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Comparison and analysis of product stage and service life uncertainties in life cycle assessment of building elements

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Abstract

Life cycle assessment (LCA) has the potential to inform building decisions from the planning process to conceptual design. As such, there is intrinsic uncertainty that needs to be explored further to allow for proper decisions to be made. These uncertainties may be related to parameter definition, such as life cycle inventory or model as service life definition. This paper aims to analyze the influence of two recognized sources of uncertainties in LCA of buildings: product stage uncertainties and uncertainties from SL during the use stage. The Monte Carlo simulation method is applied to conduct uncertainty analysis of the LCA results of four building elements, namely, external cement plaster, external clay brick wall, external painting and internal painting. The functional unit is 1 m^2 of each building element. Three different building reference study periods are considered: 50, 120 and 500 years. A global warming potential impact category is chosen since it is one of the most significant indicators for climate change mitigation strategies. Results indicate that SL uncertainties are greater than product stage uncertainties for the four building elements analyzed. Furthermore, based on the findings from this study, distribution choice influences the uncertainty analysis results in Monte Carlo simulation. Standardizing modeling of SL in the LCA of buildings could guide building LCA practitioners and researchers and lead to more comparable results.

1. Introduction

The relevance of life-cycle-based environmental information is internationally recognized, with the potential to inform building decisions from the planning process to conceptual design, as well as support the choice of suppliers for green material and whole building labeling [1] and waste management strategies [2].

Life cycle assessment (LCA) has widespread applications and has been widely used, but due to uncertainties, some authors identify that the final results can be unreliable [3]. Uncertainty analysis is an essential aspect of LCA [4, 5]. These uncertainties are mainly due to the errors in input parameters, the definition of the system boundary, and scenario assumptions [6]. They are related to the choice of analytical models, which can be summarized as a parameter, scenario, and model uncertainties [6, 7].

Contemplating the explicit interpretation of the degree of uncertainty and sensitivity is important for comparative assertions [8]. Uncertainty analysis in LCA provides an understanding of the variation in and expected bounds of the life cycle impacts [9]. This enhances comparisons and makes the interpretation of results more reliable.

There are different methods to evaluate the uncertainties in LCA, such as Monte Carlo sampling, Latin hypercube sampling, quasi Monte Carlo sampling, analytical uncertainty propagation, fuzzy interval arithmetic [4] and Taylor series expansion [10]. Monte Carlo sampling has had the most frequent and widespread application [4]; it estimates uncertainties by employing random numbers obtained through a roulette-like machine of the kind utilized in the casinos of Monte Carlo, after which the method is named [11].

Although the relevance of uncertainty analysis is undeniable, less than 20% of LCA studies published between 2014 and 2018 reported any kind of uncertainty analysis [12]. Parameter uncertainty is the most often reported [12]. In the context of the construction sector, consideration of uncertainty analysis in LCA is not consistent [5].

Uncertainty assessment has been focused on different sources. Häfliger *et al* [13] analyzed the uncertainties from database choices, system boundary definitions and replacement scenarios of building materials. Grant *et al* [14] investigated the importance of service life (SL) assumptions in building LCA impact results. Blengini and Di Carlo [15] evaluated the LCA impact of building through data quality indicators. Zhang *et al* [6] assessed uncertainty in the LCA of building emissions, detailing the influence of stochastic parameters represented as probability distributions on the results.

A small number of authors have been studying the SL variability, represented by uncertainty analysis. SL can be defined as the period of time after installation during which a building element or an assembled system (part of works) meets or exceeds the technical requirements and functional requirements [16–18]. The SL measure is not objective as the concept of utility may vary. A conventional limit is usually adopted to establish the end of SL of a building element, considering various acceptance criteria [19]. Grant *et al* [14], Hoxha *et al* [10], Hoxha *et al* [3], Aktas and Bilec [20], Grant and Ries [21], Robati *et al* [9] and Morales *et al* [22, 23] focused on quantifying the uncertainties related to SL in the LCA of buildings. However, existing studies have not demonstrated the influence of statistical parameter assumptions used to model SL uncertainties.

Therefore, this paper aims to analyze the influence of uncertainties associated with the product stage and those with SL definition in the LCA of building elements using Monte Carlo simulation. The analysis seeks to demonstrate the influence of the distribution choice regarding the SL uncertainty analysis. Four building elements are considered in this study, namely, external cement plaster, external clay brick wall, external painting and internal painting. In addition, a comparison between the uncertainties from the product stage versus the uncertainties from SL is conducted.

2. Methods

This study follows LCA stages as described in ISO 14040:2006 [24] and ISO 14044:2006 [25]. Section 2.1 describes the assumptions for the LCA, detailing the objective and scope of the LCA. Section 2.2 describes the life cycle inventory data used in the study. Section 2.3 details the framework of the uncertainty analysis. Section 2.4 describes the scenarios considered in the study. Section 2.5 specifies the life cycle impact category adopted for the analysis.

2.1. Objective and scope

The main goal of this LCA was to evaluate the life cycle impacts of one square meter of the following building elements: external cement plaster, external clay brick wall, external painting and internal painting. Clay brick is one of the oldest building materials and among the most common construction materials found all over the world [26, 27]. In addition, interest in the sustainable benefits of brick is growing in countries where clay brick is not the typical choice due to its labor-intensive construction system [28].

Building elements, as defined here, are major components common to most buildings. Elements usually perform a given function, regardless of the design specification, construction method or materials used [29]. These building elements were selected due to their different characteristics, especially regarding the frequency of replacement. Cement plaster and clay brick were chosen because they have a longer life and high SL variability [23]. External and internal painting were included to verify the uncertainties from building elements that have a shorter SL. The scope is cradle to grave and contemplates, according to EN 15978:2011 [16], product stage impacts (modules A1 to A3), the use stage or SL impacts (module B4) and the end-of-life stage (modules C1 to C4).

The study considers global data sets from Ecoinvent version 3.3. This choice is justified because the SL data applied in the use stage modeling is an average of data from different regions of the globe [23].

2.2. Inventory analysis

The life cycle inventory data are based on the cut-off system model [30], considering background life cycle inventory data for each building element from the Ecoinvent database version 3.3. Market data sets from the global location are used. This choice is consistent with the SL data considered, which covers several countries on different continents. A global data set represents the average of the global production of some activity. An activity represents a unit process of human activity and its exchanges with the environment and other human activities [30]. The market data sets are used since they represent the consumption mix and one or more inputs of the same product from the different transforming activities that are located within the geographical delimitation of the market and transportation [30].

