Global warming and ozone depletion potentials caused by emissions from HFC and CFC banks due structural damage.

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Abstract

Fluorocarbons are an important class of greenhouse gases, currently responsible for a non-negligible share of global emissions. CFCs are known to be linked to the depletion of the stratospheric ozone layer. CFCs and HFCs also have a high GWP. The Montreal Protocol banned the production of CFCs and, more recently, the Kigali Amendment established the phase-out of high-GWP HFCs over the coming decades. CFCs and HFCs banks are expected to continue generating emissions during the present century, however. These banks consist of CFCs and HFCs contained mainly in insulation foams, HVAC and refrigeration systems. It has been demonstrated in practice that structural and other damages caused by natural hazards (NHs) can lead to emissions from such banks. Conventional approaches that include NHs in the Life Cycle Assessment (LCA) of buildings focus mainly on the embodied carbon metric, usually examined as part of the economic input-output procedure. These issues are not considered in LCAs currently applied to Disaster Waste Management. Such methods do not take into account the potential release of high-GWP compounds in the event of extensive damage or collapse, so the related carbon footprint may may generally be underestimated. Since CFCs are banned in the vast majority of manufacturing processes, their ozone depletion potential (ODP) based on such an approach is close to zero. This paper describes a recently-proposed framework that incorporates the concept of content release ozone depletion potential (CODP), based on analytical tools that enable this ODP to be taken into account using current methods for conducting LCAs on buildings that include NHs. A case study conducted to test the proposed framework is also reported.

Keywords: natural hazards, LCA, performance-based earthquake engineering (PBEE), structural safety, HFC banks, CFC banks, disaster waste management (DWM)

List of Abbreviations

Abbreviation	Definition
AC	Air Conditioning
BOM	Bill of Materials
CGEP	Content release GHG Emission Potential
CODP	Content release Ozone Depletion Potential
DWM	Disaster Waste Management
EIO	Economic Input-Output
GHG	Greenhouse gas
GWP	Global Warming Potential
HVAC	Heath, Ventilation and Air Conditioning
IM	Intensity Measure
LCA	Life Cycle Assessment
LS	Limit State
NH	Natural Hazard
NSC	Non-structural Component
ODP	Ozone Depletion Potential
PBEE	Performance Based Earthquake Engineering
PGA	Peak Ground Acceleration
QRA	Quantitative Risk Analysis
RC	Reinforced Concrete
RL	Rate of Leakage

1. Introduction

1.1. Background and motivation

Due to their capacity to deplete the ozone layer, chlorofluorocarbons (CFCs) were gradually phased out between 1995 and 2010 in accordance with the Montreal Protocol of 1989 [1; 2]. Since the protocol's enforcement, the ozone layer has reportedly started healing [3]. CFCs have been widely used in several applications

such as aerosol sprays, refrigerant or foaming agents for insulation materials. Significant residual quantities of CFCs therefore still exist in so-called "CFC banks". Since these banks are continuing to emit CFCs into the environment, their study and quantification is still a subject of research. In particular, [4], recently revised upward the estimates on the expected emissions from CFC banks to 5 million tons of CFCs, mainly CFC-11 and CFC-12, during the present century. Whilst CFCs are characterized by a high ozone depletion potential (ODP), where CFC-11 is taken as reference with an ODP equal to 1, they also have a significant global warming potential (GWP). When their GWP is taken into account, emissions from CFC banks in the same timeframe amount to 35 billion tons CO_2eq. When CFCs were banned, they were briefly replaced with hydrochlorofluorocarbons (HCFCs), and then with hydrofluorocarbons (HFCs), which are still in use today. Unlike CFCs, HFCs have a negligible ODP, but can have a high GWP. They are used in various applications and HFC banks are still growing [5].The magnitude of the emissions from these HFC banks was estimated to contribute 0.3-0.5°C to global warming by 2100 [6; 7]. To mitigate such effects, the Kigali Amendment [8; 9] was added to the Montreal Protocol to introduce a gradual phase-out of high-GWP HFCs in the coming decades. SHFC banks are nonetheless expected to release up to 2 billion of CO_2eq a year before their emissions start to decline in the 2030s [9]. Despite the magnitude of the possible impact linked to CFCs and HFCs banks, any prediction is potentially affected by significant uncertainties due mainly to the differences between top-down and bottom-up estimates [4; 10; 11], and to the complexity of the actual emission mechanisms [12].
Along this vein, the main mechanisms of emissions relate to the operational leakage of refrigerants [13; 14] and the slower release from foams [15; 16]. Another, little explored mechanism of emission is linked to structural safety. Such a mechanism is based on the fact that collapse or damage of buildings and their relevant structural or non-structural elements can lead to the release of CFCs or HFCs. This phenomenon can be triggered at a large scale by natural hazards (NHs) as emphasized in a quantitative assessment by [17] regarding the 2011 Tohoku Earthquake and qualitatively by [18] concerning the 2004 Sumatra-Andaman Earthquake. There is also evidence of a possible release of these chemicals following the 2005 Hurricane Katrina [19]. In this respect, environmental guidelines provide recommendations on disaster waste management (DWM) that also cover appliances containing CFCs or HFCs [20; 21]. As a matter of fact, if properly treated, debris containing CFCs and HFCs could be hugely limited in their environmental impact [22].

Along this line, the release of harmful chemicals into the environment has been investigated within the analyses of NH-induced technological ("Natech") disasters [23]. Whilst Natech events are known to result in direct contamination due to leakage of polluting substances, the issue of the chemicals' global warming effects have only recently been investigated [24]. Likewise, the problem of the environmental impact of NHs has been explored by several studies on the LCA of buildings - among others, see [25; 26]. However, such studies focused on the impact caused by building materials and repairing costs evaluated through the embodied carbon metric [27; 28] or the economic input-output (EIO) approach [29]. Remarkably, a building embodied carbon is significant even when compared with the carbon footprint of its energy consumption [30]. Moreover, whilst the vast majority of the current research on this topic[31; 32], identifies the environmental variable with CO_2eq, few researchers consider the ODP effect [33; 34]. This is understandable because, now that CFCs have been banned, building materials and production processes encompass a negligible ODP, as assessed for concrete and steel by [35; 36]. Nowadays, even if the ODP is still measured in CFC-11eq, it is not linked to the release of actual CFCs but rather to the production of nitrous oxide (N_2O), which can lead to ozone losses through specific catalytic cycles [37]. Unlike the direct release of CFCs, their impact in terms of ODP is more negligible and more difficult to assess. Nitrous oxide (N_2O) is always part of a mixture of nitrogen oxides (NOx), which can have different effects both parallel and serial (ET, AP, POCP), only apparently in contrast with each other. Eutrophication, acidification, ozone formation at low altitudes (where it is toxic to humans) and greenhouse gases are consequences of emissions during the combustion of fossil fuels. At tropical latitudes, NOx can also contribute to reducing stratospheric ozone (ODP), as its cycle is sensitive to temperature. Ozone can also be destroyed by the action of free radicals, the most important of which are OH·, NO· (one of the most efficient), Cl· and Br·. Chlorine and bromine radicals derive mainly from CFCs and HCFCs, with an ozone-depleting effect that became concentrated at the North Pole in the last decades of the previous century, giving rise to the "ozone hole". Besides, according to [38], the springtime stratospheric ozone depletion is consistently followed by surface temperature and precipitation anomalies with signs consistent with a positive Arctic Oscillation, namely, warm and dry conditions over southern Europe and Eurasia and moistening over northern Europe.

