Adaptation Optimization of Residential Buildings under Hurricane Threat considering Climate Change in a Life-cycle Context

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Abstract:

Due to urbanization, the number of residential buildings in the coastal areas has increased significantly. Additionally, due to the increase in sea surface temperature associated with climate change, the intensity and frequency of hurricanes has increased substantially. This paper presents a systematic framework for the optimal adaptation of residential buildings at a large scale under various scenarios of impending climate change during a long term interval. Different adaptation strategies are investigated to ensure adequate structural performance and to mitigate the damage loss and adverse consequences to the society. A genetic algorithm based optimization process is adopted to determine the optimal adaptation types associated with buildings within an investigated region. The framework considers the probabilistic occurrence models of hurricanes, structural vulnerability of typical residential buildings, possible climate change scenarios, and optimization of various climate adaptation strategies in a life-cycle context. The proposed approach is illustrated on residential buildings located in Miami-Dade County, Florida.

Key words: Climate change; Adaptation; Life-cycle loss; Optimization; Residential buildings; Hurricanes

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1. Introduction

With a large percent of population living in the coastal areas, research associated with retrofit/adaptation strategies to reduce the threat of hurricanes to the society is of critical importance. Additionally, due to the effects of climate change and population growth, the damage of buildings under hurricanes has the potential to increase significantly in the coastal areas. The majority of the residential buildings in the United States is made of light-frame structures, which are vulnerable to the wind-related hazards. Therefore, wind-related vulnerability of structures has received increasing attention. The majority of previous studies have focused on the structural performance and loss assessment under hurricanes (Pinelli et al. 2004; Gurley et al. 2005; Vickery et al. 2006; Li and Ellingwood 2009). This paper aims to propose a framework to aid the optimal adaptation of residential buildings considering climate change effects in a life-cycle context.

Nowadays, temperature, precipitation, sea level, and coastal storms are all rising at elevated rates, which are related with the greenhouse gas (GHG) emissions. Based on Cayan et al. (2008), due to the continuing increases of global GHG emissions, the temperature in California is expected to increase by 1.5 - 4.5°C by end of this century. According to Emanuel (2005), the increase in temperature of 1°C can result in an increase of the peak wind speed of a cyclone by 5%. Along with changes in climatic conditions, the earth faces irreversible and catastrophic consequences. Therefore, climate change is an issue that should be recognized worldwide and increased attention must be placed on strategies to design and maintain infrastructure systems that are safe, damage tolerant, and sustainable to cope with the climate change. Understanding how climate change affects the life-cycle performance of buildings is needed to improve preparedness prior to extreme disasters (Dong and Frangopol 2016). Consequently, there is an urgent need for an investigation of building performance under the impact of climate change and this aspect is addressed in this paper.

The previous studies associated with climate change were mainly dealing with the modeling of changing climate and studies on the structural adaptation are still needed. The majority of current performance assessment of buildings under hurricanes assumed that wind speeds are stationary with time without considering the climate change effects. In this paper, the non-stationary aspects with regard to wind climatology will be considered in the performance evaluation process; this can lead to improved preparedness prior to disasters by incorporating the effects of climate change. The effects associated with continuing change in intensities and probabilities of hurricanes are investigated in this paper.

Generally, the structural vulnerability under wind-related hazard is associated with wind speed. The structural performance loss under hurricanes can be represented by the structure showing significant signs of distress, which may include the collapse of the roof or the loss of lateral capacity of the shear walls or a transverse wall. The collapse of roof is assumed to occur when all the roof sheathing is lost; while the loss of lateral capacity of the building occurs when the shear wall capacity is exceeded for the entire building. Accordingly, several vulnerability models for buildings subjected to wind hazard have been developed (Huang et al. 2001; Ellingwood et al. 2004; Lee and Rosowsky 2005; van de Lindt and Dao 2009). In this paper, a structural vulnerability function in terms of wind speed is adopted.

The traditional approach of cost–benefit analysis considering the changes in construction and design has been used to compare the costs of implementing proposed changes at some point in the future with the estimated discounted reduction in life-cycle loss. The cost-benefit analysis will be conducted herein to investigate the efficiency associated with different structural adaptation strategies and incorporated within the optimization process to determine the optimal adaptation strategies. The adaptation strategies associated with retrofit/strengthen actions are investigated herein. An adaptation strategy can improve structural performance significantly. Relatively little attention has been addressed to quantify the costs and benefits of climate adaptation strategies (e.g., retrofitting, strengthening, and enhanced designs to reduce vulnerability). Bjarnadottir et al. (2011) computed the cost effectiveness of adaptation strategies using deterministic cost-benefit analysis; Stewart and Deng (2015) investigated the climate adaptation for Australian housing considering strengthening the new houses; Unnikrishnan and Barbato (2016) conducted the performance-based cost-benefit analysis of different storm mitigation actions on residential buildings without considering climate change; Li et al. (2016) investigated the effects of time-variant hurricane intensity and frequency on the building damage. The importance of recognizing and identifying optimal adaptation strategies under climate change in a life-cycle context is needed and addressed in this paper. Furthermore, to the best of authors' knowledge, there is no research reported to establish the optimum adaptation plans of residential buildings under hurricane at a large scale considering uncertainties and climate change effects.

The main purpose of this paper is to conduct the performance assessment and optimization process of built infrastructure under hurricanes by incorporating possible climate scenarios and to propose a decision making tool to determine the optimal structural adaptation of residential buildings. This paper will assess the damage performance, life-cycle loss, cost-effectiveness of adaptation measures, and optimal adaptation plans for residential buildings in a life-cycle context. The proposed approach is illustrated on a residential area located in Miami-Dade County, Florida.

2. Performance assessment of buildings under hurricane

The structural vulnerability under wind-related hazard can be expressed as a function of wind speed. In order to investigate building performance under hurricanes, the hazard scenario and intensity associated with the wind speed should be firstly identified. A Poisson process provides a reasonable model of hurricane occurrence (Georgiou 1985). Assuming hurricane occurrences as a Poisson process, the probability that n hurricanes will occur within a time interval [0, t_{int}] is

$$P(N=n)=\frac{(\lambda t_{\mathrm{int}})^{n}\exp(-\lambda t_{\mathrm{int}})}{n!} \quad (1)$$

where λ is the mean occurrence rate of hurricanes. For a stationary hurricane process, λ is constant over time. The prediction of the wind associated with a hurricane has been widely investigated by Georgiou (1985), Huang (1999), and Cui and Caracoglia (2016). Generally, the Weibull distribution is an appropriate model of the wind speed. Based on the recorded hurricane wind speeds of Miami-Dade County, Florida, the hurricane wind speed can be fitted by a Weibull distribution (Li et al. 2016). The Weibull distribution is associated with a model of the 3-s gust wind speed. The cumulative distribution function (CDF) of the hurricane wind speed v is

$$F_V(v)=1-\exp\left[-\left(\frac{v}{u}\right)^{\alpha}\right] \quad (2)$$

where u and α are two site-specific parameters for the Weibull distribution associated with wind speed.

