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Life cycle assessment of a typical European single-family residence and its flood related repairs

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Abstract: Floods are a constant threat to ecosystems, humans, infrastructure and assets. The combination of increased urbanization and rising sea levels makes it a concern of increasing societal importance. This study offers a new perspective on environmental impact assessment of flood related repairs related to a single-family residence using life cycle assessment. A typical European house built in the 2010's is modelled in the life cycle assessment framework with focus on items damaged by a flood. Flood damage is assessed on the detail level of the house's different components using flood depth as the indicator of damage level. A life cycle inventory is built individually for each considered item group affected by flooding. The influence of flood depths and house ages are studied. The results show that the main impacts of flood related repairs come from the replacement of the wooden flooring, the water heater and furniture. Overall, flood related repairs add between 3.5 and 17.8% of environmental impacts to the life cycle of the house depending on house age and flood depth; deeper water and bad timing in relation to maintenance cycles causing more impacts. Moreover, a very high positive correlation between environmental and economic impact is found in most impact categories.

Keywords: LCA; Life cycle assessment; Flood; Flood repairs; Residential.

1. Introduction

The residential sector is one of the anthropologic activities with the highest impact on the environment, amounting to 40% of global energy use and 38% of global greenhouse gases emissions (UNEP, 2012). To assess this environmental burden, Life Cycle Assessment (LCA) is often used. Numerous LCAs have assessed the impact of residences or of the built environment (Goldstein et al., 2018; Khasreen et al., 2009; Lasvaux et al., 2017; Roux et al., 2016; Vilches et al., 2016). However, amongst the various life cycle phases of a house, the regular maintenance and the repairs needed after a natural disaster are seldom within the scope. Few examples choose to include earthquake, hurricane or flood related repairs (Matthews et al., 2016; Sarkisian, 2014; Sudret et al., 2014).

Accounting for half of the occurrences and mortality of natural disasters and resulting in the largest insured losses of all natural catastrophes, flooding is a constant threat to ecosystems, humans, and infrastructure (Guha-Sapir, 2016; Munich Re, 2017). The interplay with other stakeholders and social implications makes flood risk management particularly difficult (Aerts et al., 2018). Moreover, this risk increases dramatically over time because of sea level rise (Arnbjerg-Nielsen et al., 2015; Hirabayashi et al., 2013) and urbanization (UN, 2014). It is a societal concern that cannot and should not be ignored, especially in the context of climate adaptation. Natural disasters and their consequences have been studied in literature, mainly within the field of risk assessment, where risk is defined as a combination of probability of occurrence and potential economic damage calculated from depth-damage curves (Aerts et al., 2018; Morita, 2008). While this is efficient in terms of economic optimization, it may be less optimal in terms of resource consumption, which may in turn lead to unnecessarily high environmental consequences. Hence more integrated assessments, such as LCA, may offer a more comprehensive and consistent view of flood damage versus flood protection.

The LCA framework has indeed recently been used to assess flood prevention, namely, infrastructure construction such as concrete walls and ripraps, while integrating avoided damage (Petit-Boix et al., 2016). It was also used to assess flood damage in the context of stormwater best management practices (Petit-Boix et al., 2017). Finally, the choice of materials and configuration of a flood resilient single family residence were optimized by combining LCA and a Monte Carlo analysis which included sea level rise (Matthews et al., 2016).

While researchers are increasingly aware of a flood's environmental consequences, it is argued that further improvement of its assessments is needed. Even when LCA is used, the impact categories are constrained to carbon footprint, water depletion and embodied energy (Matthews et al., 2016). By conducting a full LCA, this study intends to avoid burden shifting by producing a thorough assessment. It also attempts to bring together the fields of resource optimization and risk assessments, notably by using the same type of depth-damage relationship. Moreover, the environmental impact of flood related repairs is compared to a baseline house with no flooding using a comparative LCA. This is believed to further extend the reach of this study by appealing to decision makers with communicative and versatile results.

The objective of this study is to develop and exemplify a methodology enabling the inclusion of flood related repairs in the LCA of a house. By analysing the results, two major questions will be answered: the amount of additional impact a house has on the environment when it is flooded once, and whether there is a correlation between economic and environmental flood damage. Moreover, the main contributor of flood related repairs' environmental impact will be identified and the importance of the house age when the flood occurs is scrutinized.

2. Method

The LCA methodology is extensively standardized through ISO 14040 and 14044 (ISO, 2006a, 2006b). It is used worldwide by decision makers in a variety of fields. The method used in this study to conduct a comparative LCA is presented in this section and consists of four main steps.

First, the aims and scope of the study are defined through the functional unit and system boundaries. All the phases of the house's lifecycle that would happen irrespective of the flood occurrence are excluded. As a result, the focus is drawn to flood related repairs and an inventory for these repairs is constructed in two stages. The first stage is the flood damage assessment based on the work of the United States Army Corps of Engineers (USACE), which allows to identify the items damaged by a flood, using maximum water depth as an indicator. Then, based on the items identified, a house is modelled in the LCA framework with characteristics chosen to represent a typical European single-family residence. Life Cycle Inventories (LCIs) are built for each of the items constituting the house, mainly using Environmental Product Declarations (EPDs). The next step is to determine the amount of each item needed for each flooding scenario, including a baseline with no flood. Finally, a sensitivity analysis is conducted to assess the robustness of the model.

2.1. Functional unit and system boundaries

The functional unit is building and maintaining a typical European single-family residence built in the 2010's over its 120 years expected lifetime. The resource consumption in relation to human use of the house are omitted. This way we focus on the resource consumption related to the physical house itself. The aim is to conduct a comparative LCA study that includes numerous scenarios through which two situations are compared, one with and one without flooding. The former consists in one scenario, the baseline, while the latter is a range of flood scenarios exploring two dimensions of the issue, namely, flood depth and the house age. The baseline scenario consists in a basic LCA of a house and is used mainly as an element of comparison whereas the flooding scenarios focus largely on flood related repairs.

The system boundaries chosen for both cases are listed in Table 1. The exclusions of the use phase, the demolition and the recycling lie in the comparative nature of the LCA as they would have to occur irrespective of whether a flood occurs or not. The construction phase is modelled as the addition of all the items making up the house, omitting construction site activities, such as excavation for the foundations or the use of scaffolding, as their impact is negligible (Lasvaux et al., 2017). It is hypothesized that the maintenance cycles will be affected by flooding, making the inclusion of the maintenance phase a necessity. Both the maintenance phase and the flood related repairs consists in complete or partial replacements of items. In the former, items that reached the end of their lifetime are replaced and, in the latter, items damaged by the flood are replaced (see section 2.2.1). Finally, given that the lifetime of the house was modelled on a decadal scale, the house's content such as cloths or consumers electronics were excluded as their short lifetimes leads their replacement to be independent of flooding.

It is argued that these scenarios and system boundaries allow to focus on flood related repairs while contextualizing them in the life cycle of the house. Given the intent to target flood related repairs, the next step is to map all processes and items involved in that phase, for different flood scenarios, and organize them in an inventory.

Table 1 - LCA system boundaries for the two cases, where X stands for excluded and ✓ for included.