And what's more, it is important to underline that specific guidelines, such as [39] that are devoted to seismic hazard, provide recommendations on how to assess the impact of NHs that do not consider the direct release of high-GWP or -ODP chemicals. Given the above-mentioned premises, neglecting the mechanism of emission from CFC and HFC banks linked to NHs and, more in general to structural and non-structural damage, can lead to their GWP being underestimated and their relevant ODP being almost completely overlooked.

1.2. Scope and core contribution

To cope with these limitations, this paper presents a study on these little explored mechanisms of emissions together with some simple analytical tools capable of taking into account the ODP effects, which can be implemented in the methods currently used to conduct LCAs on buildings that also integrate NHs. The paper's Section 2 introduces an extension to the ODP of the framework based on the Content Release GHG Emission Potential (CGEP) proposed by [24]. Then, an application to the case study of a residential building is provided in Section 3. Moreover, in the same section, the sources of CFCs and HFCs are discussed alongside our assumptions and a comparison with results from other studies. Successively, Section 4 presents an overview of the relationships between the different sources of CFCs and HFCs, possible damage modes and limit states (LSs) and their relevant mechanisms of emission. In Section 5 brief discusses the implications for DWM. The main conclusions of the study are drawn in Section 6 together with some comments on future developments.

2. CODP: an extension of the CGEP framework

The original CGEP framework was introduced by [24] to integrate the assessment of the GWP impact of NHs. The framework builds on the empirical evidence that damage-induced release of high-GWP compounds can result in a significant environmental impact. This was found to be especially true in the case of specific classes of industrial components dealing with high-GWP agents. The original work applied the CGEP to case studies from the refrigeration, electrical and medical industries. The results showed that the effects in terms of GWP were several orders of magnitude higher than those identified using embodied carbon methods. Conversely, the present work extends the procedure to ODP effects. For the sake of clarity, the main equations that characterize the methodology are reported below. On such premises, the assessment technique encompasses four main steps that follow the same logical order as the CGEP framework.

(a) evaluation of the Content release Ozone Depletion Potential (CODP)

(b) assessment of the probability of a structural failure induced by a NH, expressed as P_{fn}

(c) assessment of the fraction of the CODP associated with P_{fn}, expressed as RL_{fn}

(d) calculation of the expected emissions relevant to the structural failure induced by the NH and indicated as EM_{Nat}

One starts from Step (a) introducing the novel CODP parameter whose calculation is straightforward, i.e.

$$CODP = \sum_{c=1}^{N_c} M_c \cdot ODP_c \tag{1}$$

where N_c is the number of high-ODP compounds contained in the system under study; M_c is the relevant mass of the c-th component and ODP is its ozone depletion potential. Unlike the GWP in the original framework, a non-negligible ODP, measured in CFC-11eq is a characteristic of a limited class of compounds, like CFCs, that contain chlorine. This procedure should therefore only be applied to cases where there is a certain content of such chemicals.
Subsequently, to evaluate the failure probability of a certain structure or component, Step (b) requires what is usually called a quantitative risk analysis (QRA) [40]. This analysis can be performed based on either the adoption of the PBEE framework [41] or specific databases, statistical data or results from other studies. The analytical formulation of P_{fn}, identical to that of the original framework, can be expressed as,

$$P_{fn} = \int_{\boldsymbol{IM_n}} P(EDP > C_{LS_f} | IM_n) d\lambda(IM_n) \tag{2}$$

where the subscript f indicates the type of failure associated with the specific limit state LS_f whilst n denotes the NH selected, which may be an earthquake, flood, tsunami, etc. It is straightforward that different damage levels entail different proportions of content release; and therefore, Step (c) consists in the assessment said proportion,

$$RL_f = \frac{COE_f(DM_f)}{CODP} \tag{3}$$

where COE_f accounts for the content release ODP emission caused by the specific damage level, defined as,

$$COE_f = \sum_{c=1}^{N_c} MR_c \cdot ODP_c \tag{4}$$

where MR_c denotes the mass of the c-th component released in the environment following DM_{fn}. Finally, Step (d) allows for the calculation of the CFC-11eq related to the limit state LS_f and the NH n as,

$$\mathbf{EM}_{fn}(ODP) = P_{fn} \cdot RL_f \cdot CODP \tag{5}$$

where (ODP) is added to $\mathbf{EM}_{fn}$ to distinguish it from the one in the original framework. Since the relevant emissions can encompass both ODP and GWP effects, which is the case for CFCs, $\mathbf{EM}_{fn}$ can be written as,

$$\mathbf{EM}_{fn} = \begin{bmatrix} \mathbf{EM}_{fn}(GWP) \\ \mathbf{EM}_{fn}(ODP) \end{bmatrix} = P_{fn} \cdot RL_f \cdot \begin{bmatrix} CGEP \\ CODP \end{bmatrix} \tag{6}$$

As we can see from Eq. (6), RL_f is supposed to be the same for both CGEP and CODP, underscoring the fact that, if a certain LS is exceeded, the involved contents would exhibit the same emission mechanism. The same applies to the different components contributing to the total CGEP and CODP. In fact, each component may have a different RL_f for a given limit state. These assumptions were not discussed in the CGEP framework. Furthermore, also Eqs. 3-6 are original of this work. It is worth noting that, whilst such a simplified assumption facilitates the application of the framework, it may not cover the complexity of the phenomenon investigated.
Hence, as in the CGEP framework, (5) can be extended to take into account different LSs and NHs according to,

$$\mathbf{EM}_n = \mathbf{EM}_{LS_1 n} + \mathbf{EM}_{LS_2 n} + \mathbf{EM}_{LS_3 n} + \dots \tag{7}$$

$$\mathbf{EM}_{Nat} = \mathbf{EM}_{eart.} + \mathbf{EM}_{tsunami} + \mathbf{EM}_{flood} + \dots \tag{8}$$

In sum, $\mathbf{EM}_{Nat}$ indicates the expected yearly emissions, which can be considered as a component of the LCA assessment.

3. Application to a case study

In this section, we present the case study of a residential building, generalized from the viewpoint of high-ODP content and considering different degrees of vulnerability linked to several NHs and construction technologies. Unlike the work of [24], which focused on specific industrial components, this choice was made to: i) provide an application as general as possible, ii) prove that, being CFCs out of any production process, even the content of a civil structure can easily result in an ODP possible impact much higher than what assessed with conventional approaches, iii) cope with the paucity of data regarding CFC banks.

3.1. CFCs and HFCs sources in buildings and theoretical size

CFCs and HFCs have been used for several decades as refrigerants in domestic HVAC&R units [42]. To assess the size of the refrigerant charge in a residential unit, we start with the AC system. As a general rule, the US Department of Energy suggests 20 BTU per square foot, or 215 BTU per m^2. This would translate in a requirement of 0.018 tons of refrigeration (TR) or 0.063 kW per m^2. According to [42], a double split AC system, taken here for reference due to its widespread use, contains a refrigerant charge of between 0.24 and 1 kg per kW. Thus, assuming an average value of 0.62 kg/kW this would result in 0.039 kg/m^2, hereafter named C_{rAC}. This simple calculation neglects the possible influence of the actual type of refrigerant, CFC or an HFC, on the size of the charge for a given refrigeration output. In this regard, the comparative study [43] showed that, for small equipment, up to 2.5 TR, the charge size for CFCs and HFCs does not vary significantly. Similarly, refrigerants are also used in domestic refrigerators, with an average size of 0.05-0.25 kg according to [44] and 0.21 kg according to [45]. Taking this latter value for reference and assuming the presence of 1 refrigerator every 100 m^2, a value compatible with the size of an average dwelling, we can write C_{rR} = 0.002 kg/m^2. The possible presence of Air Source Heat Pumps (ASHP), which share much of their working mechanism with AC systems , was not considered because their mass adoption is a fairly recent trend [46].

