Quantitative integration of probabilistic fire risk assessment with LCA of buildings: the environmental impact of thermal insulation design.

Rocco di Filippo[a], Luca Possidente[b], Nicola Tondini[a], Oreste S. Bursi[a]

[a]*Depart. of Civil, Env. & Mechanical Engineering, University of Trento, Via Mesiano 77, Trento, 38123, Italy*
[b]*Depart. of Civil, Env. & Mechanical Geomatic Engineering, University College of London UCL, London, WC1E 6BT, UK*

Abstract

Given the ever-growing importance of environmental sustainability, greater attention has been paid in the last few decades to the energy consumption of buildings. As often documented, a significant share of such consumption is due to the thermal regulation of buildings' interior spaces. In this regard, proper thermal insulation has been proven to be highly effective in reducing energy needs. To increase the minimum insulation requirements, many national policies have been introduced or revised, indeed. Besides, a large share of currently used thermal insulation is polymeric. Based on recent major fires, these materials were found to have increased, in several cases, the severity of fires' consequences. On the other hand, natural insulation materials, especially those not combustible, have a lower impact on fire development but also lower thermal insulation performances. The optimization problem, with fire safety on one side and energy performances on the other, has been the subject of recent research. Nonetheless, due to the numerous uncertainties, such optimization is usually discussed in a qualitative manner. Conversely in this paper, full probabilistic methods applied to fire risk assessment are found to be a reliable strategy for a quantitative approach. Furthermore, fire events are proven to be linked to a few types of environmental consequences, including direct greenhouse gas emissions. Thus, a quantitative integration of fire risk-based environmental impact of thermal insulation, applied to a general case study, is presented.

Keywords: LCA, Performance structural fire engineering (PSFE), thermal insulation, Structural safety, Fire risk assessment

---

1. Introduction

1.1. Background and motivation

In 2019, the building sector accounted for 37% of the global CO_2 emissions [1]. A significant share of which is the result of energy consumption for heating and cooling [2]. With respect to this, it is well-known that thermal insulation of the building envelope can significantly reduce such energy needs [3; 4; 5]. Thus, to improve the overall energy efficiency of the buildings' stock, policymakers have introduced stricter requirements with regard to thermal insulation. Indeed, building regulations have, progressively in the last 3 decades, set lower U-value limits of new fabric elements and standardised the calculation methodology with ISO 6946 [6]. This trend is confirmed by a review of several different regulations presented in [7]. Moreover, it has to be noted that these thresholds tend to be lower in case of renovation of the existing buildings stock compared to new constructions. For reference, such limits have reached, for roofs and walls respectively, 0.16 and 0.2 W/m^2K in the UK [8], 0.27-0.19 and 0.38-0.22 W/m^2K in Italy depending on the climate zone [9]. Along this line, plastics-based polymeric materials constitute a significant part of thermal insulation solutions [10].

Besides, this class of materials is, by its nature, combustible [11]. This characteristic has been found to have worsened fire consequences in several past accidents [12; 13]. Reportedly, some of them have also resulted in a loss of human life, such as the 2019 Grenfell Tower fire, the deadliest residential fire in the UK since World War II, with 72 casualties [14]. Hence, to mitigate this risk, several countries have introduced specific fire performance requirements for thermal insulation materials [15].

On the other hand, some inorganic fibrous insulation materials, like glass and stone wool, are excellent fire-retardants [16]. Still, since they also possess lower insulation capabilities, they are not a straightforward choice when the thermal insulation of a building has to be designed. Conversely, this can possibly result in an optimization process based on a multi-performance evaluation. More in detail, the problem of performing such optimization has been analyzed by [17; 18; 19]. In particular, one term of the trade-off, i.e. the environmental impact of energy savings, is well-known and based on the concept of carbon emission intensity [20]. Meanwhile, the lack of effective methods to assess the impact of an increased fire risk was found to be a significant barrier to overcome [18]. The intrinsic complex nature of fire risk has also represented a limit, forcing a simplified approach to the problem [17; 19]. While the influence of thermal insulation on structural design has been studied with quantitative approaches [21], fire risk-based considerations have been made in a qualitative or simplified way.

With reference to this, probabilistic methods have already been applied to quantitatively assess the environmental impact of risks for buildings. Specifically, these methods have been developed for natural hazards such as earthquakes [22; 23; 24], winds [25] and tsunamis [26]. Moreover, the FEMA guideline [27] provides procedures and tools to practically integrate seismic hazard effects with LCA assessment. These methodologies mainly focus on calculating the climate change potential, expressed in CO_2 equivalent, related to repair, reconstruction or maintenance activities following seismic-related damages. Such a type of assessment mostly relies on two methodologies: the economic input-output method (EIO-LCA) and the bill of materials (BOM) approach. The EIO-LCA method [28] takes as input the costs of each activity and transforms them, through dedicated sector-level data matrices, into the relevant environmental impact in terms of CO_2 equivalent. The BOM approach, instead, leverages statistical databases [29; 30] able to quantify the embodied energy and/or carbon associated with a certain quantity of material. On the other hand, few studies have also focused on the emissions of high-GWP compounds as another part of damage-related environmental impact [31; 25].

As for fire risk, full probabilistic methods have been developed and applied to evaluate the relevant impacts. Indeed, though meaningful indications can be obtained by using Performance-Based Fire Engineering (PBFE) with a deterministic approach [32], a Probabilistic Structural Fire Engineering (PSFE) framework should be developed for the assessment of fire risks and the definition of the expected damage of a structure. Despite the numerous contributions on full probabilistic structural applications, for instance, in earthquake engineering, only in recent years have probabilistic models for fire structural performance attracted the interest of the scientific community [33; 34]. In particular, fire fragility curves quantifying the probability of exceeding defined damage or limit states were mainly proposed for steel structures, owing to their significant vulnerability to thermal attack. Nigro et $al.$ [33] employed Monte Carlo simulation to generate a large number of fire scenarios and assessed the probability of fire-induced progressive collapse in a steel office building with car park fire scenarios in the underground garage. Similarly, probabilistic distributions of parameters affecting both the demand and the capacity generated with Monte Carlo simulation were used in [35] to identify the prevailing parameters in deriving fire fragility curves for steel frame buildings. In [36], fire fragility curves for a five-storey steel frame were developed, considering seismic and non-seismic design, different thicknesses of fire protection and fires distributed on the entire ground floor area with increasing fire loads q. Steel structural applications were studied in industrial contexts as well, as in [37; 38], in which fire fragility curves were proposed for industrial steel pipe-racks subjected to localised fires, enabling the assessment of risk in petrochemical plants in respect to fire hazard induced by loss and ignition of typical liquid fuels. Recent studies explored the potential of using fragility analysis in reinforced concrete buildings in fire. In [39] a quantified damage scale, together with associated fragility curves, was proposed for reinforced concrete columns and slab, whilst in [40] a framework for deriving fire fragility curves was applied to an RC frame. A further step was taken by Ni et *al*. [41], which integrated fragility analyses in a framework for the probabilistic estimation of economic losses due to fire in RC buildings. Still, these methods have not yet been applied to assess environmental impacts with the exception of fire direct emissions [34].

1.2. Scope and core contribution

This paper presents an integrated methodology to evaluate the effect of thermal insulation on fire risk and its relevant environmental impact. Consequently, such contribution is expected to provide a viable strategy to: i) assess the environmental impact of fire risk; ii) solve the quantification issue in the optimization problem dealing with thermal insulation performances and fire performances. In this manner, a direct comparison between the environmental impacts of combustible and incombustible thermal insulation is realized. Moreover, a simplified application of the methodology to a general case study is presented. Along this vein, Section 2 introduces an overview of the proposed procedure. Hence, the simplified case study, the main hypotheses and the quantification process of the fire risk impact are provided in Section 3.2. Section 3.3 instead, presents a brief assessment of the effects of thermal insulation performance. The main conclusions are drawn in Section 4 together with future developments.

2. Overview of the proposed procedure

We define the methodology presented in this section, "Multi-performance ANalysis with Fire Risk-based Environmental Impact assessment" (MANFREdI). As a necessary simplification, we will consider the thermal insulation design as the only factor influencing both the building's energy consumption and fire risk. MANFREdI framework is based on the comparison between the environmental impacts of thermal insulation related to: i) energy consumption, ii) fire risk. The procedure to determine i) and ii) are presented in subsections 2.1 and 2.2 respectively. The overall scheme of the procedure is depicted in Fig. 1.

2.1. MANFREdI framework - Environmental impact of energy consumption

The procedure's steps are listed below:

(I) Thermal insulation designs definition;

(II) U-values calculation;

(III) Energy consumption assessment;

(IV) Energy consumption to impact conversion;

Step (I) consists in determining, for each part of the external envelope of the building, the type of insulation material, I_t, with its thermal conductivity k_{I_t} and the chosen thickness δ_{I_t}. This allows determining the U-value which constitutes Step (II). The U-value, or thermal transmittance, can be calculated as follows:

$$U_{I_t} = \frac{1}{\sum_{nc} \frac{\delta_{nc}}{k_{nc}} + \frac{\delta_{I_t}}{k_{I_t}}} \tag{1}$$

where nc pertains to the n components of the envelope with the exception of thermal insulation. Step (III) involves the assessment of the energy consumption on the basis of the resulting U-value. It is important to underline that a building's energy consumption depends on several factors. We assume however that, fixed all the other factors, the energy consumption will be a function of the thermal insulation design alone. This assumption can be expressed as:

$$Ec = f(U_{I_t}) \tag{2}$$

where Ec is the building's energy consumption relevant to a specific U-value. This evaluation can be performed in a simplified manner with static methods based on the concept of heating and cooling degrees days (HDD and CDD) [42]. More accurate results can however be obtained with dynamic and simulation-based models [43; 3]. The final Step (IV) requires the transformation of the energy consumption in a measure of the relevant environmental impact. A common measure of this impact is GHG emissions which relate to the global warming effect. This value is usually measured in terms of $CO_{2.eq}$ and can be calculated according to:

$$EM_{Ec_{I_t}} = Ec_{I_t} \cdot GWP_E \tag{3}$$

where $EM_{Ec_{I_t}}$ is the emission value linked to the energy consumption and GWP_E represents the global warming potential of the energy mix production. This metric, also called carbon density, is commonly employed to evaluate the environmental impact of energy consumption [44; 45]. To conclude, the goal of the framework is to evaluate the difference between two distinct designs which can be analytically expressed as:

$$\Delta EM_{Ec_{I_{1-2}}} = EM_{Ec_{I_1}} - EM_{Ec_{I_2}} \tag{4}$$

where $EM_{Ec_{I_1}}$ and $EM_{Ec_{I_2}}$ are the emissions relevant to the two different design I_1 and I_2.