A vulnerability model estimates the building damage caused by wind and various models have been investigated previously (Huang et al. 2001; Ellingwood et al. 2004; Lee and Rosowsky 2005; van de Lindt and Dao 2009). Huang et al. (2001) developed a damage model for single family housing units using Southeastern U.S. insurance data resulting from hurricanes Hugo and Andrew. Accordingly, the building damage ratio D_r associated with single family units is expressed as (Huang et al. 2001)

$$D_{r0}(v_s) = \begin{cases} \exp(0.252 v_s - 5.823)/100 & v_s \le 41.4 m/s \\ 1 & v_s > 41.4 m/s \end{cases} \quad (3)$$

$$D_{r0}(v) = f_1 \cdot f_2 \cdot D_{r0}(v_s) \quad (4)$$

where v_s is the surface wind speed; and f_1 and f_2 are the parameters to adjust the wind speed and location of the investigated buildings. This model is based on the mean surface wind speed with a 10-min duration, while wind contour maps in ASCE-7 are associated with 3-s gust (ASCE 2006). A factor f_1 of 0.7 is adopted to adjust the 3-s gust stipulated in wind speed maps to the surface wind speed. The effect of location of the buildings on the vulnerability analysis is considered by using f_2. This damage assessment model has been widely adopted within structural damage assessment under wind effects (Huang et al. 2001; Bjarnadottir et al. 2011; Li et al. 2016). Other vulnerability models can also be incorporated to investigate the building performance under hurricanes.

3. Climate change scenarios

Climate change can increase the climate-related hazard frequency and intensity; in turn, this can cause an increase of structural damage and loss under hazard effects. In order to investigate the performance of buildings under changing climate, it is necessary to identify the possible future warming climate scenarios. Generally, future climate scenarios are projected by defining GHG emissions considering changes in population, economy, technology, energy, and land use. The Intergovernmental Panel on Climate Change (IPCC 2014) stated that the warming of the climate system is unequivocal and the changing climate can affect hundreds of millions of people by increasing the intensity and frequency of coastal hurricane and flooding. The hurricane wind speeds are predicted to increase by 10% in 50 years due to climate change (Bjarnadottir et al. 2011). Based on the climate change scenario proposed by the Intergovernmental Panel on Climate Change (IPCC), the frequency and intensity of hurricanes depend on the Representative Concentration Pathways (RCP) scenarios (van Vuuren et al. 2011). The probability density function (PDF) of the wind speed under the changing climate is investigated herein; additionally, the corresponding effects of the increasing wind speed on the buildings are compared with the cases associated without considering climate change.

The effects associated with continuing change in intensities and frequencies of extreme wind associated with hurricanes are investigated herein. Specifically, the quantitative effects of climate change on wind engineering are investigated, considering hurricane frequency and intensity. A modified Weibull distribution with time-dependent parameters is adopted. To describe a non-stationary wind process due to climate change, the parameters associated with wind are treated as time-variant. The time-varying CDF of the wind speed during a hurricane is

$$F_V(v,t) = 1 - \exp[-(\frac{v}{u(t)})^{\alpha(t)}] \quad (5)$$

$$u(t) = u_0 + f_u t^{\varsigma_u} \quad (6)$$

$$\alpha(t) = \alpha_0 + f_\alpha t^{\varsigma_\alpha} \quad (7)$$

where u_0 and α_0 are the two site-specific parameters for the Weibull distribution without considering climate change; f_u is the annual hazard intensity amplification coefficient associated with u considering the climate change; f_α is annual amplification coefficient for α considering the climate change effects; and ς represents the changing rate associated with the parameters for the Weibull distribution. $\varsigma = 1$ indicates a linear increase, while $\varsigma > 1$ denotes a non-linear increase. Considering the effects of climate change, the probability of occurrence of the natural hazard is increasing. Herein, the hurricane occurrence rate $\lambda(t)$ is also assumed to be time-varying due to the changing climate and can be expressed as (Dong and Frangopol 2016)

$$\lambda(t) = \lambda_0 + f_o t^{\zeta_o} \tag{8}$$

in which f_o is the annual increment in the occurrence rate of hurricanes and λ_0 is the occurrence rate without considering climate change.

4. Loss assessment in a life-cycle context

The losses estimated should include losses caused by both structural damage and property (e.g. contents and nonstructural components). The direct repair loss is calculated based on the damage ratio associated with a structure under a given hurricane scenario. Indirect losses can also be considered within the loss assessment process. Furthermore, hurricanes may cause environmental impact, as new materials are used and greenhouse gases are emitted during repair and rehabilitation actions after a hurricane event (Stewart et al. 2013). Indirect losses were estimated for Hurricane Katrina as \$42 billion or 39% of direct losses (Hallegatte 2008). The damage loss in monetary term is investigated in this section. Given the wind intensity associated with the hurricane event, the damage ratio of the building can be computed using Eqs. (3) and (4). Then, the expected loss l of the building under the occurrence of the hazard can be computed as

$$l = C_d \cdot D_r \tag{9}$$

$$C_d = C_{Di} + C_{Idi} + C_{Envi} = C_{Di}(1 + r_{IDr} + r_{DEnr}) \tag{10}$$

where C_d is the investigated building failure cost; D_r is the damage ratio of the building under a given hurricane scenario; C_{Di} is the direct cost (e.g., construction cost); C_{Idi} is the indirect cost; C_{Env} is the environmental cost; r_{IDr} is the ratio between the indirect and direct cost; and r_{DEnr} is the ratio between environmental and the direct cost. The repair loss, related to the hurricane induced structural damage, is emphasized herein. This cost depends on local labor cost, availability of materials, and local construction practices, among others. Given more information, indirect and environmental loss can also be incorporated within the consequence evaluation process.