Another application for both CFCs and HFCs has been as foaming agents for insulation layers in buildings and appliances. Domestic refrigerators are insulated with panels made of foam containing CFCs, HFCs or other foaming agents introduced following bans or gradual phase-out policies. As reported by [45], an average-sized refrigerator contained a surprising 1 kg of CFCs in its foam insulation, 4 times more than the refrigerant. As the percentage of such foaming agents in PU insulation has not shifted notably from an average 10% [45; 44] we can assume that the content of HFCs would be much the same. Again, assuming one refrigerator every 100 m^2 we can write C_{fR} = 0.01 kg/m^2.

The last source to quantify relates to CFCs, mainly CFC-11, used as a foaming agent in buildings' walls and roof [44]. This is a very peculiar source for two reasons: i) the reference life of these building components can span several decades, ii) unlike domestic appliances, this source pertains to structural or non-structural components (NSC) with an important bearing on general structural safety issues. Although this source could account for the vast majority of CFC banks, its quantification is challenging due to a general scarcity of data [47]. The values calculated here are mainly based on the data presented in a report commissioned by the California Environmental Protection Agency [48]. The report dates from 2011 and, to quantify the CFCs banks emissions, provides an estimation of the stock of insulation foam present in California buildings. From there we retrieve that a stock of 9.18 million single-family houses (SFH) contained a cumulative insulation foam volume of 9.8 million m^3. According to the US Census Bureau, a typical SHF is roughly 2,200 square feet or 210 m^2 in size. The density of the PU foam used in walls and roofing is around 40 kg/m^3 and, before the ban, the content of CFC was around 10% [45; 48]. On such premises, we can calculate the expected content of CFCs pertaining to foam insulation as follows:

$$C_{fI} = (9.8 \cdot 40 \cdot 0.1) \div (9.18 \cdot 216) = 0.02\ kg/m^2 \tag{9}$$

The above equation neglects some factors that might influence the result. First, SFHs have been taken as an example because it is easy to retrieve their average surface areas. Multi-family houses (MFHs) and commercial buildings also contain insulation foam, however, with their corresponding CFC/HFC content. Second, after CFCs were banned, foaming agents containing HFCs were around for roughly 15 years, according to [48], before they were replaced with hydrocarbons. Among these, a popular product is pentane, which features a zero ODP and GWP. Finally, Table 1 below lists the different content calculated in this subsection:

Table 1: Residential building - CFC/HFC possible content

Source	Type	Parameter	Quantity (g/m^2)
AC	Refrigerant Charge	C_{rAC}	39
Refrigerator	Refrigerant Charge	C_{rR}	2
Refrigerator	Foaming Agent	C_{fR}	10
Walls Insulation	Foaming Agent	C_{fI}	20

Whilst AC is the single biggest potential source of CFC/HFC, the content of foaming agents is not far behind. This goes to show that we need to take both types of content into account in any assessment of these chemicals' potential release.

3.2. Preliminary considerations for real applications

The framework presented here is intended as a tool for assessing the environmental consequences of structural or non-structural damage prompting the release of CFCs/HFCs. It is therefore crucial to assess the characteristics and size of such emissions to establish their CGEP and CODP. In Subsection 3.1 we estimate the theoretical content, then use the results for our case study calculations. As a necessary premise, it is important to underline that the actual CFC/HFC content of residential buildings should take the following four factors into account:

(i) The prevalence of appliances, AC and insulation varies, based on several conditions.

Appliances like refrigerators, relevant to both C_{rR} and C_{fR}, are present in almost every household in developed countries [49]. Conversely, AC systems exhibit a more variegated prevalence. For reference, in the EU, AC systems are posed to grow in diffusion from 9.2% in 2015 to 37.6% in 2050 [50]. Furthermore, in 2018, the IEA reported that 90% of households in Japan and the US, 6% in China and 5% in India had AC systems installed [51]. More in general, the adoption of appliances and AC systems in various countries correlates with their climate and level of economic development [52; 50].

(ii) CFCs-based appliances have gradually been retired due to their finite remaining useful life (RUL).

The RUL is typically described using probability distributions calculated on the basis of statistical data. According to [53; 54], the resulting survival rate (SR) can be approximately described by the CDF of a Weibull distribution evaluated as follows,

$$SR(t) = 1 - \exp^{-t/\lambda^k} \tag{10}$$

where t is the age of the appliance in years, λ and k are the scale and shape factors, respectively. For reference, from [53] we can retrieve the two parameters for domestic refrigerators, also empirically validated by [55], $\lambda_R = 18.76$ and $k_R = 2.15$, and AC units, $\lambda_R = 17.45$ and $k_R = 2.34$. These values generates the SR curves depicted in Figure 1.

As shown in Fig. 1, an estimated 10% of these appliances would still be operational after 30 years.

(iii) The GWP of the HFCs most commonly used in several applications varied over time due to successive emission mitigation policies.

As discussed earlier, several institutions, among others the EU [56] and the US with its SNAP regulation [57], decided to phase out high-GWP HFCs. For reference, widely used refrigerants such as R410A (GWP = 2088) or R401a (GWP = 1300) are being replaced with refrigerants with a lower or negligible GWP. An example of these are R32 (GWP = 677) and R600a (GWP = 0). Thus, the age of a given appliance is therefore likely to affect its GWP.

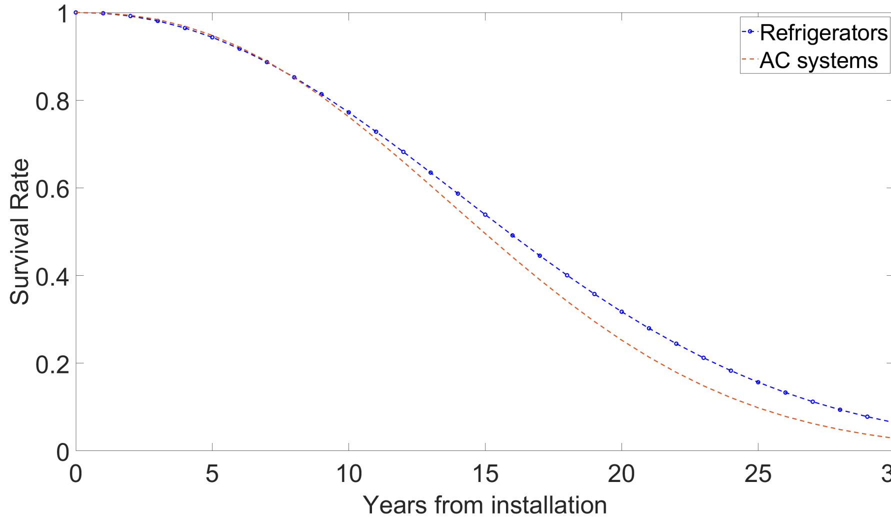

Figure 1: Survival rate of refrigerators and AC systems

(iv) The contents of refrigerant charges and foaming agents decrease over time due to operational leakage.

The most important source of CFC/HFC emissions in the form of refrigerants lies in operational leakage, which occurs in both refrigeration and AC systems. The rate of leakage can vary from 0.1%/year, typical of domestic applications, up to 10%/year, more likely for commercial systems [58; 59]. To a lesser degree, there is also some operational leakage from insulation foams. According to multiple sources [60; 44; 47] CFCs and HFCs in insulation foams produce a significant emission, in the order of 10%, during the installation phase, but much smaller afterwards, with operational leakages as low as 0.25%/year. The age of an installation, and its operational history and level of maintenance can therefore also affect the size of its CFC/HFC content.