2.2. MANFREdI framework - Environmental impact of fire risk

The procedure's steps are listed below:

(a) Thermal insulation designs definition;

(b) Additional fire load density calculation;

(c) Fire risk loss analysis;

(d) Damage to impact conversion;

Step (a) is identical to Step (I) defined in Subsection 2.1. Step (b) involves the quantification of the additional fire load density provided by the thermal insulation materials, to be determined as follows:

$$q_{I_t} = \frac{M_{I_t} \cdot Hc_t}{A_f} \tag{5}$$

where M_{I_t} and Hc_t are the mass and the heat of combustion density of the thermal insulation. A_f is the floor area of the structural unit which is insulated. Reportedly, fire load is an effective indicator of the vulnerability and the relevant loss in case of fire [41; 35]. This step underlines two main hypotheses, the first of which is that insulation materials can effectively contribute to a fire. In the case of combustible plastic-based materials, hypothesis i) is supported by empirical and experimental evidence. Several past building fires have been somehow worsened by the contribution of insulation materials, especially polymeric ones, as reported in [12; 13]. It has to be noted however that existing standards have been continuously updated, also considering past accidents' experience, to improve the safety of these materials towards fire. Their approach is based on testing façade installations or simpler specimens' reaction to fire under a given scenario, involving, among other parameters, a certain heat flux for a given time [15]. In this respect, specific testing protocols and thresholds are defined. Recent experimental data show that standards-compliant installation of polymeric thermal insulation can nonetheless contribute to fire [46; 47]. Some of these experimental works consider ideal installations [48] but also the possibility of realistic imperfections [49; 50]. Available knowledge cannot however fully determine to which extent current standards may prevent complying polymeric insulation to contribute to a fire. The second assumption is that the additional fire load would not be negligible. Although this may depend on vulnerability conditions and the already present fire load, a value in the order of 10^2 MJ/m^2 should be significant. Any non combustible insulation materials, like glass and stone wool, will hence have no meaningful influence on the fire load. Conversely, it is well known that these materials [48] and other non-conventional alternatives [51] offer fire protection, which could limit the fire spread and the expected consequences of a fire with a given fire load. The possible beneficial effects of these materials will however not be considered in this framework. Step (c) involves a fire risk loss analysis. Recent methodologies entail full probabilistic approaches derived from the PEER PBEE framework [52] which, based on the total probability theorem, allow for an independent evaluation of hazard, fragility, damage and loss. The analytical formulation of the PBEE framework reads,

$$\lambda(DV) = \int\int\int P(DV|DM)dP(DM|EDP)dP(EDP|IM)d\lambda(IM) \tag{6}$$

where $\lambda(IM)$ is the hazard expressed as its rate of occurrence with a certain intensity measure (IM); $dP(EDP|IM)$ denotes the probability that the system under study will experience a response EDP conditioned to IM, this term is usually expressed as a fragility curve [53; 36; 41]; $dP(DM|EDP)$ indicates the probability that a given response will result in a damage DM; $P(DV|DM)$ describes the conditional probability of a particular decision variable, usually expressed in terms of fatalities or economic costs, with respect to the damage measure. Finally, $\lambda(DV)$ is the rate of occurrence of a decision variable exceeding a given threshold; in other words, a measure of the expected effects of the specific hazard on the system under study. Along this line, Step (c) modifies the PBEE framework to a fire probabilistic damage analysis which can be written as follows:

$$P(DM|F) = P(DM|EDP > C) \cdot P(EDP > C|q_{cIt})\lambda(q_{cIt}) \cdot P(F) \tag{7}$$

where $P(DM|F)$ represents the probability of a certain damage in case of fire with a certain probability of occurrence $P(F)$. $P(EDP > C|q_{cIt})\lambda(q_{cIt})$ implies that the chosen IM in this framework is the fire load. C is the capacity limit coupled to a certain limit state and q_{cIt} is the combined fire load calculated as follows:

$$q_{cIt} = q_e + q_{It} \tag{8}$$

where q_e is the expected fire load density of the building without thermal insulation. It is important to underline that q_e usually follows a normal distribution while q_{It} will be considered deterministic in this study. The underlining concept is that an increased combined fire load q_{cIt} will lead to an increased $P(EDP > C|IM = q_{cIt})$ and, therefore, $P(DM|F)$. It is noteworthy that other research [19] have highlighted how insulation materials have been, in some reported cases, the source of the fire itself. Consequently, $P(F)$ may be influenced by the design of the thermal insulation. This effect will however be neglected in this work.

Step (d) realizes the conversion from damage to environmental impact. In order to adapt the PBEE framing equation (6) to LCA, DV is assumed to be a sustainability indicator and is usually expressed in CO_2 equivalent. This is generally done starting from the reparation costs or the bill of materials (BOM) and associating them with a certain impact [54; 55; 27]. The degree of complexity and the overall accuracy of such conversions may vary. Overall, different approaches show a variability range of 20% [54], proving to be rather robust. Direct emissions of high-GWP compounds [31; 25] or CO_2 from combustion [34] are another class of damage-related environmental impact possibly not negligible. We can therefore write:

$$EM_{F_{I_t}} = EM_{rDM_{I_t}} + EM_{dDM_{I_t}} \tag{9}$$

where $EM_{F_{I_t}}$ is the emission value linked to the fire risk. EM_{rDM} and EM_{dDM} are the emissions generated by repair activities and other chemicals' direct release, respectively. To conclude, similarly to Eq 4 we can write:

$$\Delta EM_{F_{I_{1-2}}} = \Delta EM_{rDM_{I_{1-2}}} + \Delta EM_{rDM_{I_{1-2}}} \tag{10}$$

3. A generalist case study application

A simplified application of MANFREdI framework is presented in this section. The object of the study will be a benchmark three-story residential RC building. The frame building consists of moment-resisting frames in both orthogonal directions with 2 bays in each direction, having a 7.0 m span length, resulting in a 14 m by 14 m square floor plan. The floor height is 3.5 m and the floor plan is depicted in Fig. 2. The overall dimensions are adapted from a fire compartment of the structure analysed in [41]. The structural elements of the floors, i.e. slabs and columns, are assumed equal to those of the corner fire compartments from [41]. Thus, we realistically assume all the columns are 0.3 x 0.3 m and the slabs 0.3 x 0.5 m.

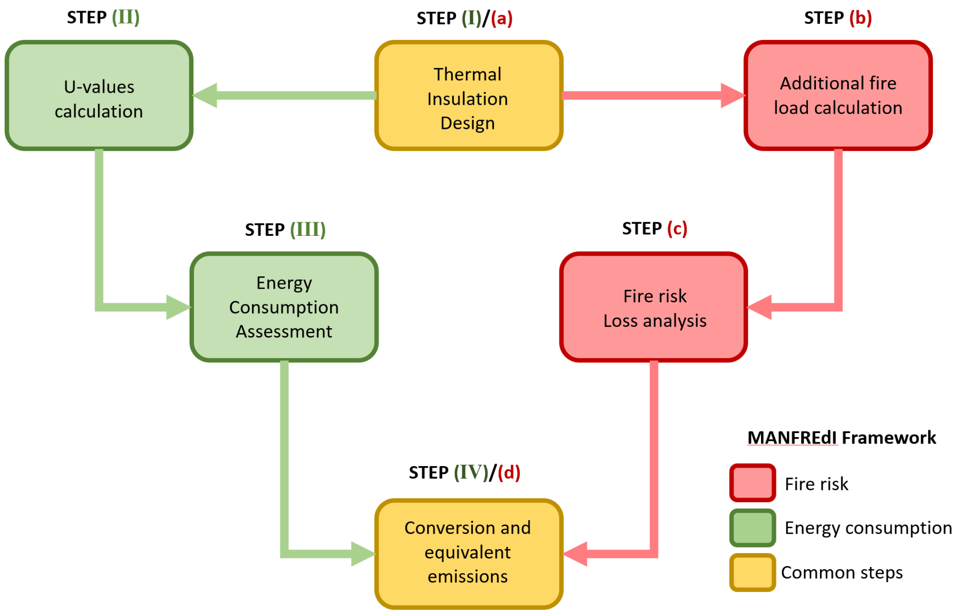

Figure 1: Procedure scheme of MANFREdI framework

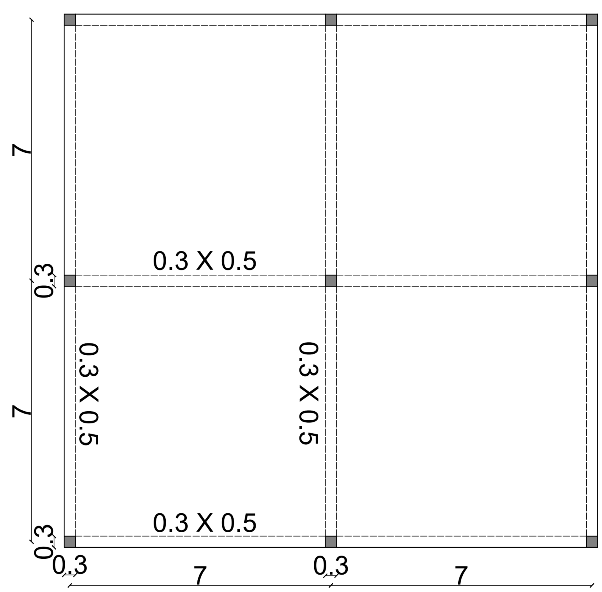

Figure 2: Floor plan and structural elements - measures in (m)