As climate change is a long-term issue, it is crucial to incorporate life-cycle engineering within the evaluation process of climate change effects on infrastructure systems and to identify its critical parameters that can significantly affect life-cycle performance. It is also necessary to quantify, in a life-cycle context, the cost and benefit of different structural adaptation strategies to improve the performance of built infrastructure under a changing climate. Thus, life-cycle engineering should be incorporated within the assessment and decision making process (Frangopol 2011). Given the occurrence of the hurricane following a Poisson process, the total life-cycle loss of the building during the time interval [0, t_{int}] can be expressed as (Wen and Kang 2001)

$$LC(t_{\text{int}}) = \sum_{i=1}^{N(t_{\text{int}})} l(t_k) \cdot e^{-\gamma t_k} \tag{11}$$

where $N(t_{int})$ is the number of hazard events that occur during the time interval; $l(t_k)$ is the expected loss at time t_k given the occurrence of the hurricane; and γ is the monetary annual discount rate. Given $N(t_{int}) = \lambda_f \times t_{int}$, the total expected life-cycle loss can be computed as (Yeo and Cornell 2005; Dong and Frangopol 2016)

$$E[LC(t_{\text{int}})] = \frac{\lambda_f \cdot l}{\gamma} \cdot (1 - e^{-\gamma \cdot t_{\text{int}}}) \tag{12}$$

where l is the expected annual loss of a building under a given hurricane event. The group of structures considered herein is a group of residential buildings, which have similar characteristics, such as number of floors, material types, and geometrical pattern. Accordingly, the buildings located in the same neighborhood and constructed during the same period can be classified as one type of building. The total loss associated with spatially-distributed buildings under a given hurricane event is

$$RL = \sum_{i=i}^{n_{bu}} l_i \tag{13}$$

where n_{bu} is the number of buildings within the investigated region (e.g., Miami-Dade County, Florida). Then, the expected total life-cycle loss of buildings within an investigated region can be computed as

$$E[TLC(t_{\text{int}})] = \frac{\lambda_f \cdot RL}{\gamma} \cdot (1 - e^{-\gamma \cdot t_{\text{int}}}) \tag{14}$$

5. Optimal structural adaptation considering life-cycle loss and cost-benefit

Adaptation actions refer to enhance building capacity by increasing the ability of individuals and groups of structures subjected to hazard effects. Adaptation actions should be adopted to prevent or to minimize potential climate change impacts to the society. The structural adaptation under climate change may include enhancement of design standards, retrofitting or strengthening of existing structures, and utilization of new material (Stewart and Deng 2012). For example, adaptation strategy can be associated with a new design of infrastructures using enhanced design codes to increase structural capacity under wind hazard.

The adaptation strategy considered herein is to enhance the existing and/or new residential buildings by improved design codes. The vulnerability of the retrofitted and/or new constructed residential buildings is expressed as

$$D_{ir}(v) = \left(\frac{1.0 - R_{ad}}{1.0} \right) \cdot D_{0r}(v) \tag{15}$$

where R_{ad} is the enhancement/reduction ratio associated with different adaptation actions. R_{ad} considered herein is assessed based on the timing (i.e., years) of building construction. The building within the Miami-Dade County, FL, is divided into four classes based on the year of construction, i.e., pre-1970, 1970-1985, 1986-1997, and after 1997. The enhancement/reduction ratio R_{ad} associated with the four classes is -0.15, 0, 0.2, and 0.3, respectively (Bjarnadottir et al. 2011). The enhancement factor associated with new construction is also investigated herein and R_{ad} is assumed to be 0.5 for the new constructed buildings. The cost associated with structural adaptation is also considered in the evaluation process. The total cost of adaptation actions for an investigated region can be expressed as

$$C_{Ada} = \sum_{i=1}^{n_{bu}} c_{i,Ada} \tag{16}$$

$$c_{i,Ada} = r_{Ada} c_{REB,i} \tag{17}$$

$$r_{Ada} = \left(\frac{1.0 - R_{ad,m}}{1.0 - R_{ad,n}} \right) \cdot r_c \tag{18}$$

where $c_{i,Ada}$ is the adaptation cost associated with building i; r_{Ada} is the ratio of adaptation action to the rebuilding cost; $c_{REB,i}$ is the rebuilding cost of the building i; r_c is the standard adaptation cost ratio; and $R_{ad,m}$ is the enhancement/reduction ratio associated with building type m (year of construction). Herein, the adaptation action refers to update the buildings that was built earlier to the buildings that was constructed later by using an updated code (Bjarnadottir et al. 2011). For instance, a building that was constructed before 1970 can be updated to the building types that was built within the time interval 1986 - 1997 or built after 1997. The adaptation cost is related with many parameters, such as structural configuration, design and construction practices, and labor cost. Thus, it is difficult to estimate the costs; while given more information this model can be easily updated and incorporated within the cost estimation process.

Cost-benefit analysis can be used to compare the cost and benefit of different structural adaptation strategies over an investigated time interval (Dong et al. 2016). The cost-benefit analysis involves determining the cost and benefit associated with structural adaptation. Quantification of the relationship between benefit and cost associated with structural adaptations can facilitate an effective decision-making process regarding the adaptation procedure. The benefit of adaptation actions performed on buildings should be evaluated considering a probabilistic hurricane model and the building performance during a certain time interval. The loss of a building with and without adaptation actions can be assessed using life-cycle analysis. The flowchart of the cost-benefit analysis of structural adaptation strategy is indicated in Figure 1. The cumulative life-cycle loss associated with hurricane loss of investigated single buildings without adaptation action can be computed by using Eq. (14). Consequently, the benefit of adaptation is evaluated by subtracting the life-cycle loss considering no adaptation from the life-cycle loss corresponding the case with adaptation performed. Therefore, the benefit associated with the adaptation plan of buildings within an investigated region can be computed as

$$B_{BS} = TLC_{BS,NA} - TLC_{BS,WA} \tag{19}$$

where $TLC_{BS,NA}$ and $TLC_{BS,WA}$ are the life-cycle loss of the buildings under hurricane effects without and with adaptation actions, respectively. Then, given the total adaptation cost of the buildings C_{Ada}, the benefit-cost indicator (B_{BS} - C_{Ada}) of adaptation strategies can be assessed. Values less than 0 indicate that adaptation is not cost-effective while values greater than 0 denote that it is beneficial to perform adaptation.

For the optimal structural adaptation management, an optimal decision should be made regarding the types of adaptation actions on the buildings within the investigated region under limited resources (Dong et al. 2014). The two objectives considered are the expected life-cycle loss and the total adaptation cost, which are employed within an optimization procedure as the objective functions selected to be minimized. The optimization process is indicated in Figure 2. As shown, firstly the optimization process sends the candidates for the design variables (i.e., adaptation actions applied at the beginning of the time interval investigated to each buildings within the investigated region) to the performance (i.e., objective 1) and cost (i.e., objective 2) modules which compute the value of each objective function associated with life-cycle loss and total adaptation cost. The outcome of the performance module is the expected total life-cycle loss during the investigated time interval, considering the hazard probability, structural vulnerability, damage, and loss. As indicated in Figure 2, the cost module of the optimization process is used to compute the total structural adaptation cost within the investigated region. Genetic algorithms (GAs) are adopted with an adequate number of generations to obtain the set of Pareto optimum solutions associated with the bi-objective problem. The bi-objective optimization problem is formulated as follows:

Given:

- Representative hurricane scenario (probability of occurrence and intensity) for the region under investigation (information associated with Eqs. (1) and (2))