Table 1 presents the description of the life cycle inventory. Five independent data quality indicators were also included, to describe those aspects of data quality that influence the reliability of the result: reliability, completeness, temporal correlation, geographic correlation and further technological correlation. Data quality indicators are semi-quantitative numbers, from 1–5, attached to a data set, where 5 is the default value and may represent unknown or non-qualified estimation, for example. These indicators were provided by Ecoinvent and are called the Pedigree matrix [31]. Since the current study applies global data sets, the consideration of the quality of these data is recommended [30].

The final disposal process considered was the market for inert waste, contemplating the landfill of all construction and demolition waste generated by the product and use stages following other similar studies such as Silvestre *et al* [32]. According to the Ecoinvent report, no direct emissions from inert material landfills (leachate) have been included in the process. The disposal process contains only exchanges to process-specific burdens such as dismantling, transportation, land use and infrastructure [33]. Future studies should be extended to include the various potential end-of-life scenarios, where reuse and recycling are factored into the analysis.

2.3. Uncertainty analysis

The uncertainties were analyzed through the Monte Carlo simulation [11]. This method has been applied to evaluate uncertainties in several LCA studies such as Robati *et al* [9], Minne and Crittenden [34], Aktas and Bilec [20], Hung and Ma [35], McCleese and LaPuma [36],and Sonnemann *et al* [37]. The current study follows a previous work [23] that compared inherent uncertainties of SL models and the uncertainties from distribution choice in the LCA of building elements. Figure 1 demonstrates the flow chart of the study demonstrating the steps from the previous study (step 1) and the steps developed in this current study (steps 2 and 3) wherein two sources of uncertainties were explored: uncertainties associated with SL and uncertainties associated with the product stage.

Step 1—uncertainties associated with SL. Step 1 of the flowchart refers to the previous study [23]. Six distributions indicated by the literature as suitable for SL were chosen to run the Monte Carlo simulation, namely gamma, Gumbel, logistic, lognormal, normal and Weibull. Two tests commonly used to find the best-fit distribution, called the goodness-of-fit (GOF) test, were applied to verify the suitability of the data to the distributions [23]. A 90% confidence interval was used and 10,000 iterations were considered to run the simulations. The uncertainty analysis from step 1 was focused on estimating the variability and distribution's influence in modeling the replacement scenario (module B4).

Steps 2 and 3 of the flow chart (figure 1) represent this current study. In this study, the SL data shown in table 2 were used to estimate the number of replacements of each building element according to each reference study period (RSP) adopted. The SL data were obtained from Morales *et al* [23]. A detailed description of the SL data considered is available in the supporting information (SI) (https://stacks.iop.org/ERIS/2/035001/mmedia).

Step 2—uncertainties associated with product stage. These uncertainties were estimated considering the default values for basic uncertainty provided by the Ecoinvent Database [30]. A detailed description of the data is available in the SI. An additional uncertainty from data quality indicators was added to the basic uncertainty using statistical parameters from the Pedigree matrix approach [24, 31]. OpenLCA v.1.9 software [38, 39] was applied to run the simulations considering 1000 iterations based on other studies, such as Minne and Crittenden [34] and Robati *et al* [9]. In this step of the analysis, the lognormal distribution [30] was chosen and a 90% confidence interval was considered. The Pedigree matrix [31, 40] data weres taken from Ecoquery, the Ecoinvent web-interface[3], and are shown in table 1.

Step 3—comparison between product stage uncertainties and SL uncertainties. To compare the uncertainties from SL to the uncertainties from the product stage, the range of global warming potential (GWP) impacts (minimum, mean and maximum) obtained from the product stage uncertainty analysis was compared to the range of GWP impacts obtained from SL uncertainty analysis. The range of impacts from uncertainties of SL was represented considering the number of replacements, which were calculated using equation (1). The best-fit distribution [23] for each building element was represented as follows: external cement plaster—Weibull; external clay brick—lognormal; external painting—Gamma and; internal painting—lognormal. The number of replacements considered is shown in table 3. In addition, the use stage was analyzed separately to compare the variability from the number of replacements of each building element.

[3] www.ecoinvent.org.

Table 1. Life cycle inventory of 1 m^2 of each building element and Pedigree matrix considered for the study. We obtained the data descriptions from Ecoquery (the web-interface at www.ecoinvent.org).

Building element	Life cycle inventory description			Amount (kg)
	Description	Process name in Ecoinvent	Pedigree matrix[a]	
External cement plaster	One layer of cement plaster, thickness = 1 cm. Materials proportion 1:4 (cement Portland and silica sand). Transportation via rail and road	Market for cement mortar	Cement and sand (4;5;5;5;3); electricity and heat (3;4;4;5;3); industrial machine (5;5;5;5;4); packing cement (4;3;5;5;3); transport (1;1;4;5;4)	91.9
External clay brick wall	Clay hollow brick, dimensions of 19 cm × 19 cm × 29 cm representing a 19 cm thick wall. Transportation via rail and road	Market for clay brick	Transport (1;1;4;5;4); clay, electricity and other process (5;5;5;5;1)	105.2
	Cement mortar for binding bricks. Materials proportion 1:4 (cement Portland and silica sand). Transportation via rail and road	Market for cement mortar	Cement and sand (4;5;5;5;3); electricity and heat (3;4;4;5;3); industrial machine (5;5;5;5;4); packing cement (4;3;5;5;3); transport (1;1;4;5;4)	27
External painting	This data set represents a specific long oil alkyd as used in architectural white colored paints. Transportation via rail, sea and road	Market for alkyd paint, white, without water, in 60% solution state	Electricity and heat (3;4;4;5;3); waste paint (5;5;5;5;5); transport (1;1;4;5;4); other process (4;5;5;5;3)	0.3
Internal painting				0.3

