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Incertezas relacionadas à modelagem da previsão da vida útil em estudos de ACV de edificações

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INCERTEZAS RELACIONADAS À MODELAGEM DA PREVISÃO DA VIDA ÚTIL EM ESTUDOS DE ACV DE EDIFICAÇÕES

Tese apresentada ao Programa de Pós-Graduação em Engenharia Civil: Construção e Infraestrutura da Universidade Federal do Rio Grande do Sul, como parte dos requisitos para obtenção do título de Doutor em Engenharia

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Esta tese de doutorado foi julgada para a obtenção do título de DOUTOR EM ENGENHARIA CIVIL, área de pesquisa CONSTRUÇÃO, e aprovada em sua forma final pelo Professor Orientador e pelo Programa de Pós-Graduação em Engenharia Civil: Construção e Infraestrutura da Universidade Federal do Rio Grande do Sul.

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A Deus e à minha família.

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"Tudo o que fizerem, façam de todo o coração, como para o Senhor"

Colossenses 3:23

RESUMO

MORALES, M.F.D. **Incertezas relacionadas à modelagem da previsão da vida útil em estudos de ACV de edificações**. 2019. Tese (Doutorado em Engenharia) - Programa de Pós-Graduação em Engenharia Civil: Construção e Infraestrutura, Escola de Engenharia, Universidade Federal do Rio Grande do Sul, Porto Alegre, 2019.

A construção de edifícios consome grandes quantidades de recursos não renováveis, consumo este que se estende ao longo de toda a vida útil das edificações. Reconhecida como um dos métodos mais completos de avaliação ambiental, a avaliação do ciclo de vida (ACV) pode fornecer o impacto ambiental causado pelos edifícios desde a sua construção inicial até a demolição, viabilizando a sua redução. Contudo, levando em consideração a longa duração dos edifícios, determinar o impacto gerado devido à produção e às substituições dos materiais utilizados durante seu uso é apenas parte do problema. Uma das dificuldades encontradas está na previsão da frequência em que os elementos construtivos serão substituídos ao longo da vida útil da construção. Esta é uma tarefa complexa que muitas vezes recebe menos atenção do que o necessário. Neste sentido, o objetivo desta pesquisa é identificar as incertezas relacionadas à previsão da vida útil de elementos construtivos selecionados e sua influência na modelagem da etapa de uso na ACV de edifícios. Ao longo deste estudo, são analisados diferentes elementos construtivos que compõem uma edificação multifamiliar construída no sistema de alvenaria estrutural de bloco cerâmico. A pesquisa está dividida em quatro fases: fase 1 - pesquisa exploratória analisando cada etapa do ciclo de vida de uma edificação; fase 2 – estudo piloto utilizando diferentes cenários de substituição dos elementos e base de dados de vida útil internacionais; fase 3 – análise da influência dos parâmetros na avaliação de incertezas da vida útil utilizando a simulação de Monte Carlo; e fase 4 – análise da influência das incertezas relacionadas à vida útil sobre os resultados da ACV. Nas fases 1 e 2 o escopo definido foi do berço ao túmulo de uma edificação com vida útil de 50 anos. Na fase 4, foram considerados dois cenários adicionais: 120 anos e 500 anos. Os resultados obtidos indicaram que a escolha do inventário do ciclo de vida afeta significativamente os impactos dos elementos construtivos. Além disso, as referências de vida útil utilizadas na modelagem da etapa de substituição dos elementos construtivos podem causar grandes variações nos resultados da ACV. Esse fato é comprovado pela variação na contribuição da etapa de substituições, entre 6% e 72%, dependendo da referência de vida útil considerada, do inventário do ciclo de vida utilizado e da categoria de impacto avaliada. Definições sobre o tipo de vida útil empregado para modelar a substituição dos elementos de construção são essenciais para reduzir as incertezas e refinar os resultados. A escolha da distribuição influencia os resultados ao aplicar a simulação de Monte Carlo na avaliação de incertezas da vida útil. Entre as seis distribuições consideradas, três se mostraram adequadas para a simulação de vida útil: gama, lognormal e *Weibull*. Neste sentido, recomenda-se que, ao avaliar incertezas provenientes da vida útil através da simulação de Monte Carlo, a seleção da distribuição seja cautelosa. Padronizar a modelagem de parâmetros, como a vida útil em ACV dos edifícios, apresenta-se como uma forma de simplificar o processo e elevar a confiabilidade dos resultados.

Palavras-chave: Avaliação de incerteza. Etapa de substituição. Vida útil. Simulação de Monte Carlo. ACV de edifícios.

ABSTRACT

MORALES, M.F.D. **Uncertainties related to service life prediction modelling in buildings LCA**. 2019. Thesis (Doctor of Science in Civil Engineering) - Postgraduate Program in Civil Engineering: Construction and Infrastructure, Engineering School, Federal University of Rio Grande do Sul, Porto Alegre, 2019.

Buildings' construction consumes large amounts of non-renewable resources, and this consumption extends over their entire life span. Recognized as one of the most comprehensive methods of environmental evaluation, life cycle assessment (LCA) can provide the environmental impacts of buildings from the construction stage to end-of-life, enabling them to be reduced. However, given the long-term of buildings, determining the impact generated due to the production and replacement of building elements during use stage is only part of the problem. One of the difficulties is to predict the frequency the building elements will be replaced over the life span of the building. This is a complex task that often gets less attention than expected. In this sense, the main objective of this research is to identify the uncertainties related to the service life of selected building elements and their influence on the modeling of the LCA use stage of buildings. Throughout the research, different building elements that are part of a multifamily building built in the ceramic clay hollow brick are studied. Four research phases are followed: phase 1 - exploratory research analyzing each stage of a building's life cycle; phase 2 - pilot study using different element replacement scenarios and international service life models; phase 3 - analysis of the influence of the parameters in the evaluation of uncertainty of the life span life using the Monte Carlo simulation and; phase 4 - analysis of the influence of service life uncertainties on LCA results. In the phase 1 and 2 the scope is defined from cradle to grave for a 50-year building life span. In the phase 4, two additional scenarios are considered: 120 years and 500 years. The results obtained indicates that the choice of life cycle inventory significantly affects the impacts of the building elements. In addition, the service life models used in modeling the building element replacement step can cause large variations in LCA results. This is confirmed by the variation in the contribution of the replacement stage, between 6% and 72%, depending on the service life model, life cycle inventory and impact category assessed. Definitions about the concept of service life used to model building element replacement is essential to reduce uncertainty and refine results. The choice of distribution influences service life uncertainty analysis results in Monte Carlo simulation. Among the six distributions considered, three distributions were suitable for this application: gamma, lognormal and Weibull. In this context, distribution choice should be carefully considered when conducting uncertainty analysis in Monte Carlo simulation. Standardizing parameter modeling, such as the service life prediction method in buildings LCA, is presented as way to simplify the process and enhance results reliability.

Keywords: Uncertainty analysis, Replacement stage, Service life, Monte Carlo simulation, Buildings' LCA.

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LISTA DE ABREVIATURAS E SIGLAS

ACV: Avaliação do Ciclo de Vida

AICV: Avaliação de Impacto do Ciclo de Vida

AD: Anderson-Darling

ADPF: Abiotic Resource Depletion Potential for Fossil Resources

ADPN: Abiotic Resource Depletion Potential for Non Fossil Resources

AP: Acidification Potential

CDW: Construction and Demolition Waste

DAP: Declaração Ambiental de Produto

DL: Design Life

EE: Escola de Engenharia

EP: Eutrophication Potential

EPD: Environmental Product Declaration

LEED: Leadership in Energy and Environmental Design

GWP: Global Warming Potential

ICV: Inventário do Ciclo de Vida

KS: Kolmogorov-Smirnov

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

MC: Monte Carlo

NORIE: Núcleo Orientado para a Inovação da Construção

ODP: Depletion Potential of the Ozone Layer

POCP: Formation Potential of Tropospheric Ozone

PPGCI: Programa de Pós-Graduação em Engenharia Civil: Construção e Infraestrutura

RSL: Reference Service Life

SL: Service Life

UFRGS: Universidade Federal do Rio Grande do Sul

SUMÁRIO

1 INTRODUÇÃO

A indústria da construção civil é reconhecida como grande geradora de impactos ambientais devido a características como o elevado consumo de matéria-prima (relacionada às grandes dimensões dos produtos), o desperdício e a baixa incidência tecnológica. Entretanto, este cenário está em processo de mudança. Com a crescente conscientização global sobre a importância de proteger o meio ambiente, o interesse na busca pelo desenvolvimento de métodos para melhor compreender e enfrentar os impactos de produtos ao longo do seu ciclo de vida tem sido despertado no contexto mundial (UNITED NATIONS ENVIRONMENTAL PROGRAM (UNEP), 2011) e também no âmbito da indústria da construção civil brasileira (CBIC, 2014).

A redução dos impactos ocasionados ao meio ambiente tem sido encorajada por importantes órgãos internacionais, como por exemplo a Organização das Nações Unidas, que adotou uma nova agenda de desenvolvimento sustentável, formada pelos 17 Objetivos de Desenvolvimento Sustentável (ODS), que devem ser implementados por todos os países do mundo até 2030. No que tange a esses objetivos, observa-se alguns fortemente ligados à redução dos impactos ambientais ocasionados pela construção civil, sendo eles: tomar medidas urgentes para combater a mudança climática e seus impactos, tornar as cidades e os assentamentos humanos inclusivos, seguros, resilientes e sustentáveis, e assegurar padrões de produção e de consumo sustentáveis (UN, 2017).

Neste sentido, muitos esforços têm sido realizados, particularmente na indústria da construção civil, buscando quantificar os impactos ambientais ocasionados pelas edificações visando a sua redução (PAULSEN; SPOSTO, 2013). Dentre os métodos de avaliação dos impactos ambientais disponíveis, destacam-se os baseadas no Ciclo de Vida como a ACV, que permite quantificar o potencial impacto ambiental associado ao ciclo de vida de produtos, tais como os edifícios, desde a extração de recursos, produção de materiais, construção, uso e operação até o fim de vida (ABNT, 2009a). A ACV é importante na determinação dos impactos gerados em cada etapa da edificação e viabiliza ações de redução dos impactos ambientais tanto em escala local quanto global.

Nesta linha, a ACV vem sendo aplicada pela construção civil de diferentes formas e pode ser utilizada desde a escala de material, auxiliando na otimização dos impactos ambientais de novos produtos, como aglomerantes, por exemplo (PASSUELLO et al., 2017), ou de produtos existentes que podem ter seus impactos reduzidos. Além disso, a ACV também é reconhecida mundialmente como um dos métodos mais completos de avaliação ambiental de edifícios (SOUST-VERDAGUER; LLATAS; GARCÍA-MARTÍNEZ, 2016) A ACV é preconizada pelas NBR ISO 14040 (ABNT, 2009a) e NBR ISO 14044 (ABNT, 2009b). Sua aplicação pela indústria da construção civil tem se tornado cada vez mais comum (PASSUELLO et al., 2014), especificamente na avaliação do desempenho ambiental de edifícios, fomentada pelo crescente número de bancos de dados e métodos disponíveis (HÄFLIGER et al., 2017). Relativamente as suas áreas de aplicação, destaca-se principalmente o campo da pesquisa. Porém, a ACV constitui-se em uma importante fonte de negócios, uma vez que tem crescido o interesse da indústria pelo serviço, suprindo sua demanda por melhoria na gestão ambiental de seus processos, bem como produzindo informação ambiental que potencializa a competitividade de seus produtos e serviços (IBCT, 2015; ORTIZ; CASTELLS; SONNEMANN, 2009).

No âmbito de edificações, a ACV já vêm sendo aplicada desde os anos 90 (FAVA, 2006). Com ampla variedade de usos, ela pode ser utilizada desde a avaliação de sistemas e elementos construtivos a edificações completas (ORTIZ; CASTELLS; SONNEMANN, 2009; SOARES; SOUZA; PEREIRA, 2006). Seu elevado potencial de atuação no processo de planejamento e projeto dos edifícios subsidia desde as decisões conceituais até as escolhas dos fornecedores, definição de materiais e até a rotulagem e certificação das edificações (FRISCHKNECHT et al., 2015). No campo das certificações e rotulagens de edifícios, a ACV pode viabilizar a obtenção de créditos para obtenção de algum selo ambiental pela edificação. Um exemplo é a certificação *Leadership in Energy and Environmental Design* (LEED), desenvolvida pelo Green Building Council[1]. Desde sua versão 4.0 é possível pontuar no LEED pelo emprego da ACV de duas maneiras: por meio de declaração ambiental de produto (DAP) dos materiais (esta DAP deve ser elaborada de acordo com a ABNT NBR ISO 14025:2015); e pela *whole-building analysis* (avaliação do edifício completo) (FRISCHKNECHT et al., 2015). A análise do edifício completo viabiliza a obtenção de três créditos na certificação, sendo necessário comprovar uma redução mínima de 10% nos impactos totais em comparação com um cenário de referência.

[1] https://new.usgbc.org/about

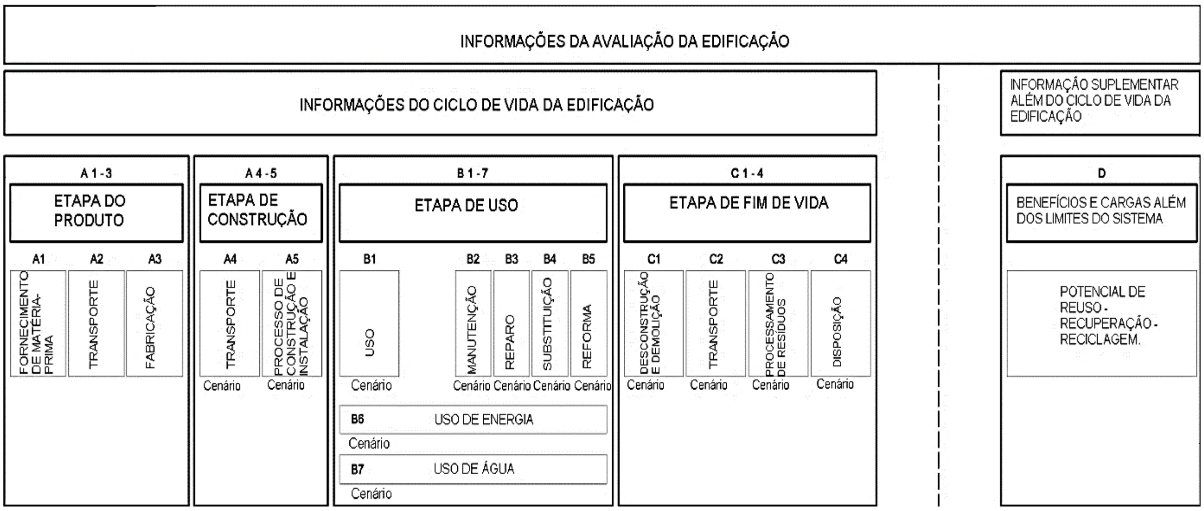
Para tal, devem ser considerados, no mínimo, três impactos de uma lista de seis e não podem exceder mais de 5%, em comparação com o cenário de referência (ANAND; AMOR, 2017).

Geograficamente, a Europa é a região onde a ACV mais vem sendo aplicada, é o continente que mais desenvolve e aperfeiçoa a ferramenta, além de ser provedor de grande parte das bases de dados de inventário utilizadas (IBCT, 2015). No contexto brasileiro, sua aplicação ainda enfrenta dificuldades, contudo, iniciativas recentes têm fomentado o desenvolvimento da ACV na construção civil nacional. Um exemplo é o projeto *Sustainable Recycling Industries* (SRI)[1] no Brasil. Este foi um projeto realizado entre os anos de 2017 e 2018, fomentado pela *Swiss State Secretariat for Economic Affairs* (SECO) que viabilizou a produção de inventários do ciclo de vida para diversas atividades da agricultura e da indústria (entre elas a da construção civil). Estes dados estão publicados na versão 3.6 da base de dados Ecoinvent e são um grande estímulo para o desenvolvimento da ACV no Brasil, tendo em vista que a construção civil, com 12% dos projetos em andamento, foi considerada a terceira maior área de pesquisa em ACV no país (IBCT, 2015).

Embora esforços ainda sejam necessários para o aprimoramento do emprego da ACV em edificações, a relevância da informação ambiental baseada no ciclo de vida é inegável (FRISCHKNECHT et al., 2015). Estes esforços de aprimoramento têm relação com a complexidade do produto da construção civil, que demanda realizar simplificações para viabilizar a aplicação do método. Uma dessas dificuldades está na padronização dos estudos de ACV de edificações (SOUST-VERDAGUER; LLATAS; GARCÍA-MARTÍNEZ, 2016). Normativas têm sido propostas de maneira a orientar o desenvolvimento de cada etapa, padronizando os resultados dos estudos. Cita-se como exemplo a CEN EN 15978:2011 que orienta o agrupamento de informações da avaliação de acordo com cada etapa do ciclo de vida, permitindo comparar resultados de cada fase (CEN, 2011a). As etapas da avaliação do ciclo de vida de uma edificação, segundo EN 15978:2011, são divididas em (Figura 1): Etapa do produto (A1 ao A3); Etapa de construção (A4 ao A5); Etapa de uso (B1 ao B7); e Etapa de fim de vida (C1 ao C4) e Módulo D (opcional). Na avaliação de uma edificação completa, as informações dos módulos A ao C são obrigatórias. Dados de reutilização, reciclagem e recuperação de energia e outras operações de valorização não incluídos no ciclo de vida do edifício podem ser avaliados opcionalmente, devendo ser inseridos no módulo D (CEN, 2011a).

[1] https://www.ecoinvent.org/about/projects/sri-project/sri-project.html#2065

Figura 1- Exibição de informações por módulo para as diferentes etapas da avaliação ambiental de edificações.



Fonte: Adaptado de CEN EN 15978 (2011).

Tais simplificações auxiliam na sua aplicação, todavia, a falta de padronização nesses procedimentos dificulta a comparação de resultados de diferentes estudos com critérios de simplificação distintos (SOUST-VERDAGUER; LLATAS; GARCÍA-MARTÍNEZ, 2016). Um exemplo de simplificação usada na ACV de um edifício ocorre na modelagem da etapa de uso, para a qual devem ser definidas as manutenções (módulo B2), os reparos (módulo B3), e a substituição de materiais e sistemas (módulo B4); bem como devem ser estimados o uso de energia (módulo B6) e o uso de água (módulo B7). Ao se referirem às etapas que constituem a fase de uso, Soust-Verdaguer, Llatas e García-Martínez (2016) observaram que a utilização de energia foi analisada em 95% dos estudos considerados por eles, enquanto substituição, reforma e reparo quase não foram incluídos. Em contraponto, uma das principais normas orientativas para elaboração de avaliações ambientais de edificações, a norma europeia EN 15643-2 (2011), recomenda considerar manutenções, reparos, substituições e a eventual remodelação da edificação. Incluir esses procedimentos nos estudos de ACV é importante, uma vez que manutenções são necessárias para garantir o cumprimento da vida útil dos componentes, sendo possível até prolongá-la (CEN, 2011b).

Algumas das causas da exclusão dessas etapas da avaliação estão relacionadas a limitações no processo de aquisição de informações. Falta de bases de dados, dados estatísticos ou outros subsídios para as estimativas das atividades que ocorrerão durante o uso da edificação tornam a etapa de uso a de maior incerteza da ACV de edificações (SOUST-VERDAGUER; LLATAS; GARCÍA-MARTÍNEZ, 2016). Em muitos estudos de ACV de edificações, buscando facilitar a modelagem, as definições de cenários de reparo, a manutenção e a substituição de materiais e sistemas, recebem atenção superficial, sendo utilizados pressupostos padrão (GRANT; RIES; KIBERT, 2014). A vida útil das construções pode variar consideravelmente e cenários que empregam suposições padrão podem gerar resultados incorretos. Para obtenção de resultados próximos à realidade, os pressupostos relativos a substituição, reparação e manutenção dos materiais e elementos da edificação devem ser definidos da maneira mais realista possível (GRANT; RIES; KIBERT, 2014).

1.1 CONTEXTO E JUSTIFICATIVA DO TEMA

Estudos indicam que as etapas de uso e operação de uma edificação podem responder pela maior parte dos seus impactos. Morales et al. (2018) identificaram que, no âmbito das edificações residenciais brasileiras, construídas pelo Programa Minha Casa Minha Vida[1], o consumo energético somado às operações de substituição dos elementos da edificação pode responder por até 70% de seus impactos de depleção abiótica de origem fóssil e potencial de aquecimento global. Moraga (2017) também observou a predominância da etapa operacional sobre os impactos totais de habitações unifamiliares brasileiras construídas em diversos sistemas construtivos. Além disso, o papel significativo do estágio de uso no ciclo de vida de um edifício foi igualmente analisado em estudos realizados em outros países da América Latina como: Chile (OYARZO; PEUPORTIER, 2014) e Colômbia (ORTIZ-RODRÍGUEZ; CASTELLS; SONNEMANN, 2010).

No que se refere às atividades que compõem a etapa de uso de uma edificação, a etapa de manutenção, reparo e substituições dos componentes e/ou elementos no ciclo de vida da edificação se destaca, tendo considerável participação nos impactos. Morales et al. (2019) quantificaram os impactos ambientais de duas unidades habitacionais brasileiras, considerando uma vida útil de 50 anos e valores de Vida Útil De Projeto (VUP) dos sistemas conforme ABNT NBR 15575-1 para modelagem da etapa de substituições dos materiais e/ou elementos. Neste estudo, foram consideradas as etapas de: produção dos materiais (módulos A1-A3); construção (módulos A4-A5); substituição dos componentes e/ou elementos (módulo B4); energia operacional (módulo B6); e fim de vida dos componentes e/ou elementos da edificação (módulos C1-C4). A partir dos resultados obtidos, observou-se que, embora a etapa de operação

[1] http://www.cidades.gov.br/habitacao/programa-minha-casa-minha-vida-pmcmv

fosse a de maior impacto em ambas tipologias, as substituições dos elementos durante a etapa de uso foi responsável por 21% a 35% dos impactos totais na tipologia unifamiliar e de 17% a 22% na tipologia multifamiliar (MORALES et al., 2019a).

Esses resultados reforçam a importância de reduzir os impactos operacionais em edificações habitacionais brasileiras, entretanto, é importante ressaltar que existem incertezas relacionadas a algumas questões de modelagem dos cenários de substituições, definidas durante a avaliação, que devem ser aprofundadas. No Brasil, por exemplo, a ABNT NBR 15575-1, constitui-se na principal fonte de pesquisa para definição do período de vida útil da edificação e de seus sistemas (Tabela 1) (ABNT, 2013).

Tabela 1 - Exemplos de vida útil de projeto de acordo com a NBR 15.575:1 (2013).

Sistema		Vida útil de projeto (em anos)		
		VUP Mínimo	VUP Intermediário	VUP Superior
Estrutura principal		≥50	≥63	≥75
Revestimento de parede aderido	Interno	≥13	≥17	≥20
	Externo	≥50	≥50	≥50
Pintura	Interno	≥3	≥4	≥5
	Externo	≥8	≥10	≥12
Esquadrias externas	Externo	≥20	≥25	≥30
Cobertura	Estrutura	≥20	≥25	≥30
	Telhamento	≥13	≥17	≥20

Fonte: Adaptado de ABNT NBR 15575-1 (ABNT, 2013).

Contudo, esta norma abrange somente edificações habitacionais (ABNT, 2013). Além disso, a ABNT NBR 15575-1 determina valores de VUP[1], e estes são baseados em três critérios de falha: (1) o efeito que uma falha no desempenho do sistema ou elemento acarreta; (2) a maior facilidade ou dificuldade de manutenção e reparação em caso de falha no desempenho; e (3) o custo de correção da falha (ABNT, 2013).

[1]VUP é o período estimado de tempo para o qual um sistema é projetado, a fim de atender aos requisitos de desempenho. Esta estimativa pressupõe o atendimento aos requisitos das normas aplicáveis, o estágio do conhecimento no momento do projeto e supõe o atendimento da periodicidade e correta execução dos processos de manutenção especificados no respectivo manual de uso, operação e manutenção (ABNT, 2013).

Como descrito, tais critérios têm seu foco em limitações técnicas ou de custo e não levam em consideração condições reais de exposição, como agentes agressivos que levam à falha ou ainda consideram questões comportamentais dos usuários.

Atualmente, existem várias abordagens para a previsão de vida útil. Grant, Ries e Kibert (2014) citam três abordagens principais para a previsão da vida útil, sendo elas: (1) os princípios da engenharia estrutural, que podem ser utilizados para estimar a integridade estrutural e a fadiga dos materiais, de acordo com o carregamento físico, as reações químicas em curso e a degradação ao longo do tempo; (2) o método do fator que oferece uma abordagem alternativa para a predição da vida útil, em que uma série de fatores são usados para modelar a vida útil de um componente; e (3) o emprego de dados empíricos oferece uma terceira abordagem de previsão da vida útil. Dados empíricos, segundos os autores, são indiscutivelmente o método de previsão mais preciso (GRANT; RIES; KIBERT, 2014). Grant, Ries e Kibert (2014) ao analisarem a importância das premissas de vida útil nos resultados da ACV de diversas opções de envoltória de edificações, encontraram diferenças nas projeções dos sistemas de parede e telhado. Neste estudo, a frequência e a intensidade das substituições foram mais influentes, porém, as diferenças na frequência e na intensidade da manutenção também foram significativas (GRANT; RIES; KIBERT, 2014).

Conforme observado em estudos anteriores, modelar a etapa de uso na ACV de edificações é um processo complexo devido a questões como definição da vida útil e tipo de intervenção (reparo, manutenção ou substituição) realizada. Tais definições, realizadas durante o processo de modelagem do cenário de estudo, são consideradas fontes de incertezas do estudo e devem ser definidas e quantificadas para garantir confiabilidade aos resultados da avaliação. Um estudo de ACV que demonstra um valor único como resultado, ignora o desvio que os resultados de saída podem ter, ou seja, podem ser enganosos (GROEN et al., 2014). Incorporar a incerteza, no entanto, aumenta a confiabilidade dos resultados e melhora a tomada de decisão (GROEN et al., 2014).

As incertezas em ACV podem ser definidas como a discrepância entre uma quantidade medida ou calculada e o seu verdadeiro valor (FINNVEDEN et al., 2009). Huijbregts (1998) menciona que as incertezas estão relacionadas a medições imprecisas, falta de dados, premissas de modelo, que são usadas para "converter" o mundo real em resultados de ACV. Já a NBR ISO 14044 (2009) define a avaliação de incertezas como um procedimento para determinar como as incertezas nos dados e pressupostos se propagam nos cálculos e como afetam a confiabilidade dos resultados da Avaliação de Impacto do Ciclo de Vida (AICV) (ABNT, 2009b). Diversos esforços têm sido feitos no intuito de classificar as fontes de incerteza em ACV, alguns tipos de incertezas conhecidos são demonstrados no Quadro 1.

Quadro 1 - Tipos de incerteza em estudos de ACV.

Fonte	Tipos de incerteza de acordo com os autores
Huijbregts (1998)	(1) Incerteza do parâmetro; (2) Incerteza do modelo; (3) Incerteza devido a escolhas; (4) Variabilidade espacial; (5) Variabilidade temporal e (6) Variabilidade entre objetos/fontes.
Björklund (2002)	(1) Dados imprecisos; (2) Falta de dados; (3) Dados não representativos; (4) Incerteza do modelo; (5) Incerteza devido a escolhas; (6) Variabilidade espacial; (7) Variabilidade temporal; (8) Variabilidade entre objetos / fontes; (9) Incerteza epistemológica; (10) Erros e (11) Incerteza de estimativa.
Lloyd e Ries (2007)	(1) Parâmetro (dados de entrada); (2) Cenário (escolhas normativas) e (3) Modelo (relações matemáticas).
Finnveden et al. (2009)	(1) Variabilidade dos dados; (2) Dados mal especificados; (3) Dados errados; (4) Dados incompletos; (5) Dados podem estar sujeitos a arredondamento; (6) As escolhas podem ter sido feitas de maneira inconsistente com o objetivo e o escopo da análise; (7) As escolhas podem ter sido feitas de maneira inconsistente entre as alternativas; (8) As relações estabelecidas podem estar erradas; (9) As relações podem ser incompletas (desconsiderando itens relevantes); (10) As relações podem ter sido implementadas incorretamente no software.
European Commission (2010)	(1) Incertezas nos dados de inventário; (2) Incertezas nos dados utilizados na avaliação de impacto; (3) Incertezas nas suposições feitas ao construir o sistema e (4) Incertezas devido a escolhas.

Fonte: Huijbregts (1998); Björklund (2002); Lloyd e Ries (2007); Finnveden et al. (2009) e European Commission (2010).

Conforme observado, existem diversos tipos de incertezas e muitos podem surgir em uma ACV típica. Considerando os tipos de incerteza definidos por Lloyd e Ries (2007), observa-se que, de maneira geral, quando a incerteza é avaliada em ACV, há a predominância de estudos com foco nas incertezas de parâmetro dos dados de inventário (entradas de processo, descargas ambientais e características tecnológicas) (LLOYD; RIES, 2007). No contexto da indústria da construção, a tendência se repete, na qual a maior parte dos estudos avaliam as incertezas de parâmetro. Como exemplo podem ser citados: Häfliger et al. (2017) que avaliaram incertezas da seleção de bases de dados de inventário e da definição dos limites do sistema; Blengini e Di Carlo (2010) que avaliaram incertezas dos dados de entrada; Hung e Ma (2009) que avaliaram incertezas dos dados de inventário e os dados de AICV juntamente com processos de normalização e ponderação; Su et al. (2016) que avaliaram incertezas dos dados de inventário; Robati, Daly e Kokogiannakis (2019) que avaliaram incertezas dos dados de inventário dos materiais e distâncias de transporte consideradas e Zhang et al., (2019) que avaliaram incertezas provenientes das emissões. Em menor número também são encontrados estudos focados na avaliação das incertezas de cenário: Häfliger et al. (2017) e Robati, Daly e Kokogiannakis (2019) avaliaram os cenários de substituição dos materiais e/ou elementos construtivos e de modelo, já Grant et al. (2014) avaliaram a influência da escolha do modelo de previsão de vida útil sobre os cenários de substituição dos materiais e ou/elementos construtivos.

Existem diferentes métodos para avaliar as incertezas em estudos de ACV. Heijungs e Huijbregts (2004) citam a variação de parâmetros/análise de cenários; métodos de amostragem; métodos analíticos e métodos não tradicionais, como a lógica Fuzzy. Já Finnveden et al., (2009) sugerem três formas com as quais as incertezas podem ser tratadas: (1) modo científico – aprimoramento pela pesquisa, buscando encontrar melhores dados, criar melhores modelos etc.; (2) modo social - discutir as questões incertas com as partes interessadas e encontrar consenso sobre dados e escolhas; e (3) modo estatístico - contrastando com as duas outras formas, não tenta remover ou reduzir a incerteza, mas incorporá-la. Lloyd e Ries (2007) mencionam a modelagem estocástica, modelagem de cenários, lógica Fuzzy, cálculos de intervalos e propagação analítica da incerteza.

Dentre os métodos citados, o método estocástico de amostragem da simulação de Monte Carlo (MC) é reconhecido como o mais comumente aplicado (GROEN et al., 2014; LLOYD; RIES, 2007). A simulação de Monte Carlo pode ser definida como um método para obter estimativas para solução de problemas matemáticos por meio de números aleatórios, como nas roletas utilizadas nos Casinos de Monte Carlo: que nomeou o método (ZIO, 2013). Na simulação de MC, a distribuição dos resultados é calculada executando o modelo várias vezes com representações de parâmetros selecionados aleatoriamente (HEIJUNGS; HUIJBREGTS, 2004).

1.2 PROBLEMA DE PESQUISA

A avaliação de incertezas não é comumente realizada nos estudos de ACV. Embora tenham sido feitos grandes esforços na sua classificação, na definição das fontes de incerteza e de aspectos metodológicos (BJÖRKLUND, 2002; GROEN et al., 2014; GUO; MURPHY, 2012), muito esforço ainda é necessário no sentido de padronizar e sistematizar este processo de avaliação (GROEN et al., 2014).

Inserida nesse contexto de incertezas nos estudos, ocorre a expansão do emprego da ACV na avaliação das edificações (HOXHA et al., 2017). Entretanto, apesar do crescimento no uso da ACV, as incertezas associadas aos resultados obtidos podem reduzir a confiabilidade dos mesmos (HOXHA et al., 2017). Além disso, a credibilidade da ACV pode ser questionada se os resultados não puderem ser acompanhados por análises adequadas de incerteza (BJÖRKLUND, 2002).

Considerar as incertezas em ACV é fundamental para garantir confiabilidade ao processo de tomada de decisão. Ratificando tal necessidade, a NBR ISO 14044 (2009) sugere a avaliação de incertezas como técnica adicional, para se compreender melhor os resultados de AICV. Neste sentido, dois passos importantes devem ser dados: a inclusão da avaliação de incertezas nos estudos, de maneira que os resultados reflitam as possibilidades decorrentes das incertezas do estudo e não apenas um valor único; e o aperfeiçoamento do processo de avaliação de incertezas por meio da padronização e sistematização.

No contexto de avaliação de incertezas de edificações, observa-se a necessidade de aperfeiçoamento na definição dos parâmetros de vida útil dos materiais e elementos de construção utilizados nos estudos de ACV. A vida útil desempenha um papel importante nos resultados observados. Entretanto, um pequeno número de trabalhos têm seu foco no detalhamento das incertezas desta etapa, sendo eles: Grant, Ries e Kibert (2014), Hoxha et al. (2014), Aktas e Bilec (2012b) e Grant e Ries (2012) que se concentraram em avaliar as incertezas dos materiais de construção e Hoxha et al. (2014; 2017) que se concentraram nas incertezas da avaliação do edifício completo.

As manutenções e substituições de componentes e elementos em edificações têm natureza dinâmica, e se entende que aspectos de modelagem dos dados, localização geográfica e aspectos comportamentais dos usuários podem ter elevada influência nos resultados. Neste sentido, demonstrar tais diferenças e semelhanças é um passo importante. Além disso embora o método de simulação de Monte Carlo seja amplamente utilizado para propagação de incertezas do inventário do ciclo de vida, ainda é pouco utilizado para demonstrar as incertezas de parâmetros de modelagem como a vida útil. Tal lacuna de estudos que demonstrem a influência da definição dos parâmetros estatísticos na avaliação das incertezas de modelo, como a seleção do método de previsão de vida útil, precisa ser preenchida de modo a agregar confiabilidade aperfeiçoando os resultados de ACV de edifícios.

1.3 QUESTÃO DE PESQUISA

Com base no problema de pesquisa, definiu-se a questão principal de pesquisa:

Quais são as incertezas relacionadas à previsão da vida útil dos elementos construtivos de uma edificação e qual a sua influência na modelagem da etapa de uso na avaliação do ciclo de vida de edifícios de um edifício?

1.4 HIPÓTESE DE PESQUISA

A incerteza proveniente da definição da vida útil dos elementos da construção é significativa no estudo de ACV de edifícios.

1.5 OBJETIVOS DA PESQUISA

O objetivo geral desta pesquisa é identificar as incertezas relacionadas à previsão da vida útil dos elementos de uma tipologia de edificação selecionada e sua influência na modelagem da etapa de uso na avaliação do ciclo de vida de edifícios.

Objetivos específicos da pesquisa:

a) identificar a participação de cada etapa do ciclo de vida sobre os impactos totais de uma edificação;

b) avaliar incertezas relacionadas ao método utilizado na previsão de vida útil dos elementos da edificação sobre os resultados da ACV;

c) avaliar as incertezas de previsão de vida útil de diversos elementos típicos de construções brasileiras por meio do método da simulação de Monte Carlo;

d) identificar as incertezas relacionadas à definição de parâmetros da simulação de Monte Carlo sobre os valores de vida útil obtidos;

e) avaliar a influência de parâmetros estatísticos definidos na simulação de Monte Carlo sobre os resultados da ACV de elementos da construção;

f) comparar incertezas provenientes da coleta de dados de inventário versus as incertezas provenientes das definições de vida útil utilizadas na modelagem da etapa de substituição dos elementos da edificação.;

g) identificar a participação da etapa de substituição nos impactos do ciclo de vida de diferentes elementos da construção;

h) definir parâmetros para a avaliação de incertezas da etapa de substituição dos elementos durante o ciclo de vida das edificações.

1.6 DELIMITAÇÕES

Este estudo concentrou seus esforços na avaliação de incertezas das operações de substituições totais dos componentes e/ou elementos construtivos da edificação. Outras delimitações também foram necessárias, tais como:

- para viabilizar o estudo, optou-se por estudar elementos comumente encontrados em edificações residenciais brasileiras.

- foram avaliadas incertezas relacionadas ao modelo, como os dados de vida útil empregados na modelagem dos cenários de substituição dos elementos. Além dessas, também foram avaliadas incertezas de parâmetros, como os dados de inventário.

- para avaliação de incertezas, embora existam outros métodos de avaliação conhecidos, optou-se por estudar apenas o método de simulação de Monte Carlo, pois este é amplamente utilizado em estudos de ACV.

- não foram considerados os benefícios da reciclagem e da reutilização de materiais nas avaliações realizadas.