Life cycle phase	Baseline	Flood
Construction	✓	✓
Maintenance (replacement, reparations)	✓	✓
Use (heating, electricity, water, etc.)	X	X
Flood related repairs	X	✓
Demolition	X	X
Recycling of construction materials	X	X

2.2. Inventory of flood related repairs

2.2.1. Flood damage assessment

Before modelling the house in the LCA framework, flood damage is assessed in order to map items in the house that are expected to be damaged and make them a priority. To do so, the flood maximum depth, denoted *FD,* was chosen as the indicator of damage. Traditionally, in the field of risk assessment, this would be done using stage-damage curves built with historical data. However, this type of curve yields values on the scale of different land uses, meaning a single damage value for roads or for commercial buildings. A single damage value for the whole residential sector is far too general for the calculations of items flows required here (cf. section 2.3). Indeed, it would mean that the house considered would be uniformly damaged, with the same proportion of repairs needed for items as different as electrical plugs and ceiling insulation. Instead, damage on single items in the house was linked to flood depth using the data from an expert opinion based report commandeered by the USACE (USACE, 2006). This economic assessment was adjusted to yield damage functions, *Di(FD)*, for each item *i* considered. The adjustment step consisted in converting economic values into relative values, using whichever was highest between the price of replacement or reparation reported by the USACE as the full damage upper limit. The output for a one-story on slab single-family residence flooded during one day with mixed fresh and salt water is reported in Table 2.

Using this data, one can map flood damage precisely: for a given flood depth, a relative damage value is attributed to each item. For example, for a flood depth of 20cm, almost a third of the wall insulation is damaged and replaced. This example shows that realistic repairs are considered in the USACE's report, in that case by taking into account the absorption property of the insulation as well as the fact that the gypsum plasterboard needs to be replaced in similar proportions.

It should be noted that basement flooding is considered in the USACE's report, which is why a flood with 0m of water is considered damaging. Moreover, flood depths up to 4.6m can be found in the USACE report. However, values higher than 2.1m are not used in this study as it could result in structural lifting (Middelmann-Fernandes, 2010). Instead, the water levels of Table 2 between 0 and 2.1m will all be considered, apart from the 0.6m level, resulting in nine flooding scenarios. These nine water depths will be assessed for all house ages, in increments of 10 years. This allows the investigation of the first dimension of the flood scenario while describing the associated uncertainty.

Table 2 - Damage depth relationship adapted from USACE (USACE, 2006)*, for a one-story on slab single-family residence flooded during one day with mixed fresh and salt water. The damage values are expressed in percentage of total replacement and greyed when maximum damage is reached.*

	Flood level (m) relative to ground floor									
Item's category	0	0.2	0.3	0.5	0.6	0.9	1.2	1.5	1.8	2.1
Heat and cool units/ducts	28.7	38.7	53	53	53	55.5	66.9	66.9	66.9	66.9
Bottom cabinets	11.4	68.2	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
Plumbing fixtures	5.6	12.7	15.3	18.8	21.6	23.4	36.7	36.7	36.7	36.7
Flooring/carpet/tile	34.2	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
Paint/wallpaper (interior)	13.9	63.8	91.7	91.7	91.7	91.7	**100**	**100**	**100**	**100**
Doors/trim	13.6	55.3	67.6	74.5	87.7	87.7	**100**	**100**	**100**	**100**
Sheetrock/(walls)	6.7	33.2	44.3	44.3	53.2	53.2	80.2	93.9	**100**	**100**
Wall insulation	6.5	32.3	42.4	42.4	52.2	61.3	87.1	**100**	**100**	**100**
Baseboard	14.6	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
Built-in appliances	13.1	33.9	67.8	78.7	86	**100**	**100**	**100**	**100**	**100**
Electrical and lighting/panel	1.1	3.7	3.7	15.3	30.5	31.6	50.8	65.6	75	81.9
Counter tops	13	26	26	26	26	61.3	**100**	**100**	**100**	**100**
Wall cabinets	21.8	33.4	33.4	33.4	33.4	33.4	56.7	**100**	**100**	**100**
Windows/trim	0	0	0	3.4	7.6	23.9	49.3	70.1	70.1	70.1
Ceiling insulation & ductwork	0	0	0	0	0	0	0	0	0	0
Roof	0	0	0	0	0	0	0	0	0	0
Exterior wall/siding	0	3	3	3	8	8	12.4	15.4	19	19
Slab/foundation	0	0	0	0	0	0	0	0	0	0
Structural frame	0.7	2.2	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Facia/soffit	0	0	0	0	0	0	0	0	0	0

2.2.2. House modelled

The single-family residence was modelled using two main sources: 1) the mapping presented in Table 2, in order to focus on elements damaged by the flood, and 2) literature references dealing with LCA of houses (Peuportier, 2001; Rasmussen and Birgisdottir, 2015) as well as flooding (Matthews et al., 2016). While diverse types of house designs exist, it was chosen to model a typical European single-family residence built in the 2010s. By modelling a recent, average house, it is argued that representative results are obtained. The resulting design is a 130m^2 house built on a concrete slab, with a brick structural frame, a 20cm thick mineral insulation and a 120 years lifetime. Figure 1 illustrates the house modelled with a floorplan, which was also used to dimension several items constituting the house. This figure includes some additional figurative elements such as beds and chairs (cf. Table 3 for list of items included in the flood damage assessment).

