 475-year, 975-year, and 2475-year and are utilized as mean in the BPT probability density functions with the coefficient of variation α = 1, 0.75, and 0.5.

As an illustration, the resulting economic consequences for the design hazard scenario under the exponential and BPT distribution are shown in Fig. 5. As shown the Poisson renewal process mostly follows BPT distribution with the coefficient of variation α = 1 under design hazard scenario. However, initially, the Poisson renewal process overestimates the long-term consequences, and approximately after 50 years, it underestimates the consequences as compared to the BPT renewal process with a coefficient of variation α = 1. Hence, considering this information, long-term sustainability and resilience are assessed based on the BPT renewal process with a coefficient of variation α = 1.

The time-dependent long-term sustainability under given hazard scenarios is assessed based on social, economic, and environmental consequences that include casualties, repair costs, carbon emissions, and embodied energy on a community level. A time horizon of 100 years is considered herein as most of the buildings in the developing world are not commonly demolished and stay operational beyond the design-based service life of 50 years. The occurrence times in the BPT renewal process are modeled by utilizing inter-arrival times that follow the BPT distribution. The number of earthquakes is determined during the investigated times based on the inter-arrival times and the investigated time horizons, and is then utilized to assess the time-dependent long-term sustainability and resilience. The long-term sustainability given considered hazard scenarios under the BPT renewal process is shown in Fig. 6. As shown, the social, economic, and environmental consequences increase during the investigated time and the magnitude of consequences is higher for high-intensity seismic hazards. For instance, the casualties at an investigated time of 50 years under considered four hazard scenarios are 887, 3237, 4500, and 5994. Similar trends for other considered sustainability indicators can be observed. Overall, the socioeconomic and environmental consequences are negligible during the first fifteen years of the investigated time and then the consequences continue to increase following the BPT renewal process.

The social, economic, and environmental consequences in terms of casualties, repair costs, and carbon emissions are presented in Fig. 7. As shown, during the investigated time, the considered sustainability indicators point to increased consequences with increasing investigated time.

Similarly, the time-dependent long-term resilience under given hazard scenarios is assessed in terms of total downtime on a community level shown in Fig. 8. A similar trend is observed for the long-term resilience in terms of increasing total downtime during the investigated time and higher values of downtimes under increasing hazard intensity

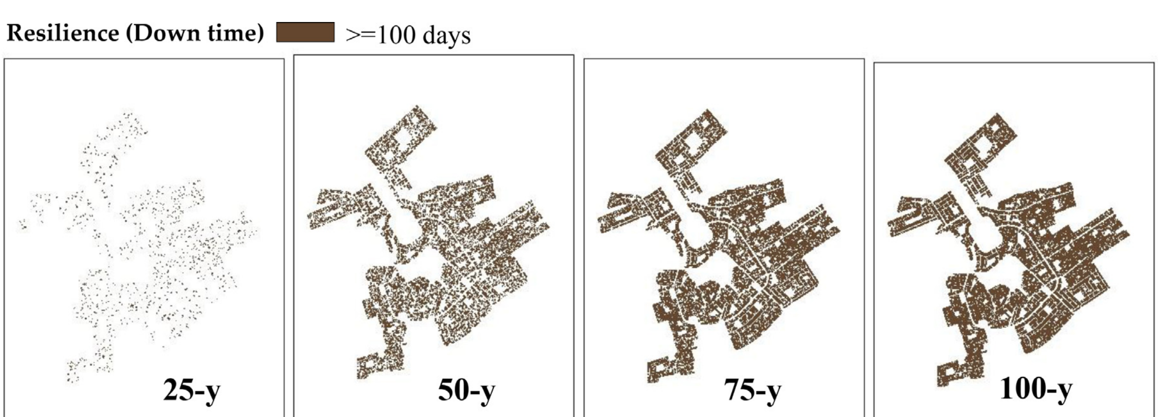

Fig. 9. Downtimes of individual buildings as a measure of community resilience during the investigated time.