- Configuration of the investigated building groups considering the physical characteristics, location, structural damage ratio of different types (Eqs. (3), (4), and (15))
- Effects of structural adaptation on the building performance within the investigated region
- Consequence evaluation of building failure under the hurricane effects (Eqs. (9) and (10))
- Climate change prediction models considering hazard intensity and frequency (Eqs. (5) to (8))
- Investigated time interval (t_{int}) and monetary annual discount rate (γ)

Find:

- Type of structural adaptations on each building within the investigated region at the beginning of the investigated time interval

Objectives:

- Minimize the total life-cycle loss associated with all the buildings within the investigated region during the investigated time interval/to maximize the benefit associated with structural adaptation actions in a life-cycle context (Eqs. (14) and (19))
- Minimize the total structural adaptation cost for the entire region under investigation (Eq. (16))

6. Illustrative example

The proposed approach is illustrated on a group of single family residential buildings located in Miami-Dade County, Florida. The buildings are classified by the distance to the shore and the year of construction. Based on the Planning Research Section (PRS 2003), in 2000 there were 452,000 single family housing units in Miami-Dade County, while about 42% (189,840) of buildings were built before 1970, about 30% (135,600) built between 1970 and 1985, about 17% (76,840) built between 1986 and 1997, and 11% (49,720) built after 1997. This survey data is adopted herein for illustrative purpose. Furthermore, 20% of these residential houses were located within 1 km of the shore, 60% of houses were located within 10 km from the shore, and the remaining 20% were located further than 10 km (PRS 2003). Based on the year of construction and location of the building, the buildings investigated herein are classified into 12 types, and denoted as 1 to 12. The 12 building types are indicated in Figure 3(a). Within Miami-Dade County, there are 27 hurricanes that occurred during the 110-year time interval and the average annual number of the hurricanes that occurred in this region is 0.245. In this paper, the annual loss and expected life-cycle loss associated with different types of buildings under hurricanes are investigated. The ultimate goal of this example is to apply the proposed bi-objective optimization methodology considering climate change and life-cycle engineering to determine the optimal structural adaptation strategies of buildings within the investigated Miami- Dade County, FL.

6.1 Building damage assessment

The initial step within the illustrative example is to compute the performance of buildings under hurricane effects. In order to compute the performance of buildings under hurricanes, the characteristics of wind speed at the locations of buildings should be identified. The wind speed associated with hurricane events is derived from existing data by fitting a Weibull distribution as indicated in Eq. (2) (Vickery et al. 2000; Li et al. 2016). Based on the recorded hurricane wind speed data in Miami-Dade County, it was found that the two Weibull parameters are u_0 = 35.9 m/s and α_0 = 2.06 (Li et al. 2016). The Monte Carlo simulation (MCs) is adopted herein to generate the random variable associated with the wind speed. Given the hurricane intensity in terms of wind speed at the locations of buildings, the damage ratio of investigated building considering the year of construction and distance to shore is computed using Eqs. (3) and (4). Three exposure categories of the buildings are considered in this paper. For the buildings within 1 km from the shore, f_2 = 0.9; while values of f_2 are 0.8 and 0.72 for the buildings located within 1-10 km and larger than 10 km, respectively (Bjarnadottir et al. 2011). Given the generated wind speed using MCs, the damage ratio of the investigated building can be assessed by using Eq. (4). Subsequently, the probabilistic damage ratio of the investigated single buildings under the extreme wind scenarios is obtained. Then given the probabilistic damage ratio, the probability of exceedance of a damage ratio associated with the buildings built during different time intervals is shown in Figure 4. As indicated, the year of construction has a large effect on the building damage ratio under hurricane scenarios and the probability of exceedance of a certain damage ratio increases with the building age. For instance, the probability of exceeding damage ratio of 0.4 is 0.29 for the building built after 1997, while this value increases to 0.34 associated for the building built before 1970.

6.2 Loss assessment of buildings

The regional loss of the buildings under hurricanes is computed based on their performance and hurricane scenarios. The expected value of the regional loss is the sum of the loss associated with all the buildings located in the investigated region. Given the probabilities of the building failure associated with different building types, the annual repair loss of a single building is computed using Eq. (9). As buildings near to coastal area are usually priced higher than those located further inland, the costs of the investigated standard single-family house in Miami-Dade County associated with the buildings within 1 *km*, and 1 to 10 *km*, and further than 10 *km* are 250,000, 225,000, and 200,000 US$, respectively. The loss associated with direct repair is emphasized in this paper. Then, the annual total direct repair losses of the buildings within 1 *km*, 1 to 10 *km*, and further than 10 *km* of the shore are computed. Given the occurrence of hurricanes, the probability of exceedance associated with the annual loss of buildings within different locations is shown in Figure 5(a). As indicated, the buildings within 1 – 10 *km* reveal the largest loss. The contribution of loss associated with buildings of different years of construction to the total loss of buildings within 1-10 *km* is shown in Figure 5(b). As indicated, the buildings built before 1970 contribute significantly to the total annual loss of the buildings located in the investigated region.

Given the occurrence model of the hurricanes and loss of the buildings under the occurrence of hurricanes, the life-cycle loss is computed using Eqs. (12) and (14). Herein, the monetary annual discount rate γ is assumed 2%. The expected total life-cycle loss associated with all the investigated buildings within the Miami-Dade County is shown in Figure 6(a). As indicated, the investigated time interval (e.g., 25, 50, 75, and 100 years from 2016) has a large effect on the expected value of the life-cycle loss of the buildings. Additionally, the effect of monetary annual discount rate on the expected life-cycle loss is also investigated. The relevant results are shown in Figure 6(b). As indicated, the annual discount rate of money can affect the expected value of the life-cycle loss significantly and, therefore, should be paid special attention.

The effects of climate change on the life-cycle loss are also investigated in this paper. Herein, the intensity amplification factor associated with wind speed is assumed to increase from 1.1 to 1.5 in 50 years associated with different climate change scenarios. The effects of climate change on the hurricane intensity are considered by using Eqs. (6) and (7). The linear increases associated with the hazard intensity and frequency are considered and $\varsigma = 1$. Herein, α is assumed to remain the same, while u is assumed to increase with time. If the wind speed increases by 10% in a 50-year time period, the $u(t)$ by year 50 will be 39.38 m/s. Accordingly, the corresponding Weibull parameters are $u(50) = 39.38$ and $\alpha(50) = 2.06$. Then, the annual loss of the buildings under different climate change scenarios considering the increase of hurricane intensity is computed. The effects on intensity amplification factor f_u on the annual loss is indicated in Figure 7. The climate change effects associated with hurricane occurrence rate are also investigated in this paper as indicated in Eq. (8). The two terms f_u and f_o are considered herein to take the hurricane intensity and frequency into account within the life-cycle loss assessment process. The expected life-cycle loss considering different climate change scenarios is shown in Figure 8. As revealed, both terms f_o and f_u have a significant effect on the total expected life-cycle loss of buildings. Based on the results presented in Figure 8, it can be concluded that the change in intensity has a larger effect on the loss than the increase associated with hazard occurrence rate.