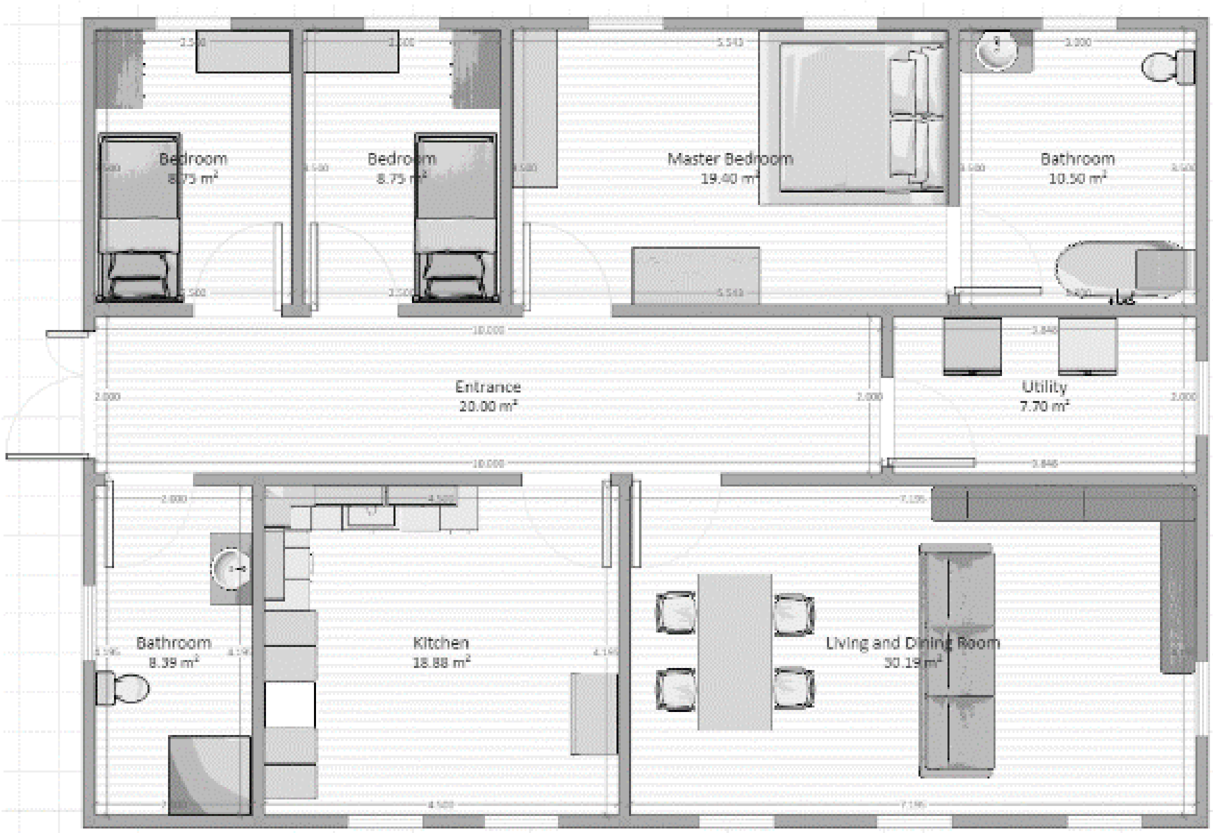

Figure 1 - Floorplan of the single-family residence modelled, with some additional figurative elements such as beds and chairs (cf. Table 3 for list of items included in the flood damage assessment).

Concretely, the house was modelled in the LCA framework as 32 separate items listed in Table 3. Most of the items selected are affixed to the house except for the wardrobes and living room furniture. An LCA and subsequent Life Cycle Inventory (LCI) were built for each of the 32 items constituting the house. To do so, Environmental Product Declarations (EPDs) of the specific products chosen were used, as it is the most representative data available.

An EPD is a collection of technical data for a given product, issued either by the manufacturer or by governmental agencies as an averaged reference. The data is mainly comprised of an LCA, but also reaches further in certain cases, with health or acoustic assessments. The results of the EPDs' LCAs were not used directly as this would have led to a limited number of impact categories and inconsistencies in LCA methodologies. Instead, the EPDs' LCIs were extracted, and the LCAs were rebuilt in SimaPro (Pré Consultants BV, 2018). High fidelity was achieved thanks to the level of detail of the EPDs' LCIs, often referencing precisely which items of different databases were used for a given material or process.

The EPDs were found on a French open database that references products declared either by the manufacturer or by the French Ministries of Housing and of Ecology (FMHE) (INIES, 2017). All the EPDs used in this study follow the traditional LCA regulation ISO 14044, and are further regulated by the French NF EN 15804 which deals with EPDs as an entity (INIES, 2017). In some cases, EPDs were replaced by literature studies, when the LCIs reported there were transparent enough. Finally, when specific data was not available, generic data from the Ecoinvent v3.2 database was used. The specific sources for each of the item modelled can be found in Table 3. Detailed LCIs for each item can be found in the [*supplementary material*]. All of the items were eventually modelled in SimaPro, using the *ReCiPe Midpoint (E) V1.13/Europe* (Goedkoop et al., 2013).

Table 3 - List of the house's items that were modelled grouped by category, alongside their sources. When no source is mentioned, the name of the Ecoinvent process used is written in italic where GLO and RER stand for global and Europe.

Category	Items modelled	Source
Heat and Cool Units/Ducts	1 kW electric radiator	(Thermor, 2015)
	Flexible ventilation duct, 12.5cm ND	(FMHE, 2014a)
	Mechanical ventilation, simple flux, 60m3/h	(Groupe Atlantic, 2015)
Bottom/wall cabinets and counter tops	Kitchen cabinet	(González-García et al., 2011)
	Living room furniture	(González-García et al., 2011)
	Wardrobe	(Iritani et al., 2015)
Plumbing Fixtures	Ceramic WC	(Ideal standard France, 2016)
	10 kW gas Water heater	(FMHE, 2016a)
	PVC pipe	(GIRPI, 2015)
	Ceramic kitchen sink	(AFISB, 2014)
	Ceramic bathroom sink	(Ideal standard France, 2015)
Flooring	Ceramic tile	*Ceramic tile, GLO*
	Wooden flooring with decorative paper	(FMHE, 2014b)
Paint (interior)	White alkyd paint	*Alkyd paint, white, RER*
Doors/Trim	Wooden entrance door	(Bel'M, 2012)
	Wooden inner door	*Door, inner, wood (GLO)*
Sheetrock/(Walls)	Gypsum plasterboard	*Gypsum plasterboard (GLO)*
Wall and ceiling Insulation	Stone wool	*Stone wool (GLO)*
Base Molding	Wooden baseboard	(FMHE, 2014c)
	Ceramic baseboard	(FMHE, 2014d)
Electrical and Lighting/Panel	Domestic cable	(FMHE, 2017)
	Domestic socket	(Legrand, 2016)
	Domestic switch	(FMHE, 2016b)
	54 W lighting	(FMHE, 2016c)
	74 W suspended lighting	(FMHE, 2016d)
	Miniature Circuit Breaker	(Schneider Electric, 2014)
Windows/Trim	Double glazed PVC framed window	*Window, PVC (GLO)*
Roof	Clay roof tile	*Roof tile, clay (GLO)*
Exterior Wall/Siding	Wooden painted siding	(FCBA, 2015)
Slab/Foundation	Foundation	(Rasmussen and Birgisdottir, 2015)
	Slab	(Rasmussen and Birgisdottir, 2015)
Structural Frame	Structural frame	(Rasmussen and Birgisdottir, 2015)

2.3. Items flows

The Item Flows (*IFs*) described in this section refer to the number of each of the 32 items needed for different scenarios. For example, the number of radiators needed when first building the house, or when a flood with a given water level occurs on a house with a given age. It is not to be confused with the reference flow of the overarching comparative LCA, which is one house for all scenarios. It is not to be confused either with the reference flows of the 32 LCAs conducted for each item. The reference flows for the items, as well as their LCIs, can be found in the [*supplementary material*].

The *IFs* for the baseline scenario are the addition of the two phases included, namely, construction and maintenance. The simplified construction phase consists in the addition of the initial quantities, denoted IQ_i, for each item *i*. The initial quantities were determined using the references of Table 3, as well as the floor plan of Figure 1, which was used as a canvas to dimension several items (e.g. lengths of ventilation ducts and water pipes or area of flooring, etc.). Additional sources and expert opinions were also used for several items which was reported in the [*supplementary materials*]. To add the maintenance phase, the initial quantities were multiplied by the ratio of the house lifetime, L_H, and the item's lifetime, L_i, leading to:

$$IF_{i,basline} = IQ_i \cdot \frac{L_H}{L_i} \qquad \text{Equation 1}$$

The outputs of this equation can be found in Table 4 alongside lifetimes, for all items. It should be noted that the technical lifetimes found in the literature references were often unrealistic and were therefore corrected, using a single unified source (ATD, 2016).

However, while being convenient, Equation 1 only yields correct results when the lifetime of the house is a multiple of the lifetime of the item considered, yielding an underestimation otherwise. Fortunately, the 120 years lifetime of the house is a multiple of most of the items' lifetimes, and the few exceptions with a lifetime of 50 years had their IFs corrected, which is noted in Table 4. To find the correct IFs for items with a 50 years lifetime, the life cycle of the house was divided in decades. For each decade, items that saw their lifetime run out were replaced. While not as straightforward as a single equation, this method allows a realistic accounting of all items, which is extensively discussed in section 4.1.

