

## **Tracing the environmental impact origin within the existing build-ing portfolio of prevailing building typologies**

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## Tracing the environmental impact origin within the existing building portfolio of prevailing building typologies

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**Abstract.** As circular economy (CE) is becoming a growing focus in the building industry due to the industries large resource consumption, waste production and environmental impacts a better understanding of buildings material composition, resource consumption and resulting environmental performance becomes increasingly important in order to support the transition towards CE. The research presented here is a stepping stone in order to investigating the existing building portfolio and the conducted analysis. It is used to get further information on what is included and where there is lack of information, in order to understand what is missing or what is needed to develop CE design strategies. Although, life cycle assessment (LCA) is increasingly used by the industry to assess these aspects, the lack of a systematic analytical approach as well as the high building complexity and diversity between buildings limits generalised knowledge from these studies. However, it is assumed that there are certain commonalities between the existing portfolio of prevailing building typologies which can be deducted. The study at hand is a part of a larger research project that aims at developing industry specific tools to support designers and decision makers select CE design strategies that improve the environmental performance and resource consumption of buildings. On the basis of a comprehensive systematic literature review (SLR) of whole building LCAs the paper at hand aims at tracing the environmental impact origin within the existing building portfolio of prevailing building typologies. To identify potentially important building parameters relevant to the resulting environmental impact performance and resource consumption of different building typologies. Based on 39 building LCA case studies that matched the specific inclusion and exclusion criteria of the SLR a focus on global warming and climate change was detected. It was found that even though buildings have different characteristics (size, typology, storeys, reference study period and location), for most of the buildings' environmental impacts were predominantly related to the production of structurally important concrete components e.g. the structural frame, the external envelope, floor slabs and walls. To point towards which CE design strategies should be used to improve the environmental performance of buildings; the environmental information from the studies was insufficient due to lack of detailed information.

## 1. Introduction

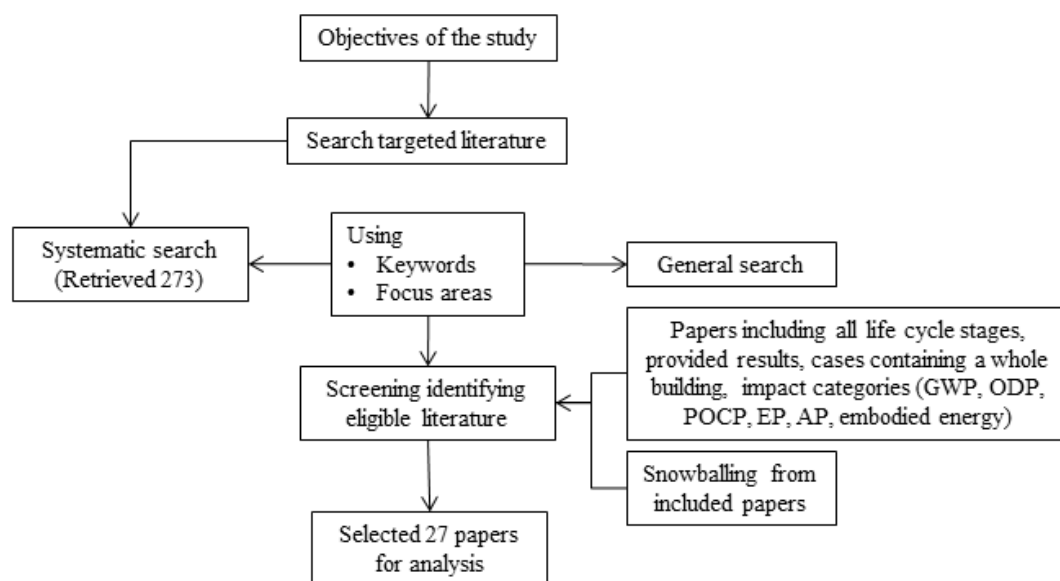
The building sector is responsible for 40% of energy consumption, 30% of greenhouse gas emission, 30% of raw materials consumption and 25% of solid waste production globally [1]. Hence the global economic growth and increasing population puts extensive pressure on the natural environment and resource reservoirs available, due to an increased demand for new construction [2]. Hence focus in the sector on resource efficiency and the circular economy (CE) has grown in recent years. Furthermore, interest in a better understanding of buildings' life cycle resource consumption and embodied environmental impacts is also growing in order to utilise the resource efficiency opportunities and seek out better design solutions [3]. A way to attain this understanding is by conducting life cycle assessment (LCA) of buildings [4]. LCA can facilitate CE decision-making by identifying the largest environmental impacts-reduction opportunities [3] and is a scientifically based method used to assess buildings' environmental impacts within a building's life cycle [5,6]. Over the last 15 years the number of published and conducted LCAs related to case studies of buildings has grown continually [7] and several standards for calculation guidelines exist. However, buildings are complex, unique, dynamic and long-lived entities, consisting of multiple components and materials, which all provide different functions, rates of replacement and degradation. Hence a building is more than the sum of its components [3] and the environmental impacts and resource consumption depend of this complex context. Systematic analysis of existing LCAs of buildings exist e.g. in Switzerland [8] and semi-systematic LCAs have been performed on buildings in Denmark for several years [9]. However, there is a need for a broader and more robust systematic analytical LCA approach to ensure that the complexity in buildings and the complex interaction between various elements are identified in appropriate manners [10]. Thus, allowing generalized learning in order to develop new design strategies and methods that help reduce environmental impacts and resource consumption and avoid focusing on optimising building components and materials of less environmental importance.