6.3 Pareto optimal solutions

The bi-objective optimization problem is solved by utilizing a process that employs GAs. The Global Optimization Toolbox imbedded within Matlab (MathWorks 2016) is adopted in this paper in order to obtain optimal adaptation strategies of the buildings located in the investigated region. The expected life-cycle loss of buildings under hurricanes has been computed previously. Given the cost of adaptation actions, the benefit associated with different adaptation plans of the buildings in a life-cycle context is investigated using Eq. (19). The structural adaptation actions considered herein are strengthen the buildings to other updated types of buildings that were constructed later. Accordingly, the types of adaptation actions are indicated in Figure 3(b). For example, the type 23 refers to adapt the buildings built during the time interval 1970-1985 to buildings built during the time interval 1986-1997. The types 11, 22, 33, and 44 mean no adaptation actions. Other types of structural adaptation strategy are shown in Figure 3(b).

The two objectives considered herein are the total structural adaptation cost and the expected life-cycle loss. Both objectives need to be minimized simultaneously. As indicated in Figure 3(a), there are 12 types of buildings investigated herein considering the year of construction and distance to the shore. Additionally, the types of structural adaptation actions are shown in Figure 3(b). The Pareto optimal front considering a time interval of 50 years is shown in Figure 9(a). The optimal structural adaptation strategies corresponding to solutions A, B, and C shown in Figure 9(a) are indicated in Figure 9(b). The detailed information on the optimal adaptation strategy considering the building and adaptation types is indicated in Figure 9(b). For example, with respect to solution B, the adaptation type 14 (i.e., update the buildings built before 1970 to the building type built after 1997) is applied to building type 2 (the building was built before 1970 and located within 1-10 *km* of the shore). The three solutions represent optimal adaptation actions that correspond to different values associated with expected life-cycle loss and total adaptation cost. C represents a low-cost high-loss solution. The adaptation strategy corresponding to solution C, shown in Figure 9(a), is represented in Figure 9(b). Solutions A and B are also indicated in Figure 9(a). Solution A is associated with the highest adaptation cost alternative; however, it yields relatively lowest life-cycle loss. Conversely, solution C is associated with the lowest adaptation cost and the highest relative consequences. It is noted that the types 11, 22, 33, and 44 in Figure 9(b) and 11(b) represent no adaptation actions.

The effects of the investigated time interval on the Pareto optimal front are also investigated herein. The time intervals considered are 50 and 100 years. The Pareto optimal fronts associated with these two different time intervals are shown in Figure 10(a). As indicated, for the same adaptation cost, the 100-year time interval always yields a higher life-cycle loss than that associated with 50-year time interval. The cost-benefit analysis is also incorporated within the optimization process of structural adaptations. Given the specific adaptation action and an investigated time interval, the associated cost and benefit are obtained. The benefit associated with the adaptation action is computed using Eq. (19). The benefit, computed as the difference between the expected life-cycle loss with and without adaptation actions, is chosen as an objective to be maximized. The other objective is the total structural adaptation cost which needs to be minimized. The Pareto optimal front considering the benefit associated with the life-cycle loss and the total adaptation cost is shown in Figure 10(b). As indicated, a larger time interval (i.e., 100-year time interval) always reveals a larger benefit under a given adaptation cost. Given the preference of the decision maker, an optimal adaptation strategy can be obtained.

In addition to the time interval, the effect of climate change on the Pareto optimal front is also investigated. Pareto optimal fronts considering changing climates are shown in Figure 11(a). Considering the similar life-cycle loss, the case considering climate change effects will result in a larger value associated with total adaptation cost than that without considering climate change. The corresponding adaptation strategies associated with optimal solutions B and D on Figure 11(a) are indicated in Figure 11(b).

7. Conclusions

This paper proposed a general computational procedure associated with optimal adaptation strategies of residential buildings subjected to hurricanes and climate change effects. The loss of buildings under probabilistic wind hazard is computed and the effects of adaptation on structural performance are considered in a life-cycle context. The optimal structural adaptation strategies are identified considering expected life-cycle loss/benefit and total structural adaptation cost under investigated time interval. The presented approach was illustrated on residential buildings located in Miami-Dade County, Florida.

The following conclusions are obtained:

1. The expected life-cycle loss of buildings under hurricane effects is significantly affected by the investigated time interval and monetary annual discount rate. These parameters should be carefully evaluated within the life-cycle performance assessment process.
2. For the case study analyzed in this paper, the buildings within 1 – 10 *km* of the shore revealed the largest loss compared with the buildings located in other regions. Furthermore, buildings built before 1970 contribute substantially to the total annual loss for the buildings located in this region.
3. The changes in the probability of occurrence and intensity of hurricanes due to climate change have significant effects on the expected life-cycle loss of the buildings within the investigated region. The change associated with hazard intensity has a larger effect on the loss than that due to the increase of the hazard occurrence rate.
4. Optimum adaptation strategies associated with residential buildings can be obtained by using a bi-objective approach, resulting in a Pareto optimal front. This allows decision makers to make informed decisions based on their particular preference.
5. The cost-benefit evaluation and optimization of adaptation actions can produce the best structural adaptation strategies considering both the expected life-cycle loss and total structural adaptation cost. The cost and benefit can be considered together to determine the effectiveness of an alternative.
6. Within the context of climate change engineering, life-cycle loss, cost-benefit analysis, and optimization can provide the decision maker important information necessary for assessment and adaptation of structural systems at a large scale. This information can be used in design, maintenance, and management optimization processes of civil infrastructure considering extreme events and climate change.