3.1. Thermal insulation design

We assume for the non-insulated envelope components a uniform $U_{nc} = 1.3W/m^2K$, compatible with conventional designs from old RC buildings. Two designs will be considered, differing in insulation materials and relevant thermal performances. The chosen materials will be EPS, plastic-based and combustible, for the design I_{EPS} and glass wool, inorganic and incombustible, for the design I_{GW}. According to [16], the thermal conductivity of EPS and mineral wool is in the range of 0.029-0.041 and 0.030-0.050 W/mK respectively. We set $k_{EPS} = 0.035W/mK$ and $k_{GW} = 0.04W/mK$. The thickness of the insulation layer for the different components of the building envelope is set to be the same for both I_{EPS} and I_{GW}. This is compatible with the fact that for a significant share of building renovations, the internal or external thickness to be added represents a major constraint. These constraints could result from local regulations in the case of external insulation and loss of usable surface for the internal one. Given the lower k, I_{EPS} will therefore deliver lower U-values. The design thickness is set to replicate, for I_{EPS}, the minimum requirements of the Italian climate zone E as defined in [9]. This zone is characterized by HDD values between 2100 and 3000. The most recent thermal requirements [9] for buildings renovations in climate zone E are listed in Table 1.

Table 1: Minimum U-values requirements - Italy, Climate Zone E

Envelope component	U-value (W/m^2K)
Roof	0.20
External walls	0.23
Floors	0.25

To reach the target U-values the necessary thicknesses are calculated with Eq. 1, rounded up at the closest higher measure in cm, and listed together with the relevant U-values in Table 2:

The thicknesses range from 0.15 m for roofs to 0.12 m for floors. As expected, given the thickness constraint, I_{EPS} is characterized by lower U-values than I_{GW}.

3.2. Fire risk assessment

3.2.1. Fire Hazard Model - Fire load calculation

Eq. 7 implies that the hazard model is the result of the combination of two components $\lambda(q_{cIt})$ and $P(F)$. In order to determine the first, the additional fire load

Table 2: Insulation thicknesses and U-values of I_{EPS} and I_{GW}

Envelope component	Thickness (m)	U-value (W/m^2K)	
		I_{EPS}	I_{GW}
Roof	$\delta_{I_{EPSr}} = \delta_{I_{GWr}} = 0.15$	0.198	0.221
External walls	$\delta_{I_{EPSw}} = \delta_{I_{GWw}} = 0.13$	0.223	0.249
Floors	$\delta_{I_{EPSf}} = \delta_{I_{GWf}} = 0.12$	0.238	0.265

density can be calculated with Eq. 5. We will neglect q_{GW} because of the intrinsic fireproof properties of fibrous inorganic materials [16; 14; 56]. Concerning q_{EPS}, we will refer to the top floor of the building which entails a floor area A_f of 196 m^2. The mass of the insulation material $M_{I_{EPS}}$ can be evaluated as follows:

$$M_{I_{EPS}} = (A_r \cdot \delta_{I_{EPSr}} + A_w \cdot \delta_{I_{EPSw}}) \cdot \rho_{EPS} \tag{11}$$

where A_r and A_w are the insulated surfaces of roofs and walls equal to 196 and 166.5 m^2 respectively. The value of A_w takes into account that 15% of the walls' surface is occupied by windows and therefore to not be insulated. ρ_{EPS} is the density of EPS, set to 34 kg/m^3 according to [16]. Given the thicknesses listed in 2 we obtain $M_{I_{EPS}} = 1730kg$. Concerning Hc_{EPS}, [57] provides a range of 32.8-39.4 MJ/kg while [58; 48] provide 30.59 MJ/kg. Even if this parameter is known to vary upon testing conditions, we will assume a fixed $Hc_{EPS} = 35$ MJ/kg. It is possible therefore to rewrite Eq. 5 as follows:

$$q_{I_{EPS}} = \frac{1730 \cdot 35}{196} = 310 MJ/m^2 \tag{12}$$

The remaining parameter q_e from Eq. 8 should therefore be selected to be compatible with a residential building. [59] provides a range of 377-409 MJ/m^2 based on a survey in Kanpur. [60] reports an average value of 391 MJ/m^2 from a Finnish survey and 320 MJ/m^2 from the US. [61] presents a wide range of 360-724 MJ/m^2 collecting several surveys from different countries. A useful review is presented by [5]. It is also important to underline that the fire load can vary significantly within the same residential building on the basis of the destination use of the room. For reference, according to the survey presented in [61], fire load density ranges from 807 MJ/m^2 in a kitchen to 393 MJ/m^2 in a dining room. It is worth noticing that $q_{I_{EPS}}$ appears to be not negligible when compared to an average q_e. We will assume a probabilistic q_e described by a Gumbel distribution, as it is commonly done for fire load [60], with $\mu_{q_e} = 400\ MJ/m^2$ and $\sigma_{q_e} = 80\ MJ/m^2$. The addition of $q_{I_{EPS}}$ leads to a new distribution with $\mu_{q_{cI_{EPS}}} = 710\ MJ/m^2$ and $\sigma_{q_{cI_{EPS}}} = 80\ MJ/m^2$, as depicted in Fig. 3.

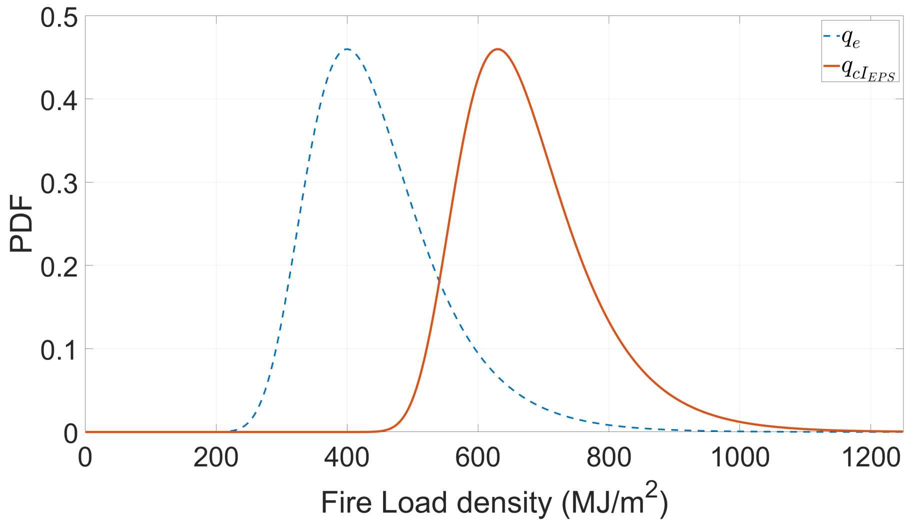

Figure 3: Fire load distributions of q_e and $q_{cI_{EPS}}$

3.2.2. Fire Hazard Model - Fire occurrence probability

As in [62; 35; 41], $P(F)$ is expressed as a yearly probability of a fire event affecting the building under study. This is consistent with relevant standards like the BS PD-7974-7 [63] and the Eurocode [64]. The probability values are often derived from analytical formulation, taking into account the use of the building and its floor space. Other characteristics, like the presence of smoke detectors, sprinkler systems and fire brigades intervention, are used to assess the probability of severe or non-severe fires. This approach presents however some limitations when compared to the actual fires statistics [65; 66]. Owing to the full probabilistic nature of the framework here presented, we will rely on these statistics to estimate the yearly fire occurrence of a residential building. For reference, from [66] we gather that in UK and US the probability of a fire in dwellings is $1.33 \cdot 10^{-3} y^{-1}$ and $1.51 \cdot 10^{-3} y^{-1}$ respectively. [67] estimated the fire probability in residential buildings in Greece using statistics from 2000 to 2019 and obtaining a rate of $0.97 \cdot 10^{-3} y^{-1}$. This value is the result of the ratio between the fires reported over a certain period and the number of occupied residential buildings. Adopting the same approach for the US, the NFPA reports that in 2020 there have been $380 \cdot 10^3$ "structural significant" fires in residential buildings [68]. From [69] we retrieve that a total of $126 \cdot 10^6$ occupied residential buildings, allowing the calculation of a fire probability of $3.01 \cdot 10^{-3} y^{-1}$. Despite the fact that these statistics hardly classify the events based on their severity or other critical characteristics such as spread and duration, the order of magnitude of $10^{-3} y^{-1}$ appears to be recurrent. We will therefore assume $P(F) = 3.01 \cdot 10^{-3} y^{-1}$.