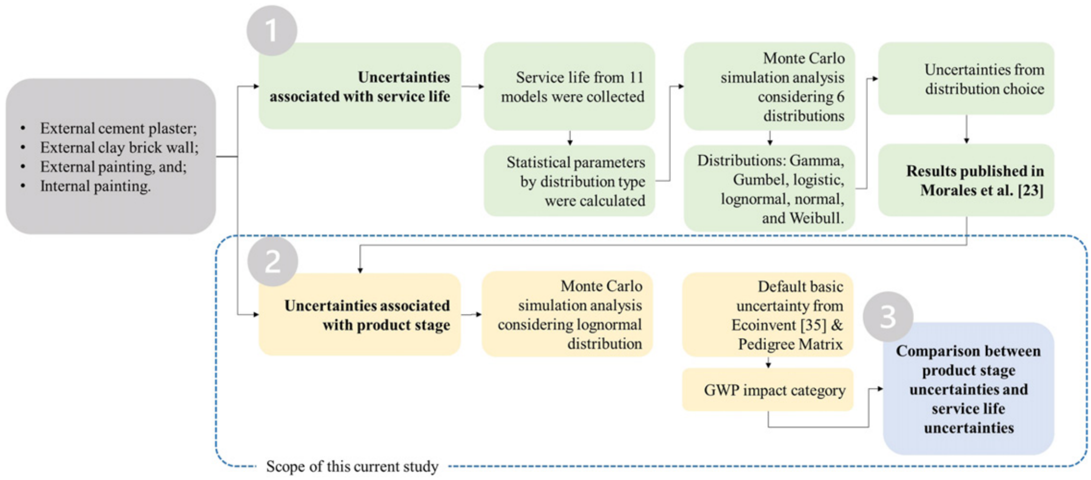

Figure 1. Flow chart of the research method for this paper. Step 1—represents the steps developed by Morales *et al* [23]. Steps 2 and 3 represent the current study.

Table 2. SL per distribution from Monte Carlo simulation using mean SL and calculated parameters. The bold values correspond to the best-fit distribution. The SL data were obtained from Morales *et al* [23].

Building element		Service life (in years) per distribution					
		Gamma	Gumbel	Logistic	Lognormal	Normal	Weibull
Cement plaster (external)	Min	33	3	-18	30	-67	**33**
	Mean	108	67	82	82	82	**107**
	Max	242	158	183	218	230	**241**
External clay brick walls	Min	57	4	-28	**57**	-101	65
	Mean	139	111	137	**135**	136	188
	Max	352	261	300	**342**	373	398
External painting	Min	**10**	5	3	6	2	9
	Mean	**15**	10	10	10	10	15
	Max	**23**	17	17	18	18	23
Internal painting	Min	5	5	2	**5**	0	6
	Mean	8	9	8	**8**	8	12
	Max	17	15	14	**16**	15	19

To model the replacement scenarios of each building element, the minimum, mean and maximum SL described in table 2 were used. Equation (1) was used to calculate the number of replacements.

$$\mathrm{NR} = \left(\frac{\mathrm{RSP}}{\mathrm{BESL}}\right) - 1, \tag{1}$$

where RSP is the building reference study period, BESL is the building element SL, and NR is the number of replacements. The number of replacements is rounded up or rounded down to integers [41].

2.4. Scenario definitions

The four building elements were hypothetically inserted in a building with three different RSPs, namely 50, 120 and 500 years. The 50 year (50 yr) scenario is selected because numerous LCA studies of buildings use an RSP of approximately 50 years [42, 43]. Considering that, some authors have mentioned an increased variability for RSP higher than 100 years compared to 50 years [13, 44], while the 120 year (120 yr) and the 500 year (500 yr) scenarios were included to assess this parameter's sensitivity to the results. This variation in the study period was also proposed by Nykjær *et al* [44] and Häfliger *et al* [44], who also considered 120 year scenarios. The 500 year scenario was used in Grant *et al* [14] and Grant and Ries [21], based on the SL of the masonry envelope materials [45].

Table 3 shows the number of replacements considered per distribution and per RSP scenario (50, 120 and 500 yr) of each building element considering, the minimum, mean and maximum SL from the Monte Carlo simulation. When the SL obtained from the Monte Carlo simulation (table 2) was a negative number or zero, the number was replaced by 1 for calculation purposes.

Table 3. Number of replacements considered per building element per distribution in each building RSP scenario studied: 50 year (50 yr), 120 year (120 yr) and 500 year (500 yr). Min. = minimum SL, mean = mean SL, and max. = maximum SL.

Building element	Considered RSP	Number of replacements considered per distribution for each RSP scenario																	
		Gamma			Gumbel			Logistic			Lognormal			Normal			Weibull		
		Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max	Min.	Mean	Max.
	50 yr	1	0	0	16	0	0	49	0	0	1	0	0	49	0	0	1	0	0
External cement plaster	120 yr	3	0	0	39	0	0	119	0	0	3	0	0	119	0	0	3	0	0
	500 yr	14	4	1	166	6	2	499	5	2	16	5	1	499	5	1	14	4	1
	50 yr	0	0	0	12	0	0	49	0	0	0	0	0	49	0	0	0	0	0
External clay brick wall	120 yr	1	0	0	29	0	0	119	0	0	1	0	0	119	0	0	1	0	0
	500 yr	8	3	0	124	4	1	499	3	1	8	3	0	499	3	0	7	2	0
	50 yr	4	2	1	9	4	2	16	4	2	7	4	2	24	4	2	5	2	1
External painting	120 yr	11	7	4	23	11	6	39	11	6	19	11	6	59	11	6	12	7	4
	500 yr	49	32	21	99	49	28	166	49	28	82	49	27	249	49	27	55	32	21
	50 yr	9	5	2	9	5	2	24	5	3	9	5	2	49	5	2	7	3	2
Internal painting	120 yr	23	14	6	23	12	7	59	14	8	23	14	7	119	14	7	19	9	4
	500 yr	99	62	28	99	55	32	249	62	35	99	62	30	499	62	32	82	41	25