3.3. Application of the simplified framework: CGEP and CODP assessment

As a first step, we calculate the CGEP and CODP of a hypothetical residential building characterized by the CFC/HFC content listed in 1. We assume that the CFC is R11, and the HFC is R134a. From [61] we can gather that $ODP_{R11} = 1$, $GWP_{R11} = 4660$, $ODP_{R134} = 0$, $GWP_{R134a} = 1300$. These values are listed in Table 2

On such basis, two different scenarios are presented, one assuming a CFC content, S_{CFC}, and another assuming HFC content, S_{HFC}. The results are going to

Table 2: CFC/HFC content scenarios

Scenario	Content	GWP	ODP
S_{CFC}	R11	4660	1
S_{HFC}	R134	1300	0

be expressed in terms of $CO_{2.eq}/m^2$ and $CFC\text{-}11_{eq}/m^2$ to make it easier to compare them with current scientific literature. We can write:

$$C_{tot} = C_{rAC} + C_{rR} + C_{fR} + C_{fI} = 0.071\ kg/m^2 \tag{11}$$

$$CGEP_{S_{CFC}} = C_{tot} \cdot GWP_{R11} = 330\ kg_{CO_{2,eq}}/m^2 \tag{12}$$

$$CODP_{S_{CFC}} = C_{tot} \cdot ODP_{R11} = 71\ g_{CFC\text{-}11_{eq}}/m^2 \tag{13}$$

$$CGEP_{S_{HFC}} = C_{tot} \cdot GWP_{R134a} = 91.5\ kg_{CO_{2,eq}}/m^2 \tag{14}$$

whereas $CODP_{S_{HFC}}$ is neglected. To establish the importance of these values, we compare them with the results obtained using current conventional approaches. First, the majority of these studies focuses on the carbon footprint, measured in $CO_{2,eq}$, to assess the possible environmental impact of building damage and repairs. The ODP effect is often neglected because the production processes used nowadays imply that building materials do not have a significant impact of this kind. For reference, according to [35] producing 1 kg of concrete results in 3.5E−5 g of $CFC\text{-}11_{eq}$, with minor variations based on the process specifications. Similarly, producing 1 kg of steel reportedly gives rise to 4.5E−5 [62] or as little as 1.6E−8 [36] g of $CFC\text{-}11_{eq}$. As a result, when [63] estimated the ODP of several buildings based on their materials alone, the values ranged from 2E−3 up to 1E−2 g $CFC\text{-}11_{eq}/m^2$ for residential ones. On the other hand, [34] presented an environmental impact assessment of a 7-storey building, made of reinforced concrete (RC) or cross-laminated timber (CLT), in case of structural collapse induced by NHs, finding an

equivalent ODP range, retrieved after some calculations, from 0.15 (RC) to 0.2 (CLT) g $CFC\text{-}11_{eq}/m^2$. To provide an additional reference, [33] calculated that the overall ODP impact of a seismic retrofit for a RC building was in the range of 10^{-4} g $CFC\text{-}11_{eq}/m^2$. Some relevant results are listed in Table 3.
Conversely, the carbon footprint of constructing and repairing buildings has been thoroughly investigated, paving the way to the inclusion of NHs in LCA analyses [31; 32]. Based on the reviews of [64; 65], we compare the embodied carbon of buildings obtained using the standard approaches with the results of Eqs. (12) and (14). In detail, [65] 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, [64] presented a review of 40 different studies, providing a 50% confidence interval of 161-374 kg CO_{2eq}/m^2 for SFHs and 341-631 kg CO_{2eq}/m^2 for MFHs. These values are compared with the results calculated in Table 4.

Table 3: ODP estimations in residential buildings

Ref.	ODP content (g $CFC\text{-}11_{eq}/m^2$)	Methods
This study - S_{CFC}	71	CODP assessment
Hu, 2020 [63]	0.002-0.01	Athena (BOM)
Salgado & Guner, 2021 [34]	0.15-0.2	TRACI (EIO)

Based on the values in Table 3, the difference between the ODP assessed using conventional methods and the results of this study appears to be significant. Table 4 also shows that, for residential buildings also, the potential carbon footprint related to high-GWP content release may be far from negligible by comparison with construction or repair activities. However, since the main goal is to realistically assess the potential effects triggered by structural or non-structural damage, two aspects have to be considered.
First, most foaming agents related emissions following a damage are not immediate. As reported by [15], the release of foaming agents from insulation materials can reach 50% of the original content over a highly-variable time span lasting even several years. On the other hand, [16] reported that a commonly-used waste disposal method such as mechanical shredding can immediately release 25% of such content and speed up the release of the remainder. Second, the operational leakage of

Table 4: Embodied Carbon evaluations in residential buildings -

Ref.	GWP content (kg CO_{2eq}/m^2)	Methods
This study - S_{CFC}	330	CGEP assessment
This study - S_{HFC}	91.5	CGEP assessment
Simonen et al., 2017 [64]	161-631	Embodied carbon - mixed Review of 40 studies
Wen et al., 2016 [65]	108-513	Embodied carbon - mixed Review of 4 studies

both refrigerants and foaming agents, discussed in the previous subsection, could realistically lower the amount still contained in the different sources.
On such premises, the CODP presented in Table 3 should be considered as an upper bound limit more than an actual representation of average conditions, the assessment of which would require additional data and investigations being highly dependent on many factors such as geography, construction and maintenance history, etc.

Nonetheless, due to the marked uncertainty and paucity of data especially in the case of CFC banks, one possible way to check the reliability of the quantities presented here, is to examine the real-case scenario results related to 2011 Tohoku earthquake [17; 66]. In detail, [66] reports that 45 million m^2 of housing surface was rebuilt following the earthquake whilst [17] registered that combined emissions of CFCs and HFCs amounted to 6.5 tons. It should be underlined first of all that: i) the values are presented as conservative due to uncertainties in emission data, including nonoperational status of some weather stations, and given the fact that foaming agent emissions are slow; ii) emissions are not differentiated by source, being them residential, commercial buildings, industrial facilities, vehicle AC systems or others. Thus, it is possible to approximately calculate a value of 0.144 kg/m^2, which is the twice the C_{tot} evaluated in Eq. (11). The validity of the approach is confirmed by the fact that the difference could be fully explained by the larger refrigerant content used in the commercial and industrial equipment [24].

3.4. Application of the simplified framework: vulnerability review and results

In this subsection, we adopt the proposed procedure for two residential buildings characterized by two construction technologies subjected to different NHs. In detail reinforced concrete (RC) buildings are assessed considering seismic hazard. Conversely, for wooden buildings we focus on wind hazard. This choice does not want to reflect any particular considerations as the goal is merely to present examples of an application of our procedure.

3.4.1. RC buildings and seismic hazard

To carry out the analysis, we rely on the empirical fragility functions developed by [67] on the basis of the effects of 1980 Irpinia and 2009 L'Aquila earthquakes. Fragility functions, F_{Rd}, can be analytically expressed as,

$$F_{Rd} = P(EDP > C_{LS}|IM = im) = \phi \left[\frac{ln(im/m_d)}{\beta_d} \right] \tag{15}$$

where ϕ indicates a lognormal cumulative distribution function whilst m_d and β_d are the median and the dispersion of the distribution.

The work presents a comprehensive categorization based on age of construction and storeys' number of the Italian stock of RC buildings. Among these, we selected post-1981 buildings, thus compliant to fairly modern seismic design, with a medium rise, i.e. 3-4 storeys. The EMS-98 damage characterization [68] adopted in [67] considers 6 grades of damage, as shown in Table 5.