By tracing conducted LCAs and the environmental impact origins within the existing building portfolio of prevailing building typologies, a fundamental knowledge from a thorough and systematic

analysis of the material composition and the typical input and output of resources within the life cycle of the buildings is achieved.

## 2. Methodology

A comprehensive systematic literature review (SLR) was conducted according to the method presented by [11]. The SLR focused on identifying and registering environmental hotspots and resource consumption found in existing building LCA case studies. The SLR considered both journal papers and “grey literature” (i.e. non-peer-reviewed scientific material). The outline of the SLR is shown in Figure 1. The Scopus database was used to search for relevant literature using a search string with a specific set of predefined keywords specifically aimed at titles, abstracts and keywords: TITLE-ABS-KEY ((building) AND (LCA OR "life-cycle assessment") AND ("case study")).



**Figure 1.** Outline of the SLR study methodology

### 2.1 Inclusion and exclusion criteria

The papers were carefully chosen using the following inclusion criteria: contain a whole building LCA of an existing building over the building’s entire life cycle, which covers four stages: production, construction, use and end-of-life. Furthermore, the papers had to contain information about: 1) in which life cycle stage the highest environmental impacts were induced, 2) which building components and materials induced the highest environmental impacts and 3) at least one of the following midpoint impact categories: global warming potential (GWP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP), acidification potential (AP), eutrophication potential (EP), (chosen based on their use for building LCAs in the EU/DGNB system [12]) and/or embodied energy. As focus was exclusively on the embodied environmental impacts related to the building materials, environmental impacts related to operational energy consumption were not taken into account. Therefore, if the studied LCAs showed that the "use stage" had the highest impact, investigations aimed at determining whether this was due to operational energy consumption or due to the replacement of materials throughout the life of the building.

### 2.2 Source selection process

All potentially relevant papers identified from the search were filtered through a screening process based on the aforementioned inclusion and exclusion criteria. From Scopus, 633 papers were identified from the search and were narrowed down to 273 by limiting the search to the three topic areas:

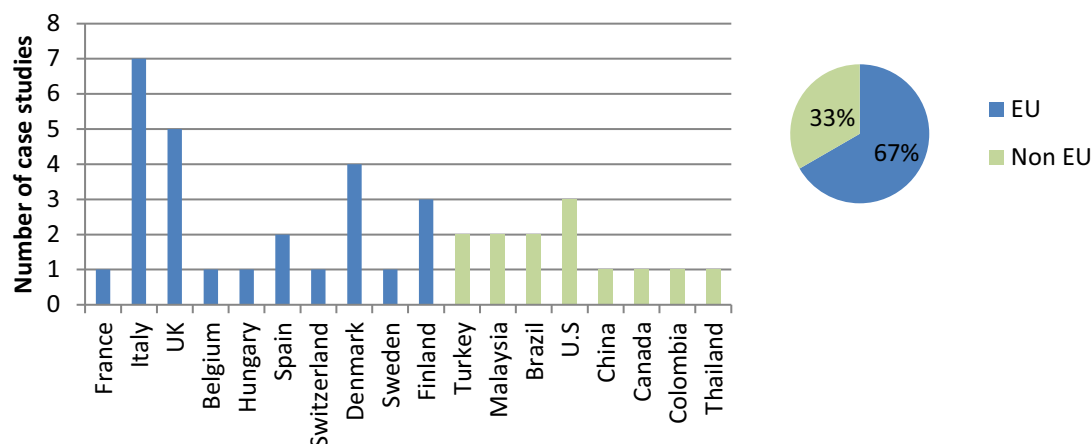
engineering, environmental science and material science, and in addition by excluding papers not related to buildings. The 273 papers were subsequently screened by reading the title and the abstracts in order to identify those papers that match the scope of the study presented in this paper, eventually yielding 54 papers. These 54 papers were further evaluated based on their comprehensiveness, the extent of the information provided, and whether or not this information aligned with the scope of the study presented here. Hence, papers containing whole building LCAs of existing buildings covering the entire life cycle were identified focusing on the LCA method used in the studies and the LCA results provided, yielding 15 relevant papers. By performing “snowballing” between these papers (using the citations in the papers or the reference lists to identify additional papers), eight additional papers were found. Grey literature fitting the selection criteria known *a priori* by the authors was also included, resulting in a total of 27 relevant papers (see appendix).

### 2.3 Information extraction

Information extracted from the papers was registered in a spreadsheet and included the following parameters potentially relevant to the resulting environmental impact performance of the case buildings studied in the papers selected: publication year, location of the conducted LCA case study, building type, material composition, number of storeys, floor area (m<sup>2</sup>), functional unit, building lifespan, life cycle inventory (LCI) database used and life cycle impact assessment (LCIA) method applied. Furthermore, the life cycle stage as well as the building components and materials with the highest environmental impacts were registered for each of the impact categories covered. In addition, as several of the studies identified focused on embodied energy, this impact indicator was also registered in order to include more studies. If the study contained more than one case building, each of these case buildings was registered separately. During the search, it was discovered that the papers used different terms to describe the life cycle stages and system boundaries. For example, the cradle-to-gate (raw materials extraction, transportation to factory and production at factory) is described both as “raw materials extraction”, “construction stage” and “A1-A3”. However, closer examination of what the papers include in cradle-to-gate indicates that the papers describe more or less the same. Hence, a common name reflecting the results extracted for the SLR was chosen following the structure of [13]. The lack of LCA (terminology and modelling) alignment between the papers leading to incomparability between the cases studied has to be taken into account when analysing the results from this SLR, i.e. LCAs can only be compared when performed using the same system boundaries, functional unit as well as LCI and LCIA method [14]. Similar issues are reported by [15], who conducted an SLR also applying predefined criteria and compared the LCAs of the different building typologies on a general level.

## 3. Results

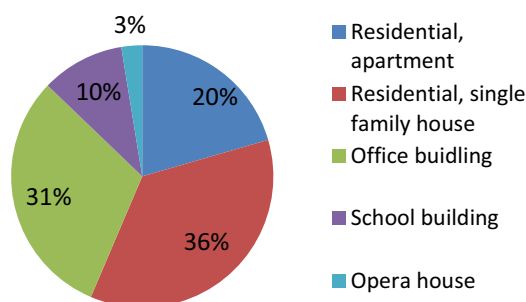
This study does not consider a temporal scope, although the papers found to be of relevance for this study were all published in the last 15 years. In the past five years, the number of publications has increased, potentially indicating growing environmental concern/focus within the building industry [15]. The spatial distribution of the papers is shown in Figure 2. Most of the case studies within the papers originate from Europe. 26 out of 39 of the studies are from Europe, with the majority from Italy with 7/39, while the UK and Denmark account for 5/39 and 4/39, respectively. The remaining cases are spread over the rest of the world in both developed and developing countries, although they are dominated by the U.S., Turkey, Brazil and Malaysia. Focus on sustainable solutions is essential for reviving economic growth. In line with this aim, Italy has engaged the 2030 Sustainable Development Goals in its National Sustainable Development Strategy 2017/2030 (NSDS) [16]. The increased UK focus on embodied environmental impacts in constructions during the Olympic games in 2012 yielded strategies intended to reduce the amount of waste generated and designing for reuse [17]. The Danish government published a report with political strategies for a strengthened construction industry in 2014 [18] and their CE strategies in 2018 [19].