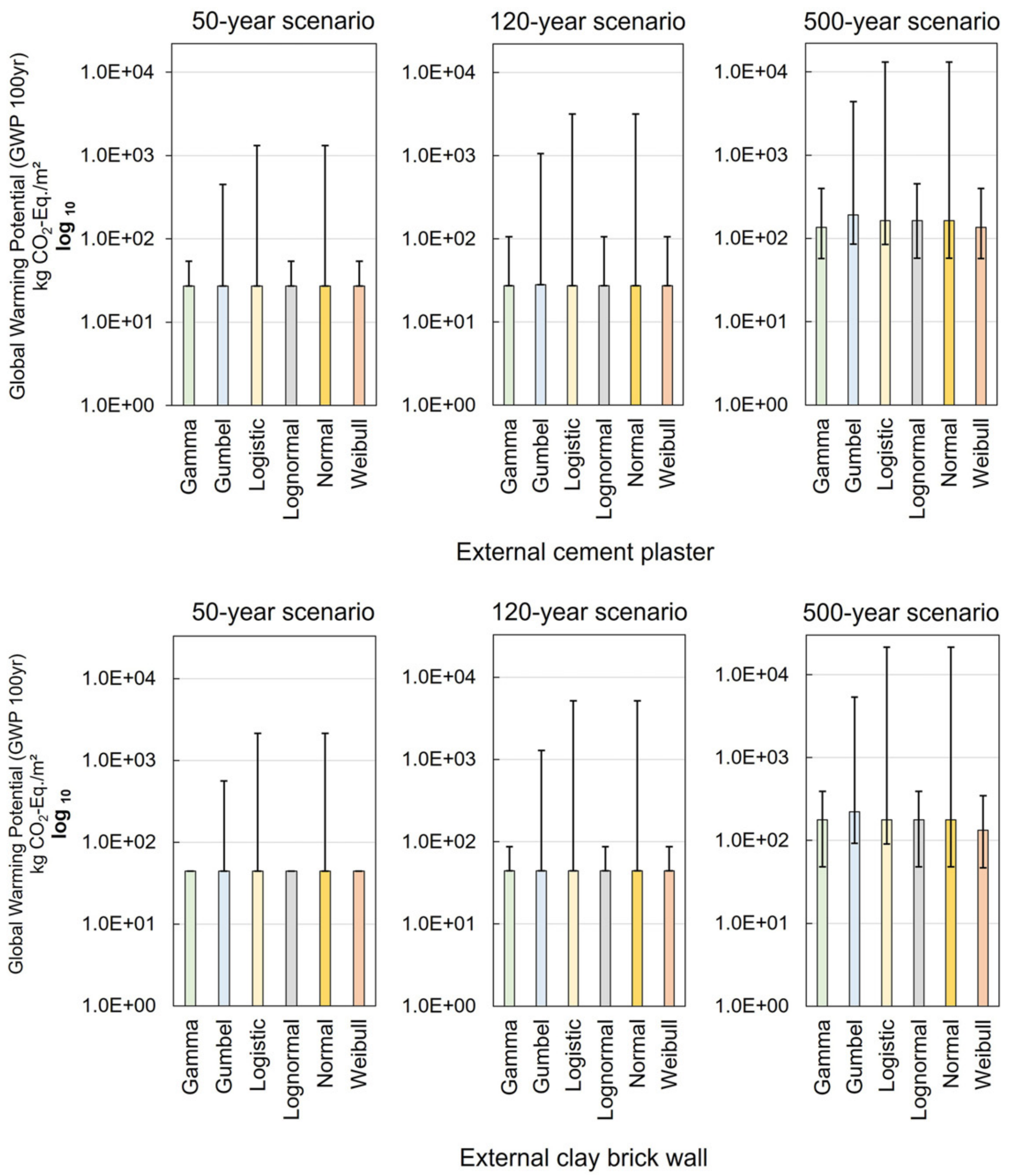

Figure 2. Global warming potential impacts from the whole life cycle of 1 m^2 of external cement plaster and external clay brick wall considering mean product stage results calculated using mean SLs from each distribution. Error bar represents the minimum and maximum values from SL uncertainties for a 90% confidence interval (logarithmic scale).

2.5. Impact assessment

Impact assessment calculation was performed in OpenLCA software 1.9 [39]. The impact category assessed was the GWP for a 100 year time horizon (GWP 100y) according to the Intergovernmental Panel on Climate Change (IPCC) [46]. The results presented here are only for the GWP impact category since it is globally recognized as one of the most significant indicators for climate change mitigation strategies [43, 47]. In addition, GWP is a common impact category assessed in several studies that address uncertainties in LCA, such as Häfliger *et al* [13], Hoxha *et al* [3], Minne and Crittenden [34], Silvestre *et al* [32], Grant *et al* [14] and Hoxha *et al* [10].

3. Results and discussion

3.1. Uncertainties associated with SL: influence of distribution choice

Figure 1 illustrates the mean GWP impacts for all life cycle stages considered in this study for external cement plaster and external clay brick wall. The error bar represents the minimum and maximum values from SL