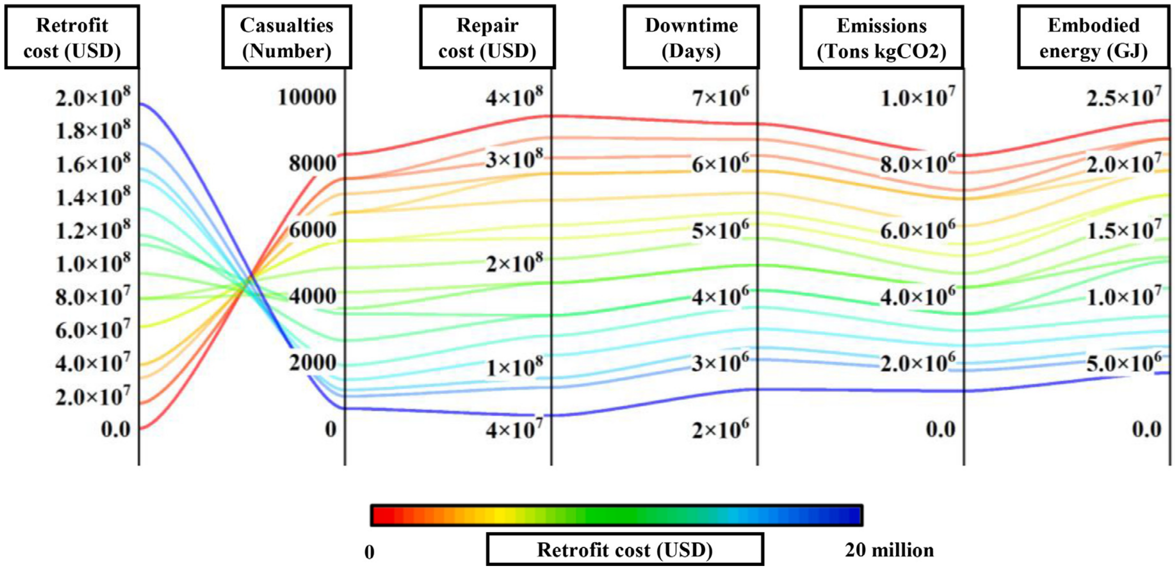

Fig. 10. Approximate Pareto-optimal solutions for resilience and sustainability performance given retrofit costs.