3.2.3. Fire vulnerability and damage to impact conversion

As a necessary part of Step (c), a probabilistic model relating fire load and damage state should be defined. From [41] we can gather such vulnerability curves developed on the basis of numerical simulations. These simulations modelled the reaction to the fire of an RC five-story office building. Each building floor, a square of 35 by 35 meters, is composed of 25, 7 by 7 meters, fire compartments. The relevant fragility curves are developed for different damage states based on specific EDPs. The relevant repair costs are also reported. The EDPs we will consider are the depth of the 300 °C isotherm, d300, which damages the steel rebars inside structural elements, and the residual vertical deflection of the floor slab, RDR. The third EDP presented by [41] is related to the vertical deflection of the columns but will be neglected since it is influenced by the load level, which would be, in the case of a 5-storey building, quite different from our case study. The RDR also depends on the load level but we consider the floor load difference between a residential building, as in this case, and a generic office, as in [41], negligible. The resulting vulnerability to fire is expressed with lognormal fragility curves relevant to different damage states and with the fire load as IM. Moreover, a cost analysis is also presented based on [70; 71]. The underlining hypothesis is that a damage state is always triggered by the capacity exceedance, which is equivalent to writing,

$$P(DM|EDP > C) = 1 \tag{13}$$

We assume the analytical formulation of the curves as follows:

$$F_{Rd} = P(EDP > C|IM = im) = \phi \left[\frac{ln(im/m_d)}{\beta_d} \right] \tag{14}$$

where ϕ indicates a lognormal cumulative distribution function while m_d and β_d are the median and the dispersion of the distribution. The curves' parameters for d300, in the specific case of a corner column, and for RDR are listed in tables 3 and 4 together with the specific EPD values, repair costs expressed as a ratio over the original construction costs. EDP thresholds for d300 are expressed in terms of fractions of the parameters c, i.e the thickness of the concrete cover over the rebar, and d, i.e. the side dimension of the cross-section. EDP thresholds for RDR are expressed in the ratio Δ/l between the vertical deformation and the square root of the product of spans in x and y directions. The relevant curves are depicted in Fig. 4 and 5.

Table 3: Fragility curves parameters - EDP d300

Damage state	EDP value	Δ_{DSn} - Repair costs % of construction costs	m_d (MJ/m^2)	β_d
$DS1_{d300}$	0<d300<c/10	4.8	270	0.081
$DS2_{d300}$	c/10<d300<c	23.6	309	0.069
$DS3_{d300}$	c<d300<d/4	39.8	522	0.23
$DS4_{d300}$	d/4<d300<d/2	263.7	1352	0.23

Table 4: Fragility curves parameters - EPD RDR

Damage state	EDP value	Δ_{DSn} - Repair costs % of construction costs	m_d (MJ/m^2)	β_d
$DS1_{RDR}$	$1/240<\Delta/l<1/120$	10	208	0.23
$DS2_{RDR}$	$1/120<\Delta/l<1/60$	86.1	308	0.09
$DS3_{RDR}$	$\Delta/l>1/60$	121.5	553	0.22

We also have to consider the hierarchical nature of such a scale where any higher damage state encompasses any lower one as well. This implies that DSs are both statistically dependent and characterized by hierarchical interchangeability. The probability of a lower DS has therefore to be reduced by the probability of the next higher one which can be analytically written as:

$$P'_{DS_n} = P_{DS_n} - P_{DS_{n+1}} \tag{15}$$

It is therefore possible to use 7 to evaluate the yearly probability of occurrence of each damage state P_{DSn}. We assume the vulnerability parameters of Table 3

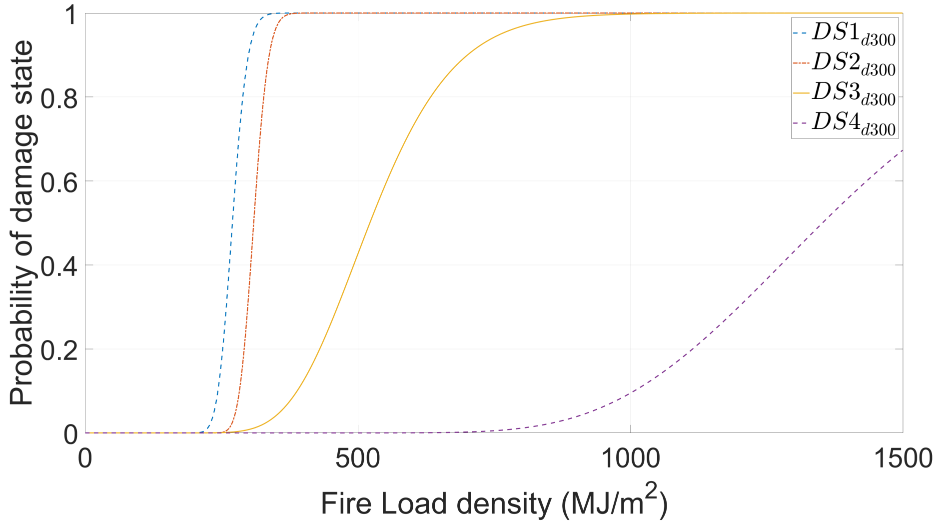

Figure 4: Fragility curves for $DS1_{d300}$, $DS2_{d300}$, $DS3_{d300}$ and $DS4_{d300}$ after [41]

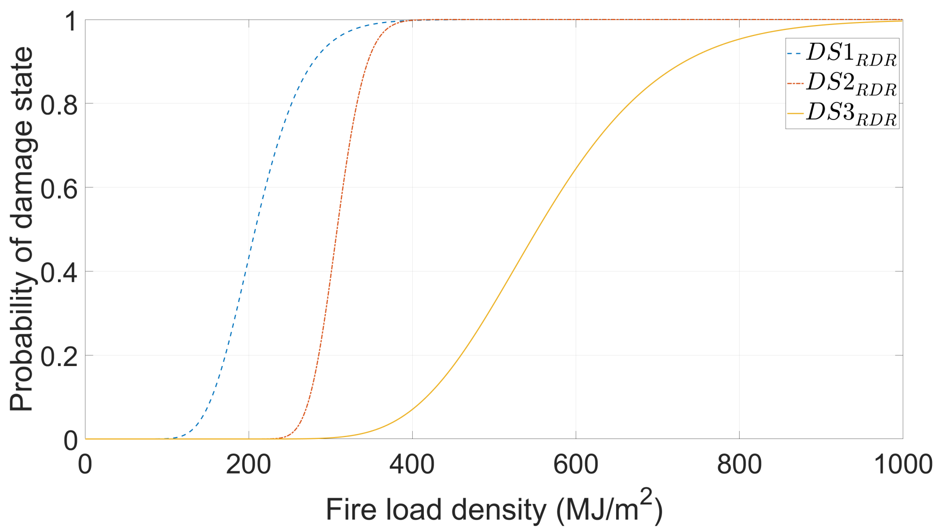

Figure 5: Fragility curves for $DS1_{RDR}$, $DS2_{RDR}$ and $DS3_{RDR}$ after [41]

to be valid for all columns and beams of the case study which, taken together, represent the 19.6%, Δ_{d300} from now on, of the total structural and non-structural cost of the building. Likewise, the floor systems which are affected by the EDP RDR are evaluated as Δ_{RDR} = 18.9%. it is important to notice that the remaining fraction of the costs is represented by internal and external infills which, according, to [41] are supposed to be completely replaced in the event of a fire independently of the fire load level. Similar considerations are made on the replacement of the internal content of the structure. For these reasons and since the framework goal is a comparison between I_{EPS} than of I_{GW}, we will neglect this part in our calculation. In the methodology here presented, the environmental impact of these costs is assumed as a corresponding fraction of the embodied carbon of the original building. This is directly derived from the EIO-LCA method, in which the economic cost is directly transformed in equivalent emissions [28; 55; 54]. The economic costs from [41] could have been taken as an absolute measure of the impact to be then transformed into an environmental variable but this would have lacked a certain degree of generalization, given the price differences between countries and other factors. The level of embodied carbon in buildings has been deeply investigated. In detail, [72] compares 4 different studies assessing the differences in the embodied carbon of wood (108-288 kg CO_{2eq}/m^2), steel (241-513 kg CO_{2eq}/m^2) and concrete (332-433 kg CO_{2eq}/m^2) buildings without distinguishing between their intended destination of use. Along the same line, [73] presented a review of 40 different studies, providing a 50% confidence interval of 161-374 kg CO_{2eq}/m^2 for single-family houses and 341-631 kg CO_{2eq}/m^2 for multi-family houses. Based on this review, we will assume an embodied carbon EC_e = 400 CO_{2eq}/m^2 for our case study. The term EM_{rDM} is then evaluated for both the EPS and GW designs as follows while all the relevant parameters are listed in Table 5:

$$EM_{rDM_{EPS}} = \sum_{n=1}^{4} P'_{DSn_{EPS}} \cdot \Delta_{DSn} \cdot \Delta_{d300} \cdot EC_e + \sum_{n=1}^{3} P'_{DSn_{EPS}} \cdot \Delta_{DSn} \cdot \Delta_{RDR} \cdot EC_e = \\ = (0.090 + 0.257) kg_{CO_{2eq}} m^{-2} y^{-1} = 0.347 kg_{CO_{2eq}} m^{-2} y^{-1} \tag{16}$$

$$EM_{rDM_{GW}} = \sum_{n=1}^{4} P'_{DSn_{GW}} \cdot \Delta_{DSn} \cdot \Delta_{d300} \cdot EC_e + \sum_{n=1}^{3} P'_{DSn_{GW}} \cdot \Delta_{DSn} \cdot \Delta_{RDR} \cdot EC_e = \\ = (0.064 + 0.201) kg_{CO_{2eq}} m^{-2} y^{-1} = 0.265 kg_{CO_{2eq}} m^{-2} y^{-1} \tag{17}$$

which leads to:

$$\Delta EM_{rDM_{I_{EPS-GW}}} = EM_{rDM_{I_{EPS}}} - EM_{rDM_{I_{EPS}}} = (0.348 - 0.265) kg_{CO_{2eq}} m^{-2} y^{-1} = \\ = 0.082 kg_{CO_{2eq}} m^{-2} y^{-1} \tag{18}$$

As expected, the fire risk related emissions are higher in the case of I_{EPS} than of I_{GW}. Table 5 shows that the damage states which contribute most to the expected