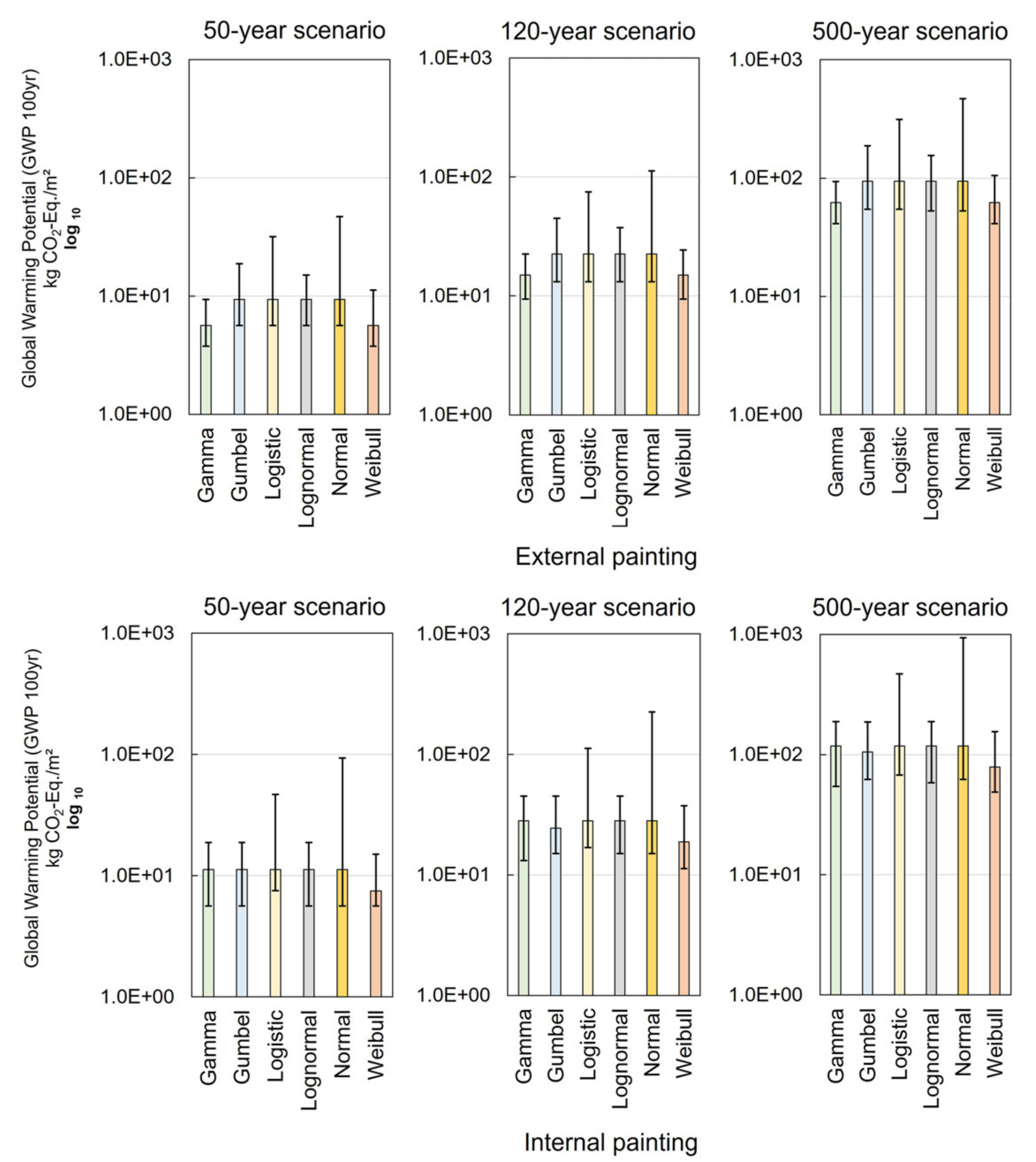

Figure 3. GWP impacts from the whole life cycle of 1 m^2 of external and internal painting considering mean product stage results calculated using mean SLs from each distribution. The error bar represents the minimum and maximum values from SL uncertainties for a 90% confidence interval (logarithmic scale).

uncertainties for a 90% confidence interval on a logarithmic scale. Considering the mean values, the trends for external cement plaster and external clay brick wall are similar to the 50 and 120 yr RSP scenarios. In the 500 yr scenario, the Weibull distribution showed a lower impact in terms of mean for both building elements. The gamma distribution also has a lower impact on external cement plaster. GWP impact (in mean) is equal in the 500 yr scenario for Gumbel, logistic, lognormal and normal distributions. The variability arising from the choice of SL parameter distributions across the means is significantly less than the range of 90% confidence described by the error bars (figure 2), which highlight the influence of the tail of each distribution.

When evaluating the uncertainties from building element SL represented by the error bar, cement plaster and clay brick wall demonstrated high variability depending on the distribution used to represent their uncertainty. For both building elements, Gumbel, logistic and normal distribution showed higher GWP variation in the three RSP scenarios. This difference is because these distributions allow negative SLs, which were converted to one-year in this study for impact calculations from the use stage.

As demonstrated in figure 3, external and internal painting showed higher variability across the mean GWP impacts than external cement plaster and external clay brick wall. Weibull distribution also demonstrated lower impacts in terms of mean for both building elements in all RSP scenarios.

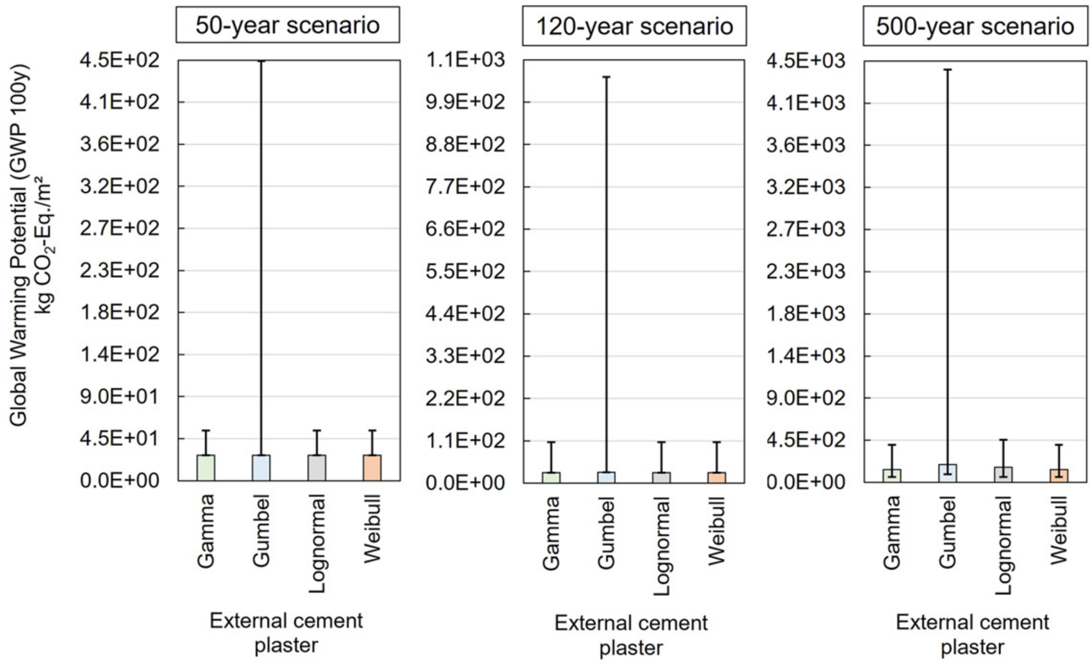

Figure 4. GWP impacts from the whole life cycle of 1 m^2 of cement plaster considering mean product stage results calculated using mean SLs excluding logistic and normal distribution results. The error bar represents the minimum and maximum values from SL uncertainties for a 90% confidence interval (linear scale).

Considering uncertainties from SL, different to cement plaster and clay brick wall, the range of impact variation in all scenarios for external and internal painting is lower. However, they still present variability. These differences in the range of GWP impacts from the four building elements are related to the high variation in the number of replacements of external cement plaster and external clay brick wall (table 3) from the six distributions used to model SL uncertainties [23].

As can be seen in figure 3, logistic and normal distributions demonstrated higher variability, especially in the 50 yr RSP scenario. In this scenario, for the logistic distribution, the variation is from 42% below to 240% above the mean for external painting. For the normal distribution, in the same RSP scenario, external painting showed variation from 40% below to 399% above the mean. Internal painting has a higher range of uncertainties for these two distributions. In the 50 yr internal painting scenario, the variation is from 33% below to 316% above the mean for the logistic distribution. For the normal distribution, variation is from 50% below to 732% above the mean.

The GWP results support previous findings that the Gumbel, logistic and normal distributions must be used carefully since they are not generally appropriate for modeling SL uncertainties [23].