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2 MÉTODO DE PESQUISA

A estratégia de pesquisa utilizada neste trabalho foi o estudo de caso com objetivo de avaliar a influência da modelagem de cenários de substituição, manutenção e reparos ao longo do ciclo de vida de uma edificação residencial localizada na região metropolitana de Porto Alegre/RS. Para tal, dividiu-se a pesquisa em quatro (4) fases conforme descrito no item 2.1.

Este trabalho partiu de uma pesquisa exploratória que viabilizou a definição da lacuna de pesquisa (fase 1). Uma vez definido o tema de estudo as demais fases foram implementadas (fases 2, 3 e 4).

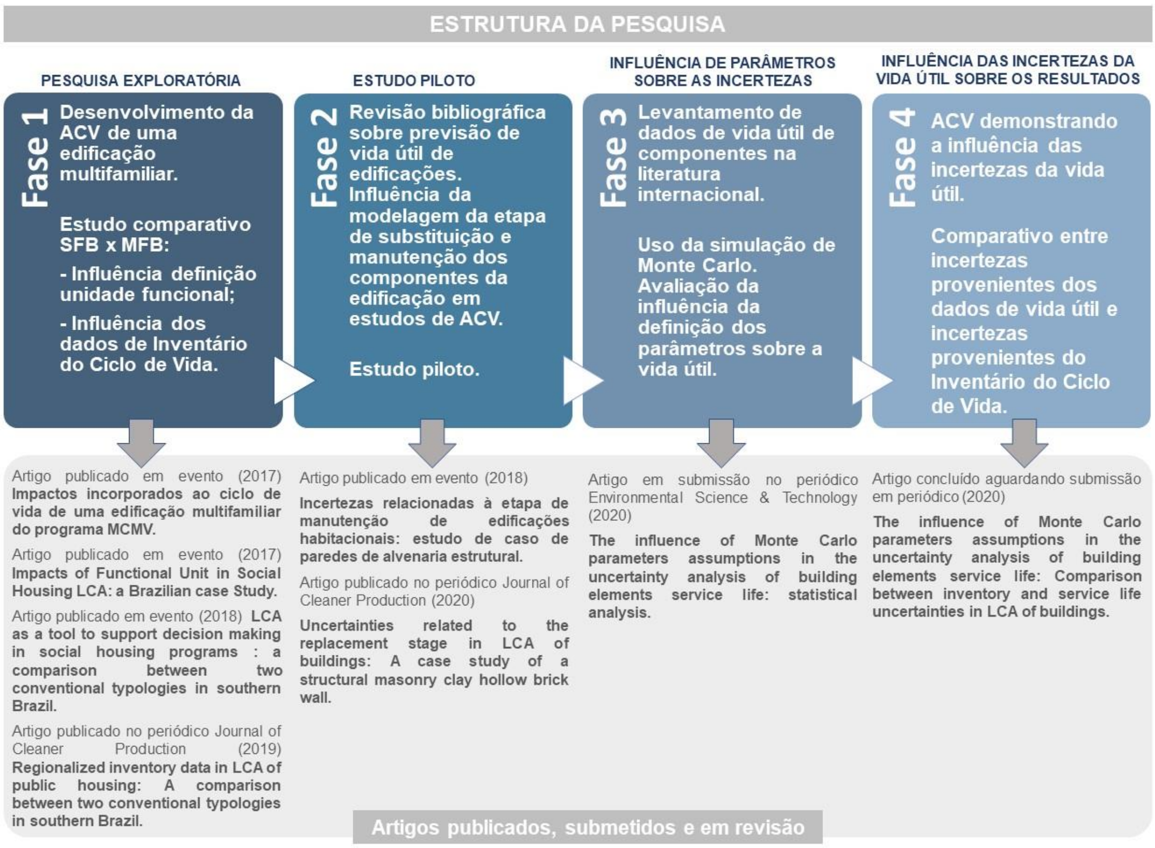
2.1 ESTRUTURA DA PESQUISA

Visando atingir ao objetivo definido, esta pesquisa foi estruturada em quatro grandes fases conforme delineamento apresentado na Figura 2. As quatro fases estabelecidas neste trabalho originam os capítulos 3, 4, 5 e 6. Cada uma das fases da pesquisa compõem um capítulo, que é iniciado com revisão bibliográfica sobre o tema seguido do método de pesquisa aplicado e os respectivos resultados e conclusões da etapa. O trabalho foi dividido no formato de artigos que por sua vez correspondem aos capítulos 3, 4, 5 e 6, totalizando quatro artigos.

Na fase 1 desta pesquisa foi desenvolvida a ACV de um estudo de caso selecionado, uma edificação multifamiliar. A fase 1 (capítulo 3), que corresponde ao artigo 1, serviu como pesquisa exploratória, através da qual foi possível identificar algumas das principais dificuldades no processo de aplicação da ACV na avaliação ambiental de edificações. Esta fase, cuja estrutura é apresentada na Figura 2 (pesquisa exploratória), foi fruto do amadurecimento sobre o tema realizado a partir de diversas publicações preliminares realizadas e citadas abaixo que, embora não constem neste documento, também foram relevantes no processo de definição do tema. Os achados resultantes da fase 1 originaram as questões de pesquisa que nortearam este trabalho, e a partir de então selecionou-se a etapa de substituição dos elementos das edificações como foco de pesquisa, tendo em vista a complexidade observada durante o processo de desenvolvimento desta fase.

Na fase 2, iniciou-se a revisão teórica sobre métodos de previsão de vida útil de materiais e elementos de construção. O artigo 2 (capítulo 4) compõe a fase 2 desta pesquisa, na Figura 2 também são feitas referências a outras publicações realizadas que, embora não constem no capítulo também fizeram parte desta etapa e são citadas ao longo do trabalho. Para esta fase também foi realizado um novo estudo de ACV, porém este foi reduzido, e apenas alguns elementos da edificação estudada na fase 1 foram selecionados. O critério de escolha aplicado foi a contribuição do elemento nos impactos totais encontrados. Nesta etapa, buscou-se identificar a influência da utilização de dados nacionais e internacionais de previsão de vida útil dos elementos nos resultados totais da ACV. Além disso, demonstrou-se a relevância do método utilizado para a previsão destas vidas úteis coletadas sobre os resultados obtidos. Com base nos resultados obtidos na fase 2, delineou-se a fase 3 da pesquisa.

Figura 2 – Estrutura da pesquisa.



As fases 3 e 4 da pesquisa receberam aporte externo. Através do Programa Doutorado Sanduíche no Exterior da CAPES, foi possível aprimorar o desenvolvimento destas etapas em conjunto com pesquisadores da *University of Florida* nos Estados Unidos, que já possuíam diversas pesquisas na temática selecionada. A fase 3 da pesquisa resultou na elaboração do artigo 3 (capítulo 5). Nesta fase, foi realizado um extenso levantamento dos dados de previsão de vida útil disponíveis para alguns dos elementos de construção mais comumente utilizados na região Sul do Brasil. Estes dados coletados serviram de base para uma análise mais aprofundada. Estas análises visaram quantificar a variabilidade destes dados, bem como demonstrar a relevância da seleção dos parâmetros quando uma avaliação de incertezas dos dados de previsão de vida útil é conduzida utilizando o método da simulação de Monte Carlo.

Por fim, na fase 4 da pesquisa foi realizada a aplicação prática em uma ACV dos achados obtidos na fase 3. O artigo 4 (capítulo 6) apresenta o desenvolvimento da fase 4. Nesta fase, quatro elementos de construção (já selecionados na fase 3) foram escolhidos para quantificar a influência da variabilidade encontrada na fase 3 sobre os resultados da ACV. Complementarmente, foram realizadas comparações das incertezas relacionadas à previsão da vida útil *versus* as incertezas relacionadas aos dados de inventário (mais comumente avaliada).

2.2 DESCRIÇÃO DAS FASES

Neste tópico cada uma das fases de pesquisa é descrita visando fornecer um panorama geral das considerações metodológicas empregadas em cada uma delas. O detalhamento minucioso de cada fase encontra-se disponível no artigo correspondente: artigo 1 – capítulo 3; artigo 2 – capítulo 4; artigo 3 – capítulo 5; artigo 4 – capítulo 6.

2.2.1 Fase 1

Na fase 1 da pesquisa, duas tipologias habitacionais comumente empregadas no Brasil foram estudadas: a) Unidade habitacional de tipologia unifamiliar com 40,10m² de área interna útil; b) Unidade habitacional de tipologia multifamiliar com 40,29m² de área interna útil. O sistema construtivo de ambas unidades habitacionais é o mesmo – parede de blocos cerâmicos estrutural. O escopo do estudo é do berço ao túmulo considerando os módulos A1 ao A5, módulo B4, módulo B6 e módulos C1 ao C4 conforme definições da EN 15978 (CEN, 2011a). Neste estudo, a unidade funcional definida é 1m² de área interna útil para uma vida útil de pelo menos 50 anos. O inventário do ciclo de vida utilizado é proveniente da base de dados Ecoinvent v.3.3, sendo utilizados dados de inventário de origem global e dados de inventário regionalizados para o Brasil. O transporte foi estimado considerando as distâncias entre o fabricante e o canteiro de obras, localizado na região metropolitana de Porto Alegre/RS. Os cenários de substituição dos elementos da edificação são definidos a partir dos valores de vida útil sugeridos pela ABNT NBR 15575-1 (ABNT, 2013). As categorias de impacto selecionadas para avaliação são aquelas previstas na EN 15804 (CEN, 2013) sendo elas: Potencial de depleção de recursos abióticos de origem fóssil (CML, 2001), Potencial de depleção de recursos abióticos de origem não fóssil (CML, 2001), Potencial de aquecimento global (IPCC, 2007), Potencial de acidificação (CML, 2001), Potencial de eutrofização (CML, 2001), Potencial de depleção da camada de ozônio (CML, 2001), Potencial de formação de ozônio troposférico (CML, 2001). Nesta etapa as incertezas não foram avaliadas. A fase 1 está descrita no capítulo 3 – artigo 1.

2.2.2 Fase 2

Na fase 2 da pesquisa o objeto de estudo é um dos elementos que compõem a edificação – a parede. Nesta etapa a unidade funcional definida é 1m² de parede estrutural construída em blocos cerâmicos para uma vida útil de 50 anos. O escopo do estudo é do berço ao túmulo considerando os módulos A1 ao A3, módulo B3, módulo B4 e módulos C1 ao C4 conforme definições da EN 15978 (CEN, 2011a). Assim como na fase 1, o inventário do ciclo de vida utilizado é proveniente da base de dados Ecoinvent v.3.3, sendo utilizados dados de inventário de origem global e dados de inventário regionalizados para o Brasil. O transporte foi estimado considerando as distâncias entre o fabricante e o local de produção da parede na região metropolitana de Porto Alegre/RS. Diferentes cenários de substituição e reparo dos componentes da parede foram propostos para discutir a incerteza relacionada à definição da vida útil nos resultados da ACV. Os cenários de substituição dos elementos da edificação são definidos a partir de diferentes referências de vida útil nacionais e internacionais. As categorias de impacto selecionadas para avaliação são as mesmas previstas na fase 1 da pesquisa (ver item 2.2.1). Na fase 2 as incertezas relacionadas aos erros na coleta de dados de inventário (WEIDEMA et al., 2013) e nos indicadores de qualidade dos dados através da abordagem da matriz pedigree (WEIDEMA; WESNAES, 1997) são avaliadas. A fase 2 está descrita no capítulo 4 – artigo 2.

2.2.3 Fase 3

A fase 3 da pesquisa, diferentemente das demais, não envolve a elaboração de uma ACV. Nesta etapa, o foco do estudo encontra-se na avaliação de incertezas dos dados de vida útil de alguns dos elementos de construção presentes nas tipologias de edificação selecionadas na fase 1 da pesquisa. A abordagem de simulação de Monte Carlo é escolhida para discutir a incerteza da vida útil em ACV de edifícios, pois este é um dos métodos mais empregados atualmente para avaliar incertezas em estudos de ACV (GROEN et al., 2014). Nesta etapa foram reunidos dados de vida útil de 15 elementos construtivos conforme segue: contrapiso de concreto armado, lajes de concreto armado, vigas de fundação, paredes externas de tijolo cerâmico, revestimento de argamassa (externo), paredes internas de tijolo cerâmico, revestimento de argamassa (interno), portas de alumínio, janelas de alumínio, estrutura do telhado, coberturas de telha cerâmica, escadas de concreto, pintura de parede externa, pintura de parede interna e pintura de teto. Nesta fase, os diferentes modelos de previsão da vida útil são comparados estatisticamente, bem como os parâmetros estatísticos (distribuição dos dados) utilizados na simulação de Monte Carlo. Diversos testes estatísticos são utilizados. Para comparações gerais são aplicados os testes: Levene´s, análise de variância (ANOVA), teste Welch e teste Kruskal-Wallis. Nas comparações por pares é utilizado o teste Mann-Whitney. Todos os testes utilizam um intervalo de confiança de 95%. A fase 3 de pesquisa envolve uma extensa análise estatística, que demonstra a relevância da definição adequada do modelo de previsão de vida útil a ser utilizado na modelagem das substituições dos elementos construtivos durante a etapa de uso da edificação. Além disso, a influência da escolha dos parâmetros estatísticos na simulação de Monte Carlo também é demonstrada. A fase 3 está descrita no capítulo 5 – artigo 3.

2.2.4 Fase 4

A fase 4 compreende a ACV de quatro elementos de construção, selecionados durante a fase 3 de pesquisa, sendo eles: revestimento de argamassa externo, parede externa de tijolo cerâmico, pintura de parede externa e pintura de parede interna. A unidade funcional definida é 1m² de cada um dos elementos selecionados. Nesta fase da pesquisa, a influência da vida útil referência da edificação sobre os impactos ambientais também é analisada. Para tal, três cenários de vida útil referência da edificação são propostos, considerando a inserção dos elementos de construção selecionados em uma edificação hipotética, sendo eles: 50 anos, 120 anos e 500 anos. O escopo do estudo é do berço ao túmulo, considerando os módulos A1 ao A3, módulo B4 e módulos C1 ao C4 conforme definições da EN 15978 (CEN, 2011a). Assim como nas fases anteriores, o inventário do ciclo de vida utilizado é proveniente da base de dados Ecoinvent v.3.3, sendo utilizados somente dados de inventário de origem global. O transporte referente ao mercado global de cada produto é considerado através do emprego de dados de mercado (*market datasets*). Os conjuntos de dados de mercado são usados porque representam o *mix* de consumo e transporte de uma ou mais entradas do mesmo produto das diferentes atividades de transformação localizadas no mercado selecionado (WEIDEMA et al., 2013). Os cenários de substituição dos elementos de construção são definidos a partir da média entre as diferentes referências bibliográficas de vida útil compiladas na fase 3 da pesquisa. O método da simulação de Monte Carlo é utilizado para avaliar as incertezas oriundas de duas fontes distintas: as incertezas associadas à vida útil e as incertezas associadas ao inventário do ciclo de vida.

2.3 SUMÁRIO DOS ARTIGOS E OBJETIVOS ESPECÍFICOS DA PESQUISA

Para uma melhor compreensão da relação entre cada artigo e os objetivos específicos traçados para a pesquisa foi elaborado o Quadro 2. Nele podem ser observados cada um dos objetivos específicos definidos bem como o respectivo artigo desenvolvido. Ressalta-se a integração entre as pesquisas desenvolvidas uma vez que os artigos e os objetivos se permeiam.

Quadro 2 – Relação entre os objetivos específicos de pesquisa traçados e os artigos apresentados nesta tese.

OBJETIVO GERAL: identificar as incertezas relacionadas à previsão da vida útil dos elementos de uma tipologia de edificação selecionada e sua influência na modelagem da etapa de uso na avaliação do ciclo de vida de edifícios.			
Objetivos específicos		Artigo no qual o objetivo foi estudado	Capítulo
a)	Identificar a participação de cada etapa do ciclo de vida sobre os impactos totais de uma edificação.	Artigo 1	Capítulo 3
b)	Avaliar incertezas relacionadas ao método utilizado na previsão de vida útil dos elementos da edificação sobre os resultados da ACV.	Artigo 2 Artigo 3	Capítulo 4 Capítulo 5
c)	Avaliar as incertezas da previsão de vida útil de diversos elementos típicos de construções brasileiras por meio do método da simulação de Monte Carlo.	Artigo 3 Artigo 4	Capítulo 5 Capítulo 6
d)	Identificar as incertezas relacionadas à definição de parâmetros da simulação de Monte Carlo sobre os valores de vida útil obtidos.	Artigo 3 Artigo 4	Capítulo 5 Capítulo 6
e)	Avaliar a influência de parâmetros estatísticos definidos na simulação de Monte Carlo sobre os resultados da ACV de elementos da construção.	Artigo 4	Capítulo 6
f)	Comparar incertezas provenientes da coleta de dados de inventário versus as incertezas provenientes das definições de vida útil utilizadas na modelagem da etapa de substituição dos elementos da edificação.	Artigo 2 Artigo 4	Capítulo 4 Capítulo 6

g)	Identificar a participação da etapa de substituição nos impactos do ciclo de vida de diferentes elementos da construção.	Artigo 2 Artigo 4	Capítulo 4 Capítulo 6
h)	Definir parâmetros para a avaliação de incertezas da etapa de substituição dos elementos durante o ciclo de vida das edificações.	Artigo 3 Artigo 4	Capítulo 5 Capítulo 6

3 REGIONALIZED INVENTORY DATA IN LCA OF PUBLIC HOUSING: A COMPARISON BETWEEN TWO CONVENTIONAL TYPOLOGIES IN SOUTHERN BRAZIL[1]

3.1 INTRODUCTION

Most construction projects will have considerable environmental impact on the environment. The construction industry should prioritize minimizing those impacts (CABEZA et al., 2014). In 2007, it was reported that construction of structures is responsible for 32% of the energy use and 18% of the greenhouse gas emission (IPCC, 2007). Depending on the type of construction, energy consumption is one of the main sources of adverse environmental impacts; residential buildings alone account for 70% of the world's total electricity consumption (U.S.DOE, 2015). In addition, the incorporated impacts, i.e., the impacts related to construction and materials production, contributes to the problem (DIXIT et al., 2012).

Many attempts have been made to quantify the environmental impacts of the construction process as a whole (OYARZO; PEUPORTIER, 2014). To aid in this quantification, the Life Cycle Assessment (LCA) emerges as a tool to identify the impacts during the life cycle of a building's, including the extraction of raw materials, production process, transport, use, and disposal. The LCA can be used to improve the environmental profile of buildings. Unfortunately, the LCA is not used on a wide-scale basis in the building industry due to methodological issues that include functional unit definition, data availability, and comparability among different studies. Additionally, the parameters that comprise a construction project, such as the type of materials used, the location of the building, construction, design, and usage are so varied that it is difficult to define the scope and goals of conducting a LCA (ABD RASHID; YUSOFF, 2015). To ensure the validity of reliable LCA studies, it is recommended to rely on national inventories from primary data (ANAND; AMOR, 2017); differences in defining parameters such as energy consumption, fuel types, and product composition contribute to undermine the validity of LCA studies (SILVA et al., 2017). To address this issue, regionalization of building stock can improve the accuracy of the results of the LCA and make it more relevant for decision-makers (YANG, 2016). Because primary data collection is not always feasible, e.g., the building industry relies on a complex supply chain,

[1] O capítulo já está publicado em formato de artigo e pode ser acessado pelo DOI:10.1016/j.jclepro.2019.117869

as an alternative, using background data with regional characteristics is a possible solution. Indeed, EN 15978:2011 states that the LCA of buildings shall reflect a building's physical reality, and will be considered being representative for the local production and technological and geographical coverage (CEN, 2011a).

To best of our knowledge, most of the LCAs related to buildings performed in Brazil are concerned with either materials or systems and do not consider the whole building. Also, most of the whole-building studies in Brazil assess embodied energy or CO_2 considering inventory perspective, and not impact assessment perspective. In spite of that, a recent study from Evangelista et al. (2018) compared the LCA of different typologies for low- and high-quality residential buildings composed of two multi-family and two single-family. The authors reported a cradle-to-grave study of the buildings, including construction and their operation. The functional unit was "square meters of total built-up area of the building per year (m2/year)." However, their inventory considered non-regionalized data from Ecoinvent v3.01, i.e not taking into account the specificity of Brazil's industrial processes (EVANGELISTA, 2017). Moreover, Paulsen and Sposto (2013) assessed a single-family public housing considering embodied energy. The authors assessed the house from cradle-to-grave perspective using as inventory the embodied energy of construction materials from different literature sources. Tavares (2006) conducted a life-cycle study of embodied energy and CO_2 in residential buildings, producing an extensive list of embodied energy inventory for construction materials. The method was applied in five types of residential buildings, with varying pre- and operational profiles.

Hence, these studies demonstrate that Brazil lacks an LCA that considers the whole-building perspective of residences using regionalized data. Embodied energy studies do not follow the same methodology as LCA; thus, their results show limited comparability. Additionally, the results may not be correlated into a succinct environment assessment due to the methodology's sum-up of different primary energy sources. Overall, the potential environmental impacts related to the Brazilian residential buildings including all life-cycle stages, such as materials production, construction, and operation, remains unanswered and deserves further study.

In the last years, the interest for environmental impacts of public housing has been raising manly because of the increasing demand in developing economies. In Brazil, a large low-income housing plan named My House My Life Program1 plans on constructing millions of housing units (BRASIL, 2017a). The potential for significant environmental impact with the construction of so many units is of concern. The main goal of this study is to evaluate the potential environmental impacts related to the life cycle of two types of a public housing project in southern Brazil. One project is composed of a single-family dwelling, i.e., houses and the second project is composed of low-rise apartment buildings. The area of each unit is similar, as is the construction material used. The study considers regionalized and non-regionalized data inventory to validate the quality of the data and the availability of such data for application of a LCA of buildings in developing economies.

3.2 METHODS

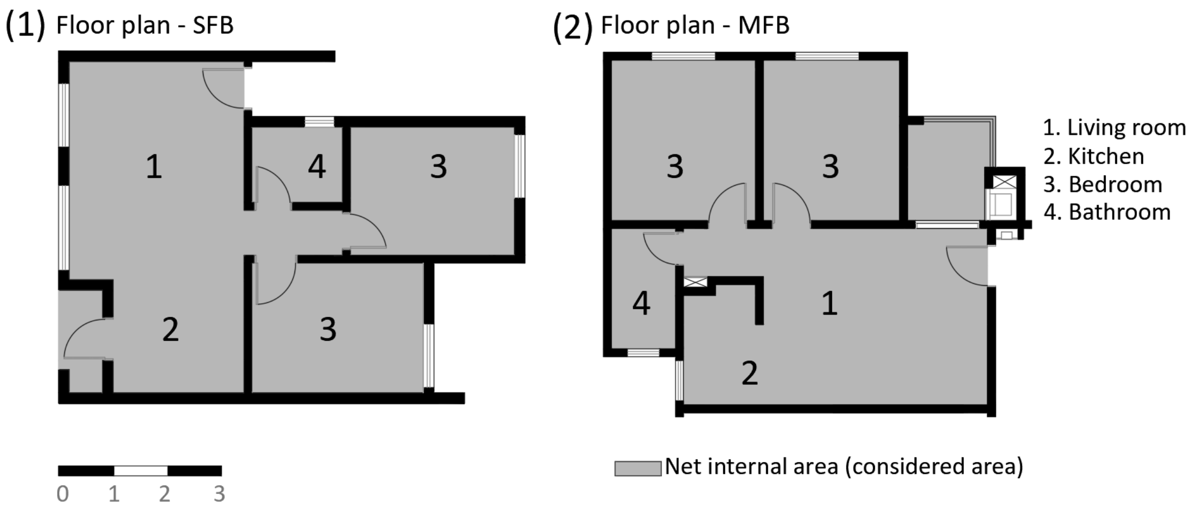
The study presented herein is based on Life Cycle Assessment (LCA) methodology, following the criteria of ISO 14040:2006 (ISO, 2006a) and ISO 14044: 2006 (ISO, 2006b).

3.2.1 Goal and scope definition

The main goal of this study was to evaluate and compare the environmental impacts of two residential dwellings types: a public housing unit consisted of (1) one single-family building (SFB) and (2) a multi-family building (MFB). The construction system for both structures was the same, constructed with structural masonry clay hollow brick, which is considered representative of the area studied. Building typologies were chosen based on what was considered representative of the area. Both buildings are located at Porto Alegre metropolitan area, southern Brazil. The MFB typology represents 67% of the dwelling units approved for construction in the region, and the SFB typology represents 33%. The construction system selected is representative of 32.6% of the wall systems built in the period from February/2012 to March/2014 (GIHABNH, 2016). Figure 3 shows the floor plans and internal characteristics of each dwelling. The SFB development consists of 315 housing units with identical plans. The MFB development consists of nine towers with five floors and 20 apartments each, totaling 180 identical housing units. Table 2 summarizes the main characteristics of the dwellings studied. In this study, the Functional Unit (FU) is defined as 1 m^2 of net internal area (NIA) in a residential building assumed to have a life span of at least 50 years. Defining the FU provides a functional reference, to ensure equivalent comparability of the LCA results (ISO, 2006a).

[1] Free translation from the Portuguese "Programa Minha Casa Minha Vida."

Figure 3 - Floor plans for each dwelling unit for both case studies: (1) single-family building (SFB) and (2) multi-family building (MFB).



The FU statement can vary among different studies since several options may be considered, e.g., gross floor area or internal area, building units, number of occupants, etc. (KHASREEN; BANFILL; MENZIES, 2009). Consequently, it is difficult to harmonize methodological choices for the building sector. For example, Morales et al. (2017) observed different ranking results according to FU definition (gross floor area, gross floor internal area, and net internal area) on buildings with similar systems and materials. This variation occurs in comparative results according to the unit dimension (MORALES et al., 2017). In this case, the function is defined per area and period of use. Considering that both residential buildings have similar plans and areas, as well as functional and technical requirements, pattern of use and service life, those are considered comparable, in accordance with EN 15978:2011 (CEN, 2011a) that defines what are functional equivalents. Furthermore, the housing market commonly considers the private useful area for sales, since this is an important point for the customer. In this sense, by using this approach, the potential impacts from the whole building construction may be considered and attributed through a comparable function. For comparison, the impacts result from the whole building are divided by the NIA (m²) of each dwelling; see Equation (1).

$$Impact\ (1m^2 NIA) = \frac{I_{total}}{A_{NIA}} \quad (1)$$

where:

I_{total} is the whole building environmental impact;

A_{NIA} is the total net internal area of each building in m². SFB = 40.29 m² and for MFB[1]= 802.00 m² (Table 2).

$Impact\ (1m^2 NIA)$ is the impact per 1m² of net internal area for each building.

Table 2 - Gross floor area, gross internal area and net internal area per dwellings unit for both typologies: single-family building (SFB) and multi-family building (MFB).

Case study		SFB	MFB
Total areas per dwelling unit	Gross floor area	44.45 m²	50.57 m²
	Gross internal area	40.29 m²	43.90 m²
	Net internal area	40.29 m²	40.10 m²
Internal areas per dwelling unit (NIA)	Living room	16.26 m²	16.00 m²
	Kitchen	5.20 m²	5.65 m²
	Bedroom	8.00 m²/8.25 m²	7.65 m² / 8.10 m²
	Bathroom	2.58 m²	2.70 m²

The scope of this study considers the cradle-to-grave cycle of a structure (according to the standard EN 15978:2011) with the following parameters: product stage and construction process stage (module A1 to A5), use stage including: building elements replacement (module B4) and energy use (B6 module), and end-of-life stage - EoL (module C1 to C4), which is similar to other studies such as Leskovar et al. (2019). The materials transport is considered for the product stage and the construction process stage (Table 3). The B4 and B6 modules were considered herein because they are expected to be different in the evaluated dwellings due to the inherent characteristics of each typology. Also, the EN 15978:2011 - module D, is out of the defined scope. Module D, is a supplementary information beyond the building life cycle, which quantifies the net environmental benefits or loads resulting from reuse, recycling, and energy recovery (CEN, 2011a). Figure 4 shows the system boundaries of the study and the

[1] Calculated by simple multiplication of the dwelling area (40.10 m²) by the number of apartments in the building (20 units).

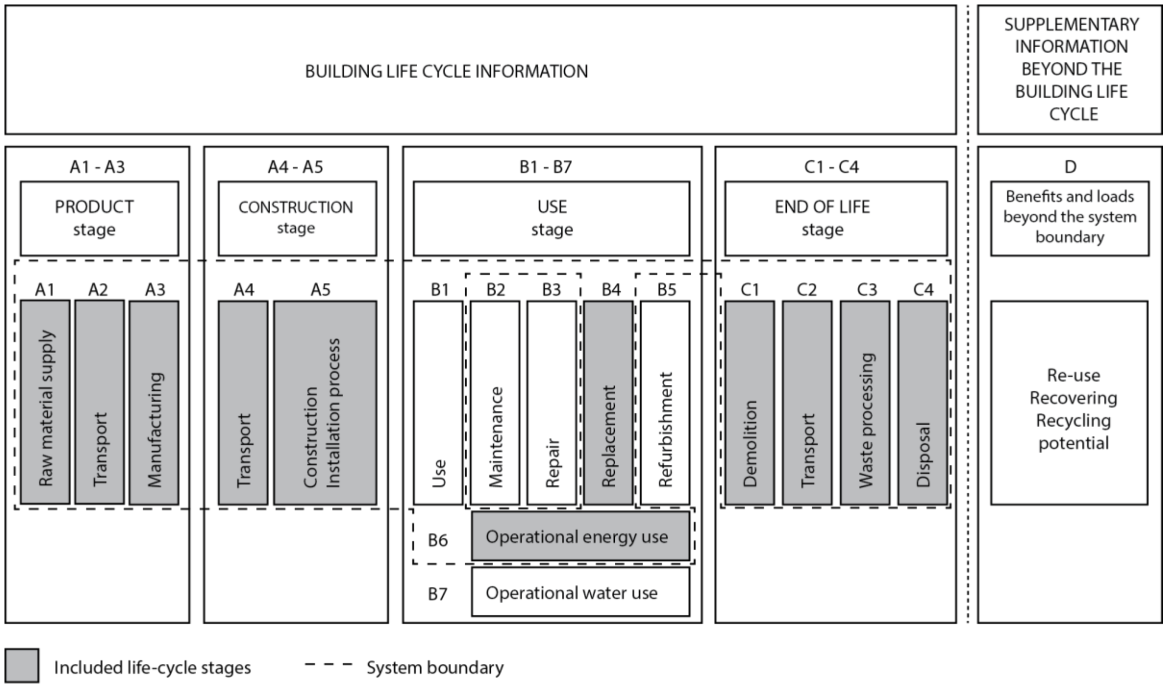
considered stages. The energy used for preparing meals and the energy required for air-conditioning were disregarded in the operational energy stage.

Table 3 - Considered transportation distance (in kilometers) per building material and modal distribution for the product stage (module A2) and construction process stage (module A4).

Building material	Distance of transportation from the extraction of raw materials to the industry (km) – module A2 according to EN 15978 (2011)	Distance of transportation from the industry to the construction site (km) – module A4 according to EN 15978 (2011)	Modal distribution
Aluminum windows/doors	4330	35	Freight lorry
Clay hollow brick	0	18	Freight lorry
Ceramic tile	0	44	Freight lorry
Cement	0	430	Freight lorry
Galvanized steel	1730	10	Freight lorry
Glass	0	600	Freight lorry
Gravel	0	120	Freight lorry
Gypsum board	2500	1327	Freight lorry
Lime	0	287	Freight lorry
Paint	50	35	Freight lorry
Reinforcing steel	1730	10	Freight lorry
Sand	0	37	Freight lorry
Stucco	0	287	Freight lorry

The method proposed by Tavares (2006) was used to estimate the electricity consumption based on the Information System on Possessions and Habits of Consumption, also known as SINPHA (BRASIL, 1999), resulting in a consumption estimate of 138.4 kWh/month (MFB) and 139.0 kWh/month (SFB) per dwelling unit (MFB). This calculation considered household income, NIA (m²) and number of occupants. Factors were applied to each of these three variables (TAVARES, 2006). This study assumed that the household income was 4.6 Brazilian monthly income (which is based on the minimum wage determined by the Brazilian government), an NIA, and the average of 3.2 habitants per dwelling (IBGE, 2010). The Brazilian behaviour data in Tavares (2006) is considered one of the best available sources for operational energy in the country aside from thermodynamic simulations. The methodology covers the energy applications from the average southern Brazil profile with SINPHA data (BRASIL, 1999) being used for some Brazilian studies such as Evangelista et al. (2018) and Paulsen and Sposto (2013).

Figure 4 - Considered life-cycle stages according to EN 15978 (2011) for single-family building (SFB) and multi-family building (MFB).



The number of replacements (Table 4) was calculated according to the design service life (for a minimum life span) as suggested by NBR 15575-1 (ABNT, 2013). For this calculation, it was selected an integer number of substitutions (not partial substitutions) according to the criteria from EN 15978:2011 (CEN, 2011a). For the end-of-life stage, it was considered the landfill of all construction and demolition waste (CDW) generated by construction and replacement. Although the Brazilian legislature recommends that waste generators should prioritize waste reduction, reuse, and recycling and treatment of solid waste in an environmentally appropriate manner (CONAMA, 2002). It was estimated that in 2015 in Brazil only 5.3% of inert waste was appropriately disposed (i.e., inert landfill, recycling units, and/or trans-shipment and sorting areas) (Brasil, 2017b). Based on this fact, it was assumed that the CDW generated in the EoL of the building is disposed via landfilled on inert landfill. Future research should include other scenarios that consider recycling.

Table 4 - Number of replacements considered for each building element. Reference: ABNT NBR 15575-1: 2013 (ABNT, 2013).

	Number of replacements considered per building element for 50 years life span						
Building element	Plaster mortar		Roofing		Painting		Windows
	Interior	Exterior	Roof	Structure	Interior	Exterior	
Number of replacements	3	2	3	2	16	6	2

3.2.2 Inventory analysis

In this study, OpenLCA 1.6 software (GREENDELTA, 2019) was used to compile the life cycle inventory. This software is coupled with the OpenLCA nexus database for Ecoinvent version 3.3 (Ecoinvent, 2016a). One of the major challenges in conducting an LCA using background data is the mismatch between the location of the construction project and the collected inventory data, as well as the lack of transparency or the inadequacy of the data for the conditions of the specific construction project (MARTÍNEZ-ROCAMORA; SOLÍS-GUZMÁN; MARRERO, 2016). As an alternative to the unavailability of local data, the LCI data regionalization is a strategy adopted by many LCA practitioners, e.g. Silva et al. (2015). In this sense, data was regionalized considering Brazilian available data from industry and academy (Moraga et al., 2018; ANICER, 2012; ANICER, 2011) to obtain representative results considering the national building stock. EN 15978:2011 recommends that the significance of the data that may influence the building assessment shall be determined and reported (CEN, 2011a). This study presents the results for regionalized data and sensitivity analysis considering global production data from the Ecoinvent database versus the regionalized ones. Factor R is used [Equation (2)] to present the difference between the environmental impact of regionalized versus non-regionalized data.

$$R\ (\%) = \frac{I_{Reg} - I_{NonR}}{I_{Reg}} \qquad (2)$$

Where:

I_{Reg} is the environmental impact of regionalized data;

I_{NonR} is the environmental impact of non-regionalized data;

R is the difference factor in percentage.

Data was regionalized considering the Brazilian electrical grid and local production processes of the following materials: concrete, reinforcing steel, sand, mortar and mortar for rendering, gravel, cement, acrylic paint, and aluminum windows. To conduct the data regionalization, background life-cycle inventory data culled from the Ecoinvent version 3.3, switching the energy matrix (inputs and amounts) to render it similar to Brazilian context (MORAGA et al., 2018). Masonry clay hollow brick and the ceramic tile inventory data were provided by the National Association of Ceramic Industry (ANICER, 2011, 2012). Table 5 shows the inventory of construction materials and a description in each one of the building elements.

Table 5 - Building elements description and mass (in kilograms) for single-family building (SFB) and multi-family building (MFB). The amounts correspond to one dwelling unit.

	SFB			MFB		
Building element	Mass (kg)	Mass contribution	Materials description	Mass (kg)	Mass contribution	Materials description
Foundation[1]	14543.8	41.1%	Concrete 25 MPa[3], steel and gravel.	4886.3	11.5%	Concrete 25 MPa[3], steel and gravel.
Floor slabs[2]	-	-	-	11282.2	26.5%	Concrete 20 MPa[4]and steel.
Concrete stairs	-	-	-	492.5	1.1%	Concrete 25 MPa[3] and steel.
Walls	16744.4	47.3%	Clay hollow brick, cement mortar and lime plaster.	25177.6	59.1%	Clay hollow brick, cement mortar, grout and reinforcing steel.
Ceiling	597.0	1.7%	Gypsum board and lime plaster.	-	-	-
Painting	68.0	0.2%	Acrylic and latex paint	60.6	0.1%	Acrylic paint
Roofing	3204.1	9.1%	Galvanized reinforcing steel and ceramic tile	625.5	1.4%	Reinforcing steel and ceramic tile.
Openings	225.0	0.6%	Aluminum windows, aluminum doors and glass.	156.7	0.3%	Aluminum windows, aluminum doors and glass.