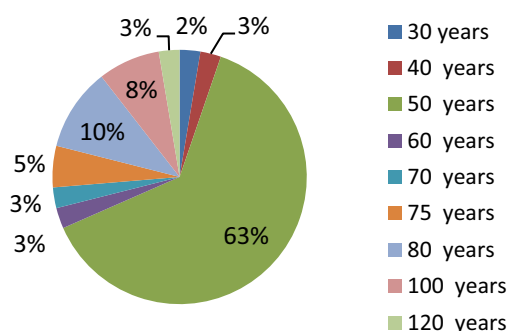
**Figure 2.** Selected building LCA case studies conducted in various countries. Divided into EU countries (blue, n=26) and non-EU countries (green, n=13)

Figure 3a shows the building typology in the case studies from the papers consisting of residential buildings (apartments and single family houses), offices, a few educational buildings and one opera house, 8/39, 14/39, 12/39, 4/39 and 1/39 respectively. Figure 3b shows that the reference study period of the buildings assessed ranges from 30 to 120 years. An applied reference study period of 50 years is dominant in the studied cases, with 24/39 occurrences. According to [20], the reference study period of a building plays an important role since the LCA methodology requires results for the construction, operation and end-of-life stage to be normalised on an annualised basis to allow for direct comparison. However, [20] and [14] both stress the issues of inadequately defined and poorly validated reference study periods in the LCA process. In particular, [20] highlights: no methodological documentation of any theoretical or empirical reasoning regarding the chosen selection of building reference study period, which varies between 25 and 100 years. However, 50 years is the most frequently applied building service life, typically justified by reference to other research also confirmed by [15], furthermore there is often no consistency in choice of building reference study period in relation to building type or geographical region and it is not stated whether the replacement of materials or construction elements during the building's reference study period is taken into account. These areas of concern are also found from the papers used in this study. Regarding the LCIA method, Figure 3c indicates that numerous impact assessment methods are applied in LCA studies. Figure 3c also shows that IPCC, CML and Eco-Indicator were the most common LCIA methods used, with respectively 19%, 17% and 17%. Furthermore, 19% of the studies did not specify the method used.