Figures 4 and 5 showed GWP impacts for external cement plaster and external clay brick wall using the gamma, Gumbel, lognormal and Weibull distribution. The results are presented in a linear scale excluding logistic and normal distributions over the 50, 120 and 500 yr scenarios. Gumbel is notably different in positive values compared to the other distributions in all scenarios; the 120 yr scenario has the highest variation. In the 120 yr scenario for external cement plaster, the variation in GWP results for the Gumbel distribution is from 0% below to 3652% above the mean. For external clay brick wall, the variation for Gumbel distribution is from 0% below to 2816% above the mean.

The remaining distributions have less variation, except in the 50 yr scenario, where there is no variation because there are no replacements.

3.2. Comparison between product stage uncertainties and SL uncertainties

Table 4 shows the GWP impact for external cement plaster and external clay brick wall per life cycle stage (i.e., product stage, use stage, and end-of-life). Uncertainties from the product stage are demonstrated as minimum, mean, and maximum. The SL uncertainties are modeled using the best fit distribution and represented as Minimum (Min SL), Mean (Mean SL) and Maximum SL (Max SL) for a 90% confidence interval. The smaller total life cycle impacts are highlighted in blue and the greater total life cycle impacts are highlighted in red.

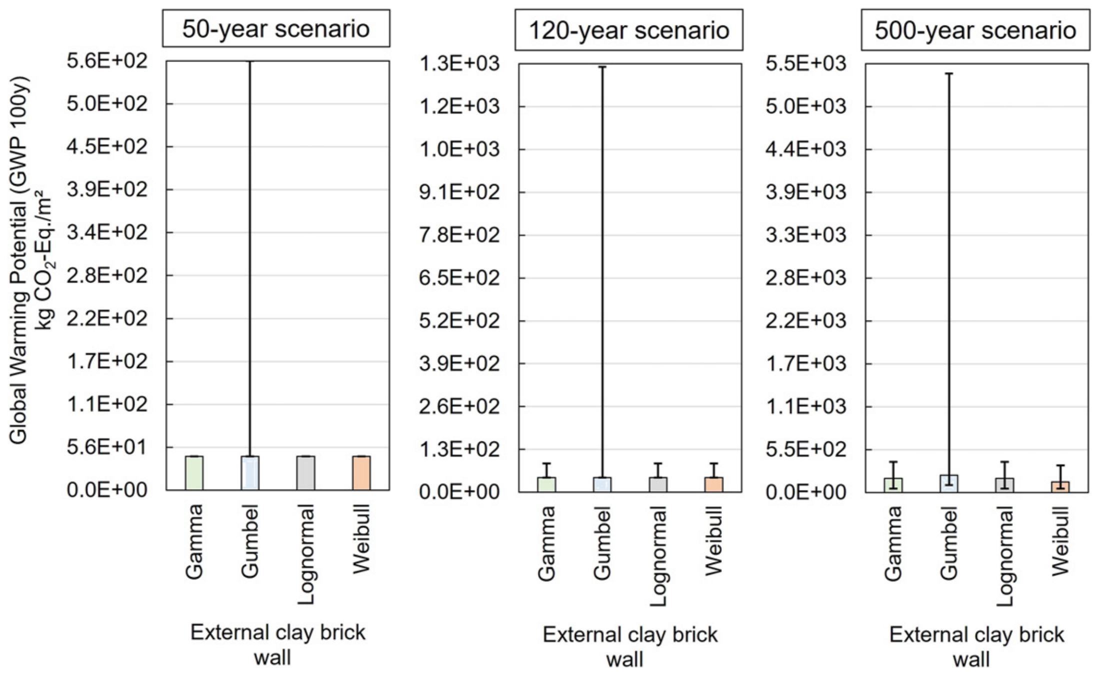

Figure 5. GWP impacts from the whole life cycle of 1 m^2 of external clay brick wall considering mean product stage results calculated using mean SLs excluding logistic and normal distribution results. The error bar represents the minimum and maximum values from SL uncertainties for a 90% confidence interval (linear scale).

When one observes the uncertainties from the product stage in table 4, considering the three RSP scenarios, external cement plaster showed a range of impacts from 18% below to 21% above the mean. The variation in external clay brick wall is ±17% of the mean.

Table 4 also demonstrates a high uncertainty coming from the SL. External cement plaster varies from +97% (50 yr scenario) to +290% (120 yr scenario) above the mean and 0% (50 and 120 yr scenario) to −58% (500 yr scenario) below the mean.

SL uncertainties have a tendency to grow as the RSP increases. In the same way, external clay brick wall (table 4) does not show variation in the 50 yr scenario but as the RSP increases the range of uncertainties grows varying from 0% to +97% of the mean in the 120 yr and from −73% to +121% of the mean in the 500 yr scenario.

For external cement plaster and external clay brick wall, the product stage (module A1–A3) is the greatest contributor with 97% of total impacts in the 50 and 120 yr scenarios. In contrast, the use stage (replacement) is the major contributor with about three quarters of total impacts in the 500 yr scenario. In the 500 yr scenario, external cement plaster is replaced four times and external clay brick wall is replaced three times (table 3). Over all three RSP scenarios, the end-of-life stage (module C1–C4) has approximately 3% of the total GWP for both building elements.

For external painting, the SL uncertainties are consistent across the scenarios (table 5). For the 50 yr scenario, the total impact varies from −50% to +67% of the mean, in the 120 yr scenario, from −60% to +50% of the mean, and from −50% to +51% of the mean for the 500 yr scenario. Internal painting has a greater range of uncertainty than external painting but is still consistent across the scenarios (table 5). The range of SL impacts varies from −100% to +67% of the mean in the 50 yr scenario, from −87% to +60% of the mean in the 120 yr scenario and from −103% to +59% of the mean in the 500 yr scenario.

The use stage is the major contributor to overall total impacts in all RSP scenarios for both building elements (table 5). However, regarding each stage's contribution, the external painting and internal painting (table 5) results demonstrate different trends when compared to external cement plaster and external clay brick wall. In the 50 yr scenario, the product stage (A1–A3) corresponds to 33% of total impacts for external painting and 17% of the total internal painting impacts. There is a correlation between the increase in RSP and the use stage's relative contribution to total impact. In the 120 yr scenario, the product stage (A1–A3) corresponds to 12% of total impacts (in mean) for external painting and 7% of total impacts (in mean) for internal painting, and in the 500 yr scenario, the product stage (A1–A3) corresponds to 3% of total impacts for external painting and 2% of total impacts for internal painting. The use stage percentage contribution increases as the building RSP increases.