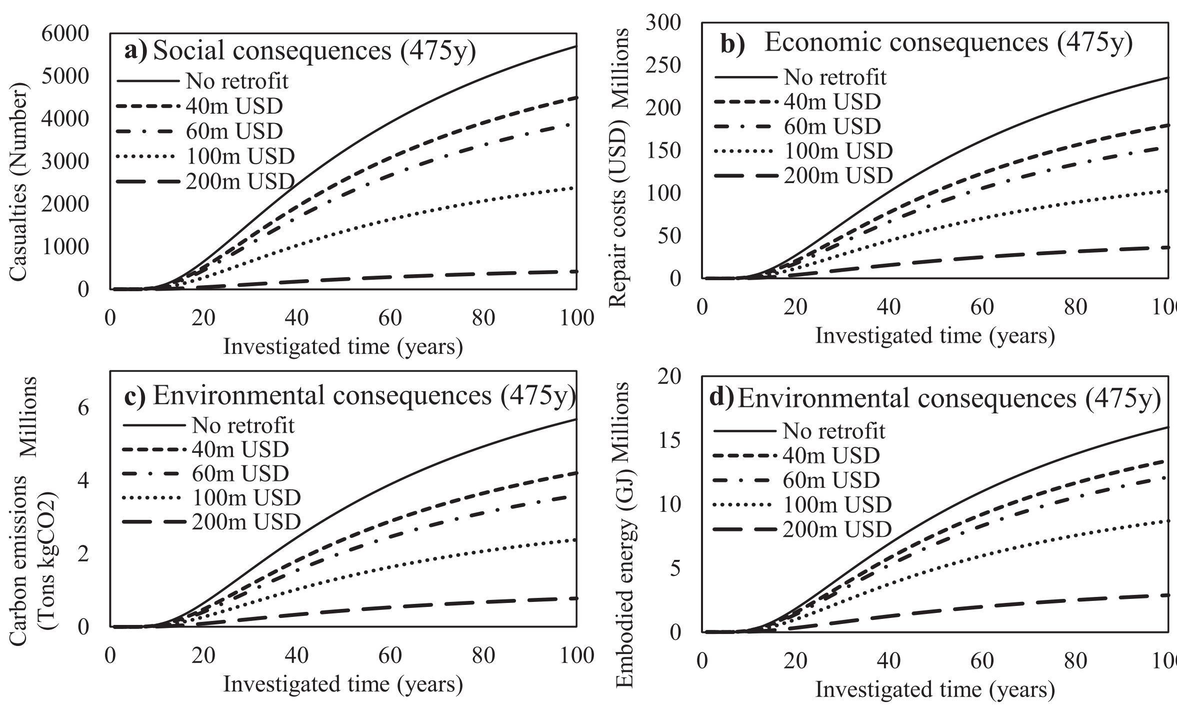

Fig. 11. Time-dependent long-term sustainability under design hazard scenario given different retrofit costs in terms of (a) social consequence (casualties), (b) economic consequence (repair costs), (c) environmental consequence (carbon emissions), and (d) environmental consequence (embodied energy).

scenarios. For instance, at an investigated time of 50 years, the total downtime days for four hazard scenarios of increasing intensity measures are 1.5, 2.58, 3.01, and 3.49 million days.

The resilience in terms of downtime is also presented in Fig. 9 with each dot indicating a building in a community building portfolio having downtime greater than 100 days. As shown, the downtime increase with increasing investigated time.

5.3. Surrogate-based retrofitted long-term sustainability and resilience

The next step is to investigate the long-term sustainability and resilience of community building portfolio given the community retrofits. The presented optimization technique provides sustainability and resilience indicators given the retrofit costs in terms of approximate Pareto-optimal solutions. The Approximate Pareto-optimal solutions in terms of casualties, repair costs, carbon emissions, embodied energy, and total downtime are determined herein. The stopping criteria for the approximate Pareto-optimal solutions are set to 200 iterations considering the balance between the convergence and computational costs.

For illustration, the approximate Pareto-optimal solutions for the design hazard scenario given five sustainability and resilience performance indicators against the retrofit costs are shown in Fig. 10. As shown, the sustainability and resilience indicators improve by increasing the retrofit costs on a community level. For instance, by applying retrofit costs of 100 million USD on a community level, the casualties, equivalent carbon emissions, and embodied energy could be reduced to 58%,

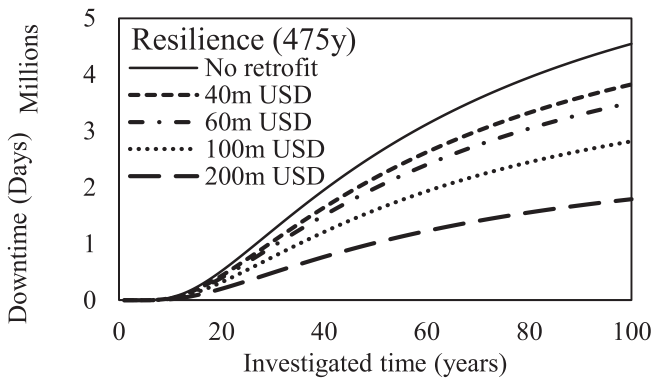

Fig. 12. Time-dependent long-term resilience under design hazard scenario given different retrofit costs in terms of total downtime days.

repair costs could be reduced to 56%, and total downtime days could be reduced to 38%. Similar observations could be made for different retrofit costs implemented on a community level.