#### a) Building typology

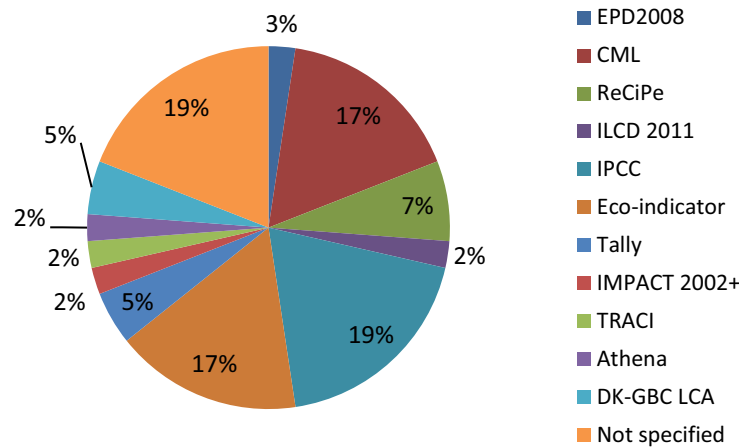


#### b) Reference study period



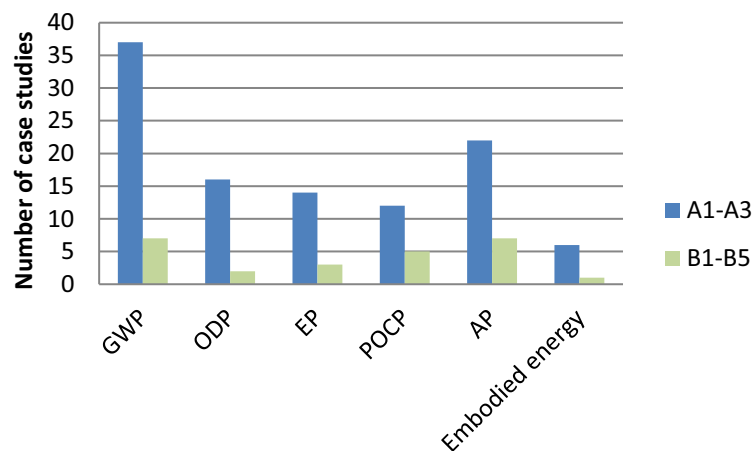


### c) LCIA method



**Figure 3.** Mapping of the identified 39 LCA case studies from selected papers, a) Building typology, b) Reference study period, c) LCIA method applied.

Figure 4 provides an overview of the registered hotspots in the life cycle stages and hotspots for building components from all case studies. The results are only shown in overall terms and are not shown in specific units. The other life cycle stages were not registered as hotspots for any of the cases and are therefore not shown in the figure.



**Figure 4.** Number of registered life cycle stage environmental hotspots.

The results presented in Figure 5 show that the production stage (A1-A3) induces the largest impacts in all categories for by far most of the investigated cases. 7/39 cases include all of the five main impact categories for the life cycle stage hotspots. 37/39 includes climate change (GWP), indicating that many studies focus on climate change when conducting LCAs due to its status of the most well-known impact category. Maintenance during the use stage only contributes around 1-5% of the impact in several of the cases and impact categories. The vast majority of the buildings in the study, 29/38, are made of concrete structures. Perhaps indicating that concrete is the prevailing material choice in contemporary building culture. Furthermore, concrete consumption in a country can be used as an indicator of economic growth in that country [21]. As the buildings are primarily made of concrete, similar environmental impact hotspots are exhibited between the buildings, namely the production stage from the structural frame, external envelope, slabs and walls.

#### 4. Discussion and conclusion

The SLR compiled environmental hotspots related to both life cycle stages and components for 39 case studies from 27 research papers. Several papers were found during the SLR process, but most of them were excluded due to lack of transparency, the limited inclusion of life cycle stages, or narrow focus, e.g. focus on specific building components, potentially overlooking determining factors for the overall environmental impact of the building.

Broadening of the keyword synonyms for “building” and “life cycle assessment” to include e.g. “house” or “dwelling” and “life cycle analysis” may lead to additional relevant papers. However, the research shows little or no deviation between the results of the case studies, suggesting that similar results would be found in other studies using these keywords. Hence, the conclusions found from this research are not expected to change.

The cases have different characteristics (size, typology, storeys, reference study periods, and materials) and are located in many different countries. The sample of cases is argued to be representative enough to provide a sound review of environmental hotspots in different building typologies. Although, the study at hand reveal that many LCAs on buildings exist varying reference study periods (ranging from 30 to 120 years) and choice of LCIA methods (11 different methods used) found between the studies indicate lack of a consistent LCA approach in the research field, yielding general conclusions difficult.

Consequently, existing environmental information on buildings is insufficient to point towards which CE design strategies should be the basis for improving buildings’ environmental impacts and resource consumption due to the lack of detailed information on material inputs and outputs, and the resulting environmental impacts, that change in magnitude and origin over time. Furthermore, it was discovered in the SLR that 37/39 studies include GWP, indicating that many studies mainly focus on GWP quantifies the greenhouse gas emissions when conducting LCA. This correlates with the popularity of GWP as a main metric. However, CE not only focuses on the environmental impacts associated with the consumption of resources but also the depletion of resources. [22] raise the issues of a poor correlation between GWP and other impact categories e.g. resource depletion. Consequently, a lack of focus on resource depletion was found as only 3/39 case studies included resource depletion impact categories such as abiotic depletion potential in their results.