For the flooding scenario, the initial quantities and therefore the construction phase are the same. However, the maintenance cycles change due to the introduction of a flood. Utilizing the damage functions introduced in section 2.2, the additional materials needed for flood related repairs are incorporated:

$$IF_{i,flood} = IQ_i \cdot \left(D_i(FD) + \frac{L_H}{L_i}\right)$$

Equation 2

Once again, items with a lifetime of 50 years stood out as incorrect. Moreover, further complexity is introduced as *IF* calculation is impacted by how old the house is when the flood occurs. Both phenomena were accounted for by using the same methodology that allowed to correct Equation 1. Floods during eleven decades of the house's lifetime where considered, from decade 1 to 11. This allowed to fully explore the second dimension of the flood scenarios, namely, the house age. The outputs are presented in section 3.1 and discussed in section 4.1.

2.4. Assessing sensitivity

A two-step sensitivity analysis is used to assess the model's robustness. The first step is a perturbation analysis where selected key parameters are varied in realistic ranges while the effect of the change on the results is expressed using sensitivity ratios, denoted *SR* and calculated via Equation 3. For example, a ratio of 0.3 means that the relative change in results is 30% of the relative change in parameter. A linear influence of a parameter will therefore be reflected by a ratio of 1.

$$SR = \frac{\frac{\Delta Results}{Initial\ result}}{\frac{\Delta Parameter}{Initial\ parameter}}$$

Equation 3

The second step of the sensitivity analysis is an assumption check where two selected hypotheses are challenged. The first is the choice of insulation, which impact is assessed by investigating the impact of a change in insulation thickness. This was chosen because of the rapidly changing and non-uniform insulation policies across Europe. The second assumption checked is the structural frame's main component, namely, the cement facing bricks. The impact on the results of replacing them by either clay or shale bricks is investigated.

3. Results

As mentioned in section 2.2.2, the results presented in this section were obtained using the *ReCiPe Midpoint (E) V1.13/Europe* (Goedkoop et al., 2013) computed through the SimaPro software. This method does not have a normalization factor for water depletion, explaining the absence of this impact category when normalized results are presented. Moreover, when all impact categories could not be presented on a figure, climate change was used. It is believed that this impact category is communicative and is often representative of general behaviours. To mitigate the bias introduced by this truncated view, all the characterized results are included in the [*supplementary material*].

3.1. Inventory

The results of the method presented in section 2.3 are gathered in Table 4. Only two house ages are displayed in this table and throughout this study because they represent all the possibilities. Indeed, floods occurring during decades 1, 5, 6, 10 and 11 yield equal *IFs* and are represented by a flood during decade 5. The same applies for floods occurring during decades 2, 3, 4, 7, 8 and 9, which are represented by a flood during decade 2. These equalities explain why only two decades are represented in Table 4. These equalities are a result of a shifting of timing of investment, which will be illustrated by Figure 3. This means that nine water depths are considered for two house ages, effectively amounting to a total of eighteen flood scenarios. The results of Table 4 are further discussed in section 4.1. More detailed results, spread over the decades of the lifetime of the house, can be found in the [*supplementary material*].

Table 4 – Initial quantities (IQ_i), lifetimes (L_i), and item flows of the baseline and two flood scenarios for all items, calculated using Equation 1 and Equation 2. The corrected values for items with a lifetime of 50years are notified in italic. A flood depth of 0.5m was used for both floods.

	IQ_i	Unit	L_i (y)	Baseline ($IF_{i,baseline}$)	Flood during decade 5 ($IF_{i,flood}$)	Flood during decade 2 ($IF_{i,flood}$)
Paint	87.7	kg	10	1053	1133	1133
Ventilation duct	21.4	m	20	129	140	140
Mechanical ventilation	1	p	20	6	6	6
Socket	30	p	20	180	185	185
Switch	16	p	20	96	99	99
MCB	1	p	20	6	7	7
Water heater	1	p	30	4	5	5
Wall light	6	p	30	24	25	25
Suspended light	9.0	p	30	36	36	36
Window	13	m²	30	52	53	53
Radiator	16	p	40	48	57	57
Kitchen cabinet	4	p	50	*12*	*16*	*12*
Living room furniture	1	p	50	*3*	*4*	*3*
Wardrobe	2.0	p	50	*6*	*8*	*6*
WC, ceramic	2	p	50	*6*	*7*	*6*
PVC pipe	36.5	m	50	*110*	*117*	*110*
Kitchen sink	1.0	p	50	*3*	*4*	*3*
Bathroom sink	2.0	p	50	*6*	*7*	*6*
Ceramic tile	65.5	m²	60	131	197	197
Wooden flooring	67.1	m²	60	135	202	202
Door, entrance	1.0	p	60	2	3	3
Door, inner	8	p	60	16	22	22
Baseboard, MDF	60.3	m	60	121	181	181
Baseboard, ceramic	64.3	m	60	129	193	193
Sheetrock	369.4	m²	120	370	534	534
Stone wool, wall	1115	kg	120	1115	1589	1589
Stone wool, ceiling	1400	kg	120	1400	1400	1400
Cable	172	m	120	172	199	199
Roof tile	6162.6	kg	120	6163	6163	6163
Siding	104.6	m²	120	105	108	108
Foundation	132	m²	120	132	132	132
Slab	132	m²	120	132	132	132
Structural frame	132	m²	120	132	137	137

3.2. Impacts over the life cycle

Looking at the impacts occurring through time allows for investigation of the contribution of each stage but also helps illustrate the way maintenance cycles shift when a flood occurs. Figure 2 shows relative climate change results for the baseline scenario plotted against time. The largest impact, by far, is the initial construction. This is due to the group of items lasting for the whole life of the house, namely, the structural frame, foundation, slab, gypsum plasterboard and insulation. The initial construction amounts to 67 % of the house's impact on climate change, and 55% on average in all impact categories.

The other large impacts occur during decades 3, 6 and 9 which is mostly due to the replacement of the items with lifetimes of 20, 30, and 60 years. One may also notice the significant impact occurring during decade 5 and 10 that accounts for 5 % of the total impact each. This highlights the fact that the model chooses to replace items with a lifetime of 50 also during decade 10, a choice that probably would not be made in a realistic setting. If this group of items were not replaced, the total climate change impact of the baseline scenario would go down by 3.9%. Given that the used-up group of items would still have to be maintained by replacement with items of shorter lifetimes, which would come with its own environmental impact, the overestimation is believed to be negligible.