Total (kg)	35382.3	100.0%	42606.7	100.0%

[1]Foundation: foundation slabs and grade beams. Disregarded deep foundations.
[2]Floor slabs: story slab.
[3]Mix proportions of the 25 MPa concrete 1:2,34:2,34 (cement, sand and gravel, respectively).
[4dc]Mix proportions of the 20 MPa concrete 1:2,43:2,43 (cement, sand and gravel, respectively).

3.2.3 Impact assessment

The selected impact assessment categories (Table 6) are recommended by EN 15978:2011 (CEN, 2011a) and EN 15804:2013 (CEN, 2013), and associated with relevant sustainability indicators, e.g. sustainable development goals of United Nations: climate action, and responsible production and consumption (UN, 2017).

Table 6 - Sources for life-cycle impact assessment (LCIA) models.

Characterization factors	Indicator	LCIA reference
Abiotic Resource Depletion Potential for fossil resources (ADP-f)	MJ (ultimate reserve)	CML (2001)
Global Warming Potential for a 100-year time horizon (GWP-100y)	kg CO_2-Eq (100a)	IPCC (2007)
Abiotic Resource Depletion Potential for Non fossil resources (ADP-n)	kg Sb-Eq. (reserve base)	CML (2001)
Acidification Potential (AP)	kg SO_2-Eq	CML (2001)
Eutrophication Potential (EP)	kg PO_4-Eq.	CML (2001)
Depletion Potential of the Ozone Layer (ODP)	kg CFC-11-Eq	CML (2001)
Formation potential of tropospheric ozone (POCP)	kg Ethene -Eq	CML (2001)

3.3 RESULTS AND DISCUSSION

The results show the impacts per square meter of net internal area for a building life span of 50 years calculated using regionalized data and considering all of the buildings stages: product stage (materials production) and construction process stage– modules A1 to A5, use stage (energy use and replacement) – modules B4 and B6, and end-of-life stage – modules C1 to C4 (Figure 5). The house (SFB) showed that it had a higher environmental impact compared to the apartment (MFB) due to the characteristics of the construction and design. Naturally, the SFB bears all roofing impacts solely, while the MFB distributes this impact over different apartment floors.

After analyzing the contribution of each stage (Figure 5), both case studies show similar trends in the most impact categories. Note: ADP-n presents a different pattern, and a substantial impact difference is identified between the typologies. Also, the AP impacts demonstrated different impact contribution per stage when considering the entire life cycle. The SFB product stage and construction process stage show 16% to 22% of participation in the total life-cycle impacts (with the exception of ADP-n at 71%) while the MFB shows 13%–18% for all categories considered. The ADP-n overlap in the SFB is due to the LCIA methodology used to evaluate non-fossil resources (reserve base) that assigns high impact numbers to elements that may be used in small quantities by the construction sector. The SFB overlap is caused by the extraction and processing of zinc for galvanizing the roofing structure, where the data used assumes losses of up to 20% for some rare metals (MORAGA, 2017). In this sense, MFB roof is not made by galvanized reinforcing steel, presenting considerably lower impacts than SFB. Also, other metals present do not have high characterization factors, which explains the difference between them. In the chosen ADP-n LCIA model, mineral resources used in large volume by the construction industry have low characterization factors (OERS et al., 2002).

The main impacts occurred during the use stage – modules B4 and B6 (energy usage and replacement of construction materials) for both dwellings in six of the seven impacts analyzed (only ADP-n shows a greater impact during the product and construction process stage). This conclusion, i.e., the role played of the use stage and particularly energy consumption in the total environmental balance is similar to that found in other studies of housing stock in other South American countries: Chile (OYARZO; PEUPORTIER, 2014), Colombia (ORTIZ-RODRÍGUEZ; CASTELLS; SONNEMANN, 2010), and Brazil (PAULSEN; SPOSTO, 2013).

The Brazilian electrical grid is composed of a high contribution of renewable energy, with hydropower is the source for more than 67% of the electricity production (Brasil, 2017c)1; other renewable energy resources (biofuels and waste; solar, tide, and wind) bring the Brazilian renewable electricity contribution near to 80%. This reliance on renewable energy is higher

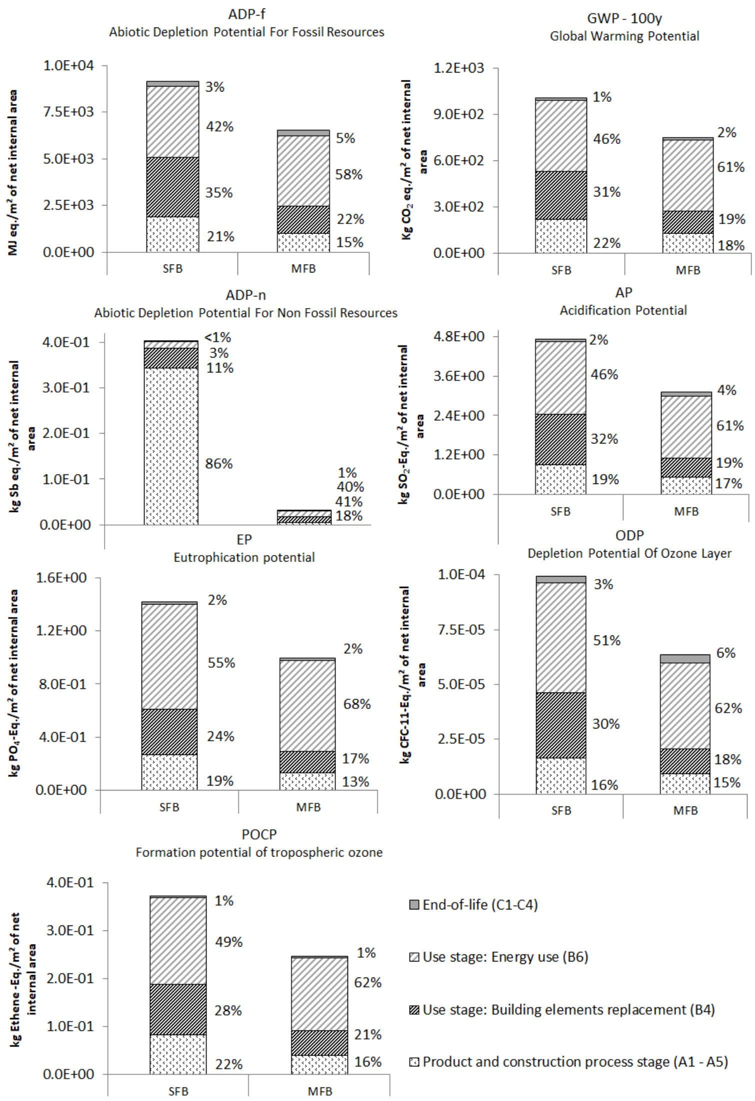
[1] This report is based on the following data sources: Brazilian data: National Energy Balance 2017 (base year 2016). Other countries and regions: IEA Data Services, IEA (International Energy Agency) website and British Petroleum statistics for 2016.

than other Latin American countries such as Colombia (68%), Chile (43%), and Venezuela (63%), as well as the World average (24% renewable) (Brasil, 2017).

Along with energy use (B6), building elements' replacement (B4) was a major impact source, surprisingly greater than that generated during the product and construction process stage (A1-A5). These results are related to the substitutions of materials according to the standard NBR 15.575-1 for the minimum design service life of materials and building elements for residential buildings. This standard design results in a short-service life that differs compared to other countries, e.g., three years for interior painting or 13 years for roofing tiles and interior wall rendering. For example, the United States database RS Means (RSMeans, 2012) considers interior painting as being done only every five years and over 70 years to replace a ceramic tile roof. The German database BNB (BBSR, 2017) considers interior painting as being done every five years, replacement of a tile roof every 50 years, and 50 years for interior wall rendering. Comparing the replacement stage with the other stages, its impacts range from 21%–35% considering total life-cycle impacts for the SFB (the exception is the ADP-n, which is 11%) and for the MFB the range is 17%–22% considering total life-cycle impacts. This was also observed by Dixit et al. (2012), who reported that construction materials that may not consist of high-initial impacts require significant maintenance impacts. Note, there is a high uncertainty related to the building elements replacement: As demonstrated by Hoxha et al., (2017), an extensive range exists in the potential service life of non-structural components because the end-of-life can be related to the user behaviour and linked with trends and market incentives. Beyond user behaviour, substitutions related to service life and performance of construction materials should be considered. The data from the Brazilian standard considers the worst-case scenario, i.e., low-performing materials necessitating frequent replacement. Despite these issues, Cabeza et al. (2014) states that the decision-making process should consider materials performance in use due to replacement impacts.

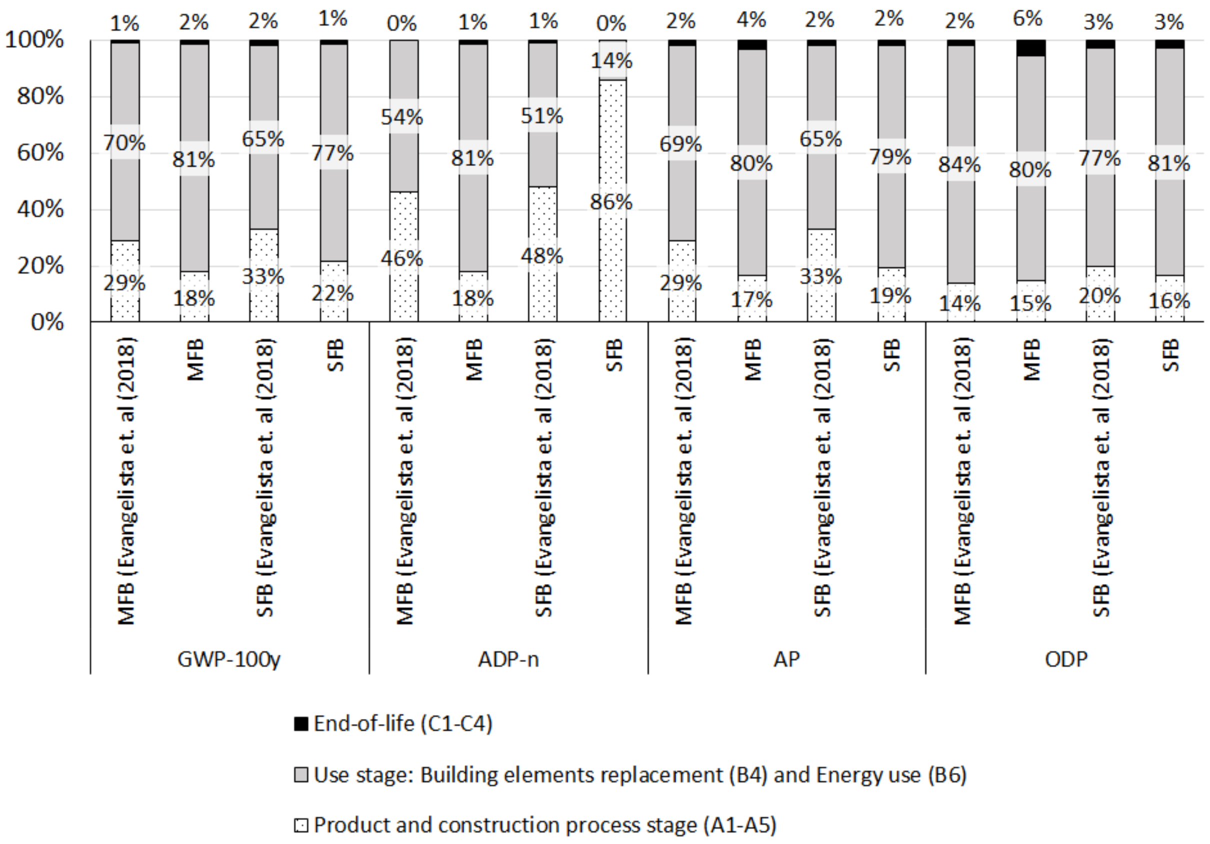
The EOL stage showed the lower participation in all impacts for the MFB (1% to 5%) and SFB (<1% to 3%). Note: as the EoL inventory was not regionalized because a lower variation is expected. Regarding the whole life cycle, the operational energy use (module B6) is the most impactful stage in both dwellings for the majority of the impact categories. Energy use is a well-known impact generator in buildings due to its larger share in life-cycle impacts (CABEZA et al., 2014) and continues to be the highest reported impact (ANAND; AMOR, 2017). A critical review from Ramesh et al. (2010) shows that 80–90% of the impacts, ranging from 150-400 kWh/m2 per year as a world average are due to use by residential customers. Based on the assessment conducted herein, operation energy use represents between 40–68% of impacts contribution (except in the case of ADP-n to SFB which is 3% due to its high impact on the product and construction process stage), which calculated 41 kWh/m2 per year for the evaluated case studies. The difference may be the results of assumptions made that are unique to Brazil, especially in the case of low-income dwellings in a humid subtropical climate. Similar energy-use trends can be observed in a low-income dwelling in the city of Brasilia (Brazil) (PAULSEN; SPOSTO, 2013).

Figure 5 - Impact results for single-family building (SFB) and multi-family building (MFB) for Abiotic Resource Depletion Potential for fossil resources (ADP-f), Global Warming Potential for a 100-year time horizon (GWP-100y), Abiotic Resource Depletion Potential for Non fossil resources (ADP-n), Acidification Potential (AP), Eutrophication Potential (EP), Depletion Potential of the Ozone Layer (ODP) and Formation potential of tropospheric ozone (POCP) per m² (NIA) using regionalized data, and contribution (in %) of product and construction process stage (A1-A5), use stage (B4 and B6) and end-of-life (C1-C4)



Comparing the impacts per life-cycle stage, per typology, with other researchers studying Brazil's impacts (Figure 6), the operational impacts showed higher contributions over the other stages. The range of values was similar in almost all comparisons. The values for MFB obtained herein versus the MFB obtained by Evangelista et al. (2018) was 80–81% versus 54–84%, respectively; the values for the SFB obtained herein versus the values for the SFB obtained by Evangelista et al. (2018) was 14–81% versus 51–77%, respectively, except for the SFB in ADP-n category due to the galvanized steel from the roofing. The operational impacts obtained by Evangelista et al. (2018) were similar, even though there were some differences in the assumptions, e.g., consideration of water consumption and electricity consumption.

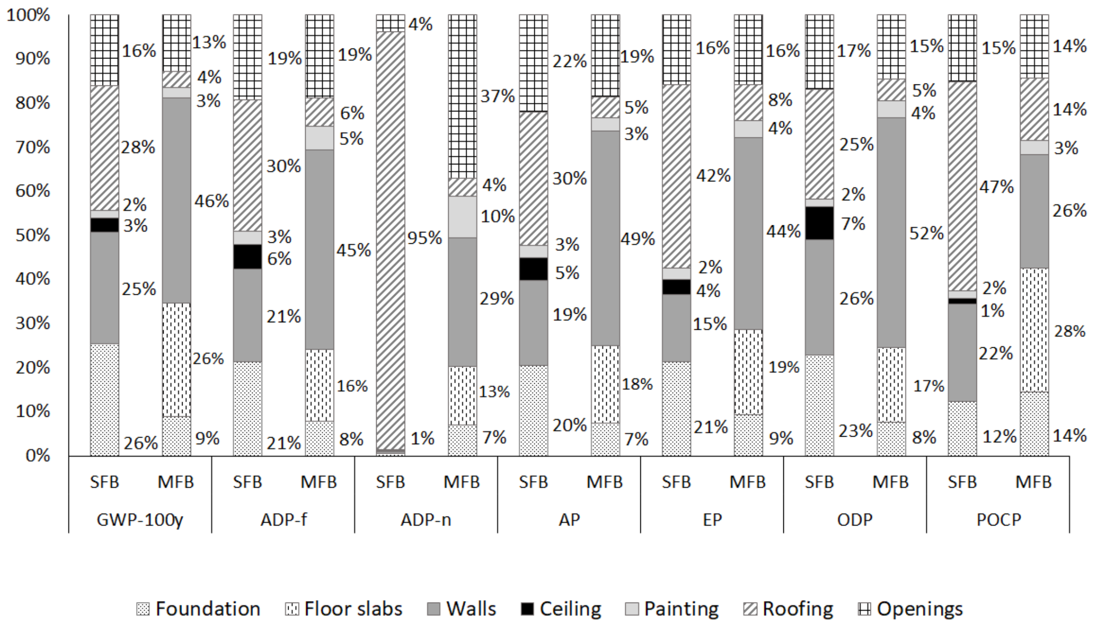
Figure 6 - Comparison (in %) per life-cycle stage for both typologies, single-family building (SFB) and multi-family building (MFB) for Global Warming Potential for a 100-year time horizon (GWP-100y), Abiotic Resource Depletion Potential for Non fossil resources (ADP-n), Acidification Potential (AP) and Depletion Potential of the Ozone Layer (ODP) impacts using regionalized data in the product and construction process stage (A1-A5), use stage (B4 and B6) and end-of-life (C1-C4) versus the results from other authors. CS2 designated by Evangelista et al. (2018) is equivalent to MFB and CS4 designated by Evangelista et al. (2018) is equivalent to SFB.



3.3.1 Analysis of the contribution during the product and construction process stage

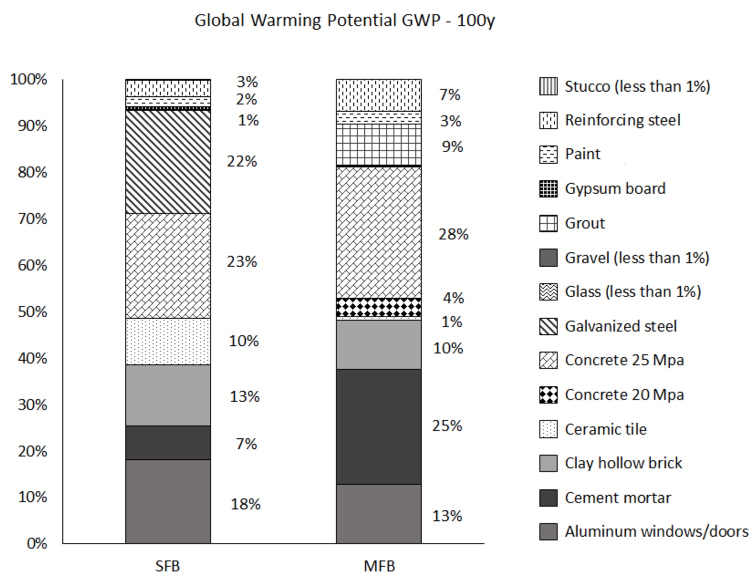
Figure 7 shows the participation of each building element impacts in the product and construction process stage (modules A1 to A5) calculated using regionalized data. In both cases, different trends are observed between the typologies (SFB, MFB) for all evaluated categories. For MFB, the wall system predominates as the most impactful in five categories (from 44%–52%), except for POCP where floor slabs predominate (28%), and for the ADP-n, which the openings (i.e., windows) were 37% of the total impact during the product and construction process stage. In contrast, for the SFB, roofing appears as the most impactful system over all others in six categories, except for the ODP; it was 26% of the total impacts followed by roofing and foundation system, respectively. These differences are due to the specific configuration of each project. While the construction of walls in the MFB accounted for 60% of the mass (Table 5) of the building, in the SFB this value is lower, naturally. Similarly, roofing accounts for 21% of the SFB mass (Table 5), while in MFB its share is 1.5%. These results are not surprising and confirm the importance of considering different dwellings characteristics during the design phase. In both cases, high optimization potential in materials selection has been observed, especially for walls (SFB, MFB), openings (SFB, MFB), roofing (SFB), and foundations (SFB), as can be seen in Figure 7.

Figure 7 - Contribution comparison (in %) per building element for both typologies, single-family building (SFB) and multi-family building (MFB) for Global Warming Potential for a 100-year time horizon (GWP-100y), Abiotic Resource Depletion Potential for fossil resources (ADP-f), Abiotic Resource Depletion Potential for Non fossil resources (ADP-n), Acidification Potential (AP), Eutrophication Potential (EP), Depletion Potential of the Ozone Layer (ODP); Formation potential of tropospheric ozone (POCP) using regionalized data in the product and construction process stage (A1-A5) for 1m² (NIA).



To elucidate the building elements contribution, the impacts per construction material (modules A1 to A3) was analysed (Figure 8). For analysis and comparison purpose the GWP-100y category is chosen since this category is commonly used by other authors, e.g. Evangelista et al. (2018) and Huang et al (2019). Cementitious materials, metals and ceramic, show the greater contribution in the total impact for both typologies. These results are similar to that reported by Franco et al. (2013), who also applied regionalization for low-rise buildings in Brazil, switching the energy mix where the cement, steel rebar, clay hollow bricks and PVC (polyvinyl chloride) tubing constituted the lion's share of the impact at over 80% embodied CO_2eq. These materials also are hotspots of concern in other countries—such as China (HUANG et al., 2019) —when considering the environmental impact of constructing residential buildings. Note: the ranking may change between different countries. In Brazil, the use of concrete has the most impact while in Shanghai/China it is steel (HUANG et al., 2019). When detailing the volume of these materials used, in the SFB typology metals are the most impactful materials due to the galvanized steel from the roofing and aluminum from the openings, followed by cementitious materials (concrete – 23% and cement mortar – 7%) and ceramic materials (clay hollow brick – 13% and ceramic tile – 10%). The MFB shows similar trends, where cementitious materials, such as concrete – 32%, cement mortar - 25% and grout – 9%, have a greater impact followed by metal materials, aluminum from the openings – 13% and reinforcing steel – 7%.

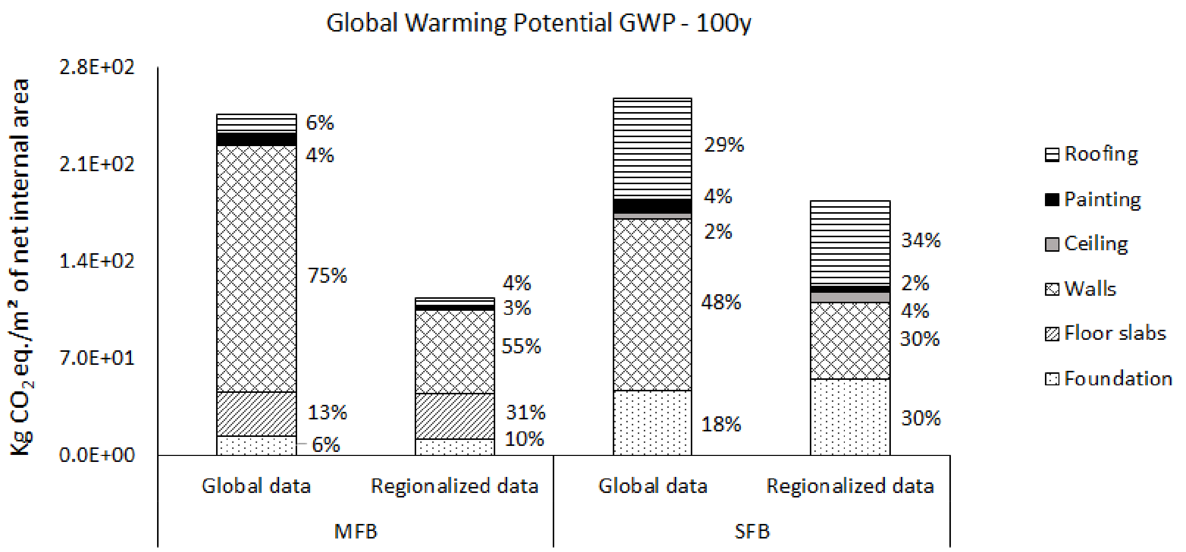
Figure 8 - Contribution comparison (in %) per building material for both typologies, single-family building (SFB) and multi-family building (MFB) for Global Warming Potential 100-year time horizon (GWP-100y) using regionalized data in the product stage (A1-A3) for 1m² (NIA).



3.3.2 Sensitivity analysis of regionalized versus non-regionalized data

Figure 9 presents a comparison of GWP results of the calculations performed using regionalized and non-regionalized (global) data. Note: there is no clear trend between regionalized and non-regionalized data for the evaluated case studies. Figure 9 indicates that neglecting data regionalization may lead to misunderstanding results for these building typologies in Brazil. These differences may be expected but challenging to infer without an appropriate regionalization process because data differences can be related to raw material acquisition, production process, logistics, and national energy matrices.

Figure 9 - Comparative results per building element for both typologies, single-family building (SFB) and multi-family building (MFB) for Global Warming Potential 100-year time horizon (GWP-100y) using global data and regionalized data in the product and construction process stage (A1-A5) for 1m² (NIA).



Specifically, the adaptation of the data on concrete production presented different tendencies (Table 7), which explains the divergences between results for the foundation system as well as the increase in the floor slab results. The R factor [Equation (1)] for the foundation system is between -20% (MFB) and +17% (SFB). While this system presents higher impacts for the MFB when considering global data, the opposite occurs for SFB. This difference is related to the system composition: in SFB, a 25 MPa concrete was applied in the foundations; in the MFB, grade beams are made of 25 MPa concrete and slabs foundations of 20 MPa concrete.

The wall system, which had a high impact factor compared to the other parameters, reduced the GWP (55–66% lower) when regionalized data are applied (Figure 7). This result confirms the importance of regionalization as it strongly affects the results. Openings elements were not compared due to the substantial differences in their characteristics. The available background dataset from Ecoinvent (window frame production, aluminum, U=1.6 W/M²k) (Ecoinvent, 2016b) has a thermal transmittance of U=1.6 W/M²k, which performs better compared to Brazilian windows in both case studies (U=5.9 W/M²k) (MORAGA, 2017).

Table 7 - Global Warming Potential 100-year time horizon (in kg CO_2-Eq) per life-cycle inventory source for both types of concrete used in both typologies, single-family building (SFB) and multi-family building (MFB), results per cubic meter of concrete.

Material description	Global	Regionalized
Concrete, 25 MPa	249.5	261.1
Concrete, 20 MPa	242.2	191.8

An important reduction in MFB roofing system impacts (approximately 65%) is observed. In contrast, in SFB the differences are lower, probably due to the galvanizing process considered in the roofing frame (according to the project specifications).

Finally, the overall results of the dwellings presented a reduction in GWP impacts between 29 and 54% when regionalized data are applied. For all systems, the obtained results are in accordance with the research by Silva et al. (2017) who reported that differences between adapted and non-adapted impact can result in discrepancies ranging between 10%–255%, with an overall average difference of 69%.

These results indicate that a guideline specifying a common methodology to assess the life cycle of buildings is needed, as results presented herein demonstrate that the results may vary substantially. This guideline is key especially for developing countries, who still lack critical databases that limit the effectiveness of conducting a valid LCA. The results infer that the use of global data may indicate hotspots that are not representative of the local scenario, indicating the need for data regionalization. Note: a comparison of different LCAs can only be valid if a common methodology is applied, or national or regional databases with regionally differentiated life-cycle assessment data that is tailored to the construction sector are available. These issues are some of the main objectives of the IEA EBC Annex 72 initiative (IEA; EBC, 2019).

3.4 CONCLUSIONS AND FUTURE TRENDS

Performing LCA in buildings in developing countries is constrained by the lack of inventory data in construction materials. This study is one of the first Brazilian study of LCAs of buildings using inventory data regionalized to local construction practices. This study demonstrates the importance of incorporating regional data since environmental impacts vary significantly compared to non-regionalized data. The differences found once when LCAs are performed that reflect construction practices and materials vernacular to Brazil validate this conclusion. The application of regionalized data can be used in the design phase to prioritize the selection of products with enhanced environmental performance through technical improvements and innovations in the construction sector. The results presented herein show the relevant differences among the construction systems from the two assessed dwellings, acknowledging the importance of evaluating different housing typologies to identify hotspots.

This study also highlights the importance of the joint efforts carried out by several research groups and government agencies to catalogue a regional inventory of data of construction materials suitable for Brazilian housing stock. Future research may consider the influence by the number of users and their behaviour when domiciled, as the use stage was shown to have the greatest environmental impact, even more than during the product and construction process stage. Currently, there is no consensus regarding estimating the operational life cycle of a building because energy consumptions are likely to change in a long term. Incorporating EoL scenarios in the building design phase is needed to reduce the impact of construction and the amount of demolition waste, even as a city faces the need for additional housing.

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4 UNCERTAINTIES RELATED TO THE REPLACEMENT STAGE IN LCA OF BUILDINGS: A CASE STUDY OF A STRUCTURAL MASONRY CLAY HOLLOW BRICK WALL[1]

4.1 INTRODUCTION

Given the growing concern of the construction industry and its environmental responsibility toward reducing its environmental impacts (CBIC, 2014), life-cycle based environmental impact studies of the construction industry are now recognized as critical in determining their contribution to global concerns reducing environmental impacts. A Life Cycle Assessment (LCA) quantifies the potential environmental impact associated with a building's life-cycle, from resources extraction, materials production, construction, use, and operation and end-of-life (ISO, 2006a).Thus, quantifying the entire life-cycle of a structure, from the planning process of buildings, to the conceptual decisions, to the supplier's choice of materials, and finally to the labeling and certification of buildings (FRISCHKNECHT et al., 2015) is necessary. The growing number of databases and methods available (HÄFLIGER et al., 2017) now make the assessment of the environmental performance of buildings based on LCA more commonplace.

The use stages of the life-cycle of a building can account for the majority of its impact, including: maintenance, repair, and replacement of materials, in addition to energy and water consumption. Morales et al. (2019) have identified that energy consumption and replacement operations can account for up to 77% of the Global Warming Potential (GWP) of a Brazilian Public Housing building. On average, the replacement stage is responsible for 24% of its impact. Evangelista et al. (2018) found similar results in studies of Brazilian housing, where about 70% of the GWP impact came from the use stage. Moraga (2017) and Paulsen and Sposto (2013) observed a predominance of the use stage in single family homes over the total impact of Brazilian single-family public housing built using different construction systems. The significant role of the use stage in a building's life-cycle was also observed in studies in Chile (OYARZO; PEUPORTIER, 2014), and Colombia (ORTIZ-RODRÍGUEZ; CASTELLS; SONNEMANN, 2010).

[1] O capítulo já está publicado em formato de artigo e pode ser acessado pelo DOI 10.1016/j.jclepro.2019.119649

These results confirm the importance of reducing the environmental impact of the housing industry during the use stage. That said, there are uncertainties related to modeling, choices of materials, spatial and temporal variability, and sources parameters (HUIJBREGTS, 1998), requiring further study. In the context of a LCA, uncertainty about the validity of various parameters used in the evaluation, such as inventory data, are an example of where the source data may be lacking or non-representative (BLENGINI; DI CARLO, 2010; SU et al., 2016), leading to empirical inaccuracy (HUIJBREGTS, 1998).

These uncertainties may come from data populating the life-cycle scenario modeling (HOXHA et al., 2017). Evaluating the long-term service life (SL) of a structure is a complex and uncertain process since the overall impact of a building is contingent on different stages: materials production, transportation to the construction site, construction of the building, use (energy consumption, water consumption, etc.), building maintenance (necessary to ensure its safety in use), and its final disposal (CEN, 2011a). Quantifying these characteristics requires several simplifications when conducting a LCA. Given the lack of standardization in these procedures makes it difficult to compare the results with studies of different regions, increasing, the uncertainty of the results (SOUST-VERDAGUER; LLATAS; GARCÍA-MARTÍNEZ, 2016).

One example of simplification used in the LCA of a building occurs in the life-cycle scenario modeling where the definition of repair, maintenance, and replacement of materials and systems is considered the stage with the most uncertainties given the lack of databases, statistics, or any other criteria (SOUST-VERDAGUER; LLATAS; GARCÍA-MARTÍNEZ, 2016). Grant et al. (2014) reported that this stage usually receives superficial attention and standard assumptions are made. As the authors point out, the construction materials used during a building's SL varies considerably, and scenarios using standard assumptions can generate incorrect results.

A small number of studies have focused on quantifying the uncertainties related to SL in the LCA of buildings. Some studies have focused on the uncertainty on the construction materials (Grant et al., 2014; Hoxha et al., 2014; Aktas and Bilec, 2012; Grant and Ries, 2012), and others have focused on the whole building (HOXHA et al., 2014, 2017). To date, no study quantifies both uncertainties: inventory data and SL of the materials in the LCA of buildings, and then detailing and comparing the influence of each one.

This paper aims to quantifying the uncertainties related to the modeling of two scenarios from the use stage [according to EN 15978: 2011 (CEN, 2011a)]: construction materials repair (B3 module) and total replacement (B4 module), by comparing different values to the available data of the SL available in the international literature. Inventory data uncertainties were analyzed by using life cycle inventory (LCI) from different regions. The quality of this data was evaluated using the Pedigree Matrix approach (WEIDEMA, 1998).

4.2 SERVICE LIFE OF CONSTRUCTION MATERIALS IN LCA STUDIES

In application of a LCA to a building, the modeling of ongoing maintenance is a complex process that considers the repair and replacement of building materials and systems during their use stage. Due to the difficulty of estimating the maintenance operations of buildings, most studies employ fixed cycles of replacement of materials and systems, which often exclude maintenance and repair of building components (GRANT; RIES; KIBERT, 2014).

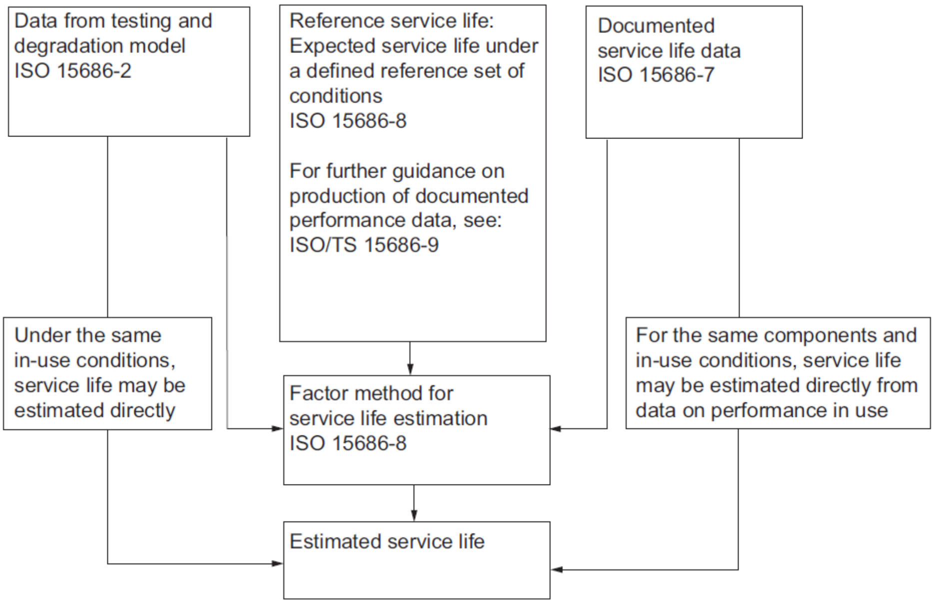
Databases cataloguing the SL of structures play an important role in LCA studies of buildings, enabling the modeling of scenarios to predict the maintenance and renovation of buildings throughout their life-cycle. Although such databases are available, they are often based on different methodologies (KÖNIG et al., 2010).

Another issue associated with the use of these databases is that they are not populated with current data and different calculation methodologies have been employed (König et al., 2010), making comparisons between them even more problematic. Using real-world building maintenance and repair data ensures the efficacy of the model, but time constraints, data acquisition, cost, and temporal relevance remain as challenges. Many empirical studies focus on one or a limited number of materials, so comparisons may require the use of different datasets. Although accelerated tests can be performed; such procedures can be time-consuming and costly (GRANT; RIES; KIBERT, 2014). Considering such variability, the results of a LCA can be significantly dependent on scenarios and assumptions regarding the duration and processes involved in the use stage (BS ISO, 2004).

There are currently three main approaches to predicting the SL of a structure: (i) the principles of structural engineering, which can be used to estimate the structural integrity and fatigue of materials according to physical loading, chemical reactions, and degradation over time; (ii) the factorial method, which provides an alternative approach to predicting the SL of a structure, where a number of factors are used to model the SL of a component; and (iii) the use of empirical data, which according to the authors, is considered the most accurate method for SL prediction (Grant et al., 2014).

Several building standards are used to calculate the SL of a structure: BS ISO 15686-1, 15686-2, 15686-3, 15686-4, 15686-5 15686-6, 15686-7, 15686-8, provide guidelines for planning the SL of new and existing buildings, which allows the modeler to estimate their SL (BS ISO, 2011). Three prediction methods are proposed using this set of standards: (1) data based interpreting the performance of the materials and components in short-term exposure tests; (2) the Reference Service Life (RSL), which is the expected SL of a component under a particular set of in-use conditions; and (3) the SL estimation using the documented service lives (Figure 10) (BS ISO, 2011).

Figure 10 - Approaches to estimating the service life of a structure according to ISO 15686-1 (BS ISO, 2011)



In Brazil, the standard ABNT NBR 15575-1: 2013 is the main standard that mention the SL of residential buildings. This standard requires that buildings must have a minimum level of performance by the different building elements and systems for a given period (CBIC, 2014). The minimum values of the Design Life (DL) are defined, which is an estimated period of time in which a system is designed in order to comply with the performance requirements established in this standard (Table A.1, Appendix A).