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Figure 1

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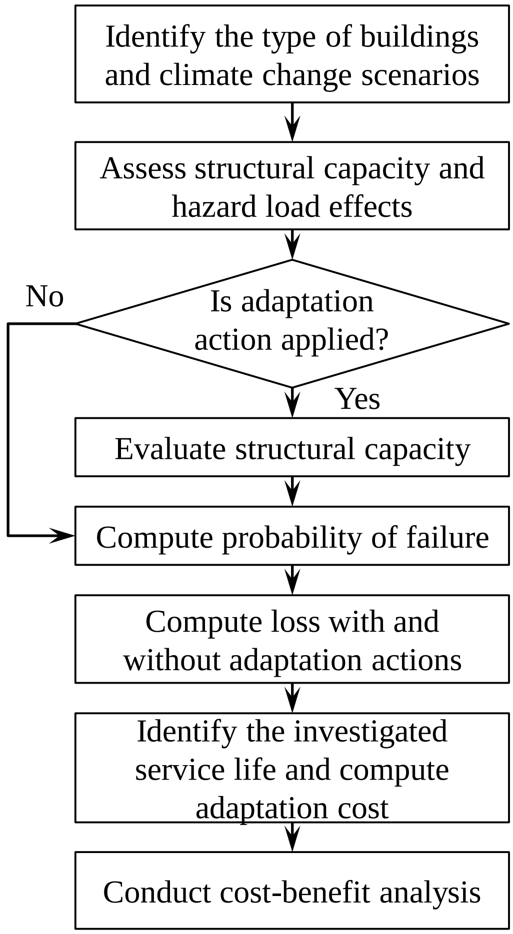
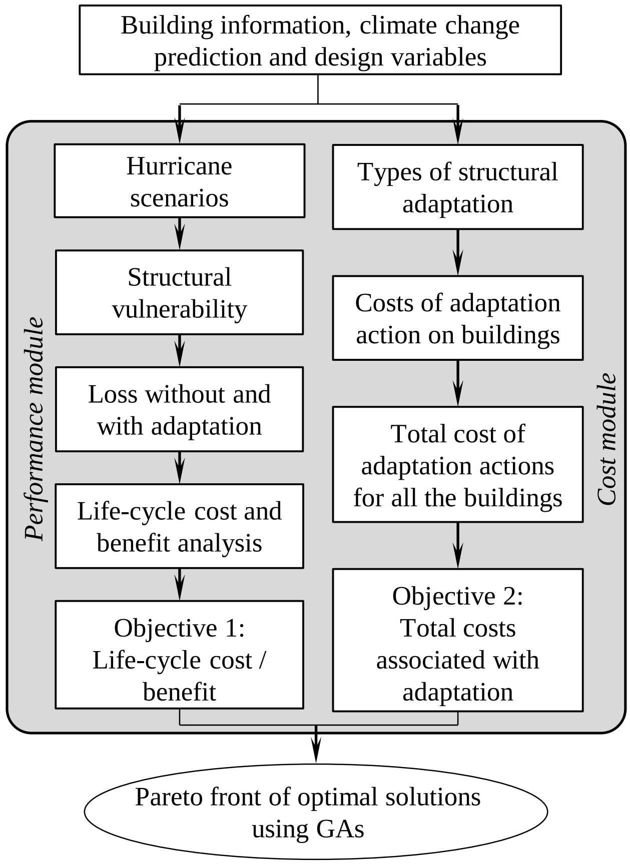


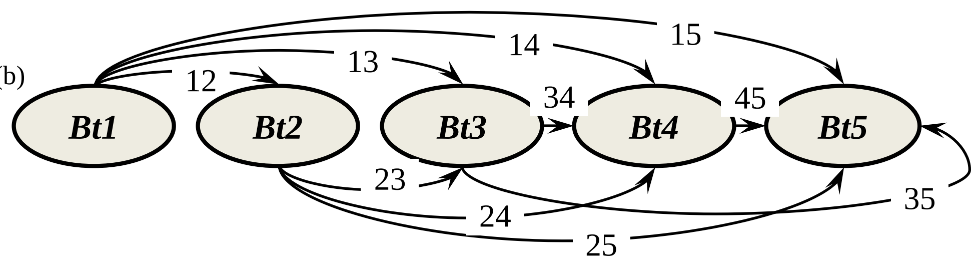
Figure 2


Building information, climate change prediction and design variables
Performance module
Hurricane scenarios
Structural vulnerability
Loss without and with adaptation
Life-cycle cost and benefit analysis
Objective 1: Life-cycle cost / benefit
Cost module
Types of structural adaptation
Costs of adaptation action on buildings
Total cost of adaptation actions for all the buildings
Objective 2: Total costs associated with adaptation
Pareto front of optimal solutions using GAs

(a)

Building types		Year of construction			
		Before 1970	1970-1985	1986-1997	After 1997
Location	Within 1 km of shore	1	4	7	10
	Within 1-10 km of shore	2	5	8	11
	Further than 10 km of shore	3	6	9	12

(b)



Note: Bt1: Buildings built before 1970; ***Bt2***: Buildings built 1970-1985
Bt3: Buildings built 1986-1997; ***Bt4***: Buildings after 1997
Bt5: New constructed buildings
ij: adaptation action associated with update the building from type ***Bti*** to type ***Btj***

Figure 4

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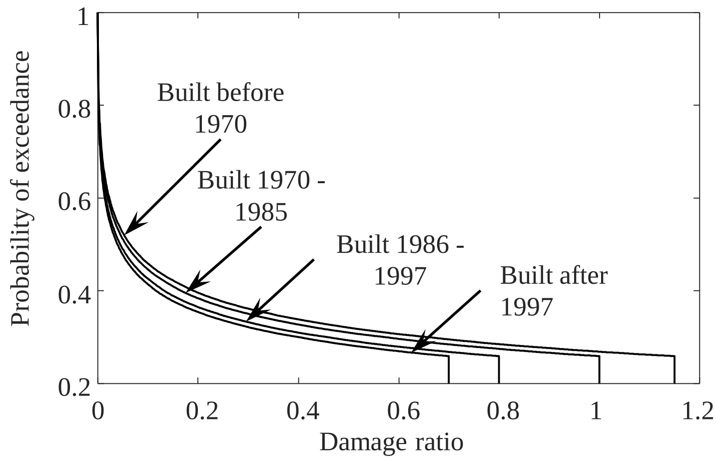

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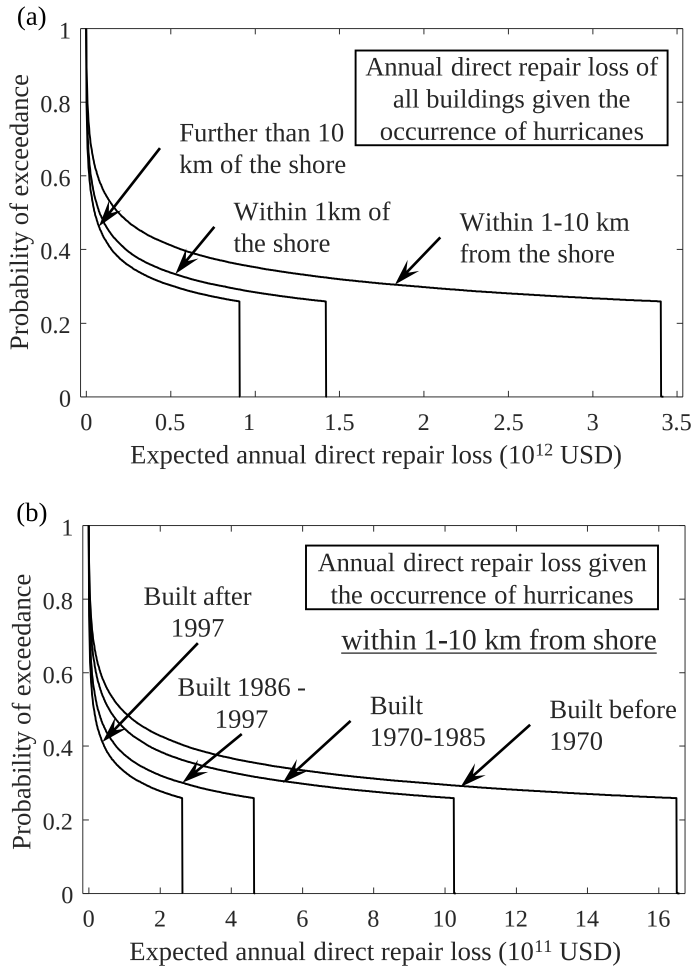