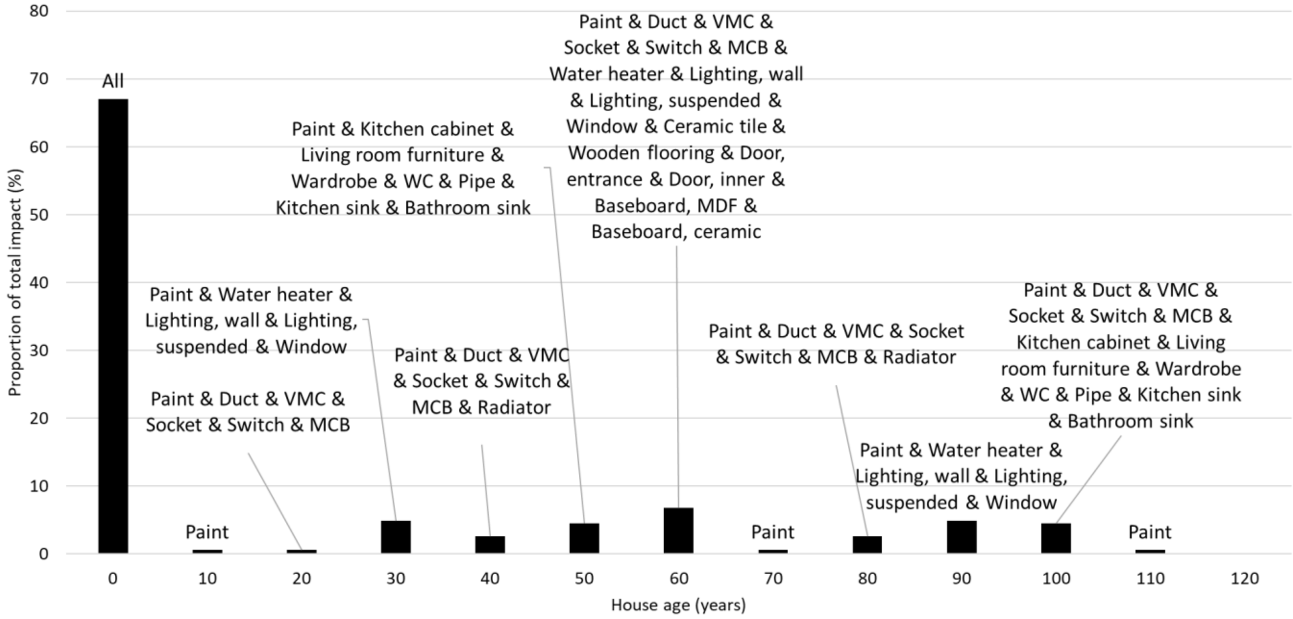

Figure 2 - Climate change results for the baseline scenario, expressed as a percentage of the total baseline impact, spread over the twelve decades of the house's life cycle. Each decade shows the list of items replaced.

Figure 3 shows the relative difference between the baseline and two floods scenarios, expressed against time and calculated from normalized climate change results. The two floods considered have water levels of 0.5m and occur during decades 2 and 5.

Before the flood occurs, there is no difference between the baseline and flood scenarios. The impact of flood related repairs is denoted by a red outline, which represents the direct component of the flood's impact. This direct impact is equal for both flood scenarios, amounting to 9.6% relative additional impact. This was expected as the *IFs* for flood related repairs and calculated identically in both cases, using the first part of Equation 2. After the flood, the maintenance cycles of several items are shifted through time because the natural disaster forces early replacements, which in turn moves impacts. This constitutes the indirect component of the flood's impact. For a flood occurring during decade 5, these shifts cancel out, and the entirety of the flood's direct impact is carried out in overall difference. On the contrary, a flood occurring during decade 2 ends up having a lower overall impact because the direct impact of the flood is mitigated by its indirect component. This will be further discussed in section 4.1, on the level of *IFs*.

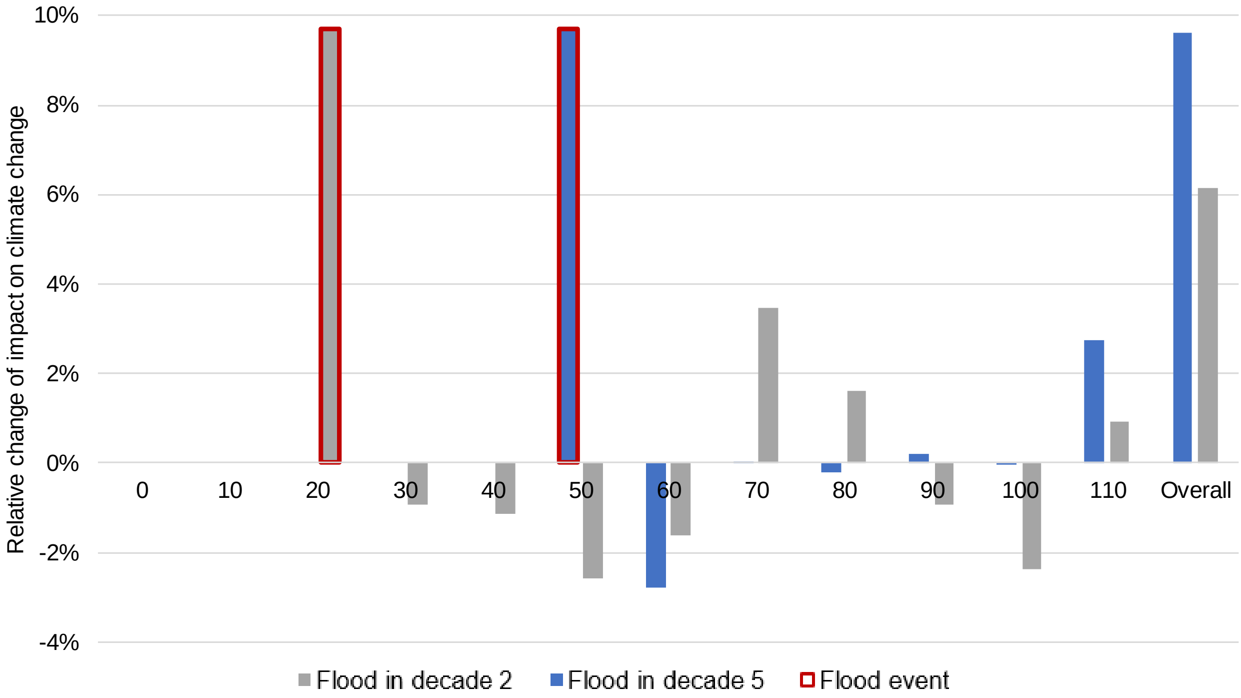

Figure 3 – Change introduced by floods of 0.5m during decade 2 and 5 relative to the baseline scenario, visualized through time and calculated from climate change normalized results.

3.3. Summed normalized results

Figure 4 provides an overview of the results summed for all items and phases. The normalized impacts of the baseline scenario for all categories are expressed in Person Equivalent (PE) with data labels while the additional impact caused by two 0.5m floods occurring during decades 2 and 5 is expressed relative to the baseline impact (%). The first observation is that, disregarding the impact category considered, the scenario with a flood during decade 5 has the highest impact, followed by the flood during decade 2. This is in line with the climate change impacts results of the precious section. On average across categories, floods during decades 2 and 5 add 7.7 and 11.8 % to the baseline scenario, respectively.

Furthermore, large disparities between categories can be observed when looking at the absolute normalized impact of the baseline in the data labels of Figure 4. Impacts range from a few tenth of PE for ozone depletion to hundreds of PE for marine ecotoxicity. Moreover, considering that this single-family residence can provide housing for an average of 3.5 individuals during 120 years, it amounts to 420PE for housing. Moreover, when looking at climate change, only 2% of the house's inhabitants' equivalent impact is spent on housing. It is lower than the 38% mentioned in the introduction because the use phase is not considered here, which is by far the most impactful (Rasmussen and Birgisdottir, 2015).