Several data that estimate the SL of materials and building elements are available internationally. These include: BEES 4.0, published in the U.S. (Lippiatt, 2007); Mithraratne and Vale (referring to generic typologies of New Zealand construction) (MITHRARATNE; VALE, 2004); and Bundesamt Für Bauwesen and Raumordnung, with SL values for buildings in Germany (BBR, 2001). Environmental Product Declarations (EPD), based on EN 15804:2013, are another source providing information for the life-cycle of entire product (CEN, 2013)

The application of SL date for use in LCA studies requires having a clear understanding of the differences between warranty service life, design (service) life, and real (service) life. According to Kelly (2007), these three concepts have different connotations when related to the SL:

a) A warranty service life is the period of warranty given by the manufacturer during which they will be willing to replace the product.

b) The DL of a component or structure is the period for which the building is designed to perform the function for which it is constructed.

c) Real service life is different from SL warranties and SL design. This concept is related to the "real" life of the component, which is difficult to estimate, but in many cases, it is beyond design SL (KELLY, 2007).

Although the environmental assessment of the building may be linked to one of these three approaches to the SL, the choice for one of them can affect the results substantially. For example, by adopting "warranty service life" data, the assessment results will be related to the manufacturer's warranty, which is maybe be of limited duration compared to the "real" life of the building element. This is an example of some of the uncertainties linked to the modeling of the use stage.

4.3 METHODS

This study follows LCA stages, as described at ISO 14040:2006 (ISO, 2006a), and ISO 14044:2006 (ISO, 2006b).

4.3.1 Objective and scope

The main goal of this LCA was to evaluate the life cycle of one square meter of structural masonry clay hollow brick wall. These type of walls, composed by modular basics units, are made from clay with the addition of water (SOUZA et al., 2016) and joined together by mortar joints (RIZZATTI et al., 2012). Per Evangelista et al. (2018), Grant and Ries (2012), and Ortiz-Rodríguez et al. (2010), a SL of 50 years' was chosen. The building element wall was selected due to its relevance in the total impact assessment of Brazilian housing buildings (MORALES et al., 2019a). This type of construction is broadly used in Brazil (MORALES et al., 2019a; RIZZATTI et al., 2012) and has a wide application in other regions of the globe. Bricks are one of the most sought after building materials used in the construction of various civil engineering structures (MURMU; PATEL, 2018).

The scope included a cradle-to-grave assessment, i.e., the product stage (A1-A3 module), use stage (B3-repair and B4-replacement modules), and end-of-life stage (C1-C4 module). The production of the wall was considered for use in the Porto Alegre's metropolitan area, Rio Grande do Sul state, Brazil. Operational impacts from energy consumption were not considered since the functional unit was one square meter of wall.

4.3.2 Inventory analysis and uncertainty assessment

The LCI data was based on the cut-off system model (WEIDEMA et al., 2013). The clay hollow brick LCI data was based on foreground data from ANICER (2012). The other materials LCI data considered were background data from the Ecoinvent version 3.3 database being regionalized for Brazil (energy matrix, inputs, and amount changes) by Moraga et al. (2018). Table 1 presents the materials considered. The construction and demolition waste (CDW) were treated as inert waste, i.e., consigned to landfill. The landfilling of all CDW generated by construction and maintenance was considered due to the short recycling rates in Brazil. Estimates show that in the year 2015, only 5.3% of inert waste in Brazil had been disposed improperly at an inappropriate location (inert landfill, recycling unit, and transshipment and sorting area) (BRASIL, 2017).

Two kinds of uncertainty were quantified for the inventory uncertainty assessment: (i) the uncertainties related to the LCI data location, which were considered by comparing LCI regionalized data to Brazil (B-LCI) and Global market data (G-LCI) (WEIDEMA et al., 2013) from Ecoinvent v3.3; and (ii) the uncertainties from errors obtained in data collection (WEIDEMA et al., 2013) and data quality indicators through the pedigree matrix approach (WEIDEMA et al., 2013; WEIDEMA; WESNAES, 1997).

A Monte Carlo simulation was used to calculate the uncertainties from data collection and data quality indicators. This method randomly varies all parameters which are restricted by the chosen uncertainty distribution (HUIJBREGTS, 1998). In this study, lognormal distribution was chosen by using 1000 iterations and a 90% confidence interval. To G-LCI, the pedigree matrix (Weidema, 1998; Weidema and Wesnaes, 1997) information was taken from Ecoquery (the Ecoinvent web-interface[1]). For the B-LCI data, the pedigree matrix values were adjusted to reflect data regionalization (Table 8). For the clay hollow brick, the pedigree matrix published in ANICER (2012) was used only for the reliability and representativeness of the data; the other materials parameters were estimated by the authors taking into account Brazilian construction methods.

Table 8 - Materials and inventory data description and Pedigree matrix considered for the study.

(to be continued)

Building element	Materials	LCI regionalized data to Brazil description (B-LCI)		Global data description (G-LCI)		Amount[c] (kg)
		Description of the LCI data applied	Pedigree Matrix[a]	Description of the LCI data applied	Pedigree Matrix[b]	
Internal walls painting	Acrylic Flat Paint	Background data modified from the Ecoinvent process of Alkyd paint production, white, water-based, product in 60% solution state (MORAGA et al., 2018).	(4;4;4;3;3)	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).	0.29
External walls painting			(4;4;4;3;3)	Market for alkyd paint, white, without water, in 60% solution state.		0.29
Internal cement plaster. Layer thickness of 1cm	Cement plaster	Sand process developed according to local production using background data from Ecoinvent (MORAGA et al., 2018). Background data modified from Ecoinvent process Cement mortar (MORAGA et al., 2018) Amount provided by data supplies.	(4;4;3;3;2)	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).	30.36
External cement plaster. Layer thickness of 2.5cm	Cement plaster		(4;4;3;3;2)	Market for cement mortar.		91.86
Clay masonry walls	Clay hollow bricks	Foreground data from ANICER (2012).	(2;3;2;4;4)	Market for clay brick	Transport (1;1; 4;5;4); Clay, electricity and other process (5;5;5;5;1).	105.21
	Mortar for binding	Sand process developed according to local production using	(4;4;3;3;2)	Market for cement mortar.	Cement and sand (4;5;5;5;3);	27.00

[1] www.ecoinvent.org

(conclusion)

	background data from Ecoinvent. (MORAGA et al., 2018). Background data modified from Ecoinvent process Cement mortar Amount provided by data supplies (MORAGA et al., 2018).			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).	
Grout (0.02 m³)	Background data modified from Ecoinvent process Concrete production 20 MPa (MORAGA et al., 2018)	(4;4;3;3;2)	Market for cement production, pozzolana and fly ash 36-55%, non-US; Market for gravel, crushed; Market for sand.	Cement (1;1;2;1;1); Gravel electricity and diesel (2;3;5;5;1); Gravel others (3;3;5;5;1); Sand (3;5;5;5;1); Transport (1;1;4;5;4).	46.19
Steel	Background data modified from Ecoinvent process Reinforcing steel (MORAGA et al., 2018)	(3;3;3;3;4)	Market for reinforcing steel.	Hot rolling steel (1;1;5;5;1); Steel low-alloyed and unalloyed (2;3;5;5;1); Transport (1;1;4;5;4).	1.04

[a] Values from Moraga et al. (2018). [b] Values from Ecoquery (the web-interface at www.ecoinvent.org). [c] Values taken from Morales et al. (2018).

4.3.3 Impact assessment

An impact assessment calculation was performed in OpenLCA software 1.6.3 (ACERO; RODRÍGUEZ; CIROTH, 2016; GREENDELTA, 2019). The impact categories used were recommended by EN 15804: 2013 (CEN, 2013); see Table A.2 (Appendix A).

4.3.4 Definition of the replacement and repair scenarios (B3 and B4 module)

Different scenarios were proposed to discuss the uncertainty related to a lack of SL data pertinent to Brazil; the only data available in Brazil are based on the DL of building elements. Consequently, a comparison with LCA results, which have been applied using documented SL data, might be incorrect due to the different assumptions from use stage modeling.

No replacement data was considered for the SL of the clay hollow bricks due to its structural function, with a minimum SL of 50 years (ABNT, 2013). For the other materials: internal painting, external painting, and cement plaster internal and external cement plaster, the set of SL values described in Table 9 were applied in the replacement scenarios of each material.

Scenarios C1 to C12 are described in Table 9. While Scenarios C1 to C5 refer to specific references, Scenarios C6 to C10 are a combination of references for internal and external covering SL applied by scenarios C1 to C5, changing the painting SL (internal and external) by the SL from EPDs (NSF, 2016a, 2016b).

The EPDs used in this study provide SL data based on industry information. In this sense, their use allows to enlarge the discussion. Thus, in scenarios C6 through C10, the SL data used in the first five scenarios (in the same sequence of appearance) were repeated, and only the SL data of the painting was changed. The EPDs used are related to water-based acrylic paints (NSF, 2016a, 2016b).

In Scenarios 11 and 12, SL data from EPDs were used for the painting (internal and external). Regarding cement plaster (internal and external), a repair (partial replacement of the material) of the system was considered and modeled, and two percentages of repair (10% - C11) and (20% - C12) were foreseen. Although some of the authors suggested SL data for these materials larger than the 50 years defined in the scope, this partial replacement approach was discussed by Grant and Ries (2012). In this sense, Scenarios C11 and C12 were proposed based on the need of punctual repairs to ensure the SL data used covered the system considered.

The calculation of the number of replacement of each building element followed the EN 15978 (CEN, 2011a) criteria, which recommends using an integer number: in the case of partial values of substitutions, the value should be rounded up (CEN, 2011a).

Finally, since the painting process has a shorter SL between the materials analyzed and its relevance during the use stage of the wall, a sensitivity analysis was conducted regarding the number of coatings of paint applied. The replacement Scenarios C1 to C5 were chosen, and the impact differences between one coat (0.15 kg of paint per m² of wall) and two coats (0.29 kg of paint per m² of wall) of paint were compared.

Table 9 - Replacement and repair scenarios used in the study and service life considered per building element.

Scenario	Country of Origin	Service life in years			
		Internal Painting	External Painting	Cement plaster internal	External cement plaster
Scenario C1 - Lippiatt (2007)	USA	4	4	100	100
Scenario C2 - Mithraratne and Vale (2004)	NZL	8	8	100	60
Scenario C3 - NBR 15575-1 (DL minimum) (ABNT, 2013)	BRA	3	8	13	20
Scenario C4 - NBR 15575-1 (DL superior) (ABNT, 2013)	BRA	5	12	20	30
Scenario C5 - Bundesamt Für Bauwesen e Raumordnung (BBR, 2001)	GER	20	20	100	100
Scenario C6 - EPD (paint) (NSF, 2016a, 2016b) + Lippiatt (2007) for cement plaster.	USA	15	5	100	100
Scenario C7 - EPD (paint) (NSF, 2016a, 2016b) + Mithraratne and Vale (2004) for cement plaster.	USA+NZL	15	5	100	60
Scenario C8 - EPD (paint) (NSF, 2016a, 2016b) + NBR 15575-1 (DL minimum) for cement plaster (ABNT, 2013).	USA+BRA	15	5	13	20
Scenario C9 - EPD (paint) (NSF, 2016a, 2016b) + NBR 15575-1 (DL superior) for cement plaster (ABNT, 2013).	USA+BRA	15	5	20	30
Scenario C10 - EPD (paint) (NSF, 2016a, 2016b) + Bundesamt Für Bauwesen e Raumordnung for cement plaster (BBR, 2001).	USA+GER	15[1]	5[2]	100	100
Scenario C11 - EPD (paint) (NSF, 2016a, 2016b) + 10% of cement plaster repair.	USA	15[1]	5[2]	10% of replacement in 50 years	10% of replacement in 50 years
Scenario C12 - EPD (paint) (NSF, 2016a, 2016b) + 20% of cement plaster repair.	USA	15[1]	5[2]	20% of replacement in 50 years	20% of replacement in 50 years

Abbreviations: United States of America (USA), New Zealand (NZL), Brazil (BRA), Germany (GER).

4.4 RESULTS

4.4.1 Comparison between uncertainties related to lci data and uncertainties from SL

Figure 11 and Figure 12 show the potential impacts of the wall's life-cycle for Scenarios C1 to C5. LCI selection highly influence the results, although the applied data were from the same database (Ecoinvent) and followed the same assumptions. Characteristics from each location, such as raw material acquisition, production process, logistics, and national energy matrices (MORALES et al., 2019a), may have influenced these results.

By including the data collection and the uncertainty in the quality of the data, considering the mean, most G-LCI scenarios showed the highest impacts. Meaningful variations of the impact of the life-cycle of the wall were observed, and the Scenario B-LCI overlapped with the G-LCI, which changed the ranking of the results (see Figure 11 and Figure 12). An example is Scenario C5 from G-LCI; although the global data demonstrated a trend showing the highest impacts, Scenario C3 from B-LCI overlapped with C5 G-LCI (considering the mean) in the POCP category. When considering the range of results, Scenario C3 from B-LCI, could have greater impact than Scenario C5 from G-LCI in other categories. Furthermore, Scenario C3 (in both B-LCI and G-LCI) has a higher uncertainty because it has greater material consumption. As the analyzed uncertainty relates to materials, the use stage modeling assumptions are one reason for an increase in this uncertainty. Also, the end-of-life cycle attributes a part of its increase because as the number of replacements grows, the CDW amount grows as well.

Analyzing the contribution differences between each stage, the product stage (A1-A3) has a higher contribution in both scenarios, G-LCI and in B-LCI, outweighing most of the other scenarios (except to B-LCI from ADPN). The mean contribution from the product stage for B-LCI data is 49% to ADPF, 40% to ADPN, 57% to AP, 59% to EP, 62% to GWP-100y, 54% to ODP and 65% to POCP. The G-LCI has mostly higher means than the B-LCI showing 64% to ADPF, 51% to ADPN, 57% to AP, 54% to EP, 68% to GWP-100y, 62% to ODP and 49% to POCP. This overlap from the product stage in both (B-LCI and G-LCI) is mainly related to the impact from clay hollow brick, which was also noted in a previous study from Morales et al. (2019).

Although the use stage (B4-replacement) is not a major contributor, and this stage contribution is similar to that founded in the product stage. To B-LCI data the mean contribution range was 28% (ODP) to 38% (ADPF) of the impact, except for the ADPN category, whereby replacement overlaps the product stage, accounting for an average of 57% for the total impact. For the G-LCI data, the mean contribution range was 30% to GWP-100y and ODP and 49% to POCP.

Figure 11 - Comparison between impacts results to ADPF, ADPN, and AP within global data (G-LCI) and Brazilian regionalized data (B-LCI) along the life cycle of 1m² of wall including the uncertainties analysis results. These scenarios represents SL data as follows: Scenario C1 – Lippiatt (2007); Scenario C2 - Mithraratne and Vale (2004); Scenario C3 - NBR 15575-1 (DL minimum) (ABNT, 2013); Scenario C4 - NBR 15575-1 (DL superior) (ABNT, 2013); Scenario C5 - Bundesamt Für Bauwesen e Raumordnung (BBR, 2001).

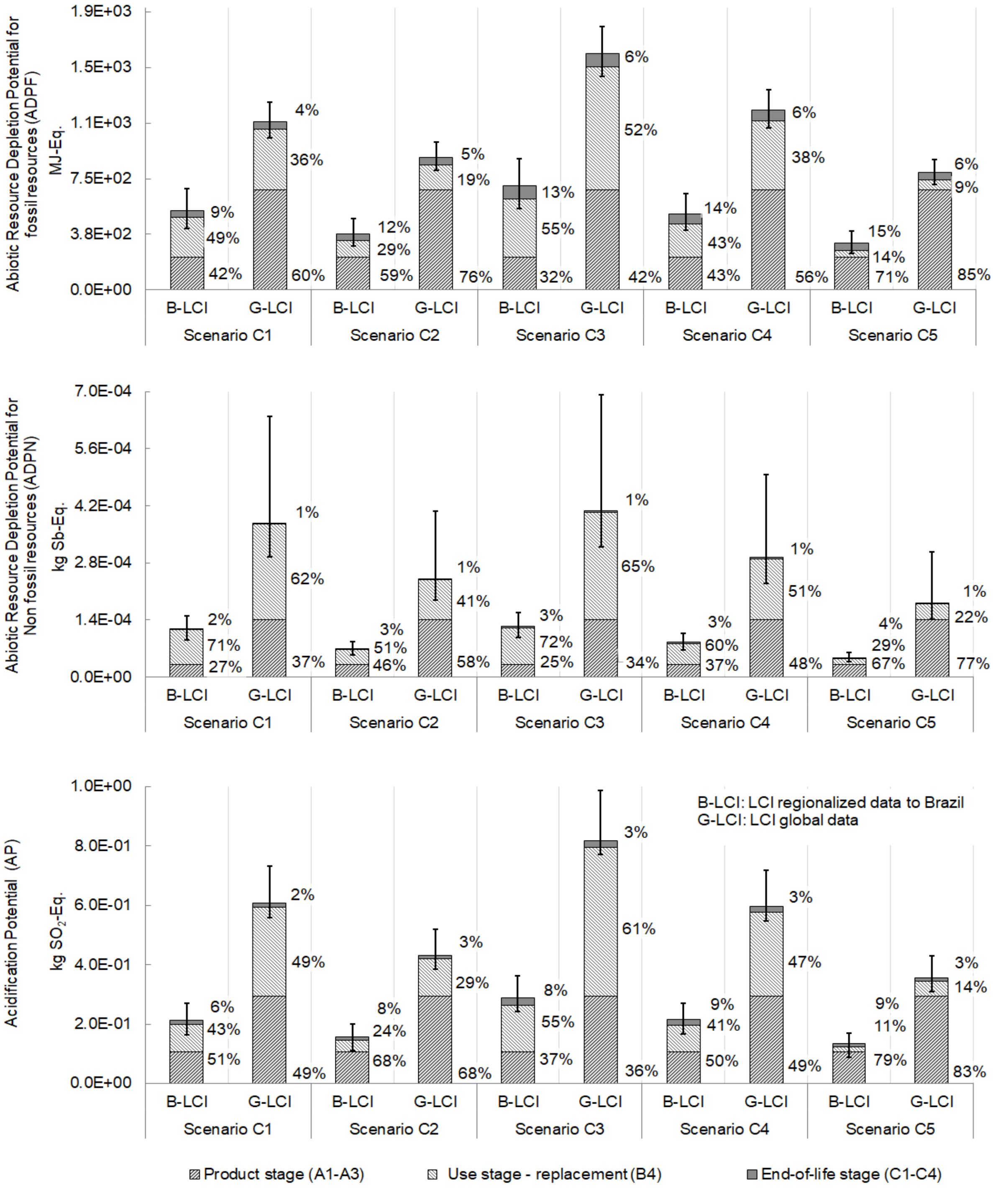
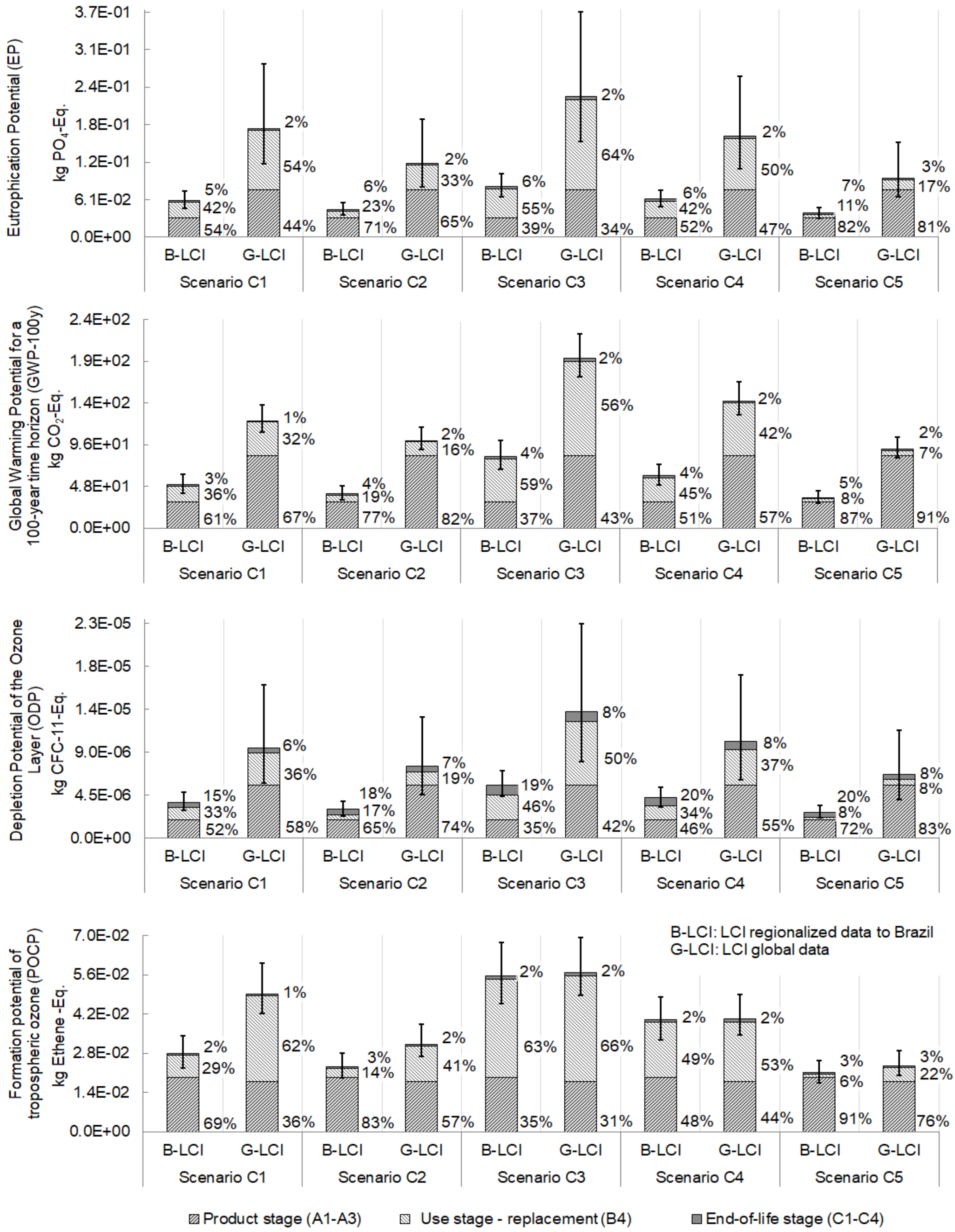


Figure 12 - Comparison between impacts results to EP, GWP-100y, ODP, and POCP within global data (G-LCI) and Brazilian regionalized data (B-LCI) along the life cycle of 1m² of wall including the uncertainties analysis results. These scenarios represent SL data as follows: Scenario C1 – Lippiatt (2007); Scenario C2 - Mithraratne and Vale (2004); Scenario C3 - NBR 15575-1 (DL minimum) (ABNT, 2013); Scenario C4 - NBR 15575-1 (DL superior) (ABNT, 2013); Scenario C5 - Bundesamt Für Bauwesen e Raumordnung (BBR, 2001).



4.4.2 Comparison between replacement and repair scenarios

Table 10 shows the mean results per life-cycle stage for all studied categories and scenarios (C1-C12). A significant influence due to the SL was observed over the total environmental impact. If scenario C5 (lowest impact) is considered as the baseline scenario, an increase between 9.4% in the POCP category (Scenario C2) and 162.4% in the ADPN category (Scenario C3) is observed. Considering the average percentage variation, ADPF shows 48.6% of variation, ADPN - 76.1%, AP - 43.8%, EP - 43.0%, GWP-100y - 46.8%, ODP - 37.5%, and POCP - 52.1%. Scenarios that present higher results are those related to the Brazilian standard NBR 15575-1 DL minimum (C3 and C8), which can be mainly explained by replacing internal and external cement plaster. The scenarios that included repair (C11 and C12) have shown smaller differences than the scenarios that considered total substitution of cement plaster.

Table 10 - Comparative between all scenarios (C1 to C12), using regionalized data (B-LCI), for the impacts: Abiotic Resource Depletion Potential for fossil resources (ADPF), Abiotic Resource Depletion Potential for Non fossil resources (ADPN), Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential for a 100-year time horizon (GWP-100y), Depletion Potential of the Ozone Layer (ODP) and Formation potential of tropospheric ozone (POCP) per 1 m² of wall per life cycle stage including the variation (%) from C5 (base scenario - minor results).

(to be continued)

	Impacts per life cycle stage scenario C1 to C12												
	Stage	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
ADPF	A1-A3	2.2E+02	2.2E+02	2.2E+02	2.2E+02	2.2E+02	2.2E+02	2.2E+02	2.2E+02	2.2E+02	2.2E+02	2.2E+02	2.2E+02
ADPF	B3											7.0E+00	1.4E+01
ADPF	B4	2.7E+02	1.1E+02	3.9E+02	2.2E+02	4.4E+01	1.3E+02	1.3E+02	2.9E+02	2.2E+02	1.3E+02	1.3E+02	1.3E+02
ADPF	C1-C4	4.8E+01	4.7E+01	9.0E+01	7.1E+01	4.7E+01	4.7E+01	4.7E+01	8.9E+01	7.1E+01	4.7E+01	4.9E+01	5.1E+01
ADPF	**Total**	**5.4E+02**	**3.8E+02**	**7.0E+02**	**5.1E+02**	**3.1E+02**	**4.0E+02**	**4.0E+02**	**6.0E+02**	**5.1E+02**	**4.0E+02**	**4.1E+02**	**4.2E+02**
ADPF	Variation (%)	70.7%	21.2%	123.4%	63.4%	0.0%	28.3%	28.3%	91.6%	63.4%	28.3%	31.1%	33.9%
ADPN	A1-A3	3.2E-05	3.2E-05	3.2E-05	3.2E-05	3.2E-05	3.2E-05	3.2E-05	3.2E-05	3.2E-05	3.2E-05	3.2E-05	3.2E-05
ADPN	B3											7.1E-07	1.4E-06
ADPN	B4	8.4E-05	3.5E-05	8.9E-05	5.1E-05	1.4E-05	4.2E-05	4.2E-05	5.8E-05	5.1E-05	4.2E-05	4.3E-05	4.3E-05
ADPN	C1-C4	1.9E-06	1.9E-06	3.6E-06	2.8E-06	1.9E-06	1.9E-06	1.9E-06	3.6E-06	2.8E-06	1.9E-06	2.0E-06	2.0E-06
ADPN	**Total**	**1.2E-04**	**6.9E-05**	**1.2E-04**	**8.5E-05**	**4.8E-05**	**7.6E-05**	**7.6E-05**	**9.3E-05**	**8.5E-05**	**7.6E-05**	**7.7E-05**	**7.9E-05**
ADPN	Variation (%)	147.5%	44.3%	162.4%	79.5%	0.0%	59.0%	59.0%	96.0%	79.5%	59.0%	62.1%	65.3%
AP	A1-A3	1.1E-01	1.1E-01	1.1E-01	1.1E-01	1.1E-01	1.1E-01	1.1E-01	1.1E-01	1.1E-01	1.1E-01	1.1E-01	1.1E-01
AP	B3											3.4E-03	6.8E-03
AP	B4	9.2E-02	3.8E-02	1.6E-01	8.9E-02	1.5E-02	4.6E-02	4.6E-02	1.2E-01	8.9E-02	4.6E-02	4.9E-02	5.3E-02
AP	C1-C4	1.3E-02	1.2E-02	2.4E-02	1.9E-02	1.2E-02	1.3E-02	1.3E-02	2.4E-02	1.9E-02	1.3E-02	1.3E-02	1.4E-02
AP	**Total**	**2.1E-01**	**1.6E-01**	**2.9E-01**	**2.1E-01**	**1.3E-01**	**1.7E-01**	**1.7E-01**	**2.5E-01**	**2.1E-01**	**1.7E-01**	**1.7E-01**	**1.8E-01**
AP	Variation (%)	57.1%	17.1%	114.1%	59.2%	0.0%	22.9%	22.9%	88.4%	59.2%	22.9%	28.3%	33.8%
EP	A1-A3	3.2E-02	3.2E-02	3.2E-02	3.2E-02	3.2E-02	3.2E-02	3.2E-02	3.2E-02	3.2E-02	3.2E-02	3.2E-02	3.2E-02
EP	B3											1.1E-03	2.1E-03

	B4	2.5E-02	1.0E-02	4.6E-02	2.6E-02	4.2E-03	1.3E-02	1.3E-02	3.6E-02	2.6E-02	1.3E-02	1.4E-02	1.5E-02
	C1-C4	2.7E-03	2.7E-03	5.1E-03	4.0E-03	2.6E-03	2.7E-03	2.7E-03	5.1E-03	4.0E-03	2.7E-03	2.8E-03	2.9E-03
	Total	**6.0E-02**	**4.5E-02**	**8.3E-02**	**6.2E-02**	**3.9E-02**	**4.7E-02**	**4.7E-02**	**7.4E-02**	**6.2E-02**	**4.7E-02**	**4.9E-02**	**5.2E-02**
	Variation (%)	53.9%	16.2%	113.5%	59.2%	0.0%	21.5%	21.5%	89.3%	59.2%	21.5%	27.3%	33.0%
GWP-100y	A1-A3	3.1E+01	3.1E+01	3.1E+01	3.1E+01	3.1E+01	3.1E+01	3.1E+01	3.1E+01	3.1E+01	3.1E+01	3.1E+01	3.1E+01
	B3											1.5E+00	3.0E+00
	B4	1.8E+01	7.5E+00	4.9E+01	2.8E+01	3.0E+00	9.0E+00	9.0E+00	4.2E+01	2.8E+01	9.0E+00	1.0E+01	1.2E+01
	C1-C4	1.7E+00	1.6E+00	3.2E+00	2.5E+00	1.6E+00	1.7E+00	1.7E+00	3.1E+00	2.5E+00	1.7E+00	1.7E+00	1.8E+00
	Total	**5.0E+01**	**4.0E+01**	**8.3E+01**	**6.1E+01**	**3.5E+01**	**4.1E+01**	**4.1E+01**	**7.6E+01**	**6.1E+01**	**4.1E+01**	**4.4E+01**	**4.7E+01**
	Variation (%)	42.6%	12.8%	135.1%	72.0%	0.0%	17.0%	17.0%	116.0%	72.0%	17.0%	25.6%	34.3%
ODP	A1-A3	1.9E-06	1.9E-06	1.9E-06	1.9E-06	1.9E-06	1.9E-06	1.9E-06	1.9E-06	1.9E-06	1.9E-06	1.9E-06	1.9E-06
	B3											6.5E-08	1.3E-07
	B4	1.2E-06	5.2E-07	2.6E-06	1.4E-06	2.1E-07	6.2E-07	6.2E-07	2.1E-06	1.4E-06	6.2E-07	6.8E-07	7.5E-07
	C1-C4	5.6E-07	5.6E-07	1.1E-06	8.3E-07	5.5E-07	5.6E-07	5.6E-07	1.1E-06	8.3E-07	5.6E-07	5.8E-07	6.0E-07
	Total	**3.7E-06**	**3.0E-06**	**5.6E-06**	**4.2E-06**	**2.7E-06**	**3.1E-06**	**3.1E-06**	**5.1E-06**	**4.2E-06**	**3.1E-06**	**3.3E-06**	**3.4E-06**
	Variation (%)	38.5%	11.6%	105.7%	55.9%	0.0%	15.4%	15.4%	88.3%	55.9%	15.4%	21.1%	26.7%
POCP	A1-A3	1.9E-02	1.9E-02	1.9E-02	1.9E-02	1.9E-02	1.9E-02	1.9E-02	1.9E-02	1.9E-02	1.9E-02	1.9E-02	1.9E-02
	B3											1.3E-03	2.5E-03
	B4	8.0E-03	3.3E-03	3.5E-02	2.0E-02	1.3E-03	4.0E-03	4.0E-03	3.2E-02	2.0E-02	4.0E-03	5.3E-03	6.5E-03
	C1-C4	6.3E-04	6.2E-04	1.2E-03	9.3E-04	6.2E-04	6.2E-04	6.2E-04	1.2E-03	9.3E-04	6.2E-04	6.5E-04	6.7E-04
	Total	**2.8E-02**	**2.3E-02**	**5.6E-02**	**4.0E-02**	**2.1E-02**	**2.4E-02**	**2.4E-02**	**5.3E-02**	**4.0E-02**	**2.4E-02**	**2.6E-02**	**2.9E-02**
	Variation (%)	31.3%	9.4%	162.1%	87.8%	0.0%	12.5%	12.5%	148.0%	87.8%	12.5%	24.5%	36.4%

Scenario C1 – Lippiatt (2007); Scenario C2 - Mithraratne and Vale (2004); Scenario C3 - NBR 15575-1 (DL minimum) (ABNT, 2013); Scenario C4 - NBR 15575-1 (DL superior) (ABNT, 2013); Scenario C5 - Bundesamt Für Bauwesen e Raumordnung (BBR, 2001); Scenario C6 - EPD (paint) (NSF, 2016a, 2016b) + Lippiatt (2007) for cement plaster; Scenario C7 - EPD (paint) (NSF, 2016a, 2016b) + Mithraratne and Vale (2004) for cement plaster; Scenario C8 - EPD (paint) (NSF, 2016a, 2016b) + NBR 15575-1 (DL minimum) for cement plaster (ABNT, 2013); Scenario C9 - EPD (paint) (NSF, 2016a, 2016b) + NBR 15575-1 (DL superior) for cement plaster (ABNT, 2013); Scenario C10 - EPD (paint) + Bundesamt Für Bauwesen e Raumordnung for cement plaster (BBR, 2001); Scenario C11 - EPD (paint) (NSF, 2016a, 2016b) + 10% repair of cement plaster; Scenario C12 - EPD (paint) (NSF, 2016a, 2016b) + 20% repair of cement plaster.

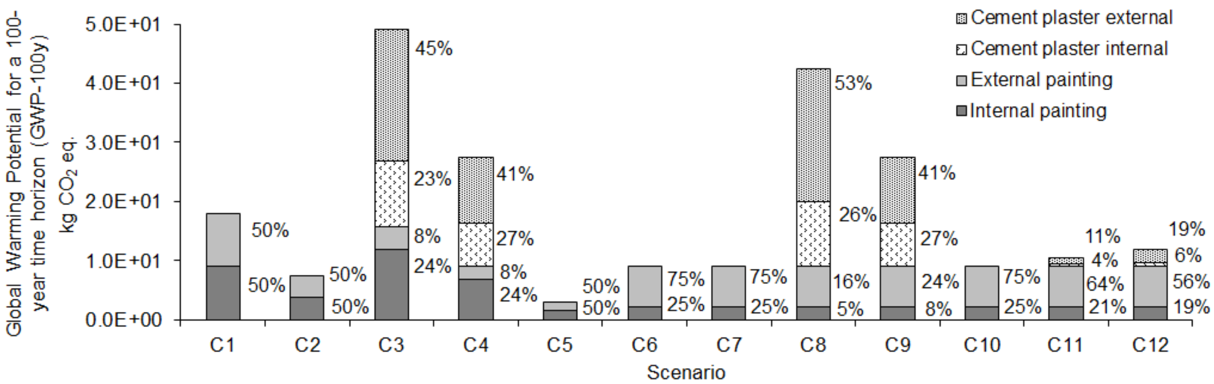
4.4.3 Material contribution analysis in the use stage

Figure 13 shows the results for the use stage of the wall (B3-repair and B4-replacement) for the GWP-100y impact category; for the other impact categories see Figure B.1 (Appendix B) and Fig C.1 (Appendix C). As previously noted, the scenarios are based on the NBR 15575-1:2013 (ABNT, 2013): Scenarios C3, C4, C8, and C9 showed the greatest impact due to its lower SL based on a DL approach.

In GWP-100y category, repainting (both internal and external) is the building element showing the highest impact considering the eight scenarios; their contribution to the total impact is as follows: C1-100%, C2-100%, C5-100%, C6-100%, C7-100%, C10-100%, C11-86%, and C12-75%. In other scenarios, the use of cement plaster (internal and external) showed a higher GWP-

100y impact, their contribution to the total impact is as follows: C3-68%, C4-67%, C8-79% and C9-67%. EP, ODP and POCP category are similar to the results shown for GWP-100y. For the ADPF and ADPN categories, repainting showed the highest impact building element in all scenarios, and for AP it was the highest impact building element in 11 scenarios (with the exception of Scenario C8). The contribution from each building element over the total impact of each scenario for each impact category is shown in Figure B.1 (Appendix B) and Fig C.1 (Appendix C).

Figure 13 - Contribution analysis of each building element during the use stage (B3-repair and B4-replacement) per m² of the wall using regionalized data (B-LCI) and considering C1 to C12 scenario for GWP-100y. Scenario C1 – Lippiatt (2007); Scenario C2 - Mithraratne and Vale (2004); Scenario C3 - NBR 15575-1 (DL minimum) (ABNT, 2013); Scenario C4 - NBR 15575-1 (DL superior) (ABNT, 2013); Scenario C5 - Bundesamt Für Bauwesen e Raumordnung (BBR, 2001); Scenario C6 - EPD (paint) (NSF, 2016a, 2016b) + Lippiatt (2007) for cement plaster; Scenario C7 - EPD (paint) (NSF, 2016a, 2016b) + Mithraratne and Vale (2004) for cement plaster; Scenario C8 - EPD (paint) (NSF, 2016a, 2016b) + NBR 15575-1 (DL minimum) for cement plaster (ABNT, 2013); Scenario C9 - EPD (paint) (NSF, 2016a, 2016b) + NBR 15575-1 (DL superior) for cement plaster (ABNT, 2013); Scenario C10 - EPD (paint) + Bundesamt Für Bauwesen e Raumordnung for cement plaster (BBR, 2001); Scenario C11 - EPD (paint) (NSF, 2016a, 2016b) + 10% repair of cement plaster; Scenario C12 - EPD (paint) (NSF, 2016a, 2016b) + 20% repair of cement plaster.