Table 5: EMS-98 damage state classification

Damage grade	RC buildings damage - Qualitative description	
	Structural	Non-structural
DS_e0	no damage	no damage
DS_e1	no damage	slight
DS_e2	slight	moderate
DS_e3	moderate	heavy
DS_e4	heavy	very heavy
DS_e5	very heavy	//

Given that our focus is entirely devoted to NSC, we selected as LSs both DS3 and DS4. This is coherent with the assumption that DS4 implies a complete non-structural damage. From [67] we gather $m_{DS_e3} = 1.417g$, $m_{DS_e4} = 2.682g$ and $\beta_{DS_e3} = \beta_{DS_e4} = 0.995$, with PGA as IM. The corresponding fragility curves are shown in Figure 2.

Hence, to evaluate all input parameters of Eq. (2), we define $\lambda(IM)$ as done by [69]. The study derived the hazard curve, depicted in Figure 6, from a probabilistic

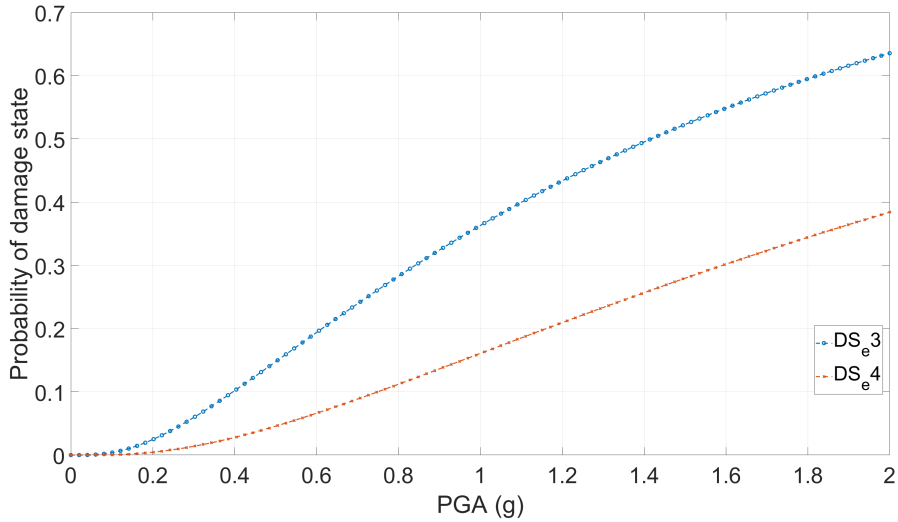

Figure 2: Fragility curves for DS_e3 and DS_e4

seismic hazard analysis (PSHA) of the Priolo Gargallo area, an earthquake-prone region in the south of Italy. We can therefore make full use of Eq. (2) and obtain the annual probabilities $P_{DS_e3} = 5.45 \cdot 10^{-5} y^{-1}$ and $P_{DS_e4} = 1.46 \cdot 10^{-5} y^{-1}$. The higher value of P_{DS_e3} reflects m_{DS_e3} being almost half of m_{DS_e4}, which results in more than ten-fold difference in the annual rate of exceedance depicted in Figure 6.

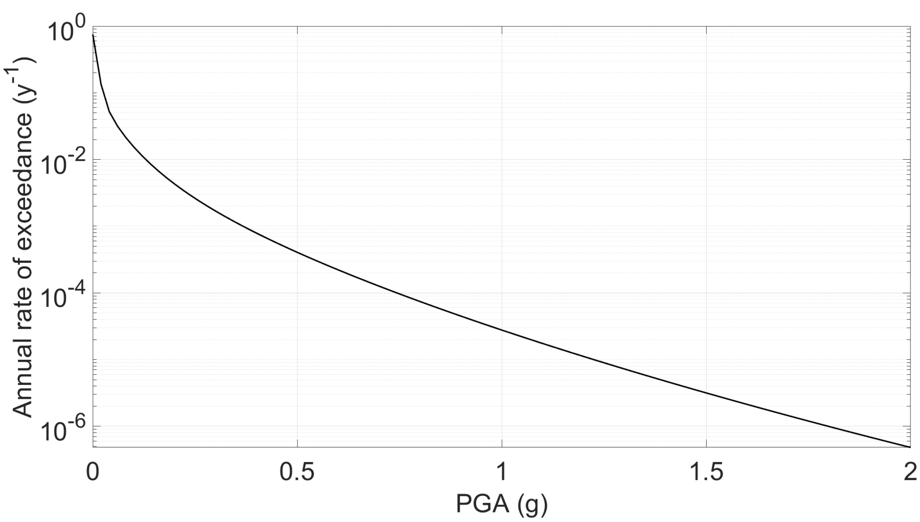

Figure 3: Seismic Hazard Curve of the Priolo Gargallo site in Italy

Concerning Step (c), we assume $RL_{DS_e4} = 1$ because it involves the highest possible damage for NSC, whereas, RL_{DS_e3} is assumed to be 0.5. Indeed, according to [67], DS3 can indicate a damage grade for non-structural elements, i.e. partitions and infills, ranging from heavy damage to collapse. That said, the purely qualitative description of the EMS-98 scale does not allow high accuracy. 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. When assessing the impact in Step (b), the probability of a lower DS therefore has to be reduced by the probability of the higher one. On such premises, we can calculate the expected impacts of both the scenarios considered. For S_{CFC} the assessment is presented below:

$$\begin{aligned} \mathbf{EM}_{DS_e3} &= (P_{DS_e3} - P_{DS_e4}) \cdot RL_{DS_e3} \cdot \begin{bmatrix} CGEP_{S_{CFC}} \\ CODP_{S_{CFC}} \end{bmatrix} = \\ &= \begin{bmatrix} 6.6 \cdot 10^{-3}\ kg_{CO_{2,eq}} \\ 1.42 \cdot 10^{-3}\ gCFC\text{-11\_eq} \end{bmatrix} m^{-2} y^{-1} \end{aligned} \tag{16}$$

$$\begin{aligned} \mathbf{EM}_{DS_e4} &= P_{DS_e4} \cdot RL_{DS_e4} \cdot \begin{bmatrix} CGEP_{S_{CFC}} \\ CODP_{S_{CFC}} \end{bmatrix} = \\ &= \begin{bmatrix} 4.81 \cdot 10^{-3}\ kg_{CO_{2,eq}} \\ 1.03 \cdot 10^{-3}\ gCFC\text{-11\_eq} \end{bmatrix} m^{-2} y^{-1} \end{aligned} \tag{17}$$

Then, with regard to S_{HFC}, we can write:

$$\begin{aligned} \mathbf{EM}_{DS_e3} &= (P_{DS_e3} - P_{DS_e4}) \cdot RL_{DS_e3} \cdot \begin{bmatrix} CGEP_{S_{HFC}} \\ CODP_{S_{HFC}} \end{bmatrix} = \\ &= \begin{bmatrix} 1.83 \cdot 10^{-3}\ kg_{CO_{2,eq}} \\ 0 \end{bmatrix} m^{-2} y^{-1} \end{aligned} \tag{18}$$

$$\mathbf{EM}_{DS_e4} = P_{DS_e4} \cdot RL_{DS_e4} \cdot \begin{bmatrix} CGEP_{S_{HFC}} \\ CODP_{S_{HFC}} \end{bmatrix} = \begin{bmatrix} 1.33 \cdot 10^{-3}\ kg_{CO_{2,eq}} \\ 0 \end{bmatrix} m^{-2} y^{-1} \tag{19}$$

The relevant results are listed in Table 6. The share of **EM** resulting from DS$_e$3 is larger then that of DS$_e$4, as shown in Figure 4. This was expected from an analytical viewpoint because the difference between P_{DS_e3} and P_{DS_e4} outweighs the relevant RLs. These results are nonetheless in line with the empirical reality