Table 5: Fire risk analysis parameters

Damage State	P_{DSn} (y^{-1})		$EM_{rDM}(P_{DSn})$ $(kg_{CO_{2,eq}}/(m^2y))$		$EM_{rDM}(P'_{DSn})$ $(kg_{CO_{2,eq}}/(m^2y))$	
	I_{EPS}	I_{GW}	I_{EPS}	I_{GW}	I_{EPS}	I_{GW}
$DS1_{d300}$	$3 \cdot 10^{-3}$	$3 \cdot 10^{-3}$	$1.1 \cdot 10^{-2}$	$1.1 \cdot 10^{-2}$	- -	$4.9 \cdot 10^{-4}$
$DS2_{d300}$	$3 \cdot 10^{-3}$	$2.8 \cdot 10^{-3}$	$5.6 \cdot 10^{-2}$	$5.3 \cdot 10^{-2}$	$1.0 \cdot 10^{-2}$	$3.7 \cdot 10^{-2}$
$DS3_{d300}$	$2.5 \cdot 10^{-3}$	$8.4 \cdot 10^{-4}$	$7.7 \cdot 10^{-2}$	$2.6 \cdot 10^{-2}$	$7.6 \cdot 10^{-2}$	$2.6 \cdot 10^{-2}$
$DS4_{d300}$	$1.9 \cdot 10^{-5}$	$1.2 \cdot 10^{-6}$	$3.8 \cdot 10^{-3}$	$2.5 \cdot 10^{-4}$	$3.8 \cdot 10^{-3}$	$2.4 \cdot 10^{-4}$
$DS1_{RDR}$	$3 \cdot 10^{-3}$	$3 \cdot 10^{-3}$	$2.3 \cdot 10^{-2}$	$2.3 \cdot 10^{-3}$	- -	$1.2 \cdot 10^{-3}$
$DS2_{RDR}$	$3 \cdot 10^{-3}$	$2.8 \cdot 10^{-3}$	$2.0 \cdot 10^{-1}$	$1.8 \cdot 10^{-1}$	$4.6 \cdot 10^{-2}$	$1.4 \cdot 10^{-1}$
$DS3_{RDR}$	$2.3 \cdot 10^{-3}$	$6.5 \cdot 10^{-4}$	$2.1 \cdot 10^{-1}$	$6.0 \cdot 10^{-2}$	$2.1 \cdot 10^{-1}$	$6.0 \cdot 10^{-2}$

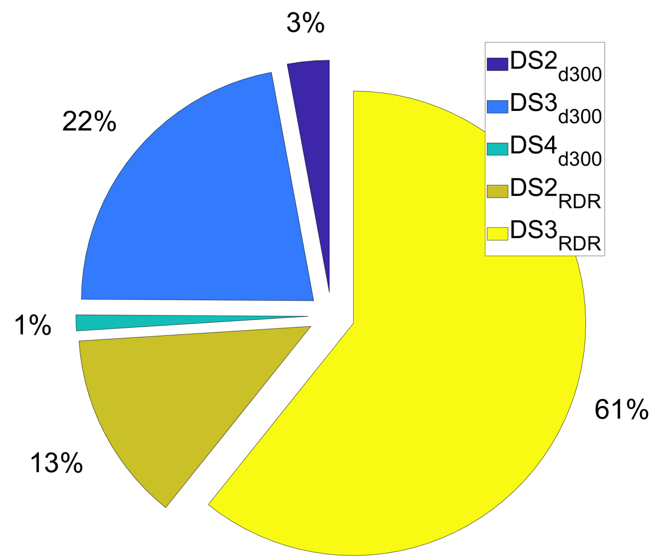

Figure 6: Contribution share of the different DSs to $EM_{rDM_{EPS}}$

yearly emissions are $DS3_{d300}$ and $DS3_{RDR}$ for I_{EPS} and $DS2_{d300}$ and $DS2_{RDR}$ for I_{EPS}, as also depicted in Fig. 6 and 7.

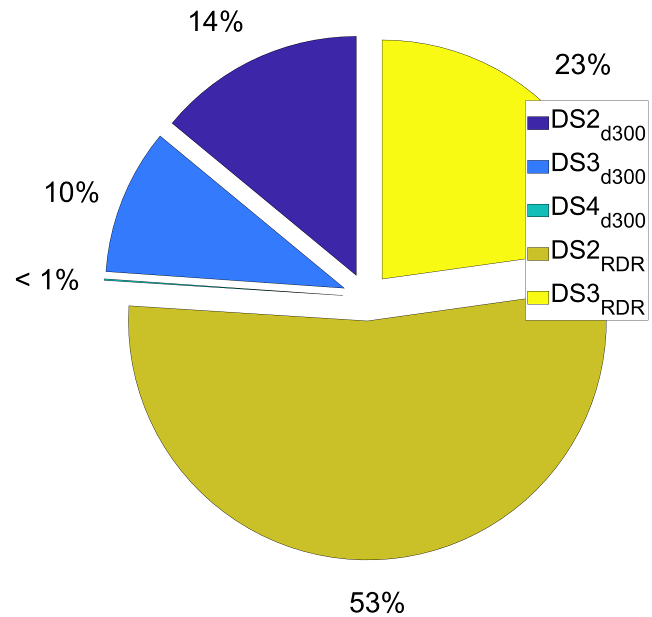

Figure 7: Contribution share of the different DSs to $EM_{rDM_{GW}}$

3.2.4. *Fire and damage-induced direct emissions*

Another class of emissions potentially triggered by fires are related to the direct release of chemicals into the environment. Indeed, the burning process can produce several compounds, including, among others, CO_2 [34]. For reference, according to a 2020 NFPA report [74], the burning of the content of an 80 m^2 apartment can lead to the release of $5.2 \cdot 10^3$ kg of CO_2. Moreover, [25] reports that damage to structural and non-structural components of a residential building can lead to a release of up to 91.5 kg CO_{2eq}/m^2 because of the high-gwp HFCs content. These two contributions are however neglected in this assessment because of the lack of details on the possible emission proportions in both I_{EPS} than of I_{GW}.

We can however assume, in agreement with the hypothesis on the contribution to fire, that the burning of the combustible $M_{I_{EPS}}$ will produce CO_2 emissions not present in the I_{GW} scenario. From [34] we gather that from the combustion of 1 kg of polystyrene, 2.2 kg of CO_2 are released. It is therefore possible to write:

$$\Delta EM_{dDM_{I_{EPS-GW}}} = EM_{dDM_{I_{EPS}}} = \frac{M_{I_{EPS}} \cdot 2.2}{196} \cdot P(F) = 0.058 kg_{CO_{2eq}} m^{-2} y^{-1} \tag{19}$$

The result of Eq. 19 shows that the contribution of $\Delta EM_{dDM_{I_{EPS-GW}}}$ is not negligible when compared to $\Delta EM_{rDM_{I_{EPS-GW}}}$ calculated in Eq. 18.

3.2.5. Fire risk emissions assessment and methodology limitations

To conclude the part related to fire risk of the MANFREdI framework, we can rewrite Eq. 4 using the results from eqs. 19 and 18:

$$\Delta EM_{F_{I_{EPS-GW}}} = (0.083 + 0.058) kg_{CO_{2eq}} m^{-2} y^{-1} = 0.141 kg_{CO_{2eq}} m^{-2} y^{-1} \quad (20)$$

In the spirit of the proposed framework, the obtained value is meant to be compared with the result of Eq. 24. It is however clear that the degree of uncertainty that may affect such a value could be potentially significant.

For instance, the cumulative fire load $\lambda(q_{cIt})$ is affected by the uncertainty related to both q_e and q_{It}. The first is difficult to determine also in a probabilistic way, given its wide range. The latter depends on the insulation material's actual flammability and the consequent contribution to fire, which is still a topic of recent research.

Likewise, the hazard model component $P(F)$, is directly proportional to ΔEM_F and is of difficult assessment for two main reasons. First, the definition of a "structural significant" fire [68] is not quantitatively defined. Second, the hazard model significantly depends on the type of building, its destination of use [66] and external factors such as proximity to fire emergency services [75] or other mitigation measures [35].

It is also noteworthy that the fire loss analysis encompasses a few sources of uncertainty. For reference, the overall vulnerability to fire can significantly depend on the opening factor of a given compartment [76]. Depending on the opening factor fuel or ventilation controlled fires can develop, attaining different gas temperatures in the compartments and determining different levels of the thermal attack and of the consequent damage. According to [76], a lower opening factor can lead to more severe damage states. The opening factor is influenced by, among other parameters, the presence of open windows during the fire, accounting also for closed windows then damaged by the fire itself. Non-structural components also play an essential role in loss estimation. Data from [41] show that they account for 61% of the construction costs and are to be entirely replaced in case of a fire. Assuming, however, for the sake of discussion, that the I_{GW} scenario would result in 15% less non-structural damage than I_{EPS} scenario, $\Delta EM_{F_{I_{EPS-GW}}}$ would increase by 53%. This is without accounting for the effects of the damages to the fire area content and the relevant direct emissions. Besides, the differences between I_{GW} and I_{EPS} could arguably influence the probability of spreading the fire to other floors or buildings, with some relevant statistics reported in [74]. This could be a direct consequence of fire protection characteristics of incombustible thermal insulation [48].