In Scenarios C6, C7 and C10, external repainting resulted in the largest impact, with 75% of GWP-100y impact for an average contribution is 46% among the 12 scenarios studied. The internal repainting contributed 50% of the replacement stage impact in Scenarios C1, C2, and C5 for an average contribution of 27%.

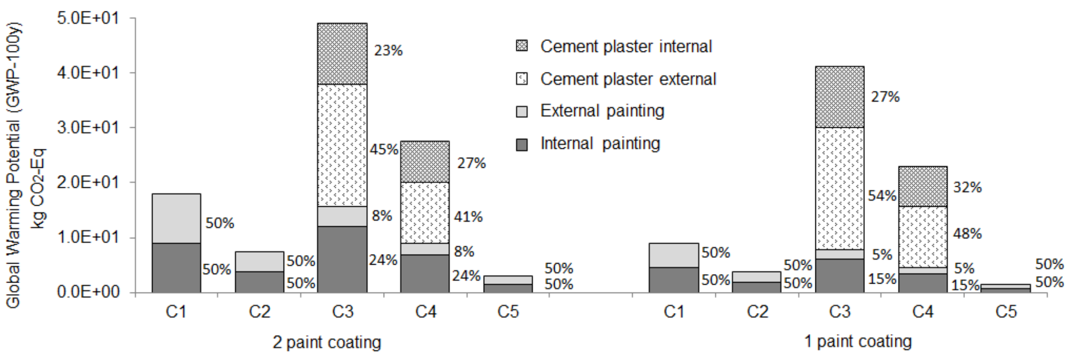
Regarding internal and external wall covering, in six (C1, C2, C5, C6, C7, and C10) of the 12 scenarios studied, no replacement was required because the SL was higher than the SL of the total wall SL (Table 9). In the scenarios requiring total replacement of the external cement plaster, this process had a greater impact (Scenarios C3, C4, C8, and C9). In scenarios C11 and C12, which considered only partial replacement, the external cement plaster was responsible for 11% and 19% of the impact, respectively. Because of the lower number of replacements, the internal cement plaster had a lower contribution, varying from 0% to 27%, with a 9% average impact.

4.4.4 Sensitivity analysis of the number of painting coatings

Figure 14 shows the differences between the application of one or two coats of paint during the use stage (B4-replacement). Considering the whole impact when considering the B4 module, a reduction of 50% in Scenarios C1, C2, and C5 was observed because in these scenarios only the building element paint was replaced. In the remaining Scenarios C3 and C4, a 16% reduction was observed due to the replacement of other building elements (cement plaster internal and external cement plaster.

When considering repairing, two important aspects should be mentioned. External repainting occurs less frequently than internal repainting in Scenarios C3 and C4. It is suggested that this criterion be re-evaluated because external elements suffer greater aggression due to exposure to the environment; Regarding the internal painting, fewer replacements were observed in Scenarios C5–C12 (twice in Scenario C5 and three times in Scenarios C6–C12). Note: because of user habits, repainting often occurs in internal spaces and note because the original paint job has reached the end of its SL.

Figure 14 - Sensitivity analysis of the number of painting coatings during the use stage (B4-replacement) for GWP-100y using regionalized data (B-LCI). Scenario C1 – Lippiatt (2007); Scenario C2 - Mithraratne and Vale (2004); Scenario C3 - NBR 15575-1 (DL minimum) (ABNT, 2013); Scenario C4 - NBR 15575-1 (DL superior) (ABNT, 2013); Scenario C5 - Bundesamt Für Bauwesen e Raumordnung (BBR, 2001).



4.5 SYNTHESIS AND DISCUSSION

The results presented in this study demonstrate how assumptions made during the initial stages of the LCA when defining the scope, such as data-quality requirements and representativeness, or product system modeling choices, or how service life is defined, will influence the environmental impact of the wall. Results show on that these choices populating the LCI can affect the results significantly between the scenarios. These results are in accordance with Morales et al. (2019), who compared the results obtained from a LCI using Brazilian regionalized data and the results obtained from a LCI using Global data to analysis the same building using the same construction materials.

These findings were also confirmed by Häfliger et al. (2017), relevant variations arising from definition of the SL of building materials. This study also demonstrated that such impact studies are highly sensitive to the background data populating the databases, reinforcing the findings reported herein that the data used to populate the LCI might be more relevant than the actual results. In addition, how service life is defined has a noticeable affect for the results in all categories, which might obscure the differences observed in a LCI between systems. This was the case in Scenario C3 from B-LCI and Scenario C5 from G-LCI.

A study of each replacement scenario verified that results from Scenario C3 (DL minimum), using the Brazilian standard NBR 15575-1:2013 (ABNT, 2013), predominated over the others in all categories. These findings show the significant influence on the results when applying DL service life (such as NBR 15575-1) versus a service life based on documented data. The DL service life from NBR 15575-1-1:2013 (ABNT, 2013) is based on three failure criteria: (1) the effects of performance failures, such as life risk or building safety; (2) the degree of complexity in performing general maintenance tasks or repairs (easy or difficult) in the event of performance failure; and (3) the cost to fix the failure (ABNT, 2013).

These criteria are not related to a real building element’s service life but are motivated by cost or technical limitations, and disregarding real conditions, such as the exposure to aggressive agents leading to failure. This feature seems related to the goal of the standard focused on applying the requirements and performance criteria for residential buildings. Building elements that last many years, such as cement plaster, have a significant affect depending on how its service life is defined and is, generally an important contributor to the overall impact. In this sense, repair scenarios should be considered as part of the LCA as it seems more possible that these building elements will be repaired as opposed to being replaced.

The importance of deepening scientific knowledge about the assumptions made in life-cycle modeling when performing LCA of buildings is clear. Defining the parameters used in the methodology for a LCA, such as SL, are essential to simplify the process of performing an environmental evaluation and its subsequent refinement. Models that capture the effects of user behavior throughout the product's life-cycle have not seen widespread use, although they are a necessary step to improve the SL databases (AKTAS; BILEC, 2012b). Considering data from real conditions improves the modeling of the replacement stage, thus reducing uncertainty and providing reliable results.

4.6 CONCLUSION AND FUTURE TRENDS

This paper considers the uncertainties related to the modeling of two scenarios from the use stage [according to EN 15978: 2011 (CEN, 2011)]: construction materials repair (B3 module) and total replacement (B4 module), by comparing different replacement scenarios based on international data. Important aspects to be improved and/or included in these studies are identified and models are constructed. Due to the lack of proper data to model buildings LCA in the Brazilian context, this study applied inventories of regionalized and global data.

The total impacts variation between the 12 scenarios with B-LCI data, considered in this study - from 9.4% (Scenario C2 - POCP category) to 162.4% (Scenario C3 - ADPN category) - reinforce that, when considering replacement scenarios, SL assumptions affect the impact results. The external repainting process is the greatest contributor (on average) on the total impacts of the replacement stage in eight scenarios. In the other four scenarios (based on DL), cement plaster has the highest impacts.

These findings highlighted the need to develop patterns to estimate the SL so these results can be comparable. Also, another point to further understand is the model uncertainties (related to SL) which could be assessed through methods such as Monte Carlo.

Results also point out that LCI selection highly influences the results, as expected. In this sense, impacts calculated from the G-LCI are higher than those from B-LCI in most scenarios. Further studies are needed to better understand the impacts of this decision.

The selection of proper SL models is key for improving buildings' sustainability. This study enhances the understanding of the consequences of this selection in buildings LCA, which results dependent on initial aim and scope definitions. Finally, results reinforce that inadequate premises of building elements life-cycle may lead to mistaken decisions during the design phase.

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5 THE INFLUENCE OF MONTE CARLO PARAMETERS ASSUMPTIONS IN THE UNCERTAINTY ANALYSIS OF BUILDING ELEMENTS SERVICE LIFE: STATISTICAL ANALYSIS[1]

5.1 INTRODUCTION

Service life estimation of building elements is critical for Life Cycle Costs Analysis and Life Cycle Assessment. In both applications, the service life plays an important role that has a great influence on the analysis and ultimately the decisions made. (BAHR; LENNERTS, 2010). Considering that the service life can affect the results, it is important to take the uncertainties into account to avoid misrepresentation of the results at the decision-making stage (ROBATI; DALY; KOKOGIANNAKIS, 2019) and make good decisions understanding the uncertainty in and divergence between outcomes for different product systems (LLOYD; RIES, 2007).

Uncertainties are related to information that is unavailable, wrong, unreliable, or show a certain degree of variability. It can be related to different sources such as data for which no value is available; data for which an inappropriate value is available; or data for which more than one value is available (HEIJUNGS; HUIJBREGTS, 2004). Huijbregts (1998) categorized the uncertainties as (1) parameter uncertainty; (2) model uncertainty; (3) uncertainty due to choices; (4) spatial variability; (5) temporal variability and (6) variability between objects/sources (HUIJBREGTS, 1998). According to Lloyd and Ries (2007) uncertainty is modeled as parameter, scenario, or model uncertainty. European Commission (2010) categorized the uncertainties in LCA results as associated to the inventory and impact assessment data; the assumptions that are made when constructing the system; and the choices that are made on key decisions.

Different methods have been used for conducting LCA under uncertainty: parameter variation/scenario analysis; analytical methods (HEIJUNGS; HUIJBREGTS, 2004); sampling methods (also known as stochastic methods), such as Monte Carlo (MC) simulation and non-traditional methods, such as fuzzy set theory (HEIJUNGS; HUIJBREGTS, 2004; LLOYD; RIES, 2007). Stochastic modeling is one of the most applied methods followed by scenario modeling and fuzzy data sets. The most common stochastic model used (LLOYD; RIES, 2007),

[1] O capítulo está em processo de submissão em formato de artigo.

MC simulation may be defined as a method for obtaining estimates of the solution of mathematical problems by means of random numbers, obtained through a roulette-like machine of the kind utilized in the casinos of Monte Carlo, which named the method (ZIO, 2013). In MC simulation the distribution of outcomes is calculated by iteratively running the model with parameter values randomly selected based on a probability distribution (HEIJUNGS; HUIJBREGTS, 2004).

MC simulation has been applied in LCA to quantify uncertainties by several authors: Blengini and Di Carlo (2010); Häfliger et al. (2017); Sonnemann, Schuhmacher and Castells (2003); Su et al. (2016). To run MC simulation the specification of a distribution describing the potential range and likelihood of values of every stochastic parameter is required. Commonly used distributions are normal, lognormal, uniform, triangular, beta, t-distribution, pert, and gamma. (HEIJUNGS; HUIJBREGTS, 2004; LLOYD; RIES, 2007).

MC uses the given distribution for each parameter, and generates output values that reflect the combined parameter uncertainties (HUIJBREGTS, 1998). So, to perform MC simulation the uncertainty distribution from the sample must be specified (HEIJUNGS; HUIJBREGTS, 2004). Some studies mentioned a distribution selection method, e.g., using chi-squared to test the fit between data and the proposed distributions (AKTAS; BILEC, 2012b). Two tests are commonly used to find the goodness-of-fit (GOF) distribution (SILVA; DE BRITO; GASPAR, 2016). Roughly one-half of studies explicitly discuss the distribution selection process. (LLOYD; RIES, 2007). To fit the distribution with the data a test is recommended if sufficient data is available (LLOYD; RIES, 2007; SONNEMANN; SCHUHMACHER; CASTELLS, 2003).

Among the studies that used the MC simulation method to characterize the uncertainties from service life, the most frequently used distribution was the normal distribution (HÄFLIGER et al., 2017; ROBATI; DALY; KOKOGIANNAKIS, 2019; SILVESTRE; SILVA; DE BRITO, 2015). However, other studies used other distributions such as Weibull (AKTAS; BILEC, 2012b), gamma (SILVA; DE BRITO; GASPAR, 2016), and the triangular distribution (AKTAS; BILEC, 2012b; SU et al., 2016). A focus on the best practices for selecting probability distributions for different types of parameters and technologies, and the methodology for quantifying the uncertainty of nonlinear parameters is important to avoid their arbitrary assignment (SU et al., 2016).

In this sense, analyzing the different potential distributions for service life data is necessary, since there is a lack of discussion of the distribution influence over the results when a stochastic approach such as Monte Carlo simulation is applied. Hence, the main purpose of this work is to examine and discuss the influence of the assumptions related to the Monte Carlo simulation of service life.

5.2 METHODS

The MC simulation approach is chosen to discuss the service life uncertainty in LCA of buildings because it is a powerful modeling tool for the analysis of complex systems, due to its capability of achieving a closer adherence to reality (ZIO, 2013).

This study follows two steps: i) Data collection and data analysis ii) Uncertainty Analysis.

5.2.1 Data collection and data analysis

The service life models used have been collected from an international literature review as in Adalberth (1997), Aktas and Bilec (2012b), Hoxha et al. (2014) and Grant; Ries and Kibert (2014). Eleven service life models were ultimately included in the study. The service life data were reviewed and organized by individually observing which materials and building elements represented similar construction types. The data were then classified using ASTM E1557-09 UNIFORMAT II (ASTM, 2015), which is the classification used in one of the most comprehensive life cycle cost databases in United States (RSMEANS, 2012).

For this study, the following fifteen building elements were selected: reinforced concrete slab on grade, reinforced concrete floor slabs, grade beams, external clay brick walls, cement plaster (external), internal clay brick walls, cement plaster (internal), aluminum doors, aluminum windows, roof structural frame, clay tile roofing, concrete stairs, external painting, internal wall painting, and ceiling painting. This choice of building elements is based on a previous building typology studied by the authors (MORALES et al., 2019a).

The descriptive statistics including the standard deviation and coefficient of variation of the service life data are calculated as in Grant, Ries and Thompson (2016) using IBM SPSS 25 (IBM, 2018). The collected data are from 11 different service life models and seven different countries. Service life model characteristics such as geographic location, methodology, and the purpose and objective of the model are noted as well.

The description of each selected service life model is detailed in Table 11. Different methods were used to estimate service life in each case. The great majority of the service life models applied data from professional experience and previous experience, an approach that is indicated by EN 15686 (BS ISO, 2011). USACE US (NEELY et al., 1991), MEANS US (RSMEANS, 2012), and ULC DE (BBSR, 2017) mentioned developing a method that involves collecting data and others resources as computational modeling. Others such as BRI NL (STEENKISTE, 2012) developed a method based on EN 15686 (BS ISO, 2011).

Table 11 - Description of each service life model selected. References: USACE US (NEELY et al., 1991); SABO SE (ADALBERTH, 1997); NZBM NZ (MITHRARATNE; VALE, 2004); HAPM UK (STANFORD, 2010); SBG DE (BBR, 2001); ATHENA CA (ATHENA, 2002); DK US (DELL'ISOLA; KIRK, 2003); BEES US (LIPPIATT; GREIG; LAVAPPA, 2010); BRI NL (STEENKISTE, 2012); Means US (RSMEANS, 2012); ULC DE (BBSR, 2017).

(to be continued)

Service life model	Acronym	Country and year	Methodology	Objective/description
U.S. Army Construction Engineering Research Laboratory (USACERL)	USACE US	United States 1991	Task frequencies were determined by applying professional experience, trade publication data, and data in manufacturers literature. The data base has been reviewed by 13 different maintenance organizations and has been determined to accurately represent the resources required to perform the tasks. A range of values is given to provide more information than one average frequency. A computer program was also created allowing facilities to be modeled by entering the components that comprise the facility given future years resource predictions.	This research was required because designers were not able to obtain reliable maintenance and repair data to support their **life-cycle cost** (LCC) analysis. This data is for use by the U.S. Army Corps of Engineers (USACE) designers in performing life-cycle cost analysis during the design of new facilities. The database provides service life, maintenance and repair frequency, maintenance materials and maintenance costs.
Swedish Association of Municipal Housing Companies	SABO SE	Sweden 1992	Data were taken from Adalberth (1997). Originally was published by Swedish Association of Municipal Housing Companies (SABO), Maintenance norm. Organization or Municipal Housing Companies, Stockholm, Sweden. (1992).	The database provides service life for several building elements.
New Zealand building materials	NZBM NZ	New Zealand 1998	Data were taken from N. Mithraratne, B. Vale. (2004). Originally was published by Alcorn A, Wood P. New Zealand building materials embodied energy coefficients database, vol. II—coefficients. Wellington: Centre for Building Performance	The database provides service life for several building elements.

(to be continued)

			Research, Victoria University of Wellington; November 1998.	
Component Life Manual: Housing Association Property Mutual (HAPM)	HAPM UK	United Kingdom 1999	Data were taken from Stanford III, Herbert, W. (2010). The service life values are based on evaluation of the data from numerous sources, especially the HAPM, which is published by Component Life Manual, Housing Association Property Mutual Ltd. (HAPM), London, UK (E. & F.N. Spon, Andover, Hants, UK.), 1999.	Service life databases provided especially meant for **contractual liabilities** and **insurance purposes**. Established a range of estimated service life values for a wide range of building components.
Sustainable Building Guidelines - Leitfaden Nachhaltiges Bauen (in German)	SBG DE	Germany 2001	The indicated service life refers to the previous experience with these materials.	Provides service life values to evaluate federal properties or buildings of Germany, focusing on the **sustainability of the building** during its planning, construction, operation maintenance, and use.
Athena – Maintenance Repair and Replacement Effects for Building Envelope Materials.	ATHENA CA	Canada and United States 2002	The report was developed based on authors experience and two sources: CSA Standard S-478-95 information and CMHC (Canada Mortgage and Housing Corporation) research report. The information was obtained or verified using the author's previous knowledge to give accuracy.	The Athena Sustainable Materials Institute is a non-profit research collaborative bringing **life cycle assessment** to the construction sector. The publication provides information about the Maintenance Repair and Replacement Effects for Building Envelope Materials.
Dell´Isola and Kirk	DK US	United States 2003	Data collected by the authors through review in 25 different maintenance sources, providing maintenance, repair, and preventive maintenance data.	The database provides service life, maintenance frequency, repair frequency and maintenance costs to enable **life-cycle costs** studies.
BEES Online: Life Cycle Analysis for Building Products	BEES US	United States 2010	The information is based on consensus standards.	**Online** web application implements a rational, systematic technique **for selecting environmentally-preferred, cost-effective** building products and designed to be practical, flexible, and transparent. The database provides service life values.
Building Research Institute- Levensduur van bouwproducten - method	BRI NL	Netherlands 2011	An update of an old Dutch catalog. Using a method, based on the ISO standard, allow to estimate the service life of building materials for the specific project-related situation. Data were taken from Van Steenkiste,	Provides service life to calculate the **life-cycle costs** of a building and determining the maintenance cycles of building components. Support environmental impact analysis of products and buildings as well.

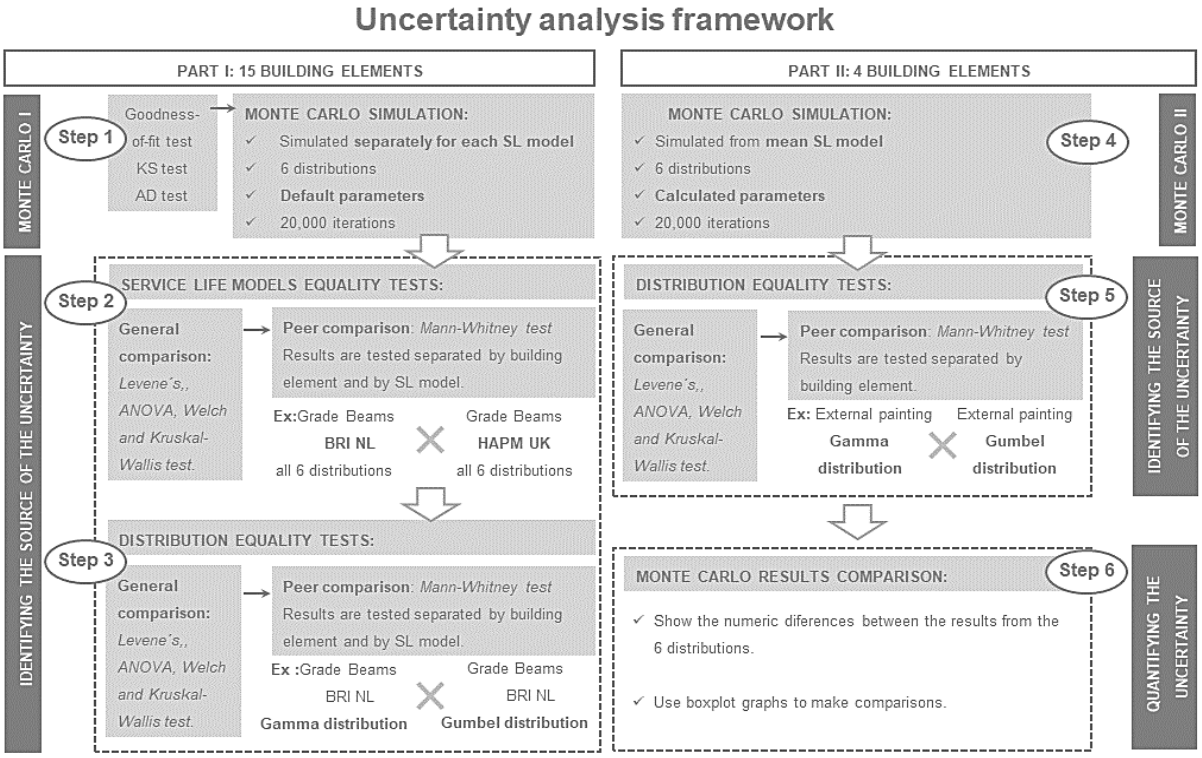
voor referentiewaarden (in Dutch)			Jona. (2012). Originally was published by SBR; VISSERING, C., Levensduur van bouwproducten – method voor reference- waarden, Rotterdam: SBR, 2011, 32p.	
RSMeans Cost planning and Estimating for Facility Maintenance	MEANS US	United States 2012	This book was designed for estimating a wide range of maintenance tasks in diverse environments, updated annually by the publication of a new version.	Provide a complete reference **and cost data source for facility managers**, owners, or other people who manage real estate. The database provides service life, maintenance and repair frequency, maintenance materials and maintenance costs.
Nutzungsdauern von Bauteilen für Lebenszyklusanalysen nach Bewertungssystem Nachhaltiges Bauen (in German)	ULC DE	Germany 2017	The information is based on literature (part of data from Sustainable Building Guidelines) as well as empirical values of experts. Research projects on the subject, service life of other institutions and regulations were evaluated, as well as a questionnaire with specialists.	The service life data from the BBSR are developed for the calculation **of life-cycle costs** (LCC) and **life cycle assessment** (LCA) of buildings in the context of the application of the BNB system (Assessment System Sustainable Building) for federal construction projects in Germany.

2.2 Uncertainty analysis

The goals of the uncertainty analysis were to identify the source of the uncertainties (part I and part II) and quantify the uncertainties (part II). Figure 15 summarizes the workflow and the methodology used.

All fifteen building elements were used to identify the sources of uncertainty and four elements, namely cement plaster (external), external clay brick walls, external painting, and internal painting were used as examples of uncertainty quantification. The four elements were chosen because they represent a range of service life and coefficient of variation. Internal and external painting have relatively short service lives and external clay brick walls and external cement plaster are relatively long. Internal and external painting are both included because internal painting has a greater coefficient of variation than external painting. Although reinforced concrete floor slab has a higher coefficient of variation it is not considered because it is a structural element that is not typically replaced over its service life.

Figure 15 - The workflow and methodology used in this study.



5.2.2 Part I: monte carlo simulation (step 1)

The first step before running the MC simulation is the GOF test conducted to check the distribution´s fit to the set of data (KVAM; VIDAKOVIC, 2007). Two tests commonly used to fit the distribution (SILVA; DE BRITO; GASPAR, 2016) were applied in this study. The Kolmogorov-Smirnov test (KS) is a general test that compares a sample with a given distribution (NEUHÄUSER, 2012). The KS test tends to be more sensitive near the center of the distribution than at the tails (KVAM; VIDAKOVIC, 2007). The, second, the Anderson-Darling test (AD) is a modification of the KS test that gives more attention to the tails (KVAM; VIDAKOVIC, 2007).

The gamma, Gumbel, logistic, lognormal, normal, and Weibull distributions have been identified as suitable to service life data (SILVA; DE BRITO; GASPAR, 2016). These distributions are the most commonly used continuous distributions and the easiest to apply by non-specialists in statistics (SILVA; DE BRITO; GASPAR, 2016). EasyFit 5.6 software was used to find the best fit of distribution to service life data as in Silva et al. (2016). EasyFit supports over 55 continuous theoretical probability distributions and applies both KS and AD tests (MATHWAVE, 2018).

Oracle Crystal Ball software (EPM, 2017a) is used to run the MC simulations with 20,000 iterations. In Part 1, the default parameters in Crystal Ball (EPM, 2017b) (Table 12) were used for the service life model and distribution comparisons. These default values are similar to the error margins reported by Saur et al. (1998) on the assessment of the second order error (data source and representativeness of the data sampling). For each building element service life from each service life model, 20,000 random possibilities are simulated for each of the six distributions. All simulated numbers are applied in the following analysis steps.

Table 12 - Crystal Ball default parameters used in the Part 1 Monte Carlo simulation (EPM, 2017b).

Distribution Parameter Defaults	Gamma	Gumbel	Logistic	Lognormal	Normal	Weibull
Location	Cell value					Cell value
Scale	Absolute cell value divided by 10	Absolute cell value divided by 10	Absolute cell value divided by 10			Absolute cell value divided by 10
Shape	2					2
Mean			Cell value	Cell value	Cell value	
Standard deviation				Absolute cell value divided by 10	Absolute cell value divided by 10	
Likeliest		Cell value				

Source: Reference and Examples Guide - Oracle Crystal Ball (EPM, 2017b).

5.2.3 Part I: identifying the sources of uncertainty (steps 2, 3, and 5)

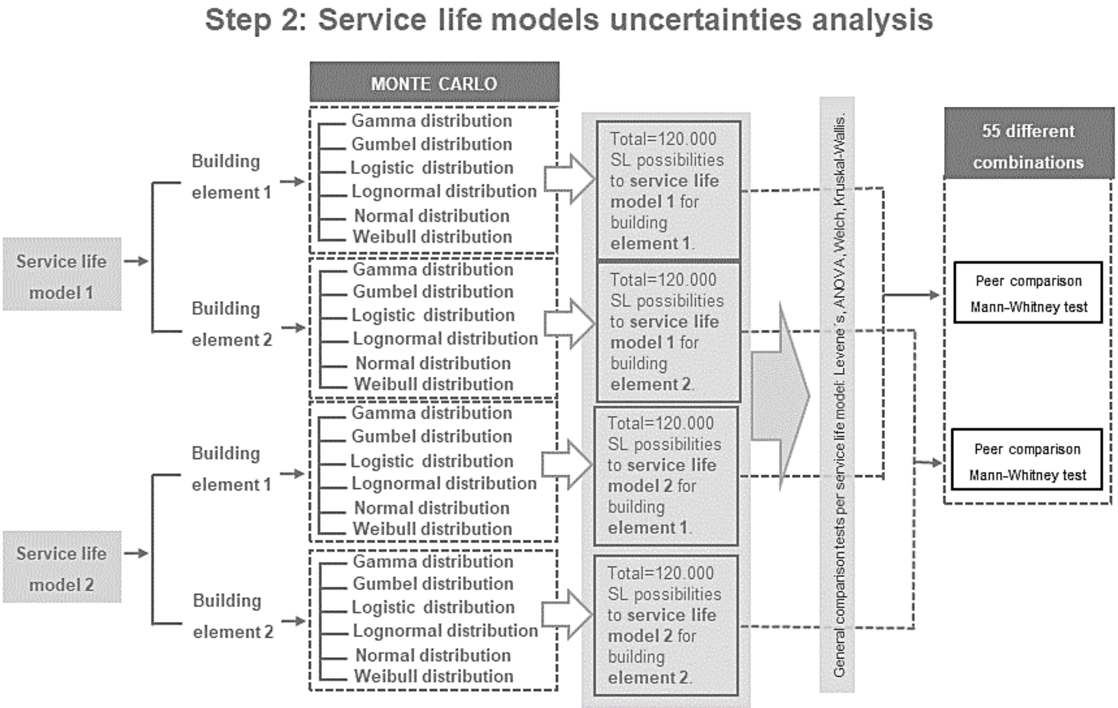
Two uncertainty sources were examined, namely the uncertainty from the service life model (step 2) and the uncertainty from the distribution selected (step 3 and step 5). To identify these uncertainties a statistical analysis is chosen. Figure 16 and Figure 17 shows the analysis flow for both. The data are statistically tested for equality using two groups of tests in both cases. Firstly, a general comparison is made to find overall equality. Secondly, a peer comparison is conducted to identify where the differences are.

1) *General comparison*: The homogeneity of variance test – (Levene´s statistic), the analysis of variance test (ANOVA), the Welch test, and the Kruskal-Wallis analysis of variance of ranks were used for the general comparison. A 95% confidence interval is used in all tests. The ANOVA test is applied because it is robust to departures from normality (GERBER; FINN, 2005; IBM, 2018). The homogeneity of variance is conducted looking for the equality of group variances since it is a condition in ANOVA. As the assumptions of normality and/or homogeneity of variance may be severely violated due to the data characteristics, an alternative procedure, the non-parametric Kruskal-Wallis analysis of variance of ranks that automatically

compare distributions across groups is recommended (GERBER; FINN, 2005). The Welch test also calculates the equality of group means and is included because it is preferred when the assumption of equal variances does not hold (IBM, 2018).

2) *Peer comparison*: to find where the differences are a pairwise analysis is conducted. The Mann-Whitney test - a non-parametric two-sample test of medians - is applied using a 95% confidence interval. This test is useful to find differences in two populations and does not assume that the populations are normally distributed (KVAM; VIDAKOVIC, 2007).

Figure 16 - Analysis flow to determine the uncertainties from service life models.



As can be seen in Figure 16, to test the equalities between the MC simulation results, the data are grouped by service life model and building element. First, the general comparison is performed followed by the peer comparison. The peer comparison considers all fifty-five possible combinations.

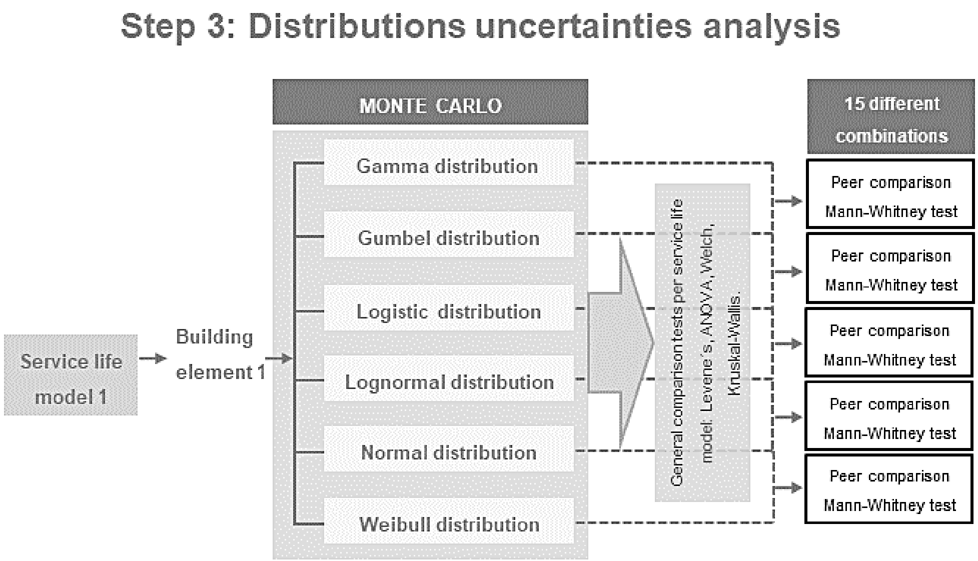
Figure 17 shows the tests carried out to find the influence of the choice of distribution. MC simulation results are grouped by service life model, building element, and distribution. The peer comparison considers all fifteen possible combinations.

To better understand the results a percentage of peer equality is calculated by the Equation (1).

$$P(\%) = \frac{E}{N} \tag{1}$$

Where P is the percentage of peer equality between the groups analyzed; E is the number of pairs that are equal according to the results from the Mann-Whitney test; N is the number of combinations tested excluding repetitions, which means if the service life model 1 is already tested versus service life model 2, the inverse combination service life model 2 versus service life model 1 is excluded from N.

Figure 17 - Analysis flow of uncertainties from the choice of distribution.



5.2.4 Part II: monte carlo simulation (step 4)

In the MC simulation from step 4, the data variation is described in statistical terms as variance, spread, standard deviation, etc. (WEIDEMA et al., 2013). The parameters are calculated using Minitab 18 software (MINITAB, 2017). For each building element, the mean of the service life models is used in each of the six distributions.

5.2.5 Part II - quantifying the uncertainty (step 6)

In step 6, the data variability from distribution choice is shown and examined using boxplot graphs.

5.3 RESULTS AND DISCUSSION

5.3.1 Data analysis

Table 13 shows the service life data for the building elements classified by UNIFORMAT over all service life models. The highlighted cells indicate the outliers (see also Figure A.1 in Appendix A).

Table 13 - Service life values (years) for eleven service life models selected from the literature review classified by the nomenclature provided by ASTM E1557-09 UNIFORMAT II (ASTM, 2015). The highlighted cells correspond to outliers (see also Figure A.1 in Appendix A).

Major Group of Elements	Group of Elements	ATHENA CA	BEES US	BRI NL	DK US	HAPM UK	MEANS US	NZBM NZ	SABO SE	SBG DE	ULC DE	USACE US
A Substructure	A Concrete slab on grade	-	100	100	50	60	75	100	50	70	50	75
	A Grade beams	-	100	100	-	60	75	-	50	100	50	-
B Shell	B Aluminum doors	-	-	75	40	20	50	60	30	50	50	65
	B Aluminum window	25	-	75	35	23	50	60	30	50	50	75
	B Cement plaster (external)	48	100	25	-	35	-	60	-	40	45	300
	B Clay tile roofing	75	70	75	-	-	70	-	30	50	50	70
	B Concrete stairs	-	100	100	50	-	75	-	50	70	50	300
	B External clay brick walls	-	200	-	75	60	75	100	50	120	50	500
	B External painting	8	-	-	-	8	5	8	10	20	15	8
	B Internal clay brick walls	-	200	100	75	60	75	100	50	120	50	500
	B Reinforced concrete floor slabs	-	100	100	50	60	75	-	50	70	50	500
	B Roof structural frame	-	75	100	40	35	-	100	30	80	50	-
C Interiors	C Ceiling painting	8	4	-	7	10	10	8	30	20	5	4
	C Cement plaster (internal)	-	100	25	-	-	75	-	-	25	50	300
	C Internal painting	8	4	-	7	6	5	8	10	20	5	4

The majority of the outliers are from USACE US model, and that is probably the result of differences in the collection and prediction method used. Moreover, some service life models constrained the service life by an estimated building life span, e.g., the ULC DE model only includes building element replacement within the first 50 years (BBSR, 2017). This assumption is based on the German Sustainable Building Assessment (BNB) system which uses a 50-year observation period (BAHR; LENNERTS, 2010; BBSR, 2017). Similarly, DK US, HAPM UK, MEANS US, and SABO SE seem to use the same idea, but it is not clearly mentioned by the authors. The variability of the data is demonstrated at Table 14 that shows the descriptive analysis for the data considered in the study.

Table 14 - Descriptive analysis of service life values (in years) collected from the literature review.

Major Group of Elements	Group Elements	Number of data points	Minimum (years)	Maximum (years)	Mean (years)	Std. Deviation	Coefficient of variation
A Substructure	Concrete slab on grade	10	50	100	73.0	21.0	28.7%
	Grade beams	7	50	100	76.4	23.6	30.9%
B Shell	Aluminum doors	9	20	75	48.9	17.1	35.0%
	Aluminum windows	10	23	75	47.3	19.0	40.2%
	Cement plaster (external)	8	25	300	81.6	91.1	111.6%
	Clay tile roofing	8	30	75	61.3	16.2	26.5%
	Concrete stairs	8	50	300	99.4	83.7	84.2%
	External clay brick walls	9	50	500	136.7	144.1	105.4%
	External painting	8	5	20	10.3	4.9	47.4%
	Internal clay brick walls	10	50	500	133.0	136.4	102.5%
	Reinforced concrete floor slabs	9	50	500	117.2	144.9	123.6%
	Roof structural frame	8	30	100	63.8	28.6	44.9%
C Interiors	Ceiling painting	10	4	30	10.6	8.2	77.7%
	Cement plaster (internal)	6	25	300	95.8	104.2	108.7%
	Internal painting	10	4	20	7.7	4.7	61.5%

The coefficient of variation across building elements by group is highly variable (Table 14). In the substructure group, the variation is lower whereas the shell building elements have a greater variability ranging from 26.5% for clay tile roofing to 123.6% for reinforced concrete floor slabs. This high variability is concentrated in wall elements, such as clay bricks and cement plaster. Additionally, the floor slab element also shows a greater variability. Since the materials which present the greater variability are the largest service life values it is possible to conclude that the variability could be related to the objective of the service life model and/or the prediction method. As shown in Table 11, the service life models have different objectives. While some models are interested in providing data for life-cycle cost analysis (RSMEANS, 2012) others have an interest in providing information for environmental studies (ATHENA INSTITUTE; MORRISON HERSHFIELD, 2006) or insurance markets (STANFORD, 2010). The service life model may constrain the service life of building elements to a shorter estimated building life because, for example, technological or economic factors may make the building obsolete before the end-of-life of the element (BS ISO, 2011).