Table 4. Comparison of the Monte Carlo simulation results of the GWP impacts per life cycle stage of 1 m^2 of external cement plaster and external clay brick wall. Product stage uncertainties are shown as minimum, mean and maximum and the range of SL uncertainties is shown as Minimum (Min SL), Mean (Mean SL), and Maximum SL (Max SL) for a 90% confidence interval.

Global warming potential (kg CO_2-Eq./m^2)										
1 m^2 of external cement plaster										
	Life cycle stage	**50 year**			**120 year**			**500 year**		
		Min SL	Mean SL	Max SL	Min SL	Mean SL	Max SL	Min SL	Mean SL	Max SL
Minimum	Product stage	22	22	22	22	22	22	22	22	22
	Use stage: replacement	22	0	0	65	0	0	304	87	22
	End-of-life	1	1	1	3	1	1	10	3	1
	Total	**45**	**22**	**22**	**90**	**22**	**22**	**336**	**112**	**45**
Mean	Product stage	26	26	26	26	26	26	26	26	26
	Use stage: replacement	26	0	0	79	0	0	369	105	26
	End-of-life	2	1	1	4	1	1	13	4	2
	Total	**54**	**27**	**27**	**109**	**27**	**27**	**409**	**136**	**54**
Maximum	Product stage	32	32	32	32	32	32	32	32	32
	Use stage: replacement	32	0	0	95	0	0	445	127	32
	End-of-life	2	1	1	5	1	1	17	6	2
	Total	**66**	**33**	**33**	**132**	**33**	**33**	**494**	**165**	**66**
1 m^2 of external clay brick wall										
Minimum	Product stage	35	35	35	35	35	35	35	35	35
	Use stage: replacement	0	0	0	35	0	0	283	106	0
	End-of-life	1	1	1	2	1	1	9	4	1
	Total	**36**	**36**	**36**	**73**	**36**	**36**	**327**	**145**	**36**
Mean	Product stage	43	43	43	43	43	43	43	43	43
	Use stage: replacement	0	0	0	43	0	0	344	129	0
	End-of-life	1	1	1	3	1	1	12	5	1
	Total	**44**	**44**	**44**	**88**	**44**	**44**	**398**	**177**	**44**
Maximum	Product stage	52	52	52	52	52	52	52	52	52
	Use stage: replacement	0	0	0	52	0	0	413	155	0
	End-of-life	2	2	2	3	2	2	15	7	2
	Total	**53**	**53**	**53**	**107**	**53**	**53**	**480**	**213**	**53**

Table 5. Comparison of the Monte Carlo simulation results of the GWP impacts per life cycle stage of 1 m^2 of external and internal painting. Product stage uncertainties are shown as minimum, mean and maximum and the range of SL uncertainties is shown as Minimum (Min SL), Mean (Mean SL) and Maximum SL (Max SL) for a 90% confidence interval.

Global warming potential (kg CO_2-Eq./m^2)										
1 m^2 of external painting										
	Life cycle stage	50 year			120 year			500 year		
		Min SL	Mean SL	Max SL	Min SL	Mean SL	Max SL	Min SL	Mean SL	Max SL
	Product stage	2	2	2	2	2	2	2	2	2
Minimum	Use stage: replacement	6	3	2	17	11	6	76	49	32
	End-of-life	0	0	0	0	0	0	0	0	0
	Total	**8**	**5**	**3**	**19**	**12**	**8**	**77**	**51**	**34**
	Product stage	2	2	2	2	2	2	2	2	2
Mean	Use stage: replacement	7	4	2	21	13	7	92	60	39
	End-of-life	0	0	0	0	0	0	0	0	0
	Total	**9**	**6**	**4**	**23**	**15**	**9**	**94**	**62**	**41**
	Product stage	2	2	2	2	2	2	2	2	2
Maximum	Use stage: replacement	9	5	2	25	16	9	111	73	48
	End-of-life	0	0	0	0	0	0	0	0	0
	Total	**11**	**7**	**5**	**27**	**18**	**11**	**114**	**75**	**50**
1 m^2 of internal painting										
	Product stage	2	2	2	2	2	2	2	2	2
Minimum	Use stage: replacement	14	8	3	36	22	11	153	96	46
	End-of-life	0	0	0	0	0	0	0	0	0
	Total	**15**	**9**	**5**	**37**	**23**	**12**	**155**	**97**	**48**
	Product stage	2	2	2	2	2	2	2	2	2
Mean	Use stage: replacement	17	9	4	43	26	13	186	116	56
	End-of-life	0	0	0	0	0	0	0	0	0
	Total	**19**	**11**	**6**	**45**	**28**	**15**	**188**	**118**	**58**
	Product stage	2	2	2	2	2	2	2	2	2
Maximum	Use stage: replacement	20	11	5	52	32	16	224	141	68
	End-of-life	0	0	0	0	0	0	0	0	0
	Total	**23**	**14**	**7**	**54**	**34**	**18**	**227**	**143**	**70**

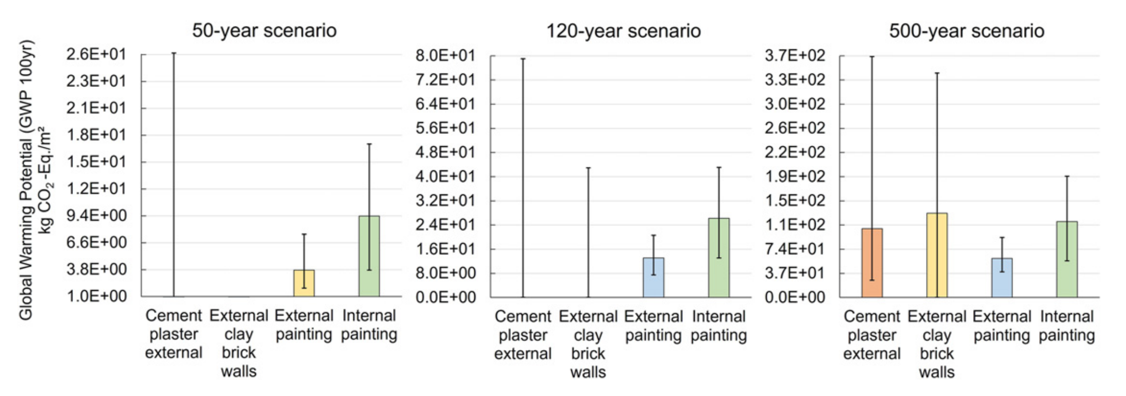

Figure 6. GWPs impacts per life cycle stage of 1 m^2 of each building element in the use stage (B4 module) considering mean life cycle impact results. Error bars represent the impact variation from SL uncertainties as modeled by Monte Carlo simulation.