Figure 6

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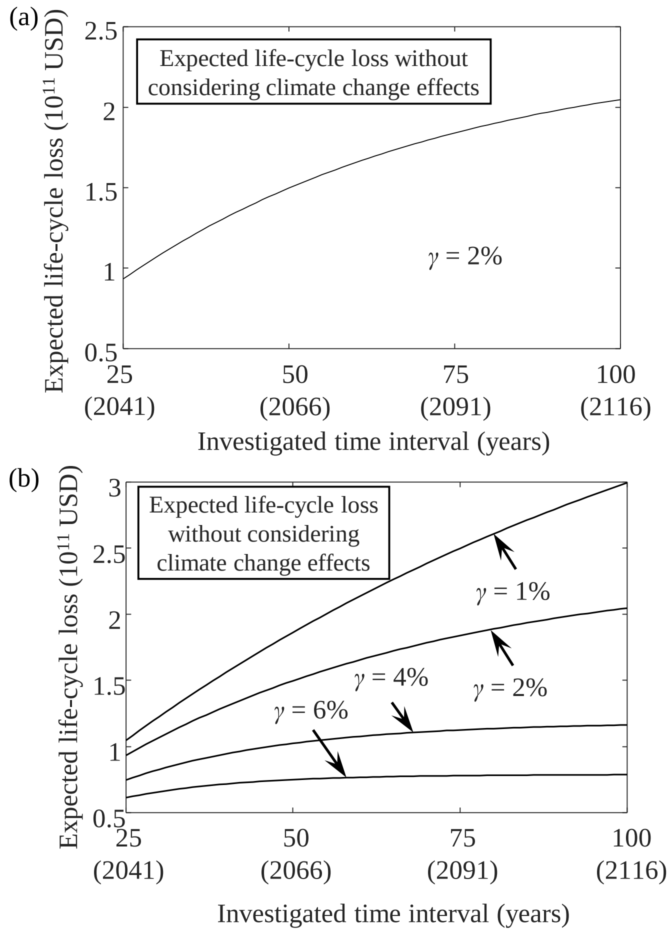

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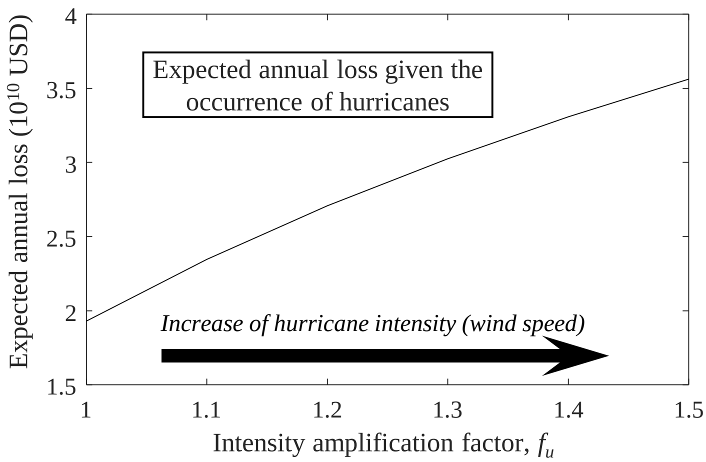

Expected annual loss given the occurrence of hurricanes
Increase of hurricane intensity (wind speed)
Expected annual loss (10^10 USD)
Intensity amplification factor, f_u
4
3.5
3
2.5
2
1.5
1
1.1
1.2
1.3
1.4
1.5

Figure 8

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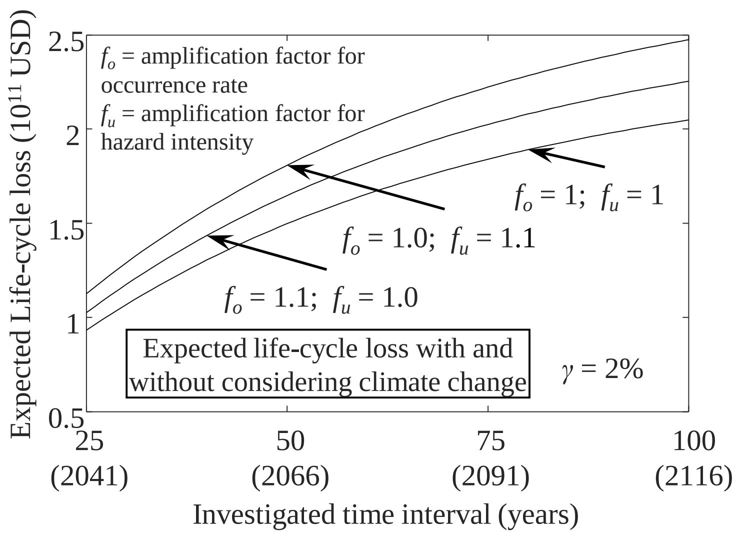

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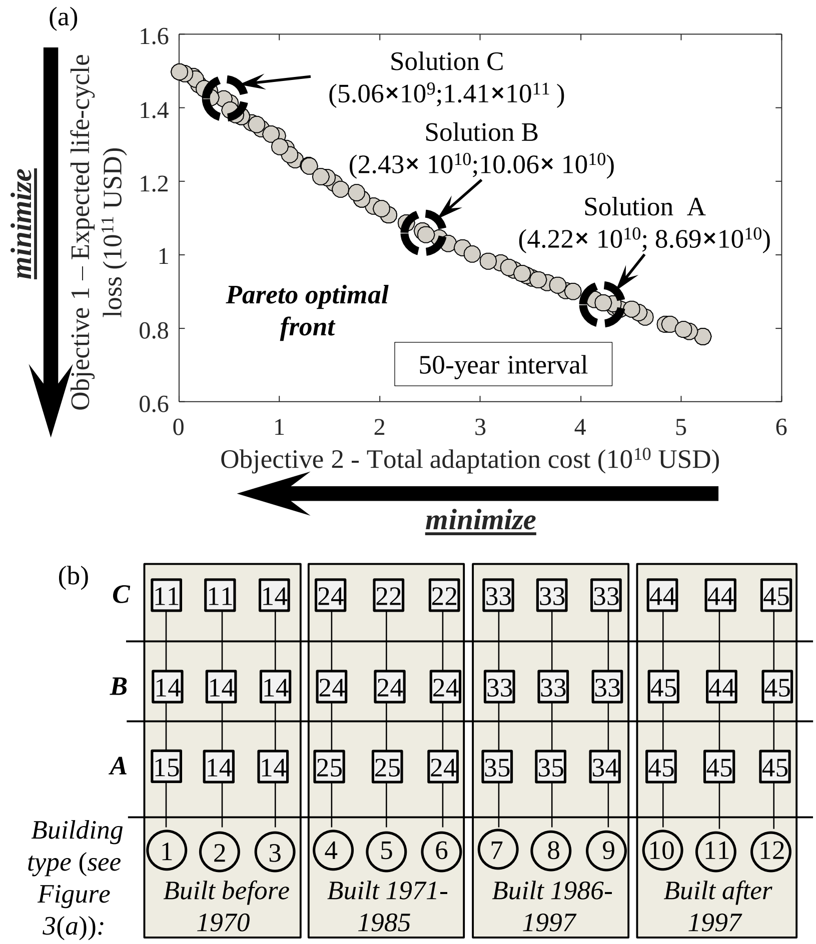