In the interiors group of elements, the variation between building elements is likely related to user choice. For example, ceiling painting has a 77.7% coefficient of variation and internal painting is 61.5%. The high coefficient of variation represents the uncertainty bounded by the life of the finish and painting for aesthetic reasons.

5.3.2 Uncertainty analysis

Table 15 shows the results obtained from the KS and AD goodness-of-fit tests. The results are organized by distribution and per constructive system. Each best fit distribution per building element is demonstrated by the highlighted cell.

According to the results of the KS test, the best fit of the six selected distributions across all building elements is Weibull, which was the best fit for 40% of the elements tested as could be observed at Table 15. Lognormal fit four building elements or 27% of the building elements. These results are similar to Aktas and Bilec (2012) but they contrast with the assumption of a normal distribution for service life made by other authors: Häfliger et al.. (2017); Robati, Daly, Kokogiannakis (2019). Based on the AD test the ranking changes to lognormal as the best fit (53%) followed by the normal distribution (20% of the building elements). Silva et al. (2016) also found the lognormal as the best fit distribution for the majority of materials durability factors in their study.

Table 15 - Goodness-of-fitness test results from the raw data collected. The highlighted numbers represent the best fit distribution for each building element.

Major Group of Elements	Group Elements	Test	Gamma	Gumbel	Logistic	Lognormal	Normal	Weibull
A Substructure	A Concrete slab on grade	KS	0.1942	0.1989	0.2117	0.2002	0.2010	0.2026
		AD	0.5325	0.6044	0.6605	0.5913	0.5811	0.5544
	A Grade beams	KS	0.2730	0.2843	0.2883	0.2809	0.2698	0.2399
		AD	0.5785	0.6639	0.6817	0.6359	0.5811	0.5566
B Shell	B Aluminum doors	KS	0.2386	0.2632	0.1961	0.2576	0.1926	0.2535
		AD	0.3453	0.5141	0.2268	0.4187	0.2074	0.4173
	B Aluminum window	KS	0.2077	0.2263	0.1640	0.2295	0.1564	0.2197
		AD	0.3516	0.4316	0.4097	0.3977	0.3478	0.3850
	B Cement plaster (external)	KS	0.3125	0.2876	0.3560	0.2355	0.3438	0.2023
		AD	0.9073	1.0166	1.3179	0.5299	1.3717	3.7374
	B Clay tile roofing	KS	0.3520	0.3801	0.3520	0.3434	0.3304	0.2859
		AD	0.8935	1.2673	0.7869	0.8887	0.7210	0.8414
	B Concrete stairs	KS	0.3314	0.3022	0.3716	0.2339	0.3720	0.2366
		AD	0.8768	0.9290	1.2292	0.6555	1.2956	4.6250
	B External clay brick walls	KS	0.3290	0.2970	0.3300	0.2144	0.3238	0.2171
		AD	0.8745	0.9812	1.2896	0.5221	1.3633	2.1880
	B External painting	KS	0.2580	0.2631	0.3233	0.2816	0.3032	0.2917
		AD	0.5751	0.5619	0.8078	0.5815	0.7766	0.9769
	B Internal clay brick walls	KS	0.3239	0.2936	0.3431	0.2007	0.3380	0.1922
		AD	1.0066	1.1103	1.4512	0.5356	1.5506	2.5686
	B Reinforcing concrete floor slabs	KS	0.4328	0.3689	0.4426	0.2848	0.4362	0.2277
		AD	1.5951	1.6203	1.9742	1.0190	2.035	2.0545
	B Roof structural frame	KS	0.1827	0.1931	0.2216	0.2041	0.1989	0.2081
		AD	0.4567	0.5065	0.6249	0.5088	0.5117	0.4711
C Interiors	C Ceiling painting	KS	0.2253	0.2601	0.3330	0.2020	0.3290	0.1805
		AD	0.5293	0.6250	0.9863	0.3800	1.0056	0.9716
	C Cement plaster (internal)	KS	0.2671	0.2611	0.3152	0.1971	0.3174	0.2375
		AD	0.3913	0.5124	0.7329	0.2969	0.7528	1.0460
	C Internal painting	KS	0.2285	0.2169	0.2713	0.1639	0.2748	0.1679
		AD	0.5948	0.5851	0.8832	0.3734	1.0023	1.9897

5.3.3 Monte carlo simulation from step 1

Table 16 shows the mean, 5th and 95th percentile values per distribution and building element. Since the goodness-of-fit tests did not clearly identify one distribution, it was decided to run the MC simulation using all six distributions. The MC simulation includes all 11 service life models. The results per service life model and distribution are available in Tables B.1, B.2, B.3, B.4, B.5 and B.6 in Appendix B.

Table 16 - Mean, minimum (5th percentile), and maximum (95th percentile) service life values (in years) from Monte Carlo Simulation of eleven service life models per distribution and building element.

Major Group of Elements	Group Elements	Service life (in years) per distribution																	
		Gamma			Gumbel			Logistic			Lognormal			Normal			Weibull		
		5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%
A Substructure	Concrete slab on grade	75.6	87.6	107.6	65.0	77.2	94.7	51.5	73.0	94.5	61.7	73.0	85.6	61.0	73.0	85.1	74.7	79.5	85.6
	Grade beams	79.1	91.7	112.6	68.0	80.9	99.1	53.9	76.4	98.9	64.5	76.4	89.6	63.9	76.4	89.1	78.1	83.2	89.6
B Shell	Aluminum doors	50.6	58.7	72.2	43.5	51.7	63.4	34.5	48.9	63.2	41.3	48.9	57.3	40.8	48.9	56.9	50.0	53.2	57.4
	Aluminum window	49.0	56.8	69.7	42.1	50.0	61.3	33.5	47.3	61.3	39.9	47.3	55.5	39.5	47.3	55.1	48.4	51.5	55.5
	Cement plaster (external)	84.5	97.9	120.0	72.6	86.3	105.9	57.2	81.6	105.7	68.9	81.6	95.6	68.2	81.6	95.0	83.5	88.9	95.7
	Clay tile roofing	63.4	73.5	90.3	54.5	64.8	79.3	43.3	61.3	79.2	51.7	61.3	71.8	51.2	61.3	71.4	62.6	66.7	71.9
	Concrete stairs	102.9	119.3	146.7	88.5	105.0	128.7	70.0	99.4	128.5	84.0	99.4	116.6	83.0	99.3	115.7	101.6	108.2	116.6
	External clay brick walls	141.6	164.0	201.5	121.6	144.5	176.9	96.4	136.7	176.9	115.4	136.6	160.3	114.2	136.6	159.1	139.7	148.8	160.3
	External painting	10.6	12.3	15.1	9.1	10.8	13.3	7.2	10.3	13.3	8.7	10.2	12.0	8.6	10.3	11.9	10.5	11.2	12.0
	Internal clay brick walls	137.8	159.6	196.2	118.4	140.6	172.4	93.8	133.1	172.3	112.3	133.0	155.7	111.1	133.0	154.9	136.0	144.8	155.9
	Reinforcing concrete floor slabs	121.3	140.7	173.0	104.3	124.0	152.3	82.6	117.2	151.7	99.1	117.2	137.3	97.9	117.2	136.4	119.9	127.6	137.6
	Roof structural frame	66.0	76.5	93.8	56.7	67.5	82.8	45.1	63.8	82.5	53.8	63.7	74.7	53.2	63.8	74.3	65.2	69.4	74.8
C Interiors	Ceiling painting	11.0	12.7	15.6	9.4	11.2	13.8	7.5	10.6	13.7	8.9	10.6	12.4	8.9	10.6	12.3	10.8	11.5	12.4
	Cement plaster (internal)	99.2	114.9	141.1	85.3	101.4	124.3	67.9	95.9	124.0	81.0	95.9	112.3	80.0	95.9	111.8	98.0	104.3	112.5
	Internal painting	8.0	9.2	11.3	6.9	8.1	10.0	5.4	7.7	10.0	6.5	7.7	9.0	5.8	6.9	8.0	7.9	8.4	9.0

5.3.4 Uncertainty analysis part I - identifying the source of the uncertainties.

Table 17 summarizes the findings by the number and percentage of equal peers.

Table 17 - Results of the peer comparison equality tests of service life models and distributions by building element.

Building element	N	Distribution Analysis			Service Life Model Analysis		
		Number of combinations tested	Number of equal peers	Percentage of equal peers	Number of combinations tested	Number of equal peers	Percentage of equal peers
A Concrete slab on grade	10	150	21	14%	45	7	16%
A Grade beams	7	105	14	13%	21	4	19%
B Aluminum doors	9	135	19	14%	36	3	8%
B Aluminum window	10	150	20	13%	45	4	9%
B Cement plaster (external)	8	120	15	13%	28	0	0%
B Clay tile roofing	8	120	19	16%	28	5	18%
B Concrete stairs	8	120	17	14%	28	4	14%
B External clay brick walls	9	135	17	13%	36	2	6%
B External painting	8	120	12	10%	28	6	21%
B Internal clay brick walls	10	150	20	13%	45	2	4%
B Reinforcing concrete floor slabs	9	135	18	13%	36	4	11%
B Roof structural frame	8	120	14	12%	28	1	4%
C Ceiling painting	10	150	25	17%	45	3	7%
C Cement plaster (internal)	6	90	9	10%	15	1	7%
C Internal painting	10	150	12	8%	45	3	7%

The statistical tests comparing the results of both the MC simulations of the two sources of uncertainties analyzed, distributions and the service life models, were the same (p-value=0.000). In all tests, the null hypothesis that assumes the groups are from equal populations (Kruskal-Wallis test), it has an equal mean (ANOVA), it has equal variances (Levene´s statistic) or it has equal means (Welch test) is rejected. In the distribution comparison, internal painting is the building element with the least number of distributions statistically equal and ceiling painting is the highest, closely followed by clay tile roofing. In the service life model comparison, statistical equality occurs only in cases where the service life before MC simulation was equal, e.g. the service life of clay tile roofing in the BRI NL as well as in ATHENA CA is 75 years and they show equality. The detailed of the Mann-Whitney test results for the building elements that show equality in the peer comparison test between service life models and distributions using are in Table C.1 and Table C.2 in Appendix C.

5.3.5 Uncertainty analysis part II- quantifying the uncertainties.

To conduct step 4 of the study, the statistical parameters used in the MC simulation are calculated from the data and are shown in Table 18. The mean service life shown in Table 14 is used in the MC simulation.

Table 18 - Calculated parameters of service life by distribution and building element used in step 4 to quantify the uncertainties using Monte Carlo simulation.

	Gamma			Gumbel		Logistic		Lognormal			Normal		Weibull		
Building element	Scale	Shape	Location	Likeliest	Scale	Mean	Scale	Mean	Std. Dev.	Location	Mean	Std. Dev.	Scale	Shape	Location
Cement plaster (external)	44.5	1.8	25.0	45.0	38.3	81.6	34.0	81.6	91.1	25.0	81.6	91.1	88.5	1.2	25.0
External clay brick walls	70.6	1.9	50.0	75.0	63.3	136.7	55.7	136.7	144.1	50.0	136.7	144.1	149.4	1.3	50.0
External painting	1.5	6.7	5.0	8.0	2.9	10.3	2.3	10.3	4.9	5.0	10.3	4.9	11.6	2.5	5.0
Internal painting	1.7	4.6	4.0	8.0	2.4	7.7	2.0	7.7	4.7	4.0	7.7	4.7	8.7	1.9	4.0

The results from the MC simulation are summarized in Table 19. The minimum, 5th percentile, mean, 95th percentile, and maximum are shown. The major differences occur at the minimum values. This is due to the differences in the tail's behavior in each distribution, particularly the Gumbel, logistic and normal distributions, that allow variables in some cases to be negative (KRISHNAMOORTHY, 2006). The normal distribution has been adopted in service life uncertainty analysis in some studies: Häfliger et al. (2017); Robati, Daly and Kokogiannakis (2019); Silvestre, Silva and Brito (2015). However, special attention should be given when using Gumbel, logistic or normal distributions, since service life is a nonnegative parameter. In these cases, bounded normal distributions or alternate distributions are recommended (LLOYD; RIES, 2007).

Figure 18 shows the boxplot graph for each building element using 90% as a confidence interval. Observing the quartile groups, a huge variability occurs due to the distribution choice. Weibull is more likely to have relatively high values in contrast with lognormal that generally tends towards lower values. Also, lognormal results were much more concentrated around the mean value. However, when considering only the three nonnegative distributions (gamma, lognormal and Weibull) the minimum, mean and maximum values are similar. Distribution choice does influence service life value.

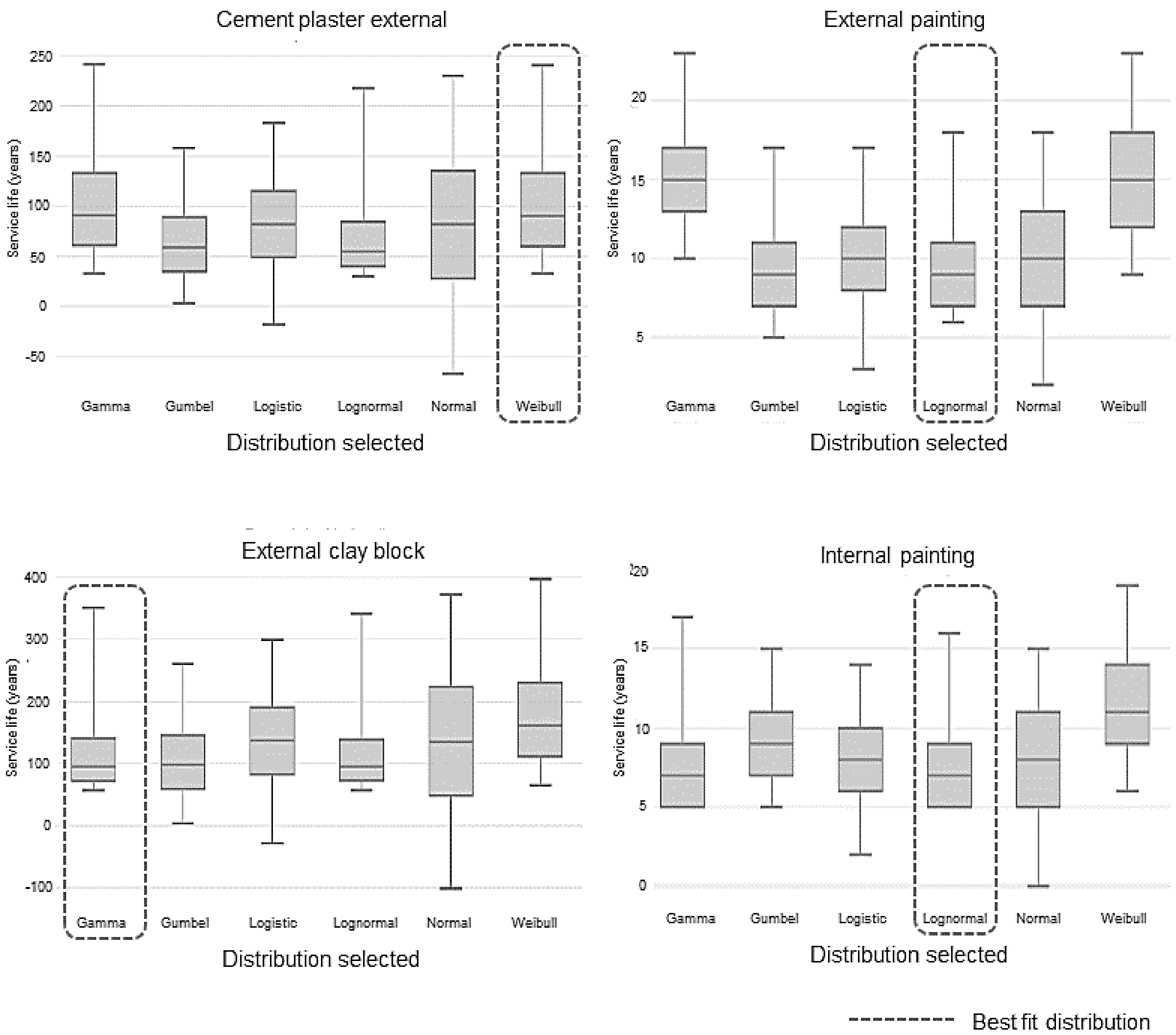
Table 19 - Service life per distribution from Monte Carlo Simulation (resulting using mean SL and calculated parameters). The highlighted cells correspond to the best fit distribution according to the Kolmogorov-Smirnov test results.

Building element		Service life (in years) per distribution						Percentage of variation (%)[1]
		Gamma	Gumbel	Logistic	Lognormal	Normal	Weibull	
Cement plaster (external)	Min.	25	-36	-255	25	-270	25	-1180%
	Min. (5%)	33	3	-18	30	-67	33	-303%
	Mean	108	67	82	82	82	107	-38%
	Max. (95%)	242	158	183	218	230	241	-35%
	Max.	592	419	483	2975	419	593	-86%
External clay brick walls	Min.	50	-75	-432	50	-431	50	-961%
	Min. (5%)	57	4	-28	57	-101	65	-255%
	Mean	139	111	137	135	136	188	-41%
	Max. (95%)	352	261	300	342	373	398	-34%
	Max.	886	694	693	4516	710	943	-85%
External painting	Min.	6	1	-16	5	-9	5	-364%
	Min. (5%)	10	5	3	6	2	9	-80%
	Mean	15	10	10	10	10	15	-33%
	Max. (95%)	23	17	17	18	18	23	-26%
	Max.	37	46	36	100	30	34	-70%
Internal painting	Min.	4	2	-14	4	-12	4	-421%
	Min. (5%)	5	5	2	5	0	6	-100%
	Mean	8	9	8	8	8	12	-33%
	Max. (95%)	17	15	14	16	15	19	-26%
	Max.	35	38	30	116	26	33	-78%

[1]The percentage of variation is the variation between the smallest service life versus the highest per each building element.

These findings also show that the influence of distribution choice on service life values depends on whether the full distribution (minimum value to maximum value) or the 5th and 95th percentiles are used. The distribution has more influence on service life values when the full distribution is used (Table 19) compared to when the values are bounded by the 5th and 95th percentiles (Figure 18).

Figure 18 - Boxplot of the Monte Carlo simulation of service life per distribution using the mean service life and calculated parameters.



Overall, the three nonnegative distributions - Gamma, Lognormal and Weibull - were found to be suitable for service life uncertainty analysis using MC simulation. The lognormal distribution is indicated for random variables that are greater than zero and positively skewed to the right (KRISHNAMOORTHY, 2006). Lognormal was the best fit for external clay brick walls and internal painting. The Gamma distribution was the best fit for external painting. This distribution is typically a good fit in situations where events occur at a constant rate and chances that more than one event occurs in a small interval of time are negligible (KRISHNAMOORTHY, 2006). The Weibull distribution is a generalized extreme value that has been applied to fatigue strength of materials, lifetime of vacuum tubes, electrical insulations and leakage failure of batteries (DEY; YAN, 2016). It is the best fit distribution for external cement plaster.

5.4 CONCLUSIONS AND FUTURE TRENDS

The choice of distribution influences uncertainty analysis results in Monte Carlo simulation. Moreover, service life prediction itself introduces significant uncertainty which indicates special attention is necessary during modeling.

Distributions that allows variables to assume negative numbers, such as normal, logistic, and Gumbel, must be used carefully since service life cannot be negative. In addition, the uncertainty changes based on the adopted confidence interval of the simulated data, which also reinforces the importance of carefully reviewing the assumptions used in the analysis. Gamma, lognormal and Weibull were found to be better choices to assess uncertainties from service life by using Monte Carlo simulation method.

Regarding the data, the range of probability is different when one of the three non-negative distributions is chosen. The lognormal distribution tends to return shorter service life compared to the gamma and Weibull distributions which tend to estimate higher service life than lognormal.

Finally, the objective of the service life model is key to making better choices regarding distributions for service life uncertainty analysis. Lognormal might be a better choice when, in general, a conservative viewpoint with shorter service life estimates are prudent, whereas gamma and Weibull may be acceptable when the building conditions warrant and the risks of a longer estimated service life are tolerable.

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6 THE INFLUENCE OF MONTE CARLO PARAMETERS ASSUMPTIONS IN THE UNCERTAINTY ANALYSIS OF BUILDING ELEMENTS SERVICE LIFE: COMPARISON BETWEEN INVENTORY AND SERVICE LIFE UNCERTAINTIES IN LCA OF BUILDINGS[1]

6.1 INTRODUCTION

The relevance of life-cycle based environmental information is internationally recognized, presenting a high potential to subsidizes the planning process of buildings, from the conceptual decisions to the supplier's choices, materials definition to the labeling of buildings (FRISCHKNECHT et al., 2015), waste management strategies (VASQUEZ, 2016) and others applications.

Life Cycle Assessment (LCA) has a widespread application and has been widely used, but due to uncertainties, some authors point that the final results can be unreliable (HOXHA et al., 2017). Uncertainty analysis is an important aspect of LCA (GROEN et al., 2014). These uncertainties are mainly due to the errors in input parameters, definition of system boundary and scenario assumptions (ZHANG; ZHENG; WANG, 2019); and can be related to the choice of analytical models, which could be summarized as parameter, scenario, and model uncertainties (LLOYD; RIES, 2007; ZHANG; ZHENG; WANG, 2019).

Contemplate explicit interpretation of the degree of uncertainty and sensitivities is important to comparative assertions (GUO; MURPHY, 2012). Uncertainty investigation in LCA gives the variation in the life cycle impacts (ROBATI; DALY; KOKOGIANNAKIS, 2019) and makes the process more reliable.

In the construction industry context, uncertainty assessment, have been focused on different sources: Häfliger et al. (2017) analyzed the uncertainties from database choices, system boundary definitions and replacement scenarios of building materials. Grant et al. (2014) investigated the importance of service life assumptions on building life cycle assessment impact results. Blengini and Di Carlo (2010) evaluated life cycle assessment impacts of building

[1] O capítulo está em processo de submissão em formato de artigo.

through data quality indicators. Recently, Zhang et al., (2019) also assessed building impacts uncertainties detailing the influence of stochastic parameters (distributions) over the results obtained.

There are different methods to assess the uncertainties in LCA: Monte Carlo sampling, Latin hypercube sampling, Quasi Monte Carlo sampling, Analytical uncertainty propagation, Fuzzy interval arithmetic (GROEN et al., 2014) and Taylor series expansion (HOXHA et al., 2014). Between these methods, Monte Carlo sampling has a widespread application (GROEN et al., 2014).

In the uncertainty assessment context a small number of studies have focused on quantifying the uncertainties related to service life in the LCA of buildings: Grant, Ries and Kibert, (2014); Hoxha et al. (2014); Hoxha et al. (2017); Aktas and Bilec (2012a); Grant and Ries (2012); Robati, Daly and Kokogiannakis (2019) and Morales et al. (2019b). However, none of these studies quantify the uncertainties related to Monte Carlo simulation parameters assumptions, such as distributions, arising from the service life; or show the impacts related to these choices over LCA results.

Therefore, this paper aims to analyze the influence of service life uncertainties in LCA of buildings by using the Monte Carlo simulation method. The analysis seeks to identify the effect from the distribution selection in the LCA results focusing on the service life applied to model the replacement stage - B4 module from EN 15978: 2011 (CEN, 2011a). Four building elements are considered in this study: external cement plaster, external clay bricks, external painting, and internal painting. Additionally, a comparison between the inventory data uncertainties obtained by the Pedigree Matrix approach (WEIDEMA, 1998) versus the uncertainties from the service life is conducted.

6.2 METHODS

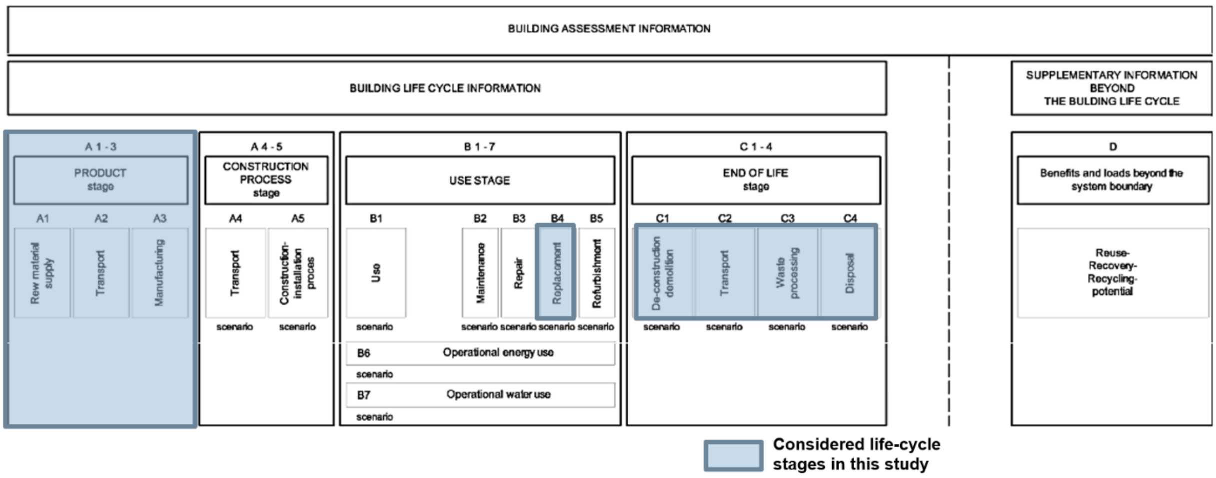
This study follows LCA stages, as described at ISO 14040:2006 (ISO, 2006a) and ISO 14044:2006 (ISO, 2006b).

6.2.1 Objective and scope

The main goal of this LCA is to evaluate the life-cycle of one square meter of four selected shell building elements: external cement plaster, external clay brick walls, external painting, and internal painting. The selection criteria of these building elements are lower service life (in mean) and higher coefficient of variation between the 15 building elements considered in part I of this study (MORALES et al., 2019c). The scope is cradle to grave and contemplates (according to the standard EN 15978:2011): product stage impacts (A1-A3 module), the use stage impacts (B4-replacement module), and the end-of-life stage (C1-C4 module). Figure 19 shows the system boundaries of the study according to EN 15978:2011 (CEN, 2011a).

The study considers global datasets from Ecoinvent version 3.3. This choice is justified by the service life measured in the use stage modeling which is an average from different regions of the globe as detailed in part I of this study: Morales et al. (2019c).

Figure 19 - Considered life-cycle stages in this study according to EN 15978 (2011) for 1m² of each building element.



6.2.2 Inventory analysis

The life cycle inventory data are based on the cut-off system model (WEIDEMA et al., 2013) considering background life cycle inventory data for each building element from the Ecoinvent database version 3.3. Market datasets from the global location are applied. A global dataset represents the average of the global production of some activity - activity represents a unit process of human activity and its exchanges with the environment and with other human activities (WEIDEMA et al., 2013). The market datasets are used because 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, as well as transportation (WEIDEMA et al., 2013).

Table 20 presents the description of the life cycle inventory and the Pedigree matrix data considered. The final disposal process considered is market for inert waste, for final disposal, contemplating the landfill of all construction and demolition waste (CDW) generated by the product and replacement stages following other similar studies such as Silvestre et al., (2015). However, future studies should be extended to include the various potential end-of-life scenarios, where reuse and recycling are factored into the analysis.

Table 20 - Materials and inventory data description and Pedigree matrix considered for the study.

Building element	Life cycle inventory description		Amount[b] (kg)	Functional unit
	Process name in Ecoinvent	Pedigree matrix[a]		
External cement plaster - layer thickness of 1cm.	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	1m²
External clay brick walls - brick dimensions of 19cmx19cmx29cm	Market for clay brick	Transport (1;1;4;5;4); Clay, electricity and other process (5;5;5;5;1).	105.2	1m²
	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	1m²
External painting	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	1m²
Internal painting			0.3	1m²

[a]Values are from Ecoquery (the web-interface at www.ecoinvent.org). [b] Amounts are from Morales et al., (2019a).

6.2.3 Uncertainty analysis

The uncertainties are analyzed in this study through the Monte Carlo simulation (ZIO, 2013). This method has been largely applied to evaluate uncertainties as observed in several LCA studies such as: Robati et al. (2019), Minne and Crittenden (2015), Aktas and Bilec (2012), Hung and Ma (2009), McCleese and LaPuma (2002) and Sonnemann et al. (2003). In the current study, two groups of uncertainties are assessed:

a) Uncertainties associated with service life – by simulating service life variability from collected data (MORALES et al., 2019c). The uncertainties from service life are generated in the Oracle Crystal Ball software (EPM, 2017a) considering 20,000 iterations and a 90%

confidence interval. Six possible distributions to service life data are considered: gamma, Gumbel, logistic, lognormal, normal and Weibull as detailed in part I of this study (MORALES et al., 2019c).

b) Uncertainties associated with life cycle inventory - by using data quality indicators. These uncertainties are calculated by statistical parameters from the Pedigree matrix approach (WEIDEMA et al., 2013; WEIDEMA; WESNAES, 1997). OpenLCA v.1.9 software (CIROTH et al., 2019; GREENDELTA, 2019) is applied to run the simulations considering 1,000 iterations based on other studies such as: Minne and Crittenden (2015) and Robati et al. (2019). In this step of the analysis, the lognormal distribution (WEIDEMA et al., 2013) is chosen and 90% of a confidence interval is considered. The Pedigree matrix (Weidema, 1998; Weidema and Wesnaes, 1997) data is taken from Ecoquery (the Ecoinvent web-interface[1]), the information is also in Table 20.

6.2.4 Impact assessment

Impact assessment calculation is performed in OpenLCA software 1.9 (CIROTH et al., 2019). The impact category assessed is Global Warming Potential for a 100-year time horizon (GWP 100y) according to IPCC (2007). The results are presented only for the GWP impact category to clarify communication. Although LCA of buildings usually covers more than one impact category, Morales et al., (2019b) found similar trends for most other environmental impact categories used in the EN 15804 standard. Besides that, this impact category was also assessed in similar studies: Häfliger et al. (2017), Hoxha et al. (2017), Minne and Crittenden (2015), Silvestre et al. (2015), Grant et al. (2014) and Hoxha et al. (2014).

6.2.5 Scenarios definition

This current study considers that the four shell building elements are hypothetically inserted in a building for which three different life span scenarios are treated: 50 years, 120 years and 500 years. The 50 years (50y) scenario is proposed due LCAs of buildings often use an operational life span of approximately 50 years as can be observed in numerous studies: Adalberth (1997), Grant et al. (2014), Grant and Ries, (2012), Hoxha et al. (2017), Nykjær et al. (2017), Zhang et al. (2019) and Morales et al. (2019b). Also, 50 years is the minimum life span recommended by the Brazilian standard ABNT 15575:2013 (ABNT, 2013). Otherwise, some authors have

[1] www.ecoinvent.org

been mentioned a great variability when service lives higher than 100 years are considered in comparison to 50 years' service lives (HÄFLIGER et al., 2017; NYKJÆR et al., 2017). Furthermore, the 120 years (120y) scenario and the 500 years (500y) scenario are proposed in order to assess the sensitivity of this parameter on the results. This variation of the study period was also proposed by Nykjær et al. (2017) and Häfliger et al., (2017) which also considered 120 years scenarios. The 500 years scenario were used in the studies developed by Grant et al. (2014) and Grant and Ries, (2012) which considered it based on the longest replacement period from the brick (NEELY et al., 1991), that was also one of the envelope materials in their case study.

To model the replacement stage (B4 module) of each building element, the minimum, mean and maximum service lives[1] from the Monte Carlo simulation made in part I of this current study (MORALES et al., 2019c) are used. These service lives are obtained from a sample which considered 11 different databases. To run the simulations, all parameters (scale, shape, location, likeliest, mean and standard deviation) are calculated based on the sample characteristics.

For the calculation of the number of replacements, the criteria used is based on equation 1. The number of replacements ≥ 0.5 are rounded up and the number of replacements < 0.5 are rounded down (ABNT, 2014).

$$NR = \frac{DBL}{BESL} \quad (1)$$

Where DBL is the defined building life span; $BESL$ is the building element service life and NR is the number of replacements.

Table 21 shows the number of replacements considered per distribution and per life span scenario (50y, 120y, and 500y) of each building element considering minimum, mean and maximum service life from Monte Carlo simulation.

[1] See Table 18 from Chapter 5.

Table 21 - Number of replacements considered per building element per distribution in each building life span scenario studied: 50 years (50y), 120 years (120y) and 500 years (500y). Min. = minimum service life, Mean = mean service life and Max. = maximum service life.

Building element	Considered life span	Number of replacements considered per distribution for each life span 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.
External cement plaster	50y	1	0	0	16	0	0	49[a]	0	0	1	0	0	49[b]	0	0	1	0	0
	120y	3	0	0	39	1	0	119[a]	0	0	3	0	0	119[b]	0	0	3	0	0
	500y	14	4	1	166	6	2	499[a]	5	2	16	5	1	499[b]	5	1	14	4	1
External clay brick walls	50y	0	0	0	12	0	0	49[c]	0	0	0	0	0	49[d]	0	0	0	0	0
	120y	1	0	0	29	0	0	119[c]	0	0	1	0	0	119[d]	0	0	1	0	0
	500y	8	3	0	124	4	1	499[c]	3	1	8	3	0	499[d]	3	0	7	2	0
External painting	50y	4	2	1	9	4	2	16	4	2	7	4	2	24	4	2	5	2	1
	120y	11	7	4	23	11	6	39	11	6	19	11	6	59	11	6	12	7	4
	500y	49	32	21	99	49	28	166	49	28	82	49	27	249	49	27	55	32	21
Internal painting	50y	9	5	2	9	5	2	24	5	3	9	5	2	49[e]	5	2	7	3	2
	120y	23	14	6	23	12	7	59	14	8	23	14	7	119[e]	14	7	19	9	4
	500y	99	62	28	99	55	32	249	62	35	99	62	30	499[e]	62	32	82	41	25

[a] Service life from the MC simulation is negative (-18) being replaced by 1 for calculation purposes. [b] Service life from the MC simulation is negative (-67) being replaced by 1 for calculation purposes. [c] Service life from the MC simulation is negative (-28) being replaced by 1 for calculation purposes. [d] Service life from the MC simulation is negative (-101) being replaced by 1 for calculation purposes. [e] Service life from the MC simulation is zero being replaced by 1 for calculation purposes.

To demonstrate clearly the *uncertainties associated with service life* and *uncertainties associated with life cycle inventory*, two groups of comparisons are analyzed: a) Influence from distribution choice over the service life uncertainties b) Comparison between life cycle inventory uncertainties versus service life uncertainties. In the second group of comparisons (b), the service life applied is based on the Monte Carlo simulation that considers the best fit distribution for each building element as defined in part I of this study (MORALES et al., 2019c). Table 22 detailed the assumptions for each comparisons group. Additionally, an uncertainty analysis from the use stage is conducted to compare the uncertainties from each building element in this module.

Table 22 - Summary of scenario analyses including the description of each group of comparisons (influence from distribution choice over the service life uncertainties and comparison between life cycle inventory uncertainties versus service life uncertainties) in this current study.