Table 6: RC building and seismic hazard - framework parameters and results

LS	P_{fn} (y^{-1})	RL_f	EM_{fn} ($kg_{CO_{2,eq}}/(m^2y)$)		EM_{fn} ($g_{CFC\text{-}11_{eq}}/(m^2y)$)	
			S_{CFC}	S_{HFC}	S_{CFC}	S_{HFC}
DS$_e$3	$5.45 \cdot 10^{-5}$	0.5	$6.6 \cdot 10^{-3}$	$1.83 \cdot 10^{-3}$	$1.03 \cdot 10^{-3}$	0
DS$_e$4	$1.46 \cdot 10^{-5}$	1	$4.81 \cdot 10^{-3}$	$1.33 \cdot 10^{-3}$	$1.42 \cdot 10^{-3}$	0

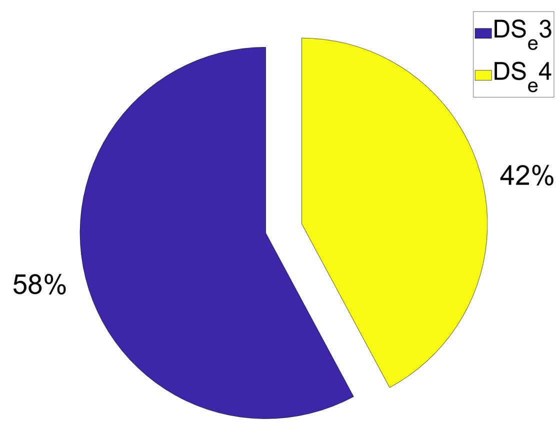

Figure 4: Shares of expected emissions for DS_e3 and DS_e4

of an earthquakes' consequences. It is well know that NSCs and lower limit states accounts for the majority of repair costs [70]. The EMS-98 scale clearly does not provide enough detail for a thorough assessment of the complexity of emissions-related impacts, however. Such quantities can be combined directly with the outputs of conventional analyses based on the embodied carbon parameter [25; 26].

3.4.2. Wooden buildings and hurricane winds hazard

Vulnerability data for wooden buildings subjected to hurricane winds are retrieved from [71], who evaluated fragility functions based on numerical simulations with the Monte Carlo method. The assessment is conducted considering several factors: i) the resistance of structural components and NSC; ii) proximity to other buildings and impacts of debris; iii) different levels of damage. With regard to i) and ii), the median conditions are selected for our example. Besides, iii) is based on an hierarchy criteria adopted within HAZUS Hurricane Model (MH) [72]. The HM scale envisages 5 damage states for residential constructions based on a mixed qualitative/quantitative description. The sections of the scale most relevant to this study are shown in Table 7.

Table 7: HAZUS-MH damage state classification

Damage state	Qualitative description	Roof/Wall cover failure	Roof/Wall structure failure
DS_w0	No damage	$\leq 2\%$	No
DS_w1	Minor damage	$>2\%$ and $\leq 15\%$	No
DS_w2	Moderate damage. Some resulting damage to interior of building from water.	$>15\%$ and $\leq 50\%$	No
DS_w3	Severe damage. Extensive damage to interior of building from water	$>50\%$	No
DS_w4	Destruction Complete roof failure and/or wall failure of wall frame	Typically $>50\%$	Yes

To simplify the framework application, we focus only on DS_w2, DS_w3 and DS_w4. From [71] we retrieve $m_{DS_w2} = 49.4m/s, m_{DS_w3} = 67.3m/s, m_{DS_w4} = 86.5m/s$ and $\beta_{DS_w2} = 0.13, \beta_{DS_w3} = 0.06, \beta_{DS_w4} = 0.06$, with wind speed as IM. The resulting fragility functions are plotted in Figure 5.

Thus, $\lambda(IM)$ is defined as in [71], reflecting the hazard level of San Francisco in the US. The annual probability of exceedance, for a given wind speed w, is described by the PDF of a Weibull distribution:

$$P(w) = k/\lambda \cdot (w/\lambda)^{k-1} \cdot \exp^{-w/\lambda^k} \tag{20}$$

where w is the wind speed, and the distribution parameters are $\lambda = 28.29$ and $k = 1.77$. The relevant curve is depicted in Figure 6.

On such basis we cano compute $P_{DS_w2} = 7.62 \cdot 10^{-2} y^{-1}$, $P_{DS_w3} = 1.05 \cdot 10^{-2} y^{-1}$ and $P_{DS_w4} = 9.12 \cdot 10^{-4} y^{-1}$. Moving on to Step (c), we have to consider the

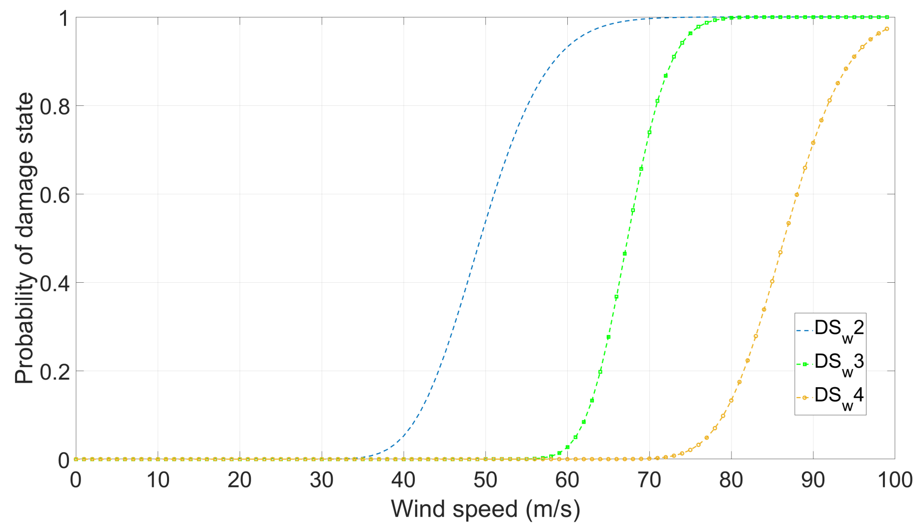

Figure 5: Fragility curves for DS_w2, DS_w3 and DS_w4

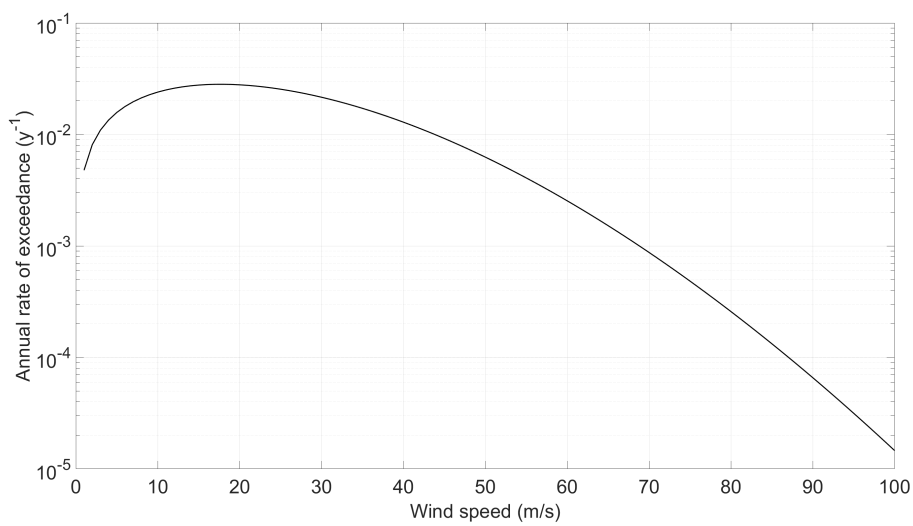

Figure 6: Wind Hazard Curve for San Francisco in the USA

differences between the several HFC/CHF sources and their implications. The release of C_{fI} release is linked directly to Roof/Wall cover failure, for instance, whereas the description of interior damage, and the consequent release of chemicals from the other sources, is only qualitative. We therefore assume that RL_{DS_e2} = 0.1, RL_{DS_e3} = 0.5 and RL_{DS_e2} = 1. Adopting the same procedure as in Subsection 3.4.1, we can complete Step (d). The relevant results are listed in Table 8.