Figure 10

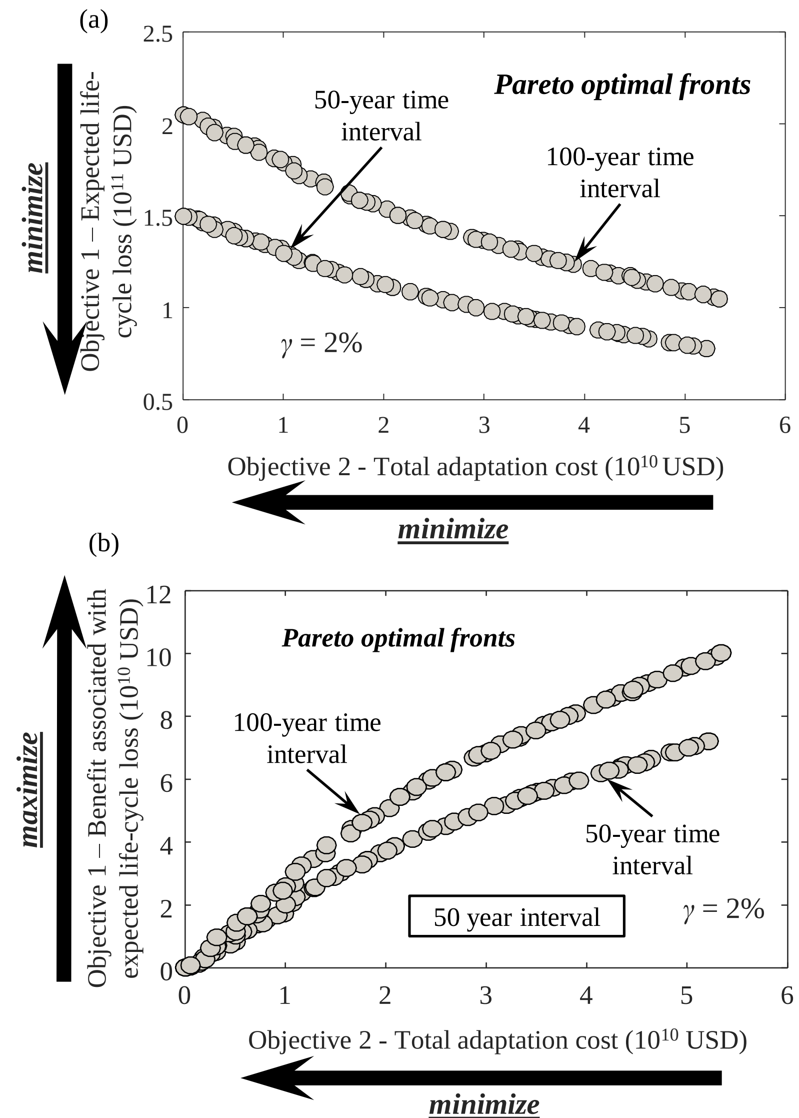
(a)
Pareto optimal fronts
50-year time interval
100-year time interval
γ = 2%
minimize
Objective 1 – Expected life-cycle loss (10^11 USD)
Objective 2 - Total adaptation cost (10^10 USD)
minimize
2.5
2
1.5
1
0.5
0
1
2
3
4
5
6
(b)
Pareto optimal fronts
100-year time interval
50-year time interval
50 year interval
γ = 2%
maximize
Objective 1 – Benefit associated with expected life-cycle loss (10^10 USD)
Objective 2 - Total adaptation cost (10^10 USD)
minimize
12
10
8
6
4
2
0
0
1
2
3
4
5
6

Figure 11

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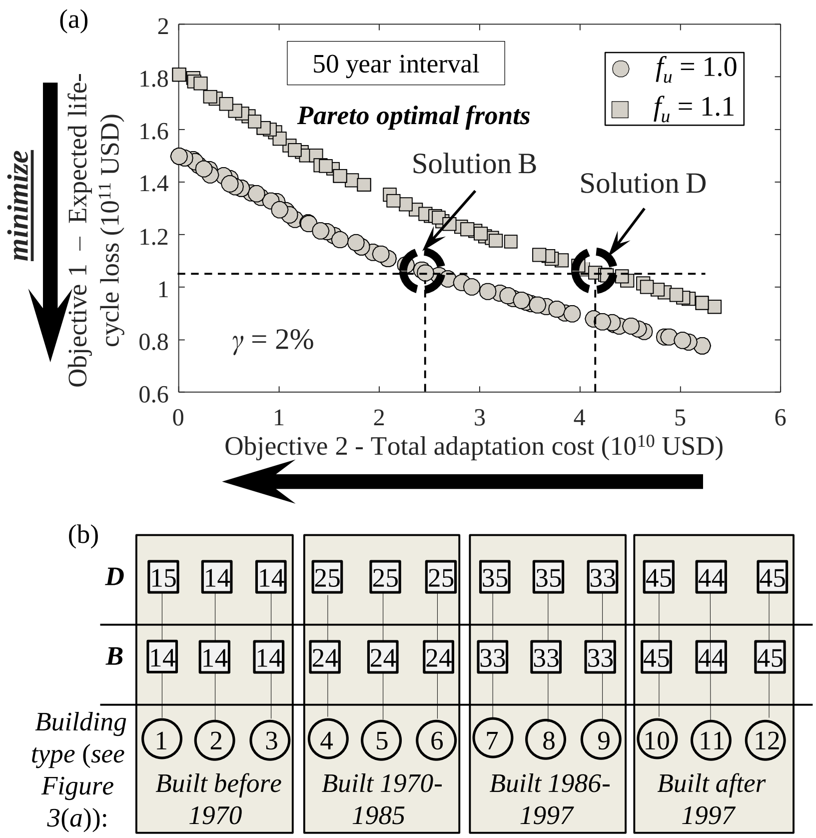

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