Description of assumptions for the two groups of comparisons			
Groups of comparisons in this study	Life cycle impact results applied	Service life data	Confidence interval
Influence from distribution choice over the service life uncertainties	Mean GWP 100y impacts results.	Range of service lives (minimum, mean and maximum) from each one of the six defined distributions: gamma, Gumbel, logistic, lognormal, normal and Weibull according to the part I of this study (MORALES et al., 2019c).	90%
Comparison between life cycle inventory uncertainties versus service life uncertainties.	Range of GWP 100y impacts by considering minimum, mean and maximum results from Monte Carlo simulation.	Range of service lives (minimum, mean and maximum) considering only the best fit distribution according to the part I of this study (MORALES et al., 2019c) per each building element as follows: External cement plaster – Weibull; Clay brick external – Lognormal; External painting – Gamma and; Internal painting - Lognormal.	90%
Uncertainty analysis in the use stage	Mean GWP 100y impacts results.	Range of service lives (minimum, mean and maximum) considering only the best fit distribution according to the part I of this study (Morales et al., 2019a) per each building element as follows: External Cement plaster – Weibull; Clay brick external – Lognormal; External painting – Gamma and; Internal painting - Lognormal.	90%

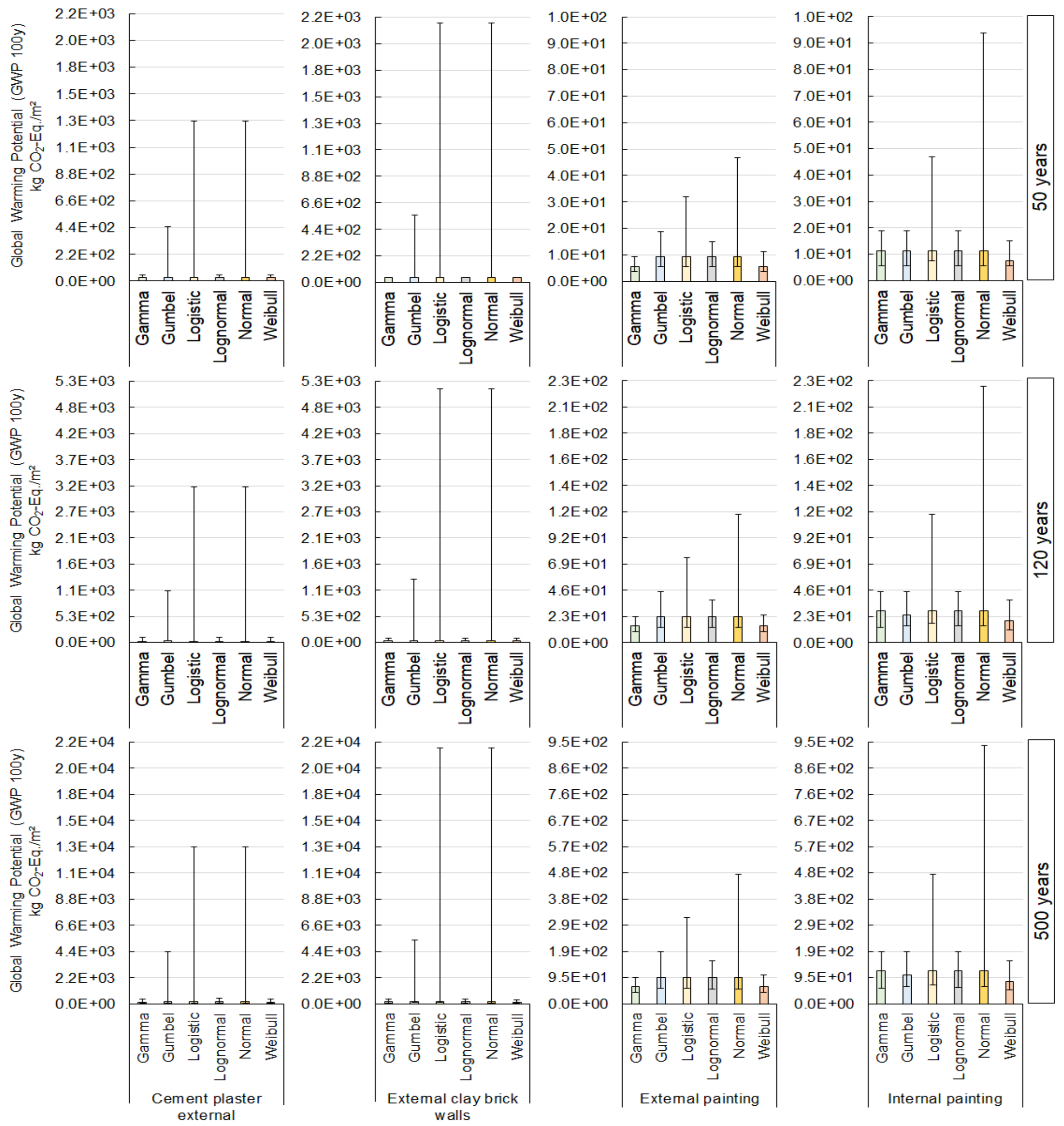
6.3 RESULTS AND DISCUSSION

6.3.1 Influence from distribution choice on service life uncertainties over the lca results

Examining the mean GWP 100y impacts results from Figure 20, a similarity of the results could be observed in all life span scenarios (50y, 120y, and 500y). The replacement stage, when modeled considering Weibull distribution, shows lower reduction between the life span scenarios followed by the gamma distribution. Gumbel distribution, logistic, lognormal and normal shows equality in terms of mean.

In contrast, when the uncertainties from service life parameters definitions are analyzed, through the error bar, the range of impacts demonstrates high sensitivity to the distribution definition. Building elements that last many years, such as cement plaster and clay brick wall, has a greater variability depending on how its distribution is defined. Observing the four building elements and the error bar from each one, logistic and normal has a higher number of replacements than the others, which are related to the characteristics from the tails of these distributions (MORALES et al., 2019c). By considering logistic and normal distribution, both external cement plaster and external clay brick wall have high variation: ranging between 0%-5.000% in its total impacts from the 50y scenario. This notorious difference is related to the lower service life provided by these two distributions (minimum service life considered is one year) for external cement plaster and external clay brick walls. As mentioned, the one-year service life is used to allow the calculations in cases of negative services lives are provided by simulations.

Figure 20 - Global warming potential along the all considered life-cycle stages (A1-A3, B4, and C1-C4 module) of 1m² of each building element considering mean life cycle impact results calculated by using mean service lives from each distribution. Error bars represent the arising impact variation from service life uncertainties by Monte Carlo Simulation for all distributions selected: gamma, Gumbel, logistic, lognormal, normal and Weibull.



In the same way, for external painting the 50y scenario by considering logistic distribution, shows 240% of positive impacts variation from the mean and 40% as negative impact variation. Considering the normal distribution, in the same life span scenario, this variation increases to 399% as positive impacts variation from the mean, keeping the 40% as negative impact variation. Internal painting also shows similar trends as external painting for these two distributions. These differences in the range of results from external cement plaster and external clay brick wall versus external painting and internal painting are related to the high coefficient of variation from the service life of these building elements. External cement plaster has 111.6% as coefficient of variation and external clay brick walls has 105.4% as coefficient of variation which is greater than external painting that has 47.4% and internal painting that has 61.5% (MORALES et al., 2019c).

The GWP results obtained from these six distributions reinforces the inadequacy to use a logistic and normal distribution to model service life uncertainties as already discussed in part I of this current study (MORALES et al., 2019c).

To better understand the effects from gamma, Gumbel, lognormal and Weibull distribution over the GWP 100y impacts, Figure 21 and Figure 22 are included. Figure 21 demonstrates GWP 100y impacts for gamma, Gumbel, lognormal and Weibull for external cement plaster. Between these four distributions, Gumbel shows a huge difference from the others increasing about 1,600% the GWP 100y of external cement plaster in the 50y scenario. The variation still higher in the 120y (variation from 0% to +3,650%) and 500y scenarios (variation from -55% to +2,211%). The other distributions have similar trends of results between them with variation from 0% to +97% in the 50y scenario and variation from 0% to +290% in the 120y scenario. In the 500y scenario, for gamma and Weibull the variation is from -58% to +193% and to lognormal the variation is from -64% to +177%.

Figure 22 demonstrated GWP 100y impacts for gamma, Gumbel, lognormal and Weibull for external clay brick. The GWP 100y impacts from Gumbel shown the greater range of impacts as follows: variation from 0% to +1,165% in the 50y scenario, variation from 0% to +2,816% in the 120y scenario and variation from -58% to +2,330% in the 500y scenario. The other distributions have similar trends of results as external cement plaster, except in the 50y scenario, where there is no variation because they have no replacements.

Figure 21 - Global warming potential along the all considered life-cycle stages (A1-A3, B4, and C1-C4 module) of 1m² of cement plaster considering mean life cycle impact results calculated by using mean service lives excluding logistic and normal distribution results. Error bars represent the arising impact variation from service life uncertainties by Monte Carlo Simulation for gamma, Gumbel, lognormal and Weibull.

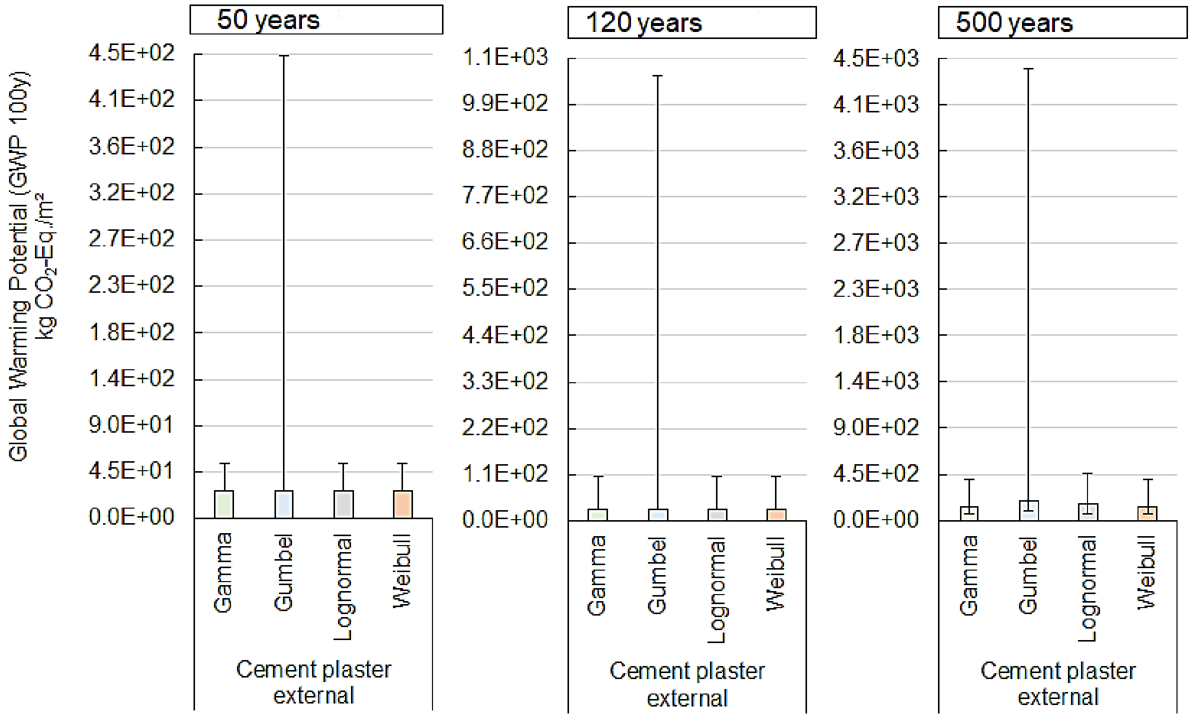
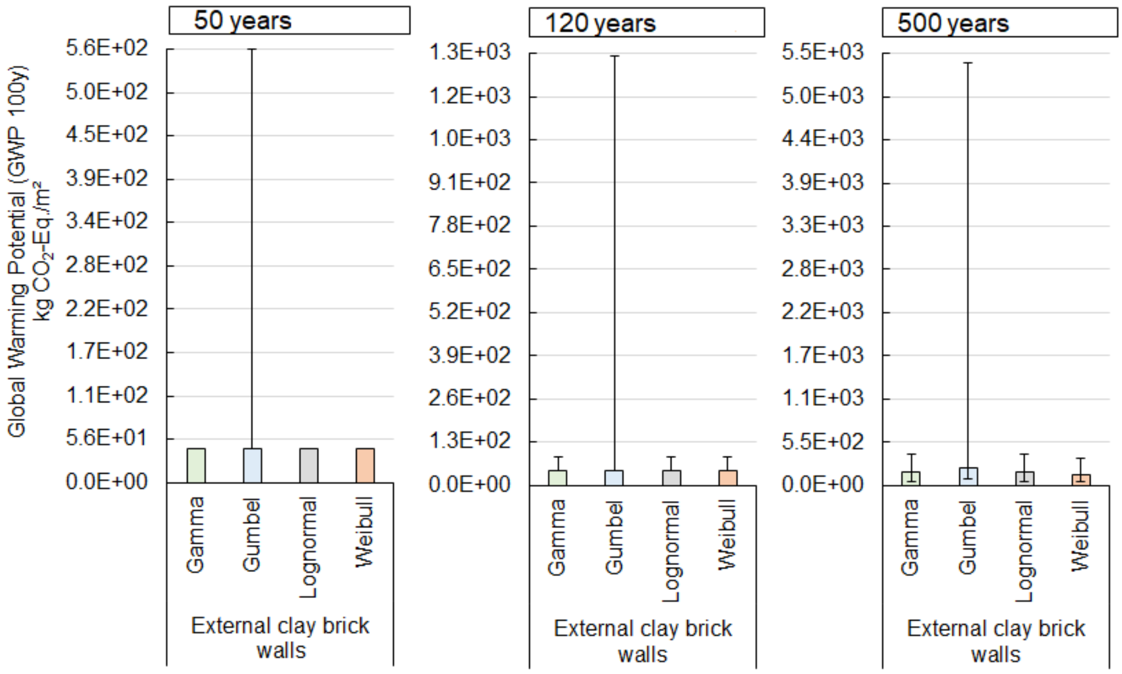


Figure 22 - Global warming potential along the all considered life-cycle stages (A1-A3, B4, and C1-C4 module) of 1m² of external clay brick wall considering mean life cycle impact results calculated by using mean service lives excluding logistic and normal distribution results. Error bars represent the arising impact variation from service life uncertainties by Monte Carlo Simulation for gamma, Gumbel, lognormal and Weibull.



6.3.2 Comparison between life cycle inventory uncertainties versus service life uncertainties

Figure 23 and Figure 24 show the GWP 100y impact for external cement plaster and external clay brick wall. Uncertainties from life cycle inventory are demonstrated as minimum Life Cycle Impact Results (LCIR), mean LCIR and maximum LCIR. The uncertainties from service life are demonstrated by considering the best fit distribution through the error bar per life cycle stage.

Observing the uncertainties from the life cycle inventory in the three life span scenarios, external cement plaster, and external clay brick has similar results. External cement plaster has a range of impacts from -18% to +21% of variation from the mean and external clay brick walls has about ±17% of the variation (Figure 23 and Figure 24).

A high uncertainty from service life is observed through the error bar from Figure 23 and Figure 24. External cement plaster has a variation from: 0% to +97% in the 50y scenario; 0% to +290% in the 120y scenario and -58% to +193% in 500y scenario. Service life uncertainties are shown a tendency to grow as the life span increases. In the same way, external clay brick (Figure 24) has an increment over the service life uncertainties following the life span increasing. In the 50y scenario external clay brick does not show variation, in the 120y scenario it varies from 0% to +97% and in the 500y scenario it varies from -73% to +121%.

Examining the contribution per considered life-cycle stage over the total impacts for external cement plaster and external clay brick, the product stage (A1-A3 module) is the greater contributor (97% of the impacts) in the 50y scenario and in the 120y scenario. In contrast, in the 500y scenario, the replacement stage is the major contributor to the total impacts for both building elements with 77% of the total impacts for external cement plaster and 73% of the total impacts for external clay brick. The end-of-life stage (C1-C4 module) has a lower contribution, around 3% to the total LCIR, for both building elements in the three life span scenarios.

Regarding the service life uncertainties for painting activities, the error bars demonstrated the service life uncertainties according to each life span scenario. For external painting the uncertainties for the 50y scenario varies from -50% to +67%. In the 120y scenario the service life uncertainties are from -60% to + 50% and, for the 500y scenario it varies from -50% to +51%. Internal painting has show greater uncertainty than external painting, in the 50y scenario the range of service life impacts varies from -100% to +67%. In the 120y scenario the service life uncertainties vary from -87% to + 60% and 500y scenario it varies from -103% to +59%.

Figure 23 - Impacts results to Global Warming Potential along the life cycle of 1m² of external cement plaster per life-cycle stage considering Monte Carlo Simulation results of life cycle inventory uncertainties as minimum LCIR (life cycle impact results), mean LCIR and maximum LCIR. Error bars represent the impact variation from service life uncertainties calculated by Monte Carlo Simulation.

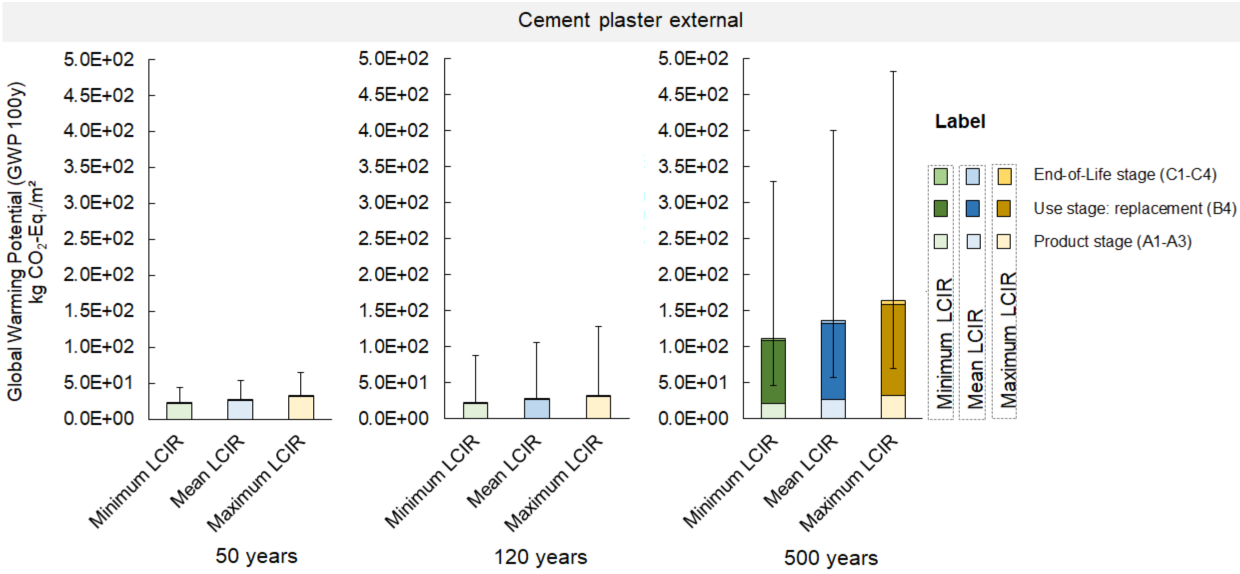
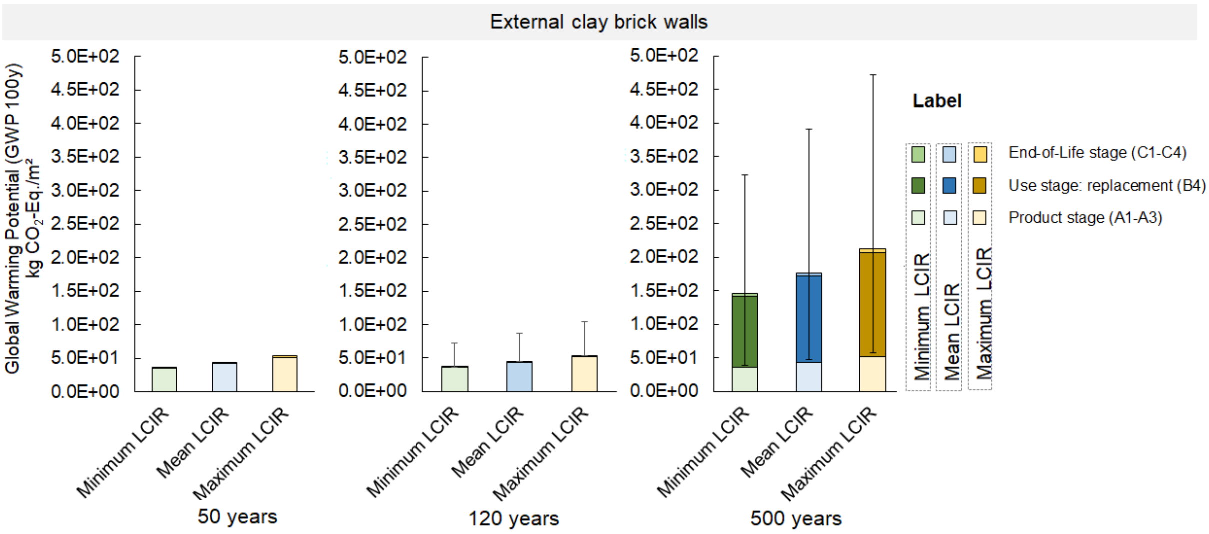
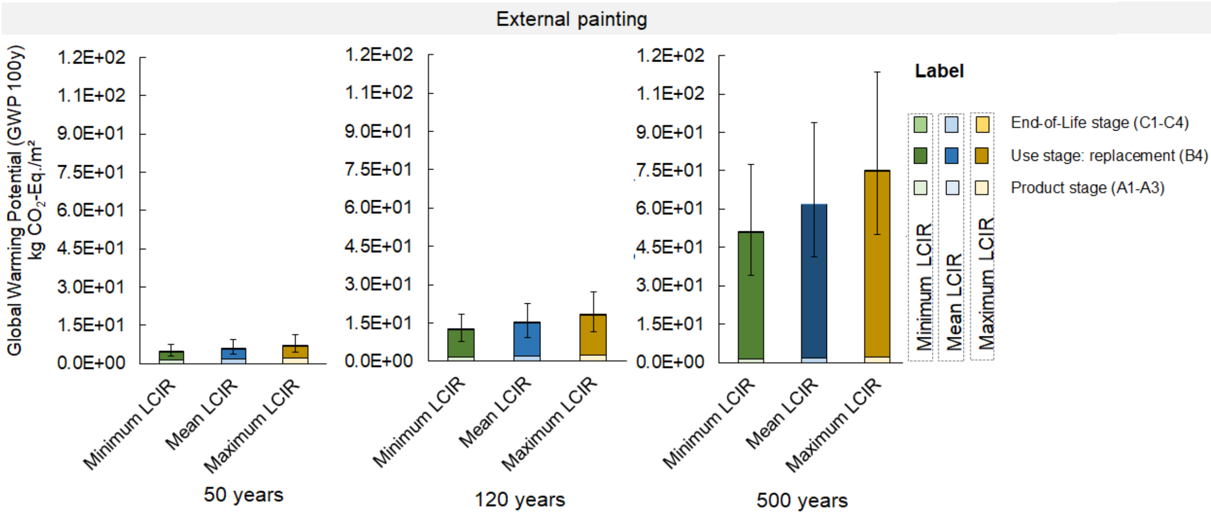


Figure 24 - Impacts results to Global Warming Potential along the life cycle of 1m² of external clay brick wall external per life-cycle stage considering Monte Carlo Simulation results of life cycle inventory uncertainties as minimum LCIR (life cycle impact results), mean LCIR and maximum LCIR. Error bars represent the impact variation from service life uncertainties calculated by Monte Carlo Simulation.



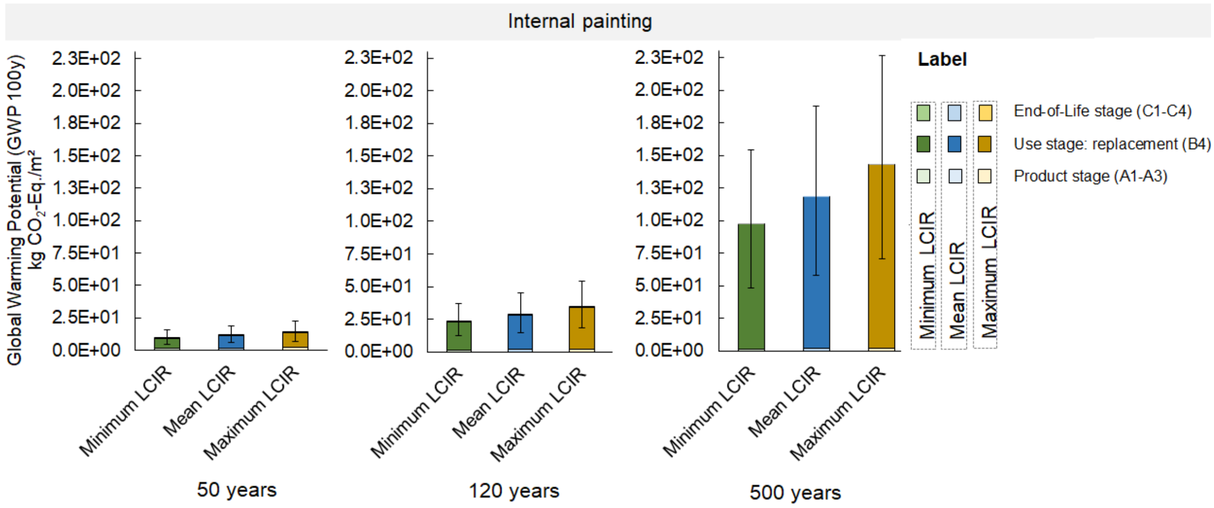
The replacement stage is the major contributor over total impacts in an all life span scenarios for both building elements. However, regarding the contribution from each stage, the results for external painting (Figure 25) and internal painting (Figure 26) demonstrates different trends for external cement plaster and external clay brick. In the 50y scenario, the product stage (A1-A3) corresponds to 33% of total impacts for external painting and 17% of total impacts for internal painting. A correlation between the increase of the building life span and the contribution of the replacement stage is observed. In the 120y scenario, the product stage (A1-A3) corresponds to 12% of total impacts for external painting and 7% of total impacts for internal painting. In the 500y scenario, the product stage (A1-A3) corresponds per 3% of total impacts for external painting and 2% of total impacts for internal painting. An important growth to the replacement stage arising from the building life span definition is observed as well.

Figure 25 - Impacts results to Global Warming Potential along the life cycle of 1m² of external painting per life-cycle stage considering Monte Carlo Simulation results of life cycle inventory uncertainties as minimum LCIR (life cycle impact results), mean LCIR and maximum LCIR. Error bars represent the impact variation from service life uncertainties calculated by Monte Carlo Simulation.



By comparing the life cycle inventory uncertainties versus service life uncertainties, the life cycle inventory uncertainties, represented by LCIR variation, are lower than the service life uncertainties, represented by the error bar, for both building elements.

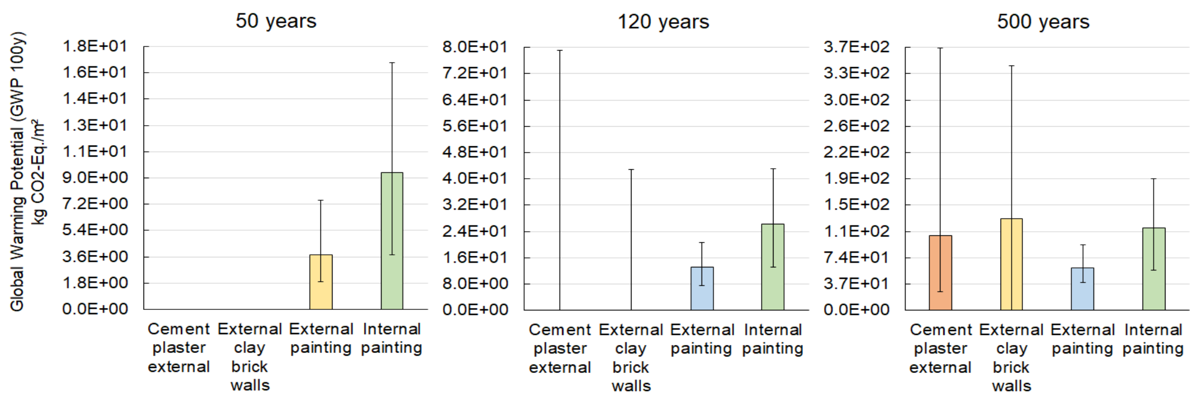
Figure 26 - Impacts results to Global Warming Potential along the life cycle of 1m² of internal painting per life-cycle stage considering Monte Carlo Simulation results of life cycle inventory uncertainties as minimum LCIR (life cycle impact results), mean LCIR and maximum LCIR. Error bars represent the impact variation from service life uncertainties calculated by Monte Carlo Simulation.



6.3.3 Uncertainty analysis in the use stage

Figure 27 compares the service life uncertainties (error bars) from each building element during the replacement stage (B4 module) over the three life span scenarios. As observed, in the 50y scenario only external painting and internal painting have a contribution to the uncertainties. In the 120y scenario, cement plaster and clay brick show uncertainties for the minimum service life which indicates that if only the mean values are considered these elements would not have influence. Concerning the 500y scenario, the uncertainties from building elements with longer service life, such as external cement plaster and external clay brick, are higher than building elements that have shorter service life as external painting and internal painting.

Figure 27 - Impacts results to Global Warming Potential along the life-cycle of 1m² of each building element in the replacement stage (B4 module) considering mean life cycle impact results. Error bars represent the impact variation from service life uncertainties calculated by Monte Carlo Simulation.



6.4 SYNTHESIS AND DISCUSSION

The findings from this study reinforced two important uncertainties sources in the LCA of building elements: service life definition, which was also observed by Grant and Ries (2012) and Silvestre et al. (2015), and distribution choice, in cases that the Monte Carlo simulation is applied.

Distribution definition affects significantly the range of LCA impacts. Note: logistic and normal distribution predicts higher number of replacements than the others which lead to an increase of the total life-cycle impact of each building element. Gumbel also shows higher variability but less than logistic and normal. Gamma, lognormal and Weibull distributions present similar trends: minor variability and, consequently, lesser number of replacements which carry to lower range of LCA impacts when these distributions are chosen. Zhang et al., (2019) also had found high variability over the uncertainties from embodied emissions due the consideration of different statistical distributions.

Based on the findings from this current study, distribution selection is recommended to be treated carefully. Distribution of parameters should be first determined by prior knowledge, given attention to the goals of the analysis. Note: uncertainties from service life are greater than life cycle inventory uncertainties for the four building elements analyzed which was also confirmed by Hoxha et al. (2014), who found that the variability for materials such as non-structural clay, paint, thermal insulation, and others seems to be essentially controlled by the service life uncertainties. Grant et al. (2014) highlighted the dependency between the life cycle impact of the building life cycle and the way in which these materials and systems are modeled over their service lives.

End-of-Life stage (C1-C4) shows a reduction in its contribution as the life span scenario is extended. This fact is due to the differences between the environmental impacts to produce the materials versus the environmental impacts to dispose of them. The environmental impacts to waste disposal are lower than the production of the materials which explains the increase in the contribution from the replacement stage. Häfliger et al. (2017) found similar correlations whereas the number of replacements increased the environmental impact from the end-of-life decreased. Incorporating end-of-life scenarios by including module D in the analysis addressing the net environmental benefits or loads resulting from reuse, recycling, and energy recovery are needed to verify its influence over life-cycle stages ranking. This needed is reinforced by Delem and Wastiels (2019) results that found about 20% of reduction for GWP impacts coming from the benefits of reuse and recycling in the whole life-cycle of construction using sand-lime bricks and hollow concrete blocks.

Regarding the life span scenario definition, an increase of the uncertainties is observed in this study. This fact was also noticed by Robati et al. (2019) that found increased impacts when assuming longer building life spans (from 50 to 150 years). Life span scenarios also influence the contribution of each life-cycle stage: Product stage (A1-A3) has a higher contribution to some building elements (cement plaster and clay bricks) in the 50y scenario. However, in the 120y scenario considering the range of results the ranking might change. This result means that the building element life span scenario choice can affect the overall relative contribution of them and influences the further actions that might be taken to reduce their environmental impact (HÄFLIGER et al., 2017).

6.5 CONCLUSIONS AND FUTURE TRENDS

This paper focuses on the evaluation of the influence of two meaningful sources of uncertainties in LCA of buildings: uncertainties associated with service life and uncertainties associated with life cycle inventory. To do so, the Monte Carlo simulation is applied by considering six different distributions and the inventory data quality is evaluated through Monte Carlo Simulation by using the Pedigree matrix.

Previous studies discussed the service life uncertainties but did not consider the influence of stochastic parameters in Monte Carlo simulation results, such as the distribution choice. Significant differences over the service lives of each building element are found depending on the distribution choice. These findings reinforce the importance of model properly the uncertainty analysis taking into account the goals of the study. Gamma, lognormal or Weibull distributions demonstrated to be better choices to assess uncertainties from service life by using Monte Carlo simulation method.

Uncertainties from service life are greater than life cycle inventory uncertainties for the four building elements analyzed. This fact demonstrates the importance of developing guidelines to model parameters such as service life, to simplify the process and make the results comparable to other studies.

Regarding the contribution of each building element to the uncertainties, building elements with longer service life as external cement plaster and external clay brick incur greater variability than building elements that have a shorter service life as external painting and internal painting. Also, a significant uncertainty from the life span scenario definition is found, as the life span scenario is extended an increase of the uncertainties is observed. Life span scenarios also influenced the contribution of each life-cycle stage. Therefore, special attention should be given to life span scenarios definitions as according to its assumption, the trends of impacts may change.

These results reinforced the relevance of defining accordingly the parameters to model the scenarios for the LCA of buildings. Future studies should consider module D as recycling and reuse in the construction industry is an important target. Additionally, the location influence of the service life data over the results could be evaluated.

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7 CONSIDERAÇÕES FINAIS

Neste trabalho foram discutidas as incertezas relacionadas à previsão e à modelagem de uma importante operação que ocorre durante o longo ciclo de utilização de uma edificação: a etapa de substituição dos elementos da edificação. Foram debatidos diversos aspectos que geram incertezas, tais como: métodos de previsão da vida útil, variabilidade dos dados existentes e a importância da definição adequada dos parâmetros estocásticos na condução da avaliação de incertezas. Por fim, os resultados foram comparados com outras reconhecidas fontes de incerteza.

A fase 1 da pesquisa possibilitou identificar e quantificar, de forma geral, algumas das incertezas em ACV de edificações. Incertezas relacionadas aos dados de inventário utilizados apresentaram elevada diferença, ao se comparar os resultados de ACV resultantes da adaptação de dados de ICV à realidade brasileira *versus* os dados de ICV globais. Tal fato, reforçou as incertezas relacionadas à seleção dos dados de ICV a serem utilizados. Além disso, também foi possível identificar que, embora as manutenções não tenham apresentado a maior contribuição sobre os impactos totais, esta etapa apresentou destacada participação, sobrepondo-se em relação à etapa de construção da edificação. Conjuntamente, outras dificuldades importantes referentes à modelagem da etapa de substituição foram observadas, tais como: ausência de bases de dados de vida útil nacionais e necessidade de critérios de definição quanto aos dados de vida útil que devem ser utilizados na modelagem da ACV.

Aprofundando a pesquisa sobre previsão de vida útil de edificações (fase 2), observou-se que existem diversas metodologias de definição da vida útil disponíveis. Dados de diversos países foram comparados na modelagem dos cenários de substituição dos elementos que compõem um sistema de paredes selecionado. Como resultado, recomenda-se que especial atenção seja dada ao se utilizar a vida útil de projeto (*design life*) como base para modelagem das substituições dos elementos e, se possível, uma análise de sensibilidade dos resultados seja conduzida. Cenários que consideraram VUP resultaram em impactos substancialmente maiores do que os demais, o que demonstra que os mesmos podem ser excessivamente conservadores e irreais para a aplicação na modelagem da etapa de substituição na ACV de edificações. Este fato decorre da abordagem utilizada para definição da VUP dos elementos e reforça as elevadas incertezas relacionadas à definição de modelos durante a etapa de desenvolvimento da ACV.

Com base nesses resultados, entende-se que um passo importante para consolidação da aplicação da ACV na avaliação de edifícios no Brasil é a elaboração de uma base de dados de vida útil, incluindo os principais elementos presentes nas edificações produzidas no âmbito nacional.

Ainda na fase 2 da pesquisa, identificou-se que elementos com menor vida útil, como a pintura, por exemplo, são sensíveis à escolha da base de dados da vida útil devido ao elevado número de substituições previstas ao longo dos 50 anos da edificação. Na mesma tendência, elementos com elevada vida útil, como revestimento de argamassa, também apresentaram grande variabilidade em sua vida útil prevista pelas bases de dados estudadas, influenciando os resultados. Estes reforçaram a importância de uma definição adequada da vida útil, tendo em vista a possibilidade de mudança no ranking dos elementos de maior impacto. Um dos problemas que podem ocorrer são escolhas errôneas de materiais e/ou elementos. Durante a análise de contribuição visando a tomada de decisão por um produto ou outro, erros poderão decorrer do emprego de valores de vida útil não adequados ao objetivo do estudo. Além das questões já levantadas, observou-se que diferenças nos impactos totais oriundas das bases de dados de vida útil não foram relacionadas apenas ao uso da VUP. Entre as bases de dados internacionais utilizadas também foram observadas diferenças, o que fundamentou o desenvolvimento da fase 3 da pesquisa.

Na fase 3 da pesquisa, foi realizado extenso levantamento na literatura internacional buscando dados de vida útil de 15 elementos tipicamente utilizados em edificações. Dados provenientes de diversos países foram utilizados e uma avaliação de incertezas, aplicando a simulação de Monte Carlo. De maneira geral, aspectos relacionados à metodologia de desenvolvimento e aos objetivos relacionados à elaboração dessas bases demonstraram influência, haja vista que, estatisticamente, não houve semelhanças entre as bases estudadas.

Uma das principais contribuições desta fase 3 e da pesquisa como um todo, é a demonstração de que a seleção de parâmetros estatísticos, neste caso a distribuição, tem elevada influência nas incertezas observadas nos resultados. Uma vez que incluir a avaliação de incertezas é de extrema importância nos estudos de ACV para garantir confiabilidade aos resultados, esses achados reforçaram a importância de selecionar adequadamente parâmetros como a distribuição estatística. Distribuições do tipo gama, lognormal ou Weibull se mostraram mais adequadas para avaliar incertezas da vida útil dos elementos de construção estudados. Entretanto, a

Lognormal pode ser uma escolha melhor, uma vez que retornou os menores valores de vida útil. Gama e Weibull também se mostraram aceitáveis, porém as condições de contorno do estudo devem ser avaliadas de moda a justificar a utilização de vidas úteis mais longas.