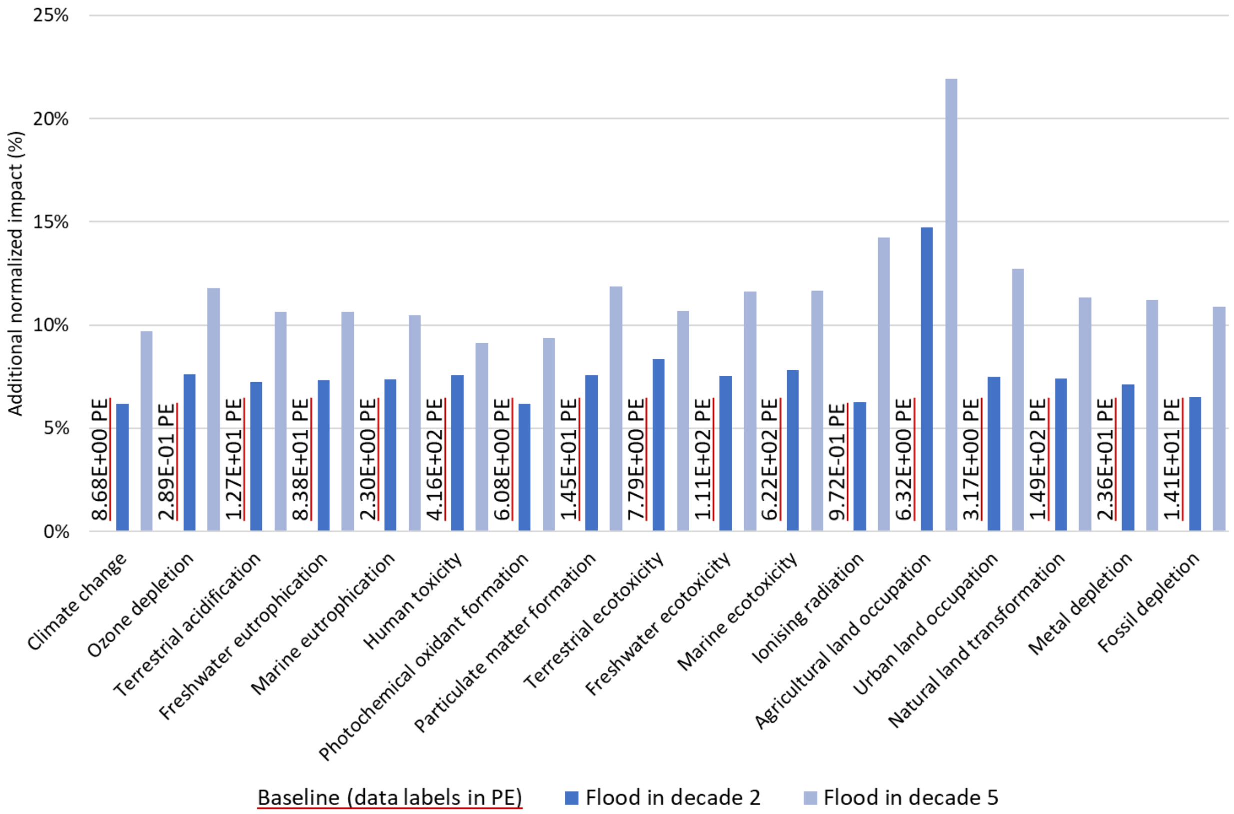

Figure 4 -Additional impact (%) of two 0.5m flood occurring during decades 2 and 5, relative to the baseline normalized results in absolute value displayed in data labels (Personal equivalent, PE), summed for all items of the house, for all impact categories. Phases as described in Table 1 are included.

3.4. Impact of flood related repairs related to flood depth

Figure 5 shows the additional damage resulting from a single flood plotted against the water level, relative to a baseline house and from four standpoints:

1) the additional environmental impact (%) caused by a flood with worst possible timing (during decade 5), calculated from the results of this study, on average for all impact categories
2) the same additional environmental impact (%) calculated identically, but for a flood with best possible timing (during decade 2)
3) the evolution of flood damage with depth (%, right axis), as calculated by the USACE (USACE, 2006) in the North-American context, relative to the maximum flood damage.

4) the evolution of flood damage with depth (%, right axis), as calculated in the work commandeered by the Joint Research Centre (JRC) (Huizinga, 2007) in the European context, relative to the maximum flood damage.

Curves 1) and 2) represent the same notion that was introduced when comparing scenarios on Figure 4. Overall, the additional environmental impact resulting from a single flood ranges from 3.5% to 17.8% from floods of 0m occurring during decade 2 to floods of 2.1m during decade 5, respectively. It is argued that realistic additional damage would fall in the area in between the two curves (denoted in blue on the figure), with the two curves representing the worse and best cases. Actual damage would depend on the precise age of the house when the flood occurs and hence on exactly how good or poor the flood timing was.

Comparing the area of realistic additional damage with curve 3) allows to conclude that the environmental impact of a flood is correlated to its economic impact, especially for low flood depths. The fact that the work of the USACE was used to model the environmental impacts in the first place is partly responsible for this result. However, if the environmental weight of the items had been distributed differently, this correlation would have been refuted. This is a major result as this correlation is often an assumption in literature and has not been verified explicitly before. The correlation can be verified for all impact categories individually, except for agricultural land occupation and ionising radiation as documented in the [*supplementary material*].

The flood damage assessment of this study is based on the work of USACE which is contextualized in the US, whereas this study intends to yield results representative for Europe. This calls for the comparison made in between curves 3) and 4). The damage function calculated by the USACE was compared to the work commandeered by the European JRC (Huizinga, 2007). It is a far-reaching attempt to catalogue traditional economic damage curves on the level of land uses, for water levels of 0 to 6m, and for the 27 countries that were in the EU in 2007. The data chosen for Figure 5 is their average findings for the residential buildings, across all the countries considered. It shows that the evolution of the two curves is similar enough to yield representative results in the range of water levels considered.