3.3. Energy savings assessment

As already discussed in Subsection 2.1, Eq. 2 can be solved by adopting different methods. In this application, we will rely on the basic HDD approach [42]. This is because it will: i) allow a simplified and straightforward procedure, ii) deliver rather general results independent of many specific characteristics of each building. In fact, despite the case-specific approximations, this approach allows the calculation of the energy related exclusively to the heat loss from the building's envelope. This reflects the goal of the proposed framework since it allows a direct comparison between, in this case study, I_{EPS} and I_{GW}. Based on a widely used analytical formulation [42; 77] we can rewrite Eq. 2 as:

$$Ec_{I_t} = 0.024 \cdot HDD \cdot \sum_n (U_{nI_t} \cdot A_n) \cdot \eta^{-1} \cdot A_f^{-1} \tag{21}$$

where HDD is the value of the heat degree days, and η is the efficiency of the heating system. We will assume HDD = 2550, which is the half value of the Italian climate zone E range. The efficiency parameter η is set equal to 0.99, reflecting the performance of a modern gas heating system. Using the values listed in Table 1 and the geometrical data from the case study, Eq.21 can be written as follows:

$$\begin{aligned} Ec_{I_{EPS}} = 0.024 \cdot HDD \cdot (A_r \cdot U_{rEPS} + A_w \cdot U_{wEPS}) \cdot \eta^{-1} \cdot A_f^{-1} = \\ = 23.7 kWhm^{-2}y^{-1} \end{aligned} \tag{22}$$

$$\begin{aligned} Ec_{I_{GW}} = 0.024 \cdot HDD \cdot (A_r \cdot U_{rGW} + A_w \cdot U_{wGW}) \cdot \eta^{-1} \cdot A_f^{-1} = \\ = 26.5 kWhm^{-2}y^{-1} \end{aligned} \tag{23}$$

As expected, the energy required to balance the heat loss is higher in the I_{GW} design. The order of magnitude of the difference between I_{GW} and I_{EPS} is confirmed by other studies involving more accurate dynamic models [3; 4; 78; 79]. It is noteworthy that we have neglected the potential cooling energy required, which would have widened the difference. This is because: i) usually there are no minimum performances required for residential buildings, ii) cooling energy consumption is still a fraction of the heating consumption, iii) overall, the cooling energy consumption shows a weaker correlation with thermal insulation [3; 79]. The solution of Eq. 4 requires converting the energy E_C to equivalent emissions. From [80] we retrieve that in the case of a natural gas boiler, by far the most common system, $GWP_E = 0.213 kgCO_{2eq} kWh^{-1}$. On this basis, we can rewrite Eq. 4 as follows:

$$\begin{aligned} \Delta EM_{Ec_{I_{EPS-GW}}} = (EM_{Ec_{I_1}} - EM_{Ec_{I_2}}) \cdot GWP_E = \\ = ((23.7 - 26.5) \cdot 0.213) kg_{CO_{2eq}} m^{-2} y^{-1} = -0.59 kg_{CO_{2eq}} m^{-2} y^{-1} \end{aligned} \tag{24}$$

The environmental benefits from the lower energy consumption are greater but comparable to the negative environmental impact of the fire risk. The equal order of magnitude of the results from Eqs. 20 and 24 proves therefore the value of the framework here presented. It is important to consider that the parameter GWP_E can significantly change depending on the heating technology and on the overall carbon density of the energy grid. For reference, a 2016 report [81] from UK Parliament provided a scenario with an air source heat pump able to deliver domestic heating with a carbon footprint as low as $0.030 kgCO_{2eq} kWh^{-1}$. This scenario, possible for the late 2030s, would lower the parameter GWP_E by 86% compared to the value used in Eq. 24. In general, the inclusion of the carbon footprint of the future energy mix is not new in LCA [44]. Another critical factor is the geometry of the building, which can strongly influence its heating energy consumption on the basis of the ratio between the envelope surface and internal volume to be heated [82].

4. Conclusions and future developments

This paper proposes a method to comparatively assess the environmental impacts of combustible or non-combustible thermal insulation based on fire risk and energy consumption. The main novelty of the presented framework is the conversion of recent probabilistic fire risk assessment approaches to environmental variables through embodied carbon metrics. This conversion allows for a direct comparison in terms of equivalent GHG emissions. A simplified application to a residential building is also shown. The main conclusions are outlined below.

- A quantitative analysis of the fire risk related to thermal insulation can be solved through a full probabilistic approach adapted from PBEE methods. The necessary fire hazard and vulnerability models can be derived from existing statistics, scientific literature and numerical simulations. The simple analytical formulation allows for a straightforward application.

- Existing experimental evidence suggests that code-compliant combustible thermal insulation could contribute to fire depending on the fire scenario and specific codes.

- The additional fire load related to code-compliant thermal insulation, depending on the climate zone and the geometric configuration, can reach values of the order of $10^2 MJ/m^2$. These values are not negligible since they fall within the same order of magnitude of the expected fire load for residential buildings.

- Direct emissions from the combustion of polymeric insulation were found to be not negligible when compared with the embodied carbon-related environmental impact of fire damages.

- Overall, the environmental benefits of a high-performance combustible thermal insulation over a low-performance non-combustible one may not be simple. For the examined case study, the equivalent emissions from reduced energy consumption and fire risk related emissions are both of the order of $10^{-1} kg_{CO_{2eq}} m^{-2} y^{-1}$

As regards further developments, the practical application of the proposed framework could be improved by future research along the following lines: i) additional experimental evidence can better quantify the effective contribution to fire of thermal insulation alongside the relevant direct emissions; ii) experimental and numerical analyses could widen the existing database of fire fragility functions for loss assessment; iii) improve the existing fire hazard statistics with a specific focus on fire severity, compartmental fire spread and influence of external factors such as emergency services intervention; iv) consider the influence on framework results of parameters such as building's geometry, climate zones and relevant requirements, the destination of use, carbon density of the energy mix and building's embodied carbon.

5. Acknowledgments

The first author was supported by Habitech SRL with the research scholarship named in memory of Eng. Gianni Lazzari.

The second author was partially supported by the UK Research and Innovation (UKRI) Institution in the framework of the project RESTORE (grant EP/X032469/1).

The fourth author acknowledges the Italian Ministry of Education, Universities and Research (MUR) in the framework of the project PNRR CN ICSC Spoke 9.

References

[1] UN, United Nations Environment Programme (2021). 2021 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector., Tech. rep., Nairobi, Kenya (2021).
URL https://globalabc.org/resources/publications/2021-global-status-report-buildings-and-construction

[2] K. Amasyali, N. M. El-Gohary, A review of data-driven building energy consumption prediction studies, Renewable and Sustainable Energy Reviews 81 (2018) 1192–1205. doi:https://doi.org/10.1016/j.rser.2017.04.095.
URL https://www.sciencedirect.com/science/article/pii/S1364032117306093

[3] X. Liu, X. Chen, M. Shahrestani, Optimization of insulation thickness of external walls of residential buildings in hot summer and cold winter zone of china, Sustainability 12 (4) (2020). doi:10.3390/su12041574.
URL https://www.mdpi.com/2071-1050/12/4/1574

[4] A. Benallel, A. Tilioua, A. Mellaikhafi, M. A. A. Hamdi, Thickness optimization of exterior wall insulation for different climatic regions in morocco, Materials Today: Proceedings 58 (2022) 1541–1548, 3rd International Congress on Materials Structural Stability. doi:https://doi.org/10.1016/j.matpr.2022.03.324.
URL https://www.sciencedirect.com/science/article/pii/S2214785322016698

[5] C. Hopkin, M. Spearpoint, D. Hopkin, A review of design values adopted for heat release rate per unit area, Fire Technology 55 (03 2019). doi:10.1007/s10694-019-00834-8.

[6] ISO, International Organization for Standardization - ISO 6946:2007 Building components and building elements — Thermal resistance and thermal transmittance — Calculation method, Standard, Geneva, CH (2007).

[7] UN, United Nations, Mapping of Existing Energy Efficiency Standards and Technologies in Buildings in the UNECE Region, ECONOMIC COMMISSION FOR EUROPE Joint Task Force on Energy Efficiency Standards in Buildings, United Nations, Geneve, 2018.
URL https://unece.org/info/publications/pub/2917

[8] HM Government, Approved Document L - Conservation of fuel and power, The Building Regulations 2010, HM Government, 2016.
URL https://www.gov.uk/government/publications/conservation-of-fuel-and-power-approved-document-l

[9] MISE, Ministero dello Sviluppo Economico, ALLEGATO E - Requisiti degli interventi di isolamento termico - Requisiti tecnici per l'accesso alle detrazioni fiscali per la riqualificazione energetica degli edifici - cd. Ecobonus., Serie generale - n. 246, Gazzetta Ufficiale, 2020.
URL https://www.gazzettaufficiale.it/eli/id/2020/10/05/20A05394/sg

[10] B. Abu-Jdayil, A.-H. Mourad, W. Hittini, M. Hassan, S. Hameedi, Traditional, state-of-the-art and renewable thermal building insulation materials: An overview, Construction and Building Materials 214 (2019) 709–735. doi:https://doi.org/10.1016/j.conbuildmat.2019.04.102.
URL https://www.sciencedirect.com/science/article/pii/S0950061819309845

[11] M. S. McLaggan, J. P. Hidalgo, J. Carrascal, M. T. Heitzmann, A. F. Osorio, J. L. Torero, Flammability trends for a comprehensive array of cladding materials, Fire Safety Journal 120 (2021) 103133, fire Safety Science: Proceedings of the 13th International Symposium. doi:https://doi.org/10.1016/j.firesaf.2020.103133.
URL https://www.sciencedirect.com/science/article/pii/S037971122030093X

[12] A. C. Y. Yuen, T. Chen, A. Li, I. M. De Cachinho Cordeiro, L. Liu, H. Liu, A. Lo, Q. Chan, G. Yeoh, Evaluating the fire risk associated with cladding panels: An overview of fire incidents, policies, and future perspective in fire standards, Fire and Materials 45 (04 2021). doi:10.1002/fam.2973.