Finalmente, na fase 4 da pesquisa, as incertezas da vida útil observadas na fase 3 foram demonstradas a partir da elaboração da ACV de elementos construtivos selecionados da edificação em estudo. No tocante aos principais achados, destaca-se que as incertezas do inventário do ciclo de vida, embora presentes, foram menores que as incertezas provenientes da vida útil. Esta informação reforça que este parâmetro relacionado à modelagem do estudo tem recebido atenção superficial e precisa ser melhor avaliado durante a definição do objetivo e escopo da ACV. Também, se demonstrou que elaborar diretrizes para modelar parâmetros como vida útil é fundamental, a padronização da modelagem de parâmetros, como a vida útil em ACV dos edifícios, pode ser uma maneira de simplificar o processo e dar confiabilidade aos resultados. Estudos futuros devem buscar desenvolver orientações quanto à seleção da vida útil para o estudo, principalmente quando o objetivo da ACV for executar comparações. Além disso, um importante passo é incluir a avaliação de incertezas na ACV de edificações.

APÊNDICE A

Capítulo 4: Uncertainties related to the replacement stage in LCA of buildings: a case study of a structural masonry clay hollow brick wall.

APPENDIX A

Table A.1 – Examples of design life according to ABNT NBR 15575:1 (2013).

Building system		Design life (years) according to ABNT NBR 15575:1		
		DL - Minimum (50 years life span)	DL - Intermediate (63 years life span)	DL - Superior (75 years life span)
Principal Structure		≥50	≥63	≥75
Adhered Wall Cladding	Internal	≥13	≥17	≥20
	External	≥20	≥25	≥30
Painting	Internal	≥3	≥4	≥5
	External	≥8	≥10	≥12

Source: NBR 15575:1/2013 (ABNT, 2013).

Table A.2. Impact categories assessed in the study.

Indicator	Unit	Method
Abiotic Resource Depletion Potential for fossil resources (ADPF)	MJ-Eq. (fossil fuels)	CML (2001)[1]
Abiotic Resource Depletion Potential for Non fossil resources (ADPN[2])	kg Sb-Eq. (elements, ultimate reserves)	CML (2001)[1,2]
Acidification Potential (AP)	kg SO_2-Eq. (average Europe)	CML (2001)[1]
Eutrophication Potential (EP)	kg PO_4-Eq. (generic)	CML (2001)[1]
Global Warming Potential for a 100-year time horizon (GWP-100y)	kg de CO_2-Eq. (100a)	IPCC (2007)[3]
Depletion Potential of the Ozone Layer (ODP)	kg CFC-11-Eq. (steady state)	CML (2001)[1]
Formation potential of tropospheric ozone (POCP)	kg ethene-Eq. (high NOx)	CML (2001)[1]

[1] CML - Institute of Environmental Science., 2001. CML's impact assessment methods and characterization factors. Leiden.

[2] The characterization factors included are from the updated version from CML (Van Oers and Guinée, 2016). Van Oers, L., Guinée, J., 2016. The Abiotic Depletion Potential: Background, Updates, and Future. Resources 5, 16. https://doi.org/10.3390/resources5010016

[3] IPCC, 2007. IPCC - Intergovernmental Panel on Climate Change. Global Warming Potential for a 100-year time horizon as in IPCC: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment., Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.).

APÊNDICE B

Capítulo 4: Uncertainties related to the replacement stage in LCA of buildings: a case study of a structural masonry clay hollow brick wall.

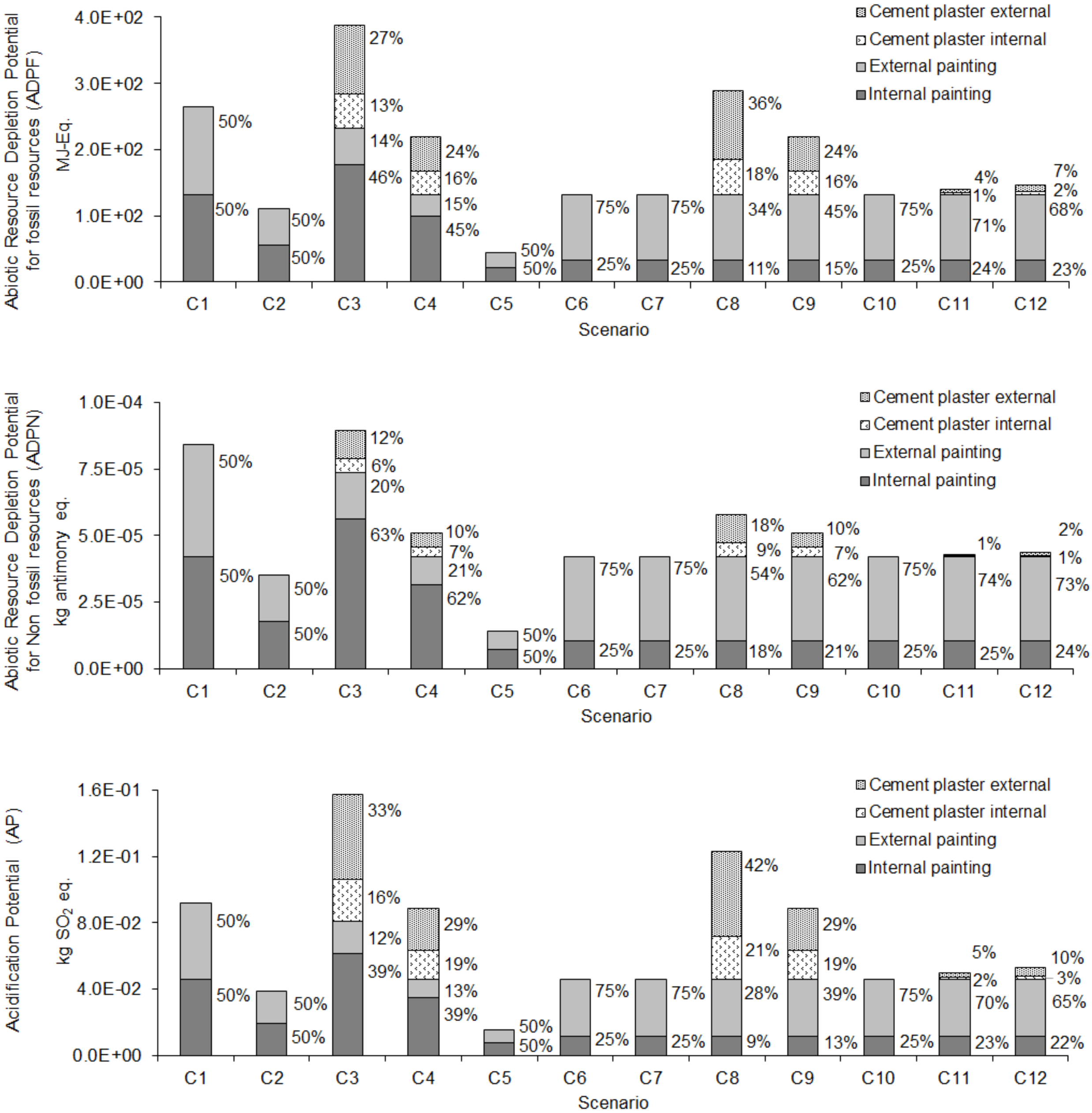


Figure B.1. Contribution analysis of each building element during the use stage (B3-repair and B4-replacement) per m² of the wall using regionalized data (B-LCI) and considering C1 to C12 scenario to ADPF, ADPN and AP. Scenario C1 - Lippiat (2007); Scenario C2 - Mithraratne e Vale (2004); Scenario C3 - NBR 15575-1 (DL minimum); Scenario C4 - NBR 15575-1 (DL superior); Scenario C5 - Bundesamt Für Bauwesen e Raumordnung (2001); Scenario C6 - EPD (paint) + Lippiat (2007) for cement plaster; Scenario C7 - EPD (paint) + Mithraratne e Vale (2004) for cement plaster; Scenario C8 - EPD (paint) + NBR 15575-1 (DL minimum) for cement plaster; Scenario C9 - EPD (paint) + NBR 15575-1 (DL superior) for cement plaster; Scenario C10 - EPD (paint) + Bundesamt Für Bauwesen e Raumordnung (2001) for cement plaster; Scenario C11 - EPD (paint) + 10% repair of cement plaster; Scenario C12 - EPD (paint) + 20% repair of cement plaster.

APÊNDICE C

Capítulo 4: Uncertainties related to the replacement stage in LCA of buildings: a case study of a structural masonry clay hollow brick wall.

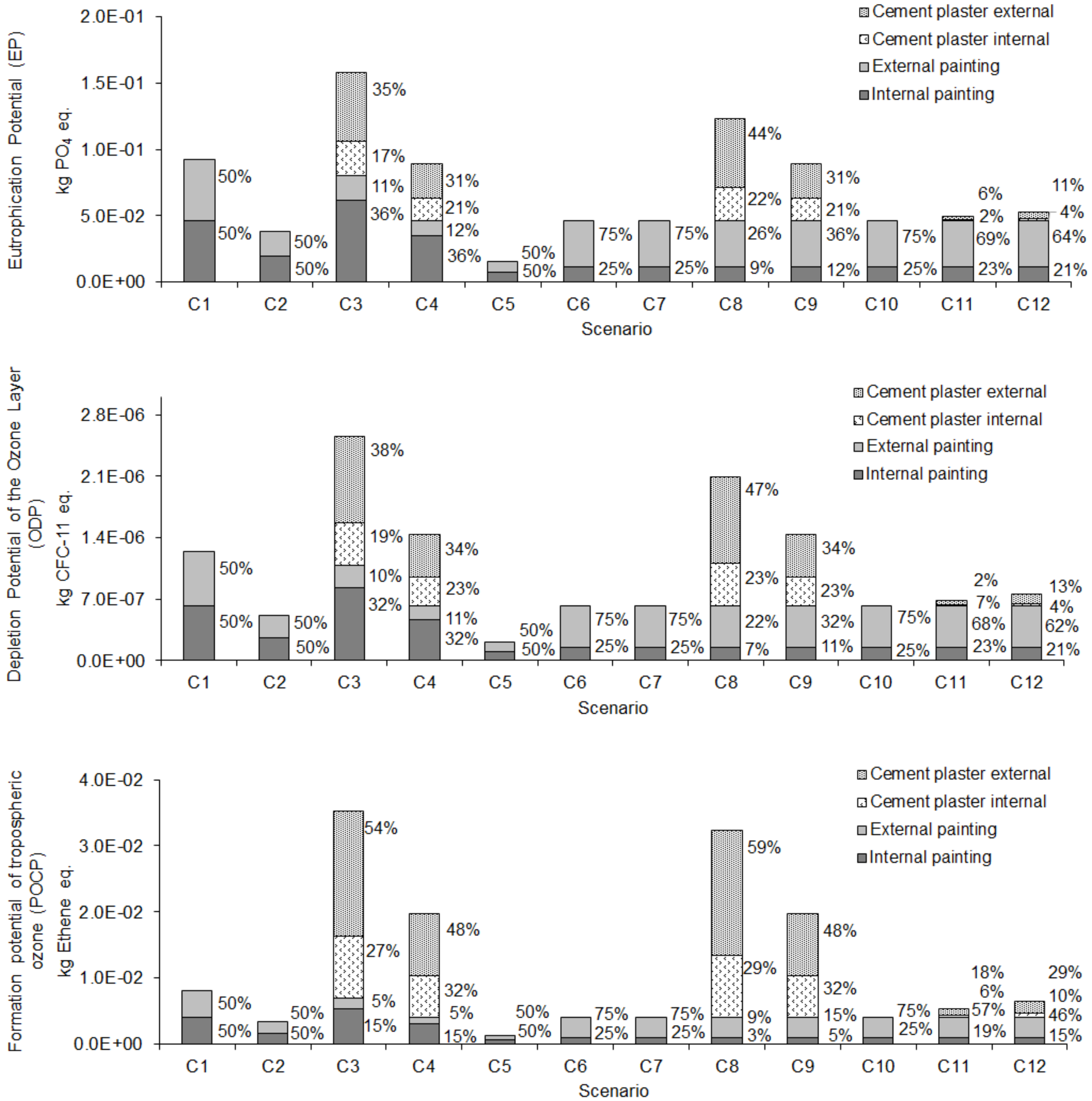
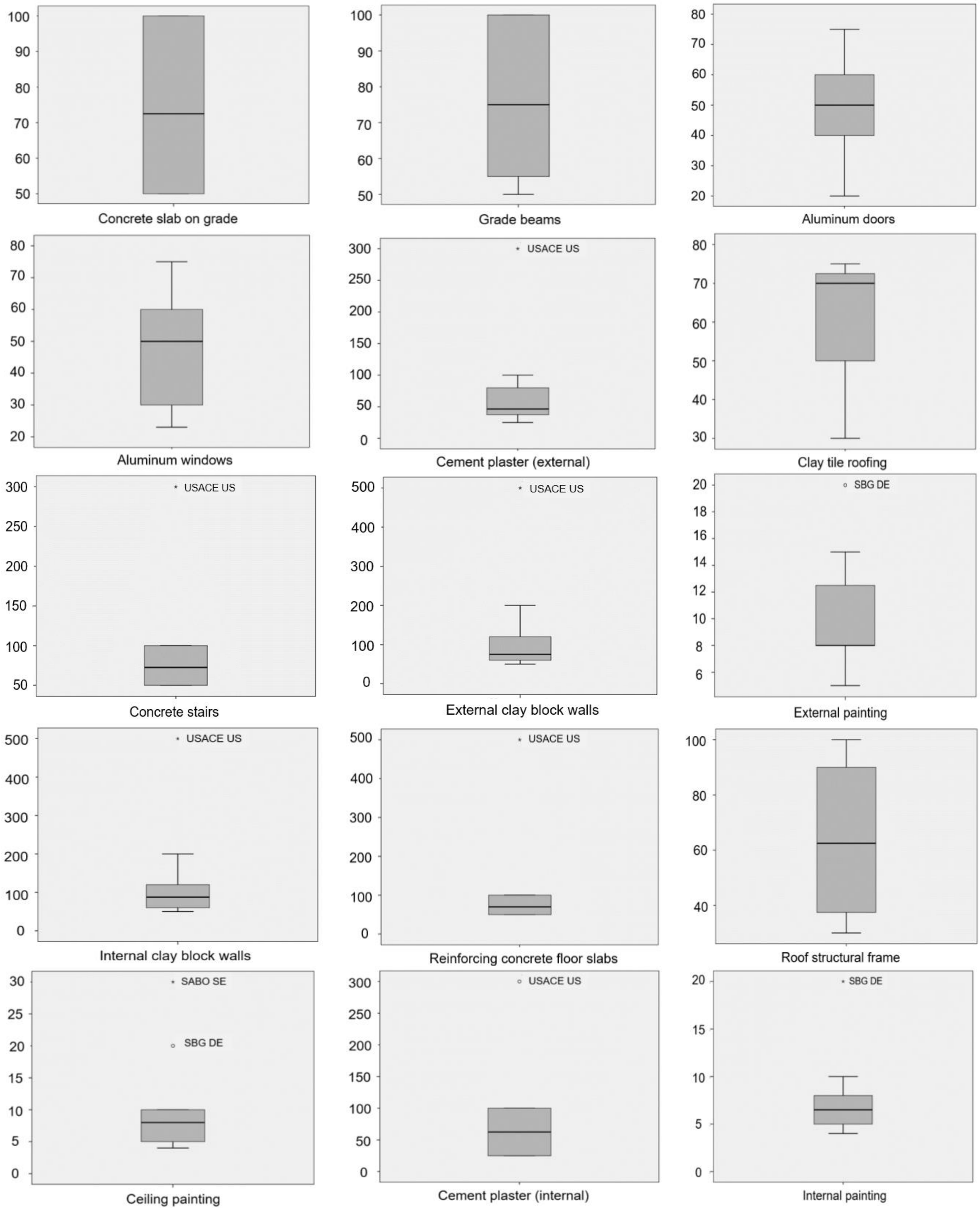


Figure C.1. Contribution analysis of each building element during the use stage (B3-repair and B4-replacement) per m² of the wall using regionalized data (B-LCI) and considering C1 to C12 scenario to EP, ODP and POCP. Scenario C1 - Lippiat (2007); Scenario C2 - Mithraratne e Vale (2004); Scenario C3 - NBR 15575-1 (DL minimum); Scenario C4 - NBR 15575-1 (DL superior); Scenario C5 - Bundesamt Für Bauwesen e Raumordnung (2001); Scenario C6 - EPD (paint) + Lippiat (2007) for cement plaster; Scenario C7 - EPD (paint) + Mithraratne e Vale (2004) for cement plaster; Scenario C8 - EPD (paint) + NBR 15575-1 (DL minimum) for cement plaster; Scenario C9 - EPD (paint) + NBR 15575-1 (DL superior) for cement plaster; Scenario C10 - EPD (paint) + Bundesamt Für Bauwesen e Raumordnung (2001) for cement plaster; Scenario C11 - EPD (paint) + 10% repair of cement plaster; Scenario C12 - EPD (paint) + 20% repair of cement plaster.

APÊNDICE A

Capítulo 5: The influence of monte carlo parameters assumptions in the uncertainty analysis of building elements service life: statistical analysis

Figure A.1 – Boxplot graph of service life values collected from literature review. Y axis is service life in years and X axis is the building element. References: USACE US (Neely et al., 1991); SABO SE (Adalberth, 1997); NZBM NZ (Mithraratne and Vale, 2004); HAPM UK (Stanford, 2010); SBG DE (BBR, 2001); ATHENA CA (Athena, 2002); DK US (Dell'Isola and Kirk, 2003); BEES US (Lippiatt et al., 2010); BRI NL (Steenkiste, 2012); Means US (RSMeans, 2012); ULC DE (BBSR, 2017).



APÊNDICE B

Capítulo 5: The influence of monte carlo parameters assumptions in the uncertainty analysis of building elements service life: statistical analysis

Table B.1 - Service life from Monte Carlo Simulation per database using GAMMA distribution in the MC simulation.

	Service life (in years) per database by GAMMA distribution																																
	ATHENA CA			BEES US			BRI NL			DK US			HAPM UK			MEANS US			NZBM NZ			SABO SE			SBG DE			ULC DE			USACE US		
	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%
A Concrete slab on grade				104	120	147	104	120	147	52	60	74	62	72	88	78	90	111	104	120	148	52	60	74	72	84	103	52	60	74	78	90	111
A Grade beams				104	120	147	104	120	147				62	72	88	78	90	111				52	60	74	103	120	147	52	60	74			
B Aluminum doors							78	90	111	41	48	59	21	24	30	52	60	74	62	72	88	31	36	44	52	60	74	52	60	74	67	78	96
B Aluminum window	26	30	37				78	90	110	36	42	52	24	28	34	52	60	74	62	72	88	31	36	44	52	60	74	52	60	74	78	90	110
B Cement plaster (external)	50	58	70	104	120	147	26	30	37				36	42	52				62	72	88				41	48	59	47	54	66	311	359	440
B Clay tile roofing	78	90	111	72	84	103	78	90	110							72	84	103				31	36	44	52	60	74	52	60	74	73	84	103
B Concrete stairs				104	120	147	104	120	148	52	60	73				78	90	111				52	60	73	72	84	103	52	60	74	311	360	444
B External clay brick walls				207	240	297				78	90	111	62	72	88	78	90	111	104	120	148	52	60	74	124	144	177	52	60	74	518	599	734
B External painting	8	10	12										8	10	12	5	6	7	8	10	12	10	12	15	21	24	29	16	18	22	8	10	12
B Internal clay brick walls				207	240	296	104	120	147	78	90	111	62	72	89	78	90	111	104	120	148	52	60	74	124	144	178	52	60	74	518	600	735
B Reinforcing concrete floor slabs				104	120	148	103	120	148	52	60	74	62	72	88	78	90	111				52	60	74	72	84	103	52	60	73	517	600	738
B Roof structural frame				78	90	110	104	120	147	41	48	59	36	42	52				103	120	148	31	36	44	83	96	118	52	60	74			
C Ceiling painting	8	10	12	4	5	6				7	8	10	10	12	15	10	12	15	8	10	12	31	36	44	21	24	29	5	6	7	4	5	6
C Cement plaster (internal)				104	120	148	26	30	37							78	90	110							26	30	37	52	60	73	311	360	441
C Internal painting	8	10	12	4	5	6				7	8	10	6	7	9	5	6	7	8	10	12	10	12	15	21	24	29	5	6	7	4	5	6

Table B.2 - Service life from Monte Carlo Simulation per database using GUMBEL distribution in the MC simulation.

	Service life (in years) per database by GUMBEL distribution																																
	ATHENA CA			BEES US			BRI NL			DK US			HAPM UK			MEANS US			NZBM NZ			SABO SE			SBG DE			ULC DE			USACE US		
	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%
A Concrete slab on grade				89	106	130	89	106	130	45	53	65	53	64	78	67	79	97	89	106	130	45	53	65	62	74	91	44	53	65	67	79	97
A Grade beams				89	106	130	89	106	130				53	64	78	67	79	97				45	53	65	89	106	129	45	53	65			
B Aluminum doors							67	79	97	36	42	52	18	21	26	44	53	65	53	64	78	27	32	39	44	53	65	45	53	65	58	69	84
B Aluminum window	22	26	32				67	79	97	31	37	45	20	24	30	44	53	65	53	63	78	27	32	39	45	53	65	45	53	65	67	79	97
B Cement plaster (external)	43	51	62	89	106	130	22	26	33				31	37	46				53	63	78				36	42	52	40	48	58	267	317	389
B Clay tile roofing	67	79	97	62	74	91	67	79	97							62	74	91				27	32	39	45	53	65	45	53	65	62	74	91
B Concrete stairs				89	106	129	89	106	130	45	53	65				67	79	97				45	53	65	62	74	91	45	53	65	267	317	388
B External clay brick walls				178	211	259				67	79	97	53	63	78	67	79	97	89	106	129	44	53	65	107	127	155	44	53	65	445	529	647
B External painting	7	8	10										7	8	10	4	5	6	7	8	10	9	11	13	18	21	26	13	16	19	7	8	10
B Internal clay brick walls				178	212	260	89	106	130	67	79	97	53	63	78	67	79	97	89	106	130	45	53	65	107	127	155	45	53	65	445	529	648
B Reinforcing concrete floor slabs				89	106	130	89	106	130	45	53	65	53	63	78	67	79	97				44	53	65	62	74	91	44	53	65	445	529	651
B Roof structural frame				67	79	97	89	106	130	36	42	52	31	37	45				89	106	130	27	32	39	71	85	104	44	53	65			
C Ceiling painting	7	8	10	4	4	5				6	7	9	9	11	13	9	11	13	7	8	10	27	32	39	18	21	26	4	5	6	4	4	5
C Cement plaster (internal)				89	106	130	22	26	32							67	79	97							22	26	32	45	53	65	267	318	389
C Internal painting	7	8	10	4	4	5				6	7	9	5	6	8	4	5	6	7	8	10	9	11	13	18	21	26	4	5	6	4	4	5

Table B.3 - Service life from Monte Carlo Simulation per database using LOGISTIC distribution in the MC simulation.

	Service life (in years) per database by LOGISTIC distribution																																
	ATHENA CA			BEES US			BRI NL			DK US			HAPM UK			MEANS US			NZBM NZ			SABO SE			SBG DE			ULC DE			USACE US		
	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%
A Concrete slab on grade				71	100	129	70	100	129	35	50	65	42	60	77	53	75	97	71	100	130	35	50	65	50	70	91	35	50	65	53	75	97
A Grade beams				70	100	129	71	100	129				42	60	78	53	75	97				35	50	65	70	100	129	35	50	65			
B Aluminum doors							52	75	97	28	40	52	14	20	26	35	50	65	42	60	78	21	30	39	35	50	65	36	50	65	46	65	84
B Aluminum window	18	25	32				54	75	97	25	35	45	16	23	30	35	50	65	42	60	78	21	30	39	36	50	65	35	50	65	53	75	97
B Cement plaster (external)	34	48	62	71	100	129	18	25	32				25	35	45				42	60	78				28	40	52	32	45	58	208	300	389
B Clay tile roofing	54	75	97	49	70	91	53	75	97							49	70	90				21	30	39	35	50	65	36	50	65	49	70	91
B Concrete stairs				70	100	129	70	100	130	35	50	65				53	75	97				35	50	64	50	70	91	35	50	65	212	300	388
B External clay brick walls				140	200	258				53	75	97	42	60	78	53	75	97	71	100	130	35	50	65	85	120	156	35	50	65	353	500	647
B External painting	6	8	10										6	8	10	4	5	6	6	8	10	7	10	13	14	20	26	10	15	19	6	8	10
B Internal clay brick walls				142	201	259	71	100	130	53	75	97	42	60	78	53	75	97	71	100	130	35	50	65	85	120	155	35	50	65	351	500	647
B Reinforcing concrete floor slabs				71	100	129	70	100	129	35	50	65	43	60	77	53	75	98				35	50	65	49	70	91	35	50	65	352	499	647
B Roof structural frame				53	75	97	71	100	129	28	40	52	25	35	45				71	100	130	21	30	39	56	80	104	35	50	65			
C Ceiling painting	6	8	10	3	4	5				5	7	9	7	10	13	7	10	13	6	8	10	21	30	39	14	20	26	4	5	6	3	4	5
C Cement plaster (internal)				71	100	129	18	25	32							53	75	97							18	25	32	35	50	65	213	300	388
C Internal painting	6	8	10	3	4	5				5	7	9	4	6	8	4	5	6	6	8	10	7	10	13	14	20	26	4	5	6	3	4	5

Table B.4 - Service life from Monte Carlo Simulation per database using LOGNORMAL distribution in the MC simulation.

	Service life (in years) per database by LOGNORMAL distribution																																
	ATHENA CA			BEES US			BRI NL			DK US			HAPM UK			MEANS US			NZBM NZ			SABO SE			SBG DE			ULC DE			USACE US		
	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%
A Concrete slab on grade				85	100	118	85	100	117	42	50	59	51	60	70	63	75	88	85	100	117	42	50	59	59	70	82	42	50	59	63	75	88
A Grade beams				84	100	117	84	100	118				51	60	70	63	75	88				42	50	59	84	100	117	42	50	59			
B Aluminum doors							63	75	88	34	40	47	17	20	23	42	50	59	51	60	70	25	30	35	42	50	59	42	50	59	55	65	76
B Aluminum window	21	25	29				64	75	88	30	35	41	19	23	27	42	50	59	51	60	70	25	30	35	42	50	59	42	50	59	63	75	88
B Cement plaster (external)	40	48	56	84	100	117	21	25	29				30	35	41				51	60	70				34	40	47	38	45	53	253	300	351
B Clay tile roofing	63	75	88	59	70	82	63	75	88							59	70	82				25	30	35	42	50	59	42	50	58	59	70	82
B Concrete stairs				84	100	117	84	100	117	42	50	59				63	75	88				42	50	59	59	70	82	42	50	59	254	300	352
B External clay brick walls				169	200	234				63	75	88	51	60	70	63	75	88	84	100	117	42	50	59	101	120	141	42	50	59	423	500	587
B External painting	7	8	9										7	8	9	4	5	6	7	8	9	8	10	12	17	20	24	13	15	18	7	8	9
B Internal clay brick walls				169	200	234	84	100	117	63	75	88	50	60	70	63	75	88	84	100	118	42	50	59	101	120	141	42	50	59	423	501	585
B Reinforcing concrete floor slabs				84	100	117	85	100	117	42	50	59	51	60	70	63	75	88				42	50	58	59	70	82	42	50	59	423	500	585
B Roof structural frame				63	75	88	84	100	117	34	40	47	30	35	41				84	100	117	25	30	35	67	80	94	42	50	59			
C Ceiling painting	7	8	9	3	4	5				6	7	8	8	10	12	8	10	12	7	8	9	25	30	35	17	20	23	4	5	6	3	4	5
C Cement plaster (internal)				85	100	118	21	25	29							63	75	88							21	25	29	42	50	59	253	300	351
C Internal painting	7	8	9	3	4	5				6	7	8	5	6	7	4	5	6	7	8	9	8	10	12	17	20	23	4	5	6	3	4	5

Table B.5 - Service life from Monte Carlo Simulation per database using NORMAL distribution in the MC simulation.

	Service life (in years) per database by NORMAL distribution																																
	ATHENA CA			BEES US			BRI NL			DK US			HAPM UK			MEANS US			NZBM NZ			SABO SE			SBG DE			ULC DE			USACE US		
	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%
A Concrete slab on grade				84	100	116	84	100	117	42	50	58	50	60	70	63	75	87	84	100	117	42	50	58	59	70	82	42	50	58	63	75	87
A Grade beams				84	100	117	83	100	116				50	60	70	63	75	87				42	50	58	83	100	117	42	50	58			
B Aluminum doors							63	75	87	33	40	47	17	20	23	42	50	58	50	60	70	25	30	35	42	50	58	42	50	58	54	65	76
B Aluminum window	21	25	29				63	75	87	29	35	41	19	23	27	42	50	58	50	60	70	25	30	35	42	50	58	42	50	58	63	75	87
B Cement plaster (external)	40	48	56	84	100	116	21	25	29				29	35	41				50	60	70				33	40	47	38	45	52	250	300	349
B Clay tile roofing	63	75	87	59	70	82	63	75	87							58	70	82				25	30	35	42	50	58	42	50	58	59	70	82
B Concrete stairs				84	100	117	84	100	116	42	50	58				63	75	87				42	50	58	59	70	81	42	50	58	250	300	349
B External clay brick walls				167	200	233				63	75	87	50	60	70	63	75	87	84	100	117	42	50	58	100	120	140	42	50	58	418	500	582
B External painting	7	8	9										7	8	9	4	5	6	7	8	9	8	10	12	17	20	23	13	15	17	7	8	9
B Internal clay brick walls				167	200	233	84	100	117	63	75	87	50	60	70	63	75	87	84	100	117	42	50	58	100	120	140	42	50	58	417	500	583
B Reinforcing concrete floor slabs				84	100	117	84	100	117	42	50	58	50	60	70	63	75	87				42	50	58	58	70	81	42	50	58	417	500	581
B Roof structural frame				62	75	87	84	100	116	33	40	47	29	35	41				84	100	117	25	30	35	67	80	93	42	50	58			
C Ceiling painting	7	8	9	3	4	5				6	7	8	8	10	12	8	10	12	7	8	9	25	30	35	17	20	23	4	5	6	3	4	5
C Cement plaster (internal)				83	100	117	21	25	29							63	75	87							21	25	29	42	50	58	250	300	350
C Internal painting	7	8	9	3	4	5				6	7	8	5	6	7	4	5	6				8	10	12	17	20	23	4	5	6	3	4	5

Table B.6 - Service life from Monte Carlo Simulation per database using WEIBULL distribution in the MC simulation.

	Service life (in years) per database by WEIBULL distribution																																
	ATHENA CA			BEES US			BRI NL			DK US			HAPM UK			MEANS US			NZBM NZ			SABO SE			SBG DE			ULC DE			USACE US		
	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%	5%	Mean	95%
A Concrete slab on grade				102	109	117	102	109	117	51	54	59	61	65	70	77	82	88	102	109	117	51	54	59	72	76	82	51	54	59	77	82	88
A Grade beams				102	109	117	102	109	117				61	65	70	77	82	88				51	54	59	102	109	117	51	54	59			
B Aluminum doors							77	82	88	41	44	47	20	22	23	51	54	59	61	65	70	31	33	35	51	54	59	51	54	59	66	71	76
B Aluminum window	26	27	29				77	82	88	36	38	41	24	25	27	51	54	59	61	65	70	31	33	35	51	54	59	51	54	59	77	82	88
B Cement plaster (external)	49	52	56	102	109	117	26	27	29				36	38	41				61	65	70				41	44	47	46	49	53	307	327	352
B Clay tile roofing	77	82	88	72	76	82	77	82	88							72	76	82				31	33	35	51	54	59	51	54	59	72	76	82
B Concrete stairs				102	109	117	102	109	117	51	54	59				77	82	88				51	54	59	72	76	82	51	54	59	307	327	352
B External clay brick walls				204	218	235				77	82	88	61	65	70	77	82	88	102	109	117	51	54	59	123	131	141	51	54	59	511	544	587
B External painting	8	9	9										8	9	9	5	5	6	8	9	9	10	11	12	20	22	23	15	16	18	8	9	9
B Internal clay brick walls				205	218	234	102	109	117	77	82	88	61	65	70	77	82	88	102	109	117	51	54	59	123	131	141	51	54	59	512	544	586
B Reinforcing concrete floor slabs				102	109	117	102	109	117	51	54	59	61	65	70	77	82	88				51	54	59	72	76	82	51	54	59	511	544	587
B Roof structural frame				77	82	88	102	109	117	41	44	47	36	38	41				102	109	117	31	33	35	82	87	94	51	54	59			
C Ceiling painting	8	9	9	4	4	5				7	8	8	10	11	12	10	11	12	8	9	9	31	33	35	20	22	23	5	5	6	4	4	5
C Cement plaster (internal)				102	109	117	26	27	29							77	82	88							26	27	29	51	54	59	307	327	352
C Internal painting	8	9	9	4	4	5				7	8	8	6	7	7	5	5	6	8	9	9	10	11	12	20	22	23	5	5	6	4	4	5

APÊNDICE C

Capítulo 5: The influence of monte carlo parameters assumptions in the uncertainty analysis of building elements service life: statistical analysis

Table C.1 – Building elements that show equality in the peer comparison test between databases by Mann-Whitney test. Identification of each database in the bottom of the Table.

	ATHENA CA	BEES US	BRI NL	DK US	HAPM UK	MEANS US	NZBM NZ	SABO SE	SBG DE	ULC DE	USACE US
ATHENA CA		-	6	-	9	-	9, 13 and 15	-	-	-	9
BEES US			1, 2, 7 and 11	-	-	6	1	--	2	-	6, 13 and 15
BRI NL				-	-	-	1, 10 and 12		2 and 14	-	4
DK US					-	8	-	1, 7 and 11	-	1, 7 and 11	-
HAPM UK						13	9	-	-	-	9
MEANS US							-	-	3 and 4	3, 4 and 15	1 and 6
NZBM NZ								-	-	-	9
SABO SE									-	1, 2, 7, 8, 10 and 11	-
SBG DE										3, 4 and 6	-
ULC DE											-
USACE US											

1 - Concrete slab on grade; 2 - Grade beams; 3 - Aluminum doors; 4 - Aluminum windows; 5 - Cement plaster (external); 6 - Clay tile roofing; 7 - Concrete stairs; 8 - External clay brick walls; 9 - External painting; 10 - Internal clay brick walls; 11 - Reinforcing concrete floor slabs; 12 - Roof structural frame; 13 - Ceiling painting; 14 - Cement plaster (internal); 15 - Internal painting.

Table C.2 – Building elements that show equality in the peer comparison test between distributions by Mann-Whitney test.

	ATHENA CA	BEES US	BRI NL	DK US	HAPM UK	MEANS US	NZBM NZ	SABO SE	SBG DE	ULC DE	USACE US
Concrete slab on grade		LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxNormal LognormalxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal
Grade beams		LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal		LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxLognormal LogisticxNormal		LogisticxLognormal LogisticxNormal	LogisticxNormal LognormalxNormal	LogisticxNormal	
Aluminum doors			LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxNormal LognormalxNormal	LogisticxLognormal LogisticxNormal
Aluminum windows	LogisticxLognormal LogisticxNormal		LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal

	LognormalxNormal			LognormalxNormal							
Cement plaster (external)	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxNormal		LogisticxLognormal LogisticxNormal		LogisticxNormal		LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal
Clay tile roofing²	LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal			LogisticxLognormal LogisticxNormal		LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxNormal	LogisticxLognormal LogisticxNormal
Concrete stairs		LogisticxNormal	LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal		LogisticxLognormal LogisticxNormal LognormalxNormal		LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal
External clay brick walls		LogisticxLognormal LognormalxNormal		LogisticxNormal	LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal
External painting	LogisticxNormal				LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxNormal	LogisticxNormal	LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal
Internal clay brick walls		-	LogisticxLognormal LogisticxNormal	LogisticxLognormal	LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal
Reinforcing concrete floor slabs		LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal		LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxLognormal LogisticxNormal
Roof structural frame		LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal	LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal		LogisticxNormal	LogisticxNormal	LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal	
Ceiling painting²	LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxLognormal LogisticxNormal		LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal	LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal LognormalxNormal
Cement plaster (internal)		LogisticxLognormal LogisticxNormal	LogisticxLognormal LogisticxNormal			LogisticxLognormal			LogisticxLognormal	LogisticxLognormal LognormalxNormal	LogisticxLognormal
Internal painting¹	LogisticxLognormal	LogisticxLognormal LogisticxNormal LognormalxNormal		LogisticxLognormal	-	LogisticxLognormal	LogisticxLognormal	LogisticxLognormal LognormalxNormal	LogisticxLognormal	LognormalxNormal	LogisticxLognormal

[1]Material with small number of distributions statistically equal. [2]Material with greater number of distributions statistically equal.

PUBLICAÇÕES RELATIVAS À TESE

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