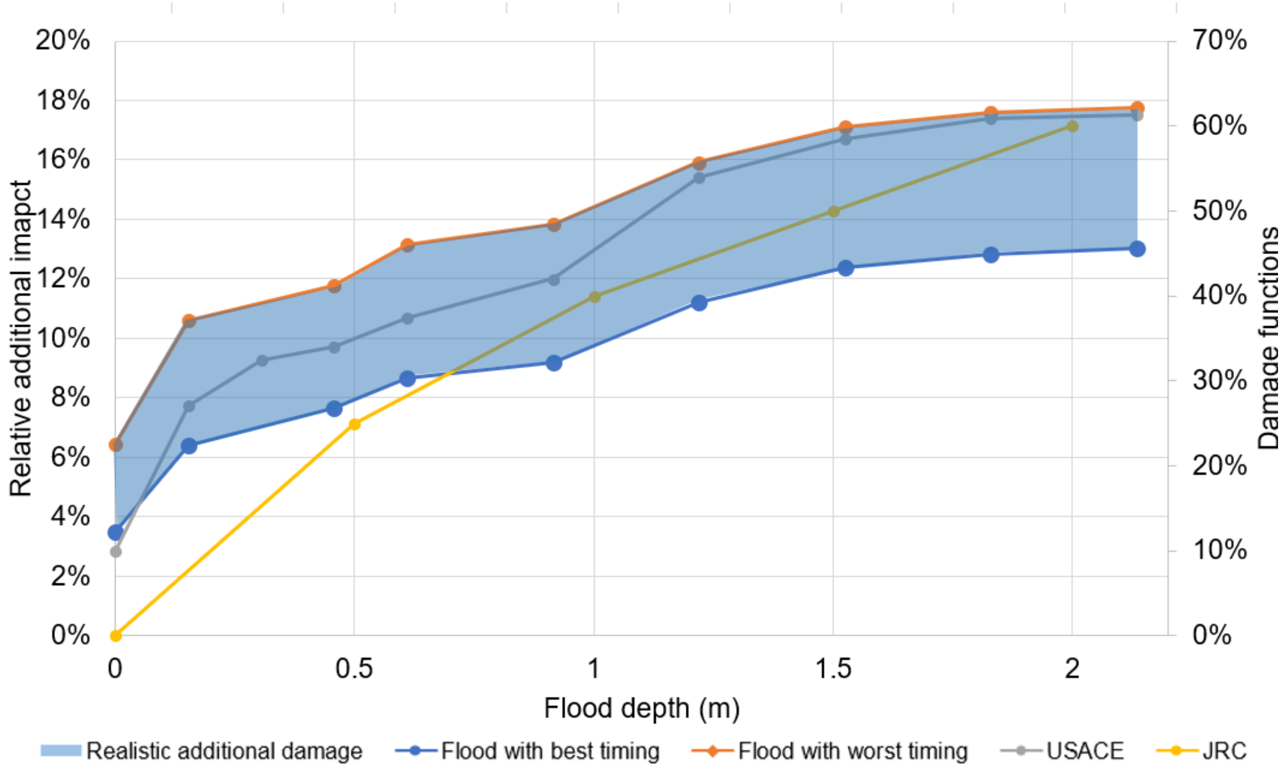

Figure 5 - Additional environmental impact caused by floods with best and worst timings relative to the baseline house (primary axis), as well as the economic damage functions from USACE and JRC for European and North-American contexts (secondary axis), plotted against flood depth (m).

4. Discussion

4.1. Limitations

It is argued that the way item flows are calculated, meaning how flood related repairs are integrated in the life cycle of the house, is a significant choice. Indeed, the method chosen determines whether the house age will have an impact on the results. By laying down *IFs* throughout the decades, amounts close to reality were obtained which account for the influence of the house age. The fact that decadal cycles of maintenance is a simplification that lead to a division of the results in a worst and a best scenario is argued to be an acceptable trade-off.

The method chosen therefore allows to account for the fact that maintenance cycles shift when a flood forces early replacement. To illustrate that, one may notice that three categories of items arise when looking at the IFs results (cf. Table 4 and [*supplementary material*]).

First, for items with a lifetime of 20 years or lower, the introduction of a flood does not impact the IF. Simply said, this group of items would have been replaced with or without flood. This result notably justifies the exclusion of the content of the house (i.e. consumers electronics or cloths), as they have even shorter lifetimes. A second group of items, with lifetimes that are higher or equal to 30 and also are a multiple of 120 years, see their IF go up with a flood, but are not impacted by the house age. Their maintenance cycle is affected by the natural disaster but can shift freely through time disregarding of when it occurs (see [*supplementary material*]). A final group of items, with a lifetime of 50years, also see their IF go up with the introduction of a flood but in different amounts depending on the age of the house age.

Representing flood damage using solely the indicator of maximum flood depth is criticized by some because it does not consider flood velocity and duration or failures occurring when structures are lifted (Huizinga, 2007; Middelmann-Fernandes, 2010; USACE, 2006). In this study, the duration of the flood is specified, and no flood depths higher than 2.1m are considered specifically to avoid the uncertainty linked to high velocity waters. Adding the fact that flood damage is assessed on the item level as opposed to land uses, it is argued that the approach chosen mitigates the limitations of stage-damage curves while fitting in the LCA framework.

Other factors are limiting, albeit to a lesser extent. The eclectic nature of the sources used for the LCIs of the 32 individual LCAs conducted on the items of the house leads to varying degrees of precision. For example, while packaging is included in most LCIs, some include specific values while other just work with assumptions based on the overall weight of the product. This means that the overall representativeness of the LCA is difficult to discuss. The difficulty of comparing these results to other study in a direct way is another limiting factor. To the authors' knowledge, the closest approach in literature is the work of Matthews conducted in 2016 (Matthews et al., 2016). However, even in that case, they dealt with the issue statistically using a Monte-Carlo analysis that accounts for sea level rise, and they studied a comparison with a flood resilient house design in the North-American context. These differences set it too far apart from our method for any worthwhile direct comparison of results. Further work was however based on this model of a single-family residence which may make for easier comparisons (Hennequin et al., 2018).

4.2. Sensitivity analysis

4.2.1. Perturbation analysis

The methodology presented in section 2.4 is used to assess the robustness of the model. The influence of 16 key parameters on the results was assessed by calculating their sensitivity ratios with Equation 3, which were averaged for all impact categories and reported on Figure 6. These were calculated using characterized results of the scenario with a flood of 0.5m occurring during decade 5. Both the parameters range of variation and the complete collection of sensitivity ratios can be found in the [*supplementary material*].

The first observation is that no parameters is overpowering the results. The maximum ratio is 0.36 for the paint usage in the natural land occupation category, and the average of all the ratios is 0.063 with a standard deviation of 0.064. The generally low ratios observed here are mostly due to the substantial number of items modelled, which all participate in the results in similar proportions. None of the parameters can be said to have an overwhelming influence on the results, which makes for a robust model.

Moreover, it can be observed that the results are most sensitive to the initial quantities of the structural frame, the lifetime and initial quantity of the furniture and windows as well as the paint usage. Finally, the results show that none of the impact categories are significantly more sensitive to the changes in parameters than another. Averaging the ratios per category yields ratios ranging from 0.046 for human toxicity to 0.076 for water depletion.