[13] T. B. Y. Chen, A. C. Y. Yuen, G. H. Yeoh, W. Yang, Q. N. Chan, Fire risk assessment of combustible exterior cladding using a collective numerical database, Fire 2 (1) (2019). doi:10.3390/fire2010011.
URL https://www.mdpi.com/2571-6255/2/1/11

[14] S. T. McKenna, N. Jones, G. Peck, K. Dickens, W. Pawelec, S. Oradei, S. Harris, A. A. Stec, T. R. Hull, Fire behaviour of modern façade materials – understanding the grenfell tower fire, Journal of Hazardous Materials 368 (2019) 115–123. doi:https://doi.org/10.1016/j.jhazmat.2018.12.077.
URL https://www.sciencedirect.com/science/article/pii/S0304389418312275

[15] Y. Li, Z. Wang, X. Huang, An exploration of equivalent scenarios for building facade fire standard tests, Journal of Building Engineering 52 (2022) 104399. doi:https://doi.org/10.1016/j.jobe.2022.104399.
URL https://www.sciencedirect.com/science/article/pii/S2352710222004120

[16] D. Kumar, M. Alam, P. X. Zou, J. G. Sanjayan, R. A. Memon, Comparative analysis of building insulation material properties and performance, Renewable and Sustainable Energy Reviews 131 (2020) 110038. doi:https://doi.org/10.1016/j.rser.2020.110038.
URL https://www.sciencedirect.com/science/article/pii/S1364032120303294

[17] K. Kalhor, N. Emaminejad, Qualitative and quantitative optimization of thermal insulation materials: Insights from the market and energy codes, Journal of Building Engineering 30 (2020) 101275. doi:https://doi.org/10.1016/j.jobe.2020.101275.
URL https://www.sciencedirect.com/science/article/pii/S2352710219312215

[18] M. Bonner, G. Rein, Flammability and multi-objective performance of building façades: Towards optimum design, International Journal of High-Rise Buildings 7 (2018) 363–374. doi:10.21022/IJHRB.2018.7.4.363.

[19] B. Roberts, M. Webber, O. Ezekoye, Development of a multi-objective optimization tool for selecting thermal insulation materials in sustainable designs, Energy and Buildings 105 (2015) 358–367. doi:https://doi.org/10.1016/j.enbuild.2015.07.063.
URL https://www.sciencedirect.com/science/article/pii/S0378778815301791

[20] B. Ang, B. Su, Carbon emission intensity in electricity production: A global analysis, Energy Policy 94 (2016) 56–63. doi:10.1016/j.enpol.2016.03.038.

[21] Y. Shen, M. Yarnold, A novel sensitivity analysis of commercial building hybrid energy-structure performance, Journal of Building Engineering 43 (2021) 102808. doi:https://doi.org/10.1016/j.jobe.2021.102808.
URL https://www.sciencedirect.com/science/article/pii/S2352710221006665

[22] A. Belleri, A. Marini, Does seismic risk affect the environmental impact of existing buildings?, Energy and Buildings 110 (2016) 149–158. doi:https://doi.org/10.1016/j.enbuild.2015.10.048.
URL https://www.sciencedirect.com/science/article/pii/S0378778815303625

[23] V. Hasik, J. P. Chhabra, G. P. Warn, M. M. Bilec, Review of approaches for integrating loss estimation and life cycle assessment to assess impacts of seismic building damage and repair, Engineering Structures 175 (2018) 123–137. doi:https://doi.org/10.1016/j.engstruct.2018.08.011.
URL https://www.sciencedirect.com/science/article/pii/S014102961830258X

[24] M. Caruso, R. Pinho, F. Bianchi, F. Cavalieri, M. T. Lemmo, A life cycle framework for the identification of optimal building renovation strategies considering economic and environmental impacts, Sustainability 12 (23) (2020). doi:10.3390/su122310221.
URL https://www.mdpi.com/2071-1050/12/23/10221

[25] R. di Filippo, O. S. Bursi, R. di Maggio, Global warming and ozone depletion potentials caused by emissions from hfc and cfc banks due structural damage, Energy and Buildings 273 (2022) 112385. doi:https://doi.org/10.1016/j.enbuild.2022.112385.
URL https://www.sciencedirect.com/science/article/pii/S0378778822005564

[26] R. A. Salgado, S. Guner, A structural performance-based environmental impact assessment framework for natural hazard loads, Journal of Building Engineering 43 (2021) 102908. doi:https://doi.org/10.1016/j.jobe.2021.102908.
URL https://www.sciencedirect.com/science/article/pii/S235271022100766X

[27] FEMA, ATC, Applied Technology Council - Methodology for Assessing Environmental Impacts, Seismic Performance Assessment of Buildings - Volume 4, Federal Emergency Management Agency (FEMA): Washington, DC, USA, 2018.

[28] S. Suh, B. Lippiatt, Framework for hybrid life cycle inventory databases: A case study on the building for environmental and economic sustainability (bees) database, The International Journal of Life Cycle Assessment 17 (06 2012). doi:10.1007/s11367-012-0393-z.

[29] G. Hammond, C. Jones, Embodied Carbon: The Concealed Impact of Residential Construction, Global Warming. Green Energy and Technology., Springer, Boston, MA., 2009. doi:10.1007/978-1-4419-1017-2_23.

[30] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, B. Weidema, The ecoinvent database version 3 (part i): overview and methodology, International Journal of Life Cycle Assessment 21 (9) (2016) 1218–1230. doi:10.1007/s11367-016-1087-8.

[31] R. di Filippo, O. S. Bursi, M. Ragazzi, M. Ciucci, Natech risk and the impact of high-gwp content release on lca of industrial components, Process Safety and Environmental Protection 160 (2022) 683–694. doi:https://doi.org/10.1016/j.psep.2022.02.042.
URL https://www.sciencedirect.com/science/article/pii/S095758202200163X

[32] L. Possidente, A. Weiss, D. de Silva, S. Pustorino, E. Nigro, N. Tondini, Fire safety engineering principles applied to a multi-storey steel building, Structures and Buildings 174 (2021) 725–738. doi:https://doi.org/10.1680/jstbu.20.00110.
URL https://www.icevirtuallibrary.com/doi/abs/10.1680/jstbu.20.00110

[33] E. Nigro, A. Bilotta, D. Asprone, F. Jalayer, A. Prota, G. Manfredi, Probabilistic approach for failure assessment of steel structures in fire by means of plastic limit analysis, Fire Safety Journal 68 (2014) 16–29. doi:https://doi.org/10.1016/j.firesaf.2014.05.020.
URL https://www.sciencedirect.com/science/article/pii/S0379711214000770

[34] B. Persson, M. Simonson, Fire emissions into the atmosphere, Fire Technology 34 (3) (1998) 266–279, copyright: Copyright 2020 Elsevier B.V., All rights reserved. doi:10.1023/a:1015350024118.

[35] T. Gernay, N. Elhami Khorasani, M. Garlock, Fire fragility functions for steel frame buildings: Sensitivity analysis and reliability framework, Fire Technology 55 (08 2018). doi:10.1007/s10694-018-0764-5.

[36] E. Cardellino, D. de Silva, E. Nigro, Estimation of Structural Fire Vulnerability Through Fragility Curves, 2022, pp. 586–593. doi:10.1007/978-3-030-91877-4_67.

[37] J. Randaxhe, N. Popa, N. Tondini, Probabilistic fire demand model for steel pipe-racks exposed to localised fires, Engineering Structures 226 (2021) 111310. doi:https://doi.org/10.1016/j.engstruct.2020.111310.
URL https://www.sciencedirect.com/science/article/pii/S0141029620339110

[38] L. Possidente, N. Tondini, J. Randaxhe, Fire fragility curves for industrial steel pipe-racks integrating demand and capacity uncertainties, Fire Technology, To be submitted - (-) –. doi:-.
URL -

[39] D. Rush, D. Lange, Towards a fragility assessment of a concrete column exposed to a real fire – tisova fire test, Engineering Structures 150 (2017) 537–549. doi:https://doi.org/10.1016/j.engstruct.2017.07.071.
URL https://www.sciencedirect.com/science/article/pii/S014102961730617X

[40] R. K. Chaudhary, T. Roy, V. Matsagar, Framework for fragility assessment of reinforced concrete portal frame subjected to elevated temperature, Structures 28 (2020) 2785–2800. doi:https://doi.org/10.1016/j.istruc.2020.10.078.
URL https://www.sciencedirect.com/science/article/pii/S2352012420306354

[41] S. Ni, T. Gernay, A framework for probabilistic fire loss estimation in concrete building structures, Structural Safety 88 (2021) 102029. doi:https://doi.org/10.1016/j.strusafe.2020.102029.
URL https://www.sciencedirect.com/science/article/pii/S0167473020301089

[42] A. Bolattürk, Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in turkey, Applied Thermal Engineering 26 (11) (2006) 1301–1309. doi:https://doi.org/10.1016/j.applthermaleng.2005.10.019.
URL https://www.sciencedirect.com/science/article/pii/S1359431105003625

[43] S. A. Al-Sanea, M. Zedan, Improving thermal performance of building walls by optimizing insulation layer distribution and thickness for same thermal

mass, Applied Energy 88 (9) (2011) 3113–3124. doi:https://doi.org/10.1016/j.apenergy.2011.02.036.
URL https://www.sciencedirect.com/science/article/pii/S0306261911001486

[44] R. Llopis, D. Calleja-Anta, A. Maiorino, L. Nebot-Andrés, D. Sánchez, R. Cabello, Tewi analysis of a stand-alone refrigeration system using low-gwp fluids with leakage ratio consideration, International Journal of Refrigeration 118 (2020) 279–289. doi:https://doi.org/10.1016/j.ijrefrig.2020.05.028.
URL https://www.sciencedirect.com/science/article/pii/S0140700720302528

[45] T. Potrc Obrecht, S. Jordan, A. Legat, A. Passer, The role of electricity mix and production efficiency improvements on greenhouse gas (ghg) emissions of building components and future refurbishment measures, The International Journal of Life Cycle Assessment 26 (2021) 1–13. doi:10.1007/s11367-021-01920-2.