The retrofit costs of 40, 60, 100, and 200 million USD is considered herein to elaborate the long-term sustainability and resilience. For that purpose, the time-dependent long-term sustainability considering social, economic, and environmental consequences in terms of casualties, repair costs, equivalent carbon emissions, and embodied energy under the design hazard scenario is shown in Fig. 11. As shown, increasing the retrofit costs reduces the social, economic, and environmental consequences, and increasing the retrofit costs on a community level results in increased long-term sustainability performance. Nonetheless, the long-term sustainability consequences increase during the investigated time. For instance, applying retrofit costs of 40, 60, 100, and 200 million USD results in reducing the casualties by 21%, 32%, 58%, and 93% i.e., the casualties without applying retrofit solution are 8254 and reduced to 6509, 5644, 3448, and 604 by applying given retrofit costs. Similar trends can be observed for other sustainability performance indicators.

The long-term resilience under the design hazard scenario and given retrofit costs is shown in Fig. 12. Similar trends can be observed for the resilience performance indicator as well i.e., the downtime increases during the investigated time, and increasing the retrofit costs on a community level decreases the total downtime indicating increased resilience. For instance, by applying the retrofits on a community level costing 40, 60, 100, and 200 million USD, a decrease of 16%, 20%, 38%, and 61% in terms of downtimes is observed.

Hence, based on the time-dependent long-term assessment and enhancement of social, economic, and environmental consequences and the downtimes, a specific mitigation solution based on different retrofit costs could be selected depending on the long-term resilience and sustainability tolerances and the budgetary constraints of the community stakeholders and decision-makers.

6. Conclusions

This study introduced a framework for enhancing long-term sustainability and resilience by employing surrogate-based multi-objective optimization as a computationally efficient alternative to conventional optimization approaches. The methodology integrated stochastic hazard occurrence modeling and subsequent assessments of damage, consequences, and downtime for all community buildings. The outcomes of these assessments are utilized to evaluate long-term sustainability and resilience. Mitigation alternatives were then employed to enhance long-term sustainability and resilience. The proposed framework was demonstrated on a community buildings portfolio.

Following conclusions may be drawn based the on the proposed framework and considered illustrative example:

1. The stochastic hazard arrival models were implemented to assess the long-term performance in terms of social, economic, and environmental consequences for the sustainability and downtimes for the resilience indicator. For instance, on a community level under design hazard scenario and during the investigated time of 50 years, the total casualties were 3237 with repair costs of 134 million USD and equivalent carbon emissions of 3.22 million tons of $kgCO_2$.
2. The resilience was assessed in terms of the percentage of buildings recovered during the investigated time and the total downtime days on a community level. For instance, under design hazard scenario, 90% of the buildings were fully recovered at day 708 during the investigated time after a hazard event.
3. Mitigation alternatives were utilized to enhance performance given seismic hazard scenarios. For instance, applying a retrofit of 40 million USD under a design hazard scenario, 21% reduction in casualties, 16% reduction in downtimes, and a 24% reduction in repair costs was observed.
4. Applying retrofits on a community level resulted in enhanced long-term sustainability and resilience performance. For instance, applying retrofit costs of 40, 60, 100, and 200 million USD results in reduced repair costs of 24%, 31%, 56%, and 85%. Similar trends were observed for other sustainability and resilience performance indicators.

In summary, the proposed framework considered stochastic hazard arrivals to evaluate the long-term resilience and sustainability and utilized these indicators to enhance the performance considering retrofit alternatives to optimize community well-being and decision-making under recurrent seismic hazard scenarios. The conclusions provided in this paper are based on the assumptions on the construction costs of individual buildings, number of people living in buildings and subsequent consequence values. Nonetheless, the conclusions may provide a roadmap to assess meaningful information to the community stakeholders and decision makers to assess and enhance the performance given mitigation alternatives.

Relevance to Resilience

The article contributes to Resilience because (1) The paper is explicitly focused on resilience and sustainability as highlighted in the paper title, (2) the paper is focused on community building portfolios resilience, and (3) the paper is focused on natural hazard resilience i.e., resilience under stochastic seismic hazards.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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