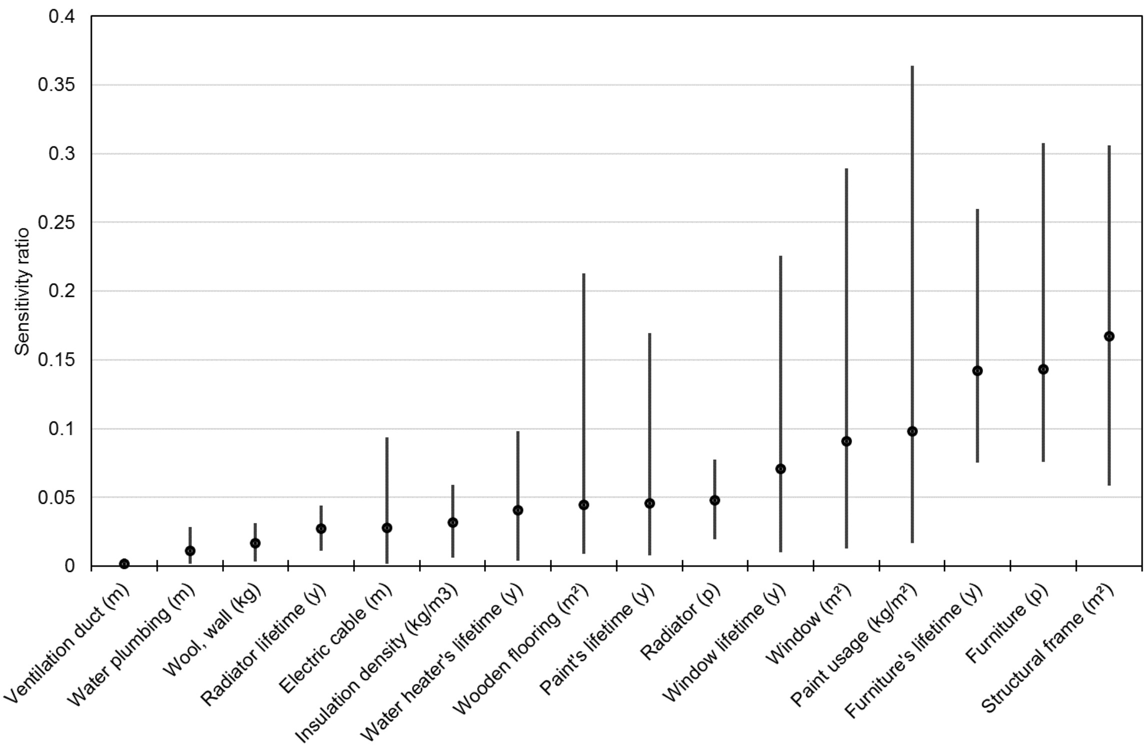

Figure 6 - Average and min/max range of sensitivity ratios for selected parameters across impact categories, calculated using Equation 3.

4.2.2. Assumption check

The result of the four assumption checks presented in section 2.4 are presented in Figure 7. The influences of the changes made to the model are compared to the scenario with a 0.5m flood during decade 50, taken as a reference. Characterized impact on climate change have been chosen to build the figure for the sake of clarity, However, whenever climate change is not representative of the behaviour of the rest of the categories, it is discussed.

A 10cm thicker insulation brings the reference flow of wall and ceiling insulation for reference scenario from 2989 to 4483kg. Using thicker stone wool insulation logically makes the impact of the reference scenario go up, by 2% in average across all impact categories. However, if the use phase of the house was included, the savings on heating might counterbalance that negative effect, making for a worthy trade-off.

The brick reference flow for clay and shale was respectively adjusted to 25410 (Littlehampton, 2017) and 24717kg (SImetric, 2016). For both types of bricks, the impact of the reference scenario goes down, by 15% and 17% for the clay and shale when looking at climate change and 8 and 5% in average across all impact categories. The large effect of these changes is due to the fact that the structural frame is a major hotspot of the baseline scenario and SimaPro results showed that the fibre cement bricks were responsible for most of that impact.

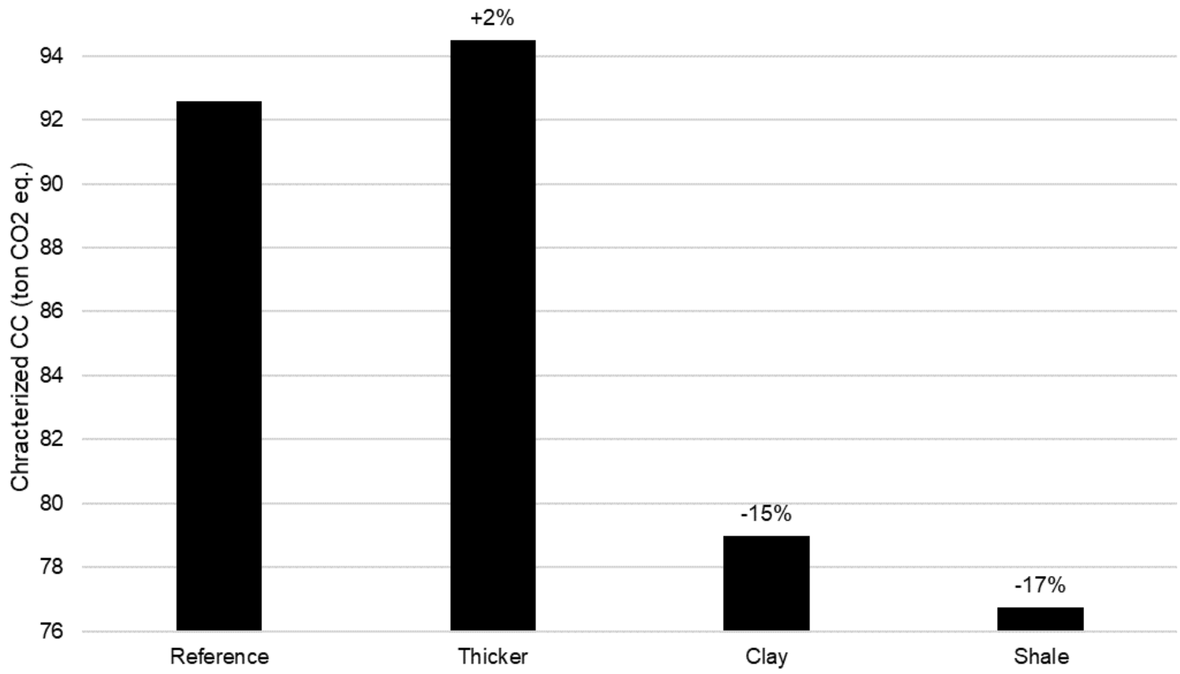

Figure 7 - Assumption check with results as characterized impact on climate change (ton CO2 eq.) and a flood of 0.5m as a reference scenario

5. Conclusion

This study has presented a holistic method to assess the environmental impact of a house's flood related repairs. It was chosen to focus on the residential portion of the built environment as it is the part most heavily affected by flood. The method was exemplified by studying a European single-family residence built in the 2010's.

The main conclusions of the study can be summarized as:

- With or without flooding, the main impact of the life cycle of a house is its construction, when omitting the use phase. The initial construction amounts to 55% of total impact when no flooding is occurring and to 50% when the house is flooded once. This is because several impactful elements are built only once at the beginning, namely, the structural frame, the foundation, the slab, the insulation and the gypsum plasterboard.
- A correlation between the economic impact of a flooding event and its environmental impact is demonstrated. It is valid for most impact categories, expect for agricultural land occupation and ionizing radiation, and between water levels of 0 and 2.1m.

- The main element of the single-family residence impacting the environment is the structural frame which makes up one fifth of the total impact. 80% of the frame's impact is due to its cement facing bricks. This could be mitigated using shale or clay bricks instead.
- The main elements of the flood related repairs impacting the environment are the wooden flooring, the water heater, and the furniture. Together, they account for half of the impact of the renovation needed after a flood.
- When a house is flooded with a water level of 0.5m, the additional environmental impact will range from 8 to 12%. The extent of the increase depends on when the flood occurs. This range will evolve from 3.5-6.4% to 13-17.5% when the water level increases from 0 to 2.1m.

This study has the ambition to be part of the foundation for further studies dealing with the environmental impact of flooding. Larger questions can be answered using this method as groundwork, notably dealing with climate change adaptation and risk assessment. For example, by building upon this LCA study one could inform decision makers on strategic options of flood risk management.

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