Table 8: Wooden building and wind hazard: framework parameters and results

LS	P_{fn} (y^{-1})	RL_f	EM_{fn} ($kg_{CO_{2,eq}}/(m^2y)$)		EM_{fn} ($g_{CFC\text{-}11_{eq}}/(m^2y)$)	
			S_{CFC}	S_{HFC}	S_{CFC}	S_{HFC}
DS_w2	$7.62 \cdot 10^{-2}$	0.1	2.51	0.69	0.54	0
DS_w3	$1.05 \cdot 10^{-2}$	0.5	1.73	0.48	0.37	0
DS_w4	$9.12 \cdot 10^{-4}$	1	0.30	$8.34 \cdot 10^{-2}$	$6.4 \cdot 10^{-2}$	0

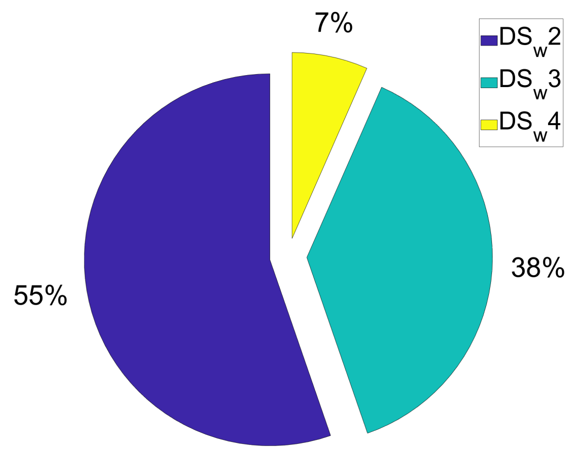

Figure 7: Shares of expected emissions for DS_w2, DS_w3 and DS_w4

It is possible to appreciate that the lower damage states are responsible for the largest share of the impacts. This is consistent with the results of Subsection 3.4.1 and the relevant considerations. The resulting proportions are shown in Figure 7. Here again, the HM scale of damage states reveals some limitations that are bound to affect its accuracy.

4. Structural and non-structural damage-emission relationships

The applicability of the framework presented here is limited by a general paucity of information regarding buildings' resistance, damage states and the mechanisms of content release. Infills and roof/wall covers, which are pertinent to content C_{fI}, are a major focus of both the EMS-98 and the Hazus MH damage scales. On the other hand, little to no information is available for NSCs relevant to C_{rAC}, C_{rR} and C_{fR}. It is not difficult to associate a structure's collapse with the complete or near-complete release of CFC/HFC contents. The consequences of low-intensity damage states have been less investigated, but they are more significant in the overall emission balance. It is important to underline that structural damage can indirectly affect NSCs. In fact, it is likely that the collapse of a complete building would definitely disrupt NSCs. Besides, the effect of a local structural damage could also result in a domino effect on NSCs. This section includes: i) a brief analysis of current methods for assessing the damage-related environmental impact of NSCs. ii) a description of possible mechanisms of emission from different CFC/HFC sources.

4.1. Damage-related environmental impact of non-structural components

It is widely recognized that NSCs account for the largest share of the costs of damage to buildings exposed to NHs [70], with earthquakes having a particularly heavy impact on such components. While specific requirements were first introduced for the seismic design of NSCs [73], the recent ASCE 7-16 [74] also contains specific provisions regarding storm surges and hurricanes for "designated NCSs". The main goals of these prescriptions are to: i) avoid injuries to people; ii) reduce repair and/or replacement costs; and iii) ensure the serviceability of such components. These negative outcomes, which are shared with other codes or guidelines, are defined by [75] as Life Safety, Property Loss and Functional Loss. In general, the two most common design approaches are the limit state design, as prescribed by ASCE or Eurocode [74; 76], or the performance-based design [77]. The latter is also used to assess the consequences of possible damage to NSCs. The FEMA-P-58 provides methods and databases for assessing the seismic performance of buildings, and also contains details about NSCs [78]. As regards cost estimations, the limitations of these databases have already been assessed, based on empirical evidence [79]. In agreement with the content of [39], such databases also provide data on the environmental consequences of damage to NSCs, in terms of equivalent CO_2. Nonetheless, as for their possible adoption within the framework presented in this paper, there are two main limitations to mention. First, the FEMA databases rely on the EIO-LCA approach with monetary costs as input, to assess the relevant environmental impact. This completely neglects the effects of any direct GHG emission consequent to a given level of damage. Second, the most frequently adopted damage levels for NSCs refer to either anchorage failure or to repairable/not repairable damages. Whilst these conditions are certainly relevant to Life Safety, Property Loss or Functional Loss, they do not necessarily relate to content emissions. This aspect is also connected to the paucity of available data, which ultimately reflects on the uncertainty affecting the fragility functions provided by FEMA databases [80].

4.2. Type of source and damage-related mechanisms of emission

The classification proposed here is based on three characteristics of the mechanisms of the emissions: i) the specific source; ii) the cause of the damage prompting the content release and iii) the characteristics of the resulting emissions.

Starting from C_{rAC}, we have to take into account that the most common design for AC systems is the double/multi split unit. In such design, the evaporator is placed inside the building whilst the condenser is located outside of it. The two subcomponents thus have different vulnerability levels. They can both be damaged directly by a loss of stability, as in the case of an anchorage failure, or indirectly following a domino effect. The failure of other structural or non-structural components could naturally affect them too. This could result in a slow, continuous release stemming from an increased operational direct emission [14] or in a sudden release of the high-GWP and/or high-ODP refrigerant. The condenser may also be exposed to other external actions, the most obvious being related to strong winds and flying debris. As a reference, the Florida Building Code, sec 301.15, [81] requires that external appliances installations be designed to withstand certain levels of wind pressure. Other external environmental actions can directly result in emissions, however. A recent study [82] analytically described the effect of corrosion on direct emissions, for instance. High level of operational vibrations can also lead to increased direct emissions even without causing any substantial damage [83]. These two last mechanisms of emissions can possibly result in an operational and continuous emission profile. Furthermore, the level of external action required to trigger such mechanism may be quite low. In short, such external actions are not exclusive to natural disasters. On the other hand, it is quite clear that weather conditions involving wind and rain can contribute to both corrosion and vibrations. It is therefore important to emphasize that even low-intensity natural actions can possibly affect the operational leakage rate of the NSCs under study.

Proceeding to C_{rR} and C_{fR}, these two types of content pertain to the same NSC, i.e. a refrigerator. In this case, instead of considering the case of industrial refrigerators, which may be double/multi-split units, we assume the single unit typical of domestic refrigerators. C_{rR} and C_{fR} are therefore characterized by the same possible causes of damage. These consist in a loss of stability or a domino effect but the emission profiles of the two sources differ. For C_{rR} it can be both continuous, due to the appliance's operational status, or immediate in the case of an instantaneous leakage of refrigerant. On the other hand, the release of foaming agent, i.e C_{fR}, is always slow and continuous. It also depends largely on how the appliance is disposed of, since proper waste management could massively reduce the consequent emissions [22].