[46] H.-W. Suh, S.-M. Im, T.-H. Park, H.-J. Kim, H.-S. Kim, H.-K. Choi, J.-H. Chung, S.-C. Bae, Fire spread of thermal insulation materials in the ceiling of piloti-type structure: Comparison of numerical simulation and experimental fire tests using small- and real-scale models, Sustainability 11 (12) (2019). doi:10.3390/su11123389.
URL https://www.mdpi.com/2071-1050/11/12/3389

[47] J. Hidalgo, J. Torero, S. Welch, Experimental characterisation of the fire behaviour of thermal insulation materials for a performance-based design methodology, Fire Technology 53 (10 2016). doi:10.1007/s10694-016-0625-z.

[48] B. Zhou, H. Yoshioka, T. Noguchi, K. Wang, X. Huang, Fire performance of eps etics facade: Effect of test scale and masonry cover, Fire Technology (12 2021). doi:10.1007/s10694-021-01195-x.

[49] R. Crewe, J. Hidalgo, M. Sørensen, M. McLaggan, S. Molyneux, S. Welch, G. Jomaas, J. Torero, A. Stec, R. Hull, Fire performance of sandwich panels in a modified iso 13784-1 small room test: The influence of increased fire load for different insulation materials, Fire Technology 54 (04 2018). doi:10.1007/s10694-018-0703-5.

[50] M. D. Hossain, M. K. Hassan, M. Akl, S. Pathirana, P. Rahnamayiezekavat, G. Douglas, T. Bhat, S. Saha, Fire behaviour of insulation panels commonly used in high-rise buildings, Fire 5 (3) (2022). doi:10.3390/fire5030081.
URL https://www.mdpi.com/2571-6255/5/3/81

[51] S. Gnanachelvam, A. Ariyanayagam, M. Mahendran, Effects of insulation materials and their location on the fire resistance of lsf walls, Journal of Building Engineering 44 (2021) 103323. doi:https://doi.org/10.1016/j.jobe.2021.103323.
URL https://www.sciencedirect.com/science/article/pii/S2352710221011815

[52] C. A. Cornell, H. Krawinkler, Progress and challenges in seismic performance assessment, PEER Center News (2000).
URL http://peer.berkeley.edu

[53] J. W. Baker, Efficient Analytical Fragility Function Fitting Using Dynamic Structural Analysis, Earthquake Spectra 31 (1) (2015) 579–599. doi:10.1193/021113EQS025M.
URL http://journals.sagepub.com/doi/10.1193/021113EQS025M

[54] M. Caruso, R. Pinho, F. Bianchi, F. Cavalieri, M. T. Lemmo, Integrated economic and environmental building classification and optimal seismic vulnerability/energy efficiency retrofitting, Bulletin of Earthquake Engineering 19 (2021) 3627–3670. doi:10.1007/s10518-021-01101-4.

[55] K. Simonen, M. Huang, C. Aicher, P. Morris, Embodied carbon as a proxy for the environmental impact of earthquake damage repair, Energy and Buildings 164 (2018) 131–139. doi:https://doi.org/10.1016/j.enbuild.2017.12.065.
URL https://www.sciencedirect.com/science/article/pii/S0378778817319710

[56] F. Blondin, P. Blanchet, C. Dagenais, Z. Triantafyllidis, L. Bisby, Fire hazard of compressed straw as an insulation material for wooden structures, Fire and Materials 44 (5) (2020) 736–746. arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1002/fam.2851, doi:https://doi.org/10.1002/fam.2851.
URL https://onlinelibrary.wiley.com/doi/abs/10.1002/fam.2851

[57] Q. Xu, C. Jin, G. Griffin, J. Hristov, D. Cvetinović, Y. Jiang, Influence of fiberglass mesh on flammability of eps used as insulation of buildings, Thermal Science 2016 (2016) 173–173. doi:10.2298/TSCI160405173X.

[58] D. Hossain, M. K. Hassan, A. C. Y. Yuen, Y. He, S. Saha, W. Hittini, Flame behaviour, fire hazard and fire testing approach for lightweight composite claddings – a review, Journal of Structural Fire Engineering ahead-of-print (04 2021). doi:10.1108/JSFE-09-2020-0027.

[59] S. Kumar, C. Rao, Fire load in residential buildings, Building and Environment 30 (2) (1995) 299–305. doi:https://doi.org/10.1016/0360-1323(94)00043-R.
URL https://www.sciencedirect.com/science/article/pii/036013239400043R

[60] J. Hietaniemi, E. Mikkola, Design Fires for Fire Safety Engineering, no. 139 in VTT Working Papers, VTT Technical Research Centre of Finland, Finland, 2010, project code: 19265.

[61] A. Bwalya, G. Lougheed, A. Kashef, H. Saber, Survey results of combustible contents and floor areas in canadian multi-family dwellings, Fire Technology 47 (2011) 1121–1140. doi:10.1007/s10694-009-0130-8.

[62] D. Lange, S. Devaney, A. Usmani, An application of the peer performance based earthquake engineering framework to structures in fire, Engineering Structures 66 (2014) 100–115. doi:https://doi.org/10.1016/j.engstruct.2014.01.052.
URL https://www.sciencedirect.com/science/article/pii/S0141029614000662

[63] The British Standards Institution, PD 7974-7 Application of Fire Safety Engineering Principles to the Design of Buildings - Part 7: Probabilistic Risk Assessment, 2019.

[64] J. R. Centre, I. for the Protection, S. of the Citizen, U. Meyer, B. Zhao, O. Vassart, L. Cajot, A. Frangi, F. Robert, Eurocodes : background and applications : structural fire design. Worked examples, Publications Office, 2014. doi:doi/10.2788/85432.

[65] M. Manes, D. Rush, Assessing fire frequency and structural fire behaviour of england statistics according to bs pd 7974-7, Fire Safety Journal 120 (2021) 103030, fire Safety Science: Proceedings of the 13th International Symposium. doi:https://doi.org/10.1016/j.firesaf.2020.103030.
URL https://www.sciencedirect.com/science/article/pii/S0379711220301272

[66] M. Manes, D. Rush, A critical evaluation of bs pd 7974-7 structural fire response data based on usa fire statistics, Fire Technology 55 (10 2018). doi:10.1007/s10694-018-0775-2.

[67] K. Georgiadis Filikas, I. Bakas, K. Kontoleon, Statistical analysis and review of fire incidents data of greece, with special focus on residential cases 2000–2019, Fire Technology (08 2022). doi:10.1007/s10694-022-01308-0.

[68] M. Ahrens, B. Evarts, Fire Loss in the United States during 2020, NFPA Research, NFPA, 2021.
URL https://www.nfpa.org/News-and-Research/Data-research-and-tools/US-Fire-Problem/Fire-loss-in-the-United-States

[69] U.S. Census Bureau, Residential Vacancies and Homeownership - Q4 2021, CB22-10, U.S. Department of Commerce, 2022.

[70] FEMA, FEMA P-58-3: Seismic performance assessment of buildings, Volume 3: Supporting electronic materials and background documentation, Federal Emergency Management Agency (FEMA): Washington, DC, USA, 2018.

[71] Gordon Group Inc. Concrete Masonry Costs with RSMeans Data 2019. 37th ed. Rockland, MA: RSMeans Co; 2018.

[72] R. Wen, S. Qi, A. Jrade, Simulation and assessment of whole life-cycle carbon emission flows from different residential structures, Sustainability 8 (8) (2016).

[73] K. Simonen, B. X. Rodriguez, C. D. Wolf, Benchmarking the embodied carbon of buildings, Technology|Architecture + Design 1 (2) (2017) 208–218. doi:10.1080/24751448.2017.1354623.

[74] M. McNamee, G. Marlair, B. Truchot, B. Meacham, Environmental impact of fires - research roadmap, Lund University Report 3228, ISSN: 1402-3504, ISRN: LUTVDG/TVBB–3228–SE (02 2020).

[75] N. Challands, The relationships between fire service response time and fire outcomes, Fire Technology 46 (2010) 665–676. doi:10.1007/s10694-009-0111-y.

[76] R. K. Chaudhary, A. Lucherini, T. Gernay, R. Van Coile, Evaluation of anticipated post-fire repair cost for resilient design of composite slab panels, Journal of Building Engineering 52 (2022) 104460. doi:https://doi.org/10.1016/j.jobe.2022.104460.
URL https://www.sciencedirect.com/science/article/pii/S2352710222004739

[77] A. Bodalal, S. Mashite, O. Aladouli, A. Ihdash, Calculation of annual heating and cooling energy requirements for residential building in different climate zones in libya, Innovative Energy Research 06 (01 2017). doi:10.4172/2576-1463.1000161.

[78] G. Feng, B. Dou, X. Xu, D. Chi, Y. Sun, P. Hou, Research on energy efficiency design key parameters of envelope for nearly zero energy buildings in cold

area, Procedia Engineering 205 (2017) 686–693. doi:10.1016/j.proeng.2017.09.885.

[79] J.-J. Kim, J. Moon, Impact of insulation on building energy consumption, IBPSA 2009 - International Building Performance Simulation Association 2009 (09 2010).

[80] C. Kaandorp, T. Miedema, J. Verhagen, N. van de Giesen, E. Abraham, Reducing committed emissions of heating towards 2050: Analysis of scenarios for the insulation of buildings and the decarbonisation of electricity generation, Applied Energy 325 (2022) 119759. doi:https://doi.org/10.1016/j.apenergy.2022.119759.
URL https://www.sciencedirect.com/science/article/pii/S0306261922010315

[81] POST, The Parliamentary Office of Science and Technology, Carbon footprint of heat generation, POSTnote (May Number 523 2016).
URL https://researchbriefings.files.parliament.uk/documents/POST-PN-0523/POST-PN-0523.pdf

[82] P. McKeen, A. S. Fung, The effect of building aspect ratio on energy efficiency: A case study for multi-unit residential buildings in canada, Buildings 4 (3) (2014) 336–354. doi:10.3390/buildings4030336.
URL https://www.mdpi.com/2075-5309/4/3/336