The product stage uncertainties, represented by minimum, mean and maximum, are lower than the SL uncertainties, represented in the figures by an error bar, for both building elements.

3.3. Uncertainty analysis in the use stage

Figure 6 compares the SL uncertainties represented in the figure by error bars from each building element during the use stage (replacement) over the three RSP scenarios. In the 50 yr scenario, only external painting and internal painting contribute to the uncertainties. In the 120 yr scenario, cement plaster and clay brick show uncertainties for the minimum SL, indicating that if the mean SL is considered, replacement of these elements would also not influence the total GWP impact. In the 500 yr scenario, the uncertainties from building elements with longer SL, such as external cement plaster and external clay brick wall, are higher than building elements that have a shorter SL, such as external and internal painting.

4. Synthesis and discussion

This study explored the influence of uncertainties associated with the product stage and uncertainties from SL in the LCA of building elements. One of the main contributions of this study is to demonstrate the relevance of the uncertainties from SL. SL of materials is important for selecting building materials for climate change mitigation [48]. However, fewer studies have focused on the assessment of these uncertainties [23].

The results presented reinforces the relevance of SL definition [21, 32] and also demonstrates the impact of distribution choice in cases when Monte Carlo simulation is applied [6, 23].

Distribution definition for modeling SL uncertainties significantly affects the range of LCA impacts. For example, the logistic and normal distribution predicts a higher number of replacements than the other distributions, leading to an increase in each building element's total life cycle impact. Logistic and normal shows variability greater than Gumbel. Gamma, lognormal and Weibull distributions present similar trends; relatively minor variability and, consequently, fewer replacements, which results in a lower level of LCA impacts when these distributions are chosen. Distribution selection is a key step to running Monte Carlo simulation since the results may be highly affected [6]. Based on the findings, distribution selection should take into account the characteristics of the data. For example, SL cannot be a negative number; in this sense non-negative distributions are recommended. To determine the best-fit distribution a GOF test may be applied [49]. In addition, the consideration of the goal of the analysis is important. For example, lognormal distribution tends to return a narrower range of SL than the gamma and Weibull distributions, which tend to estimate a wider range of SL [23].

When comparing the uncertainties from the product stage versus the uncertainties from SL, SL contributes the greatest uncertainty for the four building elements analyzed. Hoxha *et al* [10] found that the variability in a building's environmental impact is essentially controlled by the SL uncertainties for materials such as nonstructural clay, paint and thermal insulation, among others. The uncertainties from input parameters such as the life-cycle inventory of the product stage of building elements and model uncertainty from SL modeling have been discussed by other authors [14]. However, none applied Monte Carlo simulation to compare both and demonstrate the influence of different sources of uncertainty such as the product stage and SL.

As the RSP grows, the uncertainty grows, demonstrating that the definition of RSP scenarios also increases uncertainty. This was also noted by Rasmussen *et al* [42], who found increased uncertainties when assuming longer building RSPs. RSP scenarios also influence the relative contribution from each life cycle stage. The product stage (A1–A3) has a higher percentage contribution to building elements such as cement plaster and clay bricks in the 50 yr scenario. However, in the range of results in the 120 yr scenario, the contribution of the product stage might change. The building element RSP scenario choice can affect the overall relative contribution of life cycle stages, and influences the action taken to reduce their environmental impacts [13, 42]. RSP scenarios that consider a shorter temporal perspective, place more emphasis on the shorter-lived building elements [42]. Furthermore, properly defining RSP could support sustainable strategies for demolition, renovation and retrofit of these buildings.

The end-of-life stage (C1–C4) shows a similar reduction in its contribution as the RSP scenario is extended. This is due to the differences between the environmental impacts to produce the materials versus the environmental impacts to dispose of them. The environmental impacts in end-of-life are generally lower than material production, which explains the increase in the use stage's contribution. Häfliger *et al* [13] found a similar relationship, where the number of replacements increases, the environmental impact from the end-of-life decreases. Incorporating end-of-life scenarios by including module D in the analysis to address the net environmental benefits or loads resulting from reuse, recycling and energy recovery are needed to verify their influence over life cycle stage ranking. This need is reinforced by the results in Dellem and Wastiels [50] that found about a 20% reduction in GWP impacts from reuse and recycling in the life cycle of construction using sand-lime bricks and hollow concrete blocks.

5. Conclusions and future trends

This paper evaluates the influence of two significant sources of uncertainties in the LCA of buildings: uncertainties associated with SL and uncertainties associated with life cycle inventory. Monte Carlo simulation is used with six different uncertainty distributions for replacement frequency and the inventory data quality is evaluated through Monte Carlo simulation using the Pedigree matrix.

Previous studies discussed the SL uncertainties but did not consider the influence of stochastic parameters, such as distribution choice, in LCA results. The results of this study found significant differences in the SL of each building element depending on the distribution choice, which ultimately influenced the magnitude of GWP impacts from the use stage.

These findings reinforce the importance of properly modeling uncertainty analysis by taking into account the study's goals. Gamma, lognormal and Weibull distributions were found to be better choices for modeling replacement frequency in SL using Monte Carlo simulation.

Uncertainties from SL are greater than product stage uncertainties for the four building elements analyzed. This fact demonstrates the importance of developing guidelines for modeling parameters such as SL to enhance the LCA of buildings and make the results comparable to other studies.

Regarding each building element's contribution to uncertainty, building elements with longer SL, such as external cement plaster and external clay brick wall, incur more significant variability than building elements that have a shorter SL such as external painting and internal painting. In addition, significant uncertainty was found from the choice of the RSP scenario; as the RSP duration is extended, an increase in uncertainty results. RSP scenarios also influenced the distribution of impacts across the life cycle stages. Therefore, attention should be given to RSP duration as the trends of impacts may change.

The results reinforce the relevance of defining the distributions appropriately when modeling parameter, model, and scenario uncertainty for the LCA of buildings. Future studies should consider module D as recycling and reuse and consider the location's influence on SL.

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Data availability

All data that support the findings of this study are included within the article (and any supplementary information files).

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