C_{IR} shares the same emission profile as C_{fR}. As possible damage mechanisms, both the EMS-98 and the Hazus HM damage scales assume that infills and partition

walls are more vulnerable than structural elements.
Direct damage due to external actions would therefore be the most likely cause of content release. The above classification is summarized in Table 9.

Table 9: Classification of damage-related mechanisms of emission

Type of source	Cause of damage	Emissions profile
C_{rAC} - Condenser	• Corrosion, vibration • Loss of stability, direct damage, domino effect	• Operational leakage • Operational or instantaneous leakage
C_{rAC} - Evaporator	• Loss of stability, domino effect	• Operational or instantaneous leakage
C_{rR}	• Loss of stability, domino effect	• Operational or instantaneous leakage
C_{fR}	• Loss of stability, domino effect	• Continuous, slow release
C_{fI}	• Direct damage	• Continuous, slow release

5. Implications for LCAs of disaster waste management

The topic of end-of-life scenarios for CFCs/HFCs is hugely important and is part of the significant research issue of landfill-related emissions. Moreover, the treatment of waste containing fluorocarbons is strictly regulated in many countries. The practices of DWM tend to be rather different from the ideal "peace-time" processes, however. Thus, while the proposed framework does not include standard end-of-life scenarios, this Section is devoted to the issues relevant to DWM. It is only recently that quantitative methods have been applied to assessing the environmental impact of DWM. The release of CFCs/HFCs has yet to be considered in this setting, although a specific approach to the treatment of this particular waste could significantly reduce its consequences [22; 84]. To assess the potential weight of these aspects, we compare different findings obtained using standard methods with the estimated effect of CFCs/HFCs release. The ODP effect is going to be neglected due to the lack of comparable results.

NHs can generate an amount of waste significantly higher than "peace-time" scenarios [85], with a significant variability that depends on the type of NH involved, the area affected, and other factors [86; 87]. DWM encompasses several activities with a certain carbon footprint, such as transport, crushing, incineration and disposal. A relevant example of how this is assessed is provided in [66], where the carbon footprint of part of the waste management following the 2011 Tohoku earthquake is calculated. The study reports a total of roughly 22.78 million tons of waste from housing stock that was damaged or collapsed. It is also reported that the relevant debris disposal, due to transport, incineration and methane emissions from landfills, potentially generated 10.95 million tons of CO_{2eq}. To facilitate our comparison we derive a simplified ratio of 0.48 kg CO_{2eq}/kg of waste. A recent study [88] presents the LCA of a simulated DWM scenario based on realistic data from few recent earthquakes. The simulation assesses the carbon footprint deriving mainly from transportation, crushing and metal separating activities. Several scenarios are considered, but the worst in terms of carbon footprint envisaged 5200 tons of CO_{2eq} for 120,000 tons of waste treated. This leads to a simplified ratio of 0.043 kg CO_{2eq}/kg of waste. On the other hand, if we only consider the release of CFCs/HFCs following the 2011 Tohoku earthquake, we obtain a total of 13.3 million tons of CO_{2eq} [17]. According to [89], the same event generated a total of 28 millions tons of waste. From these figures, we can calculate a simplified ratio of 0.475 CO_{2eq}/kg.

The figures in Table 10 go to show why it is important to consider the potential emission of CFCs/HFCs, but the uncertainty associated with such an assessment is rather high. As mentioned earlier, few guidelines recommend specific practices for managing appliances containing these chemicals [20; 21]. In theory, properly implemented, specific practices could vastly mitigate this mechanism of CFC/HFC emissions, but it is unclear to what extent this has been done in the past, or might be done after future disasters. For reference, the 2005 Katrina Hurricane generated a massive amount of waste, including from 750,000 [90] to almost 900,000 [19; 21] household appliances in Louisiana. Among them, 390,000 contained "Freon" which was properly disposed of [19]. Taking the conservative reference of 0.21 kg per domestic refrigerator, disregarding the far bigger charges typical of AC units, this many appliances would have contained a total of roughly 80 tons of refrigerant. On the other hand, [21] reports that, in the three most affected counties in Mississippi, only 0.68 tons of refrigerant were actually salvaged from the processing of 490,000 appliances. One explanation for this significant difference could be that DWM

Table 10: Carbon footprint of DWM: comparison of studies

Ref.	Carbon footprint (kg CO_{2eq}/kg of waste)	Causes
This study, based on [89; 17] the 2011 Tohoku earthquake	up to 0.475	CFCs/HFCs emission
Pan et. al., 2014 [66] 2011 Tohoku earthquake	0.48	Transport, incineration and methane emissions from landfills
Amato et al., 2019 [88] Few recent earthquakes	0.043	Transport, crushing and metal separation

would not be effective against an instantaneous leakage of refrigerant,which is one of the mechanisms of emission listed in Table 9. Some of the refrigerators had to be reportedly thrown away after the food they contained had rotted due to the failure of the electricity infrastructure [19], underlining the importance of indirect effects. From the numbers involved, we gather that the scale of the refrigerator disposal process was massive. In fact, the appliances left on the streets were sometimes decorated and became a form of folk art and protest [91]. There is almost no documented evidence of how the foam insulation was treated, however, although its environmental impact could have been higher than that of the release of refrigerants.

6. Conclusions and future developments

This paper describes a little-explored mechanism of emission from HFC and CFC banks linked to structural and non-structural damage caused by NHs. It also presents a framework for including NHs in LCAs of buildings, and extending the latter to cover ozone depletion effects. The application of this framework to buildings based on several technologies and exposed to different types of NH is also discussed, along with the implications of disaster waste management for environmental impact assessments. The main conclusions are outlined below.

- Damage induced by natural hazards to structural and non-structural components is, *de facto*, a mechanism of emissions from CFC/HFC banks. This has been demonstrated on various levels of detail for several recent major natural disasters. The overall volumes of such a mechanism remain difficult to assess, however.

- The magnitudes of the GWP related to the embodied carbon and the CFC/HFC content of residential buildings are comparable. The latter can reach 330 kg CO_{2eq}/m^2 compared with up to 631 kg CO_{2eq}/m^2 for embodied carbon. Assessing the CFC/HFC content of residential buildings could therefore improve the accuracy of current methods that include NHs in LCAs.

- The ODP related to the content of CFCs in residential buildings accounting for up to 71 g $CFC\text{-}11_{eq}/m^2$, can vastly exceed the ODP resulting from standard assessments based on present databases for construction materials, which ranges from 0.002 to 0.2 g $CFC\text{-}11_{eq}/m^2$. Where there are CFCs, their contribution should be considered in assessing the potential ODP impact of NHs that damage buildings. In this respect, extending the CGEP framework to ODP effects does not pose additional feasibility issues.

- The currently-used scales for classifying damage states are of limited use for assessing potential CFCs/HFCs emissions. This is especially true for non-structural components, and for damage that would not affect their serviceability or involve a risk for a building's occupants.

- Disaster waste management plays a critical role in the prevention of CFC/HFC emissions. The carbon footprint of conventional waste treatment activities, up to 0.48 kg CO_{2eq}/kg of waste, is potentially similar to the effects of such emissions, up to 0.475 kg CO_{2eq}/kg of waste. This means that environmental impact assessments of disaster waste management should also include the consequences of proper CFC/HFC recycling and/or disposal.

As regards further developments, research of this type of emissions could be deepened along the following lines: i) to generate and report more recent data on CFC/HFC banks; ii) to improve the assessment of CFC/HFC banks, focusing on the diffusion of their different applications; iii) to formalize new limit states relating to the prevention of CFC/HFC emissions, with specific design guidelines; iv) to analyze real disaster waste management practices, and quantify their impact on CFC/HFC emissions; v) to extend the proposed framework to include end-of-life scenarios.

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