Despite the lack of consistency between the LCAs it was, however, found from the SLR that, the largest embodied environmental impacts primarily are induced in the buildings’ production stage (A1-A3) in all environmental impact categories investigated. As mentioned, the 39 case studies were dominated by concrete buildings. Due to the use of similar construction materials between the case buildings, the results between the different building types do not differ much. As a result, the environmental impacts at the production stage originate from the structurally important concrete components, e.g. structural frame, the external envelope, the ground slabs and the walls contributed with large environmental impacts in the production stage of the buildings. These studies indicate that due to the large environmental impacts in the production stage, impact reductions can be obtained by addressing more focus to the design stage. Furthermore, focusing on optimising the constructions or substituting concrete with less environmentally problematic materials would be a way to address the large environmental impacts from structural concrete elements.

Appendix: Systematic literature review (SLR) overview

Reference	Publication Year	Year of origin	Location	Material composition	Stores	Concept (new-build/refurbishment)	Floor area [m <sup>2</sup> ]	FU	Service life [years]	Life cycle stage hotspots						Building component hotspots						Database	LCIA method
										GWP	ODP	EP	POCP	AP	Embodied energy	GWP	ODP	EP	POCP	AP	Embodied energy		
[7]	2016		Italy	Masonry	2	New-build	4036	1 m2, yr	100	A1-A3	A1-A3	A1-A3	A1-A3	A1-A3		Structure	Structure	Structure	Structure	Structure	Floors (concrete, steel)	Ecoinvent 2.2	EPD2008
[23]	2016	2014	Turkey	In-situ reinforced concrete	5	New-build	1250	1 m2	50	A1-A3						Floors (concrete, steel)						ICE database	
[24]	2015	2008	Sweden	prefab Concrete	5	new-build	11,003	1 m2	50	A1-A5						Structure (concrete)						IVL Miljödata-bas Bygg	
[23]	2016	2014	Turkey	In-situ reinforced concrete	12	New-build	1200	1 m2	50	A1-A3						Floors (concrete, steel)						ICE database	
[25]	2014	1975	Hungary	Prefab reinforced concrete	10	Refurbishment	6770	1 m2	80	A1-A3, B1-B5				A1-A3, B1-B5		Envelope ext.						Ecoinvent v 2.0	CML
[26]	2013	2008	Italy	Reinforced concrete, bricks	4	New-build	1827	1 m2, yr	50	A1-A5, B1-B5												Ecoinvent	Eco-indicator 99, IPCC 2008
[27]	2008	1965	Italy	Reinforced concrete	10	New-build	6110	1 m2, yr	40	A1-A3	A1-A3	A1-A3	A1-A3	A1-A3		Concrete	Concrete	Concrete	Concrete	Steel	Steel	Field measured data	SEMC and Eco indicator 99
[28]	2017	2012	China, in cold region	In-situ concrete	17	new-build	17558	whole building	50	A1-A3					A1-A3	Concrete, steel							IPCC 2007
[29]	2018		Malaysia	Hybrid concrete & timber	1	New-build	155	Whole building	50	A1	A1			A1								Ecoinvent + MYLCID data	ReCiPe midpoint int [H]
[29]	2018		Malaysia	Hybrid steel and timber	1	New-build	155	Whole building	50	A3	A3			A3								Ecoinvent + MYLCID data	ReCiPe midpoint int [H]
[30]	2018	1939	France		1	Refurbishment	59	1 m2, yr	50	A1-A3	A1-A3			A1-A3		Structure	Structure					Ecoinvent v. 3.3	ILCD 2011 midpoint+
[31]	2010	2007	Italy	Reinforced concrete & masonry	2 + basement	New-build	250	1 m2, yr	70	A1-A3	A1-A3	A1-A3	A1-A3	A1-A3								Ecoinvent 2.0 and site measurements	IPCC 2007
[32]	2005		Switzerland	Concrete	3	New-build	266	m2, yr		A1-A3, B1-B5				A1-A3, B1-B5								Okeneventure for Energiesysteme ESU	CML
[33]	2015		Denmark	Concrete	1	new-build	149	1 m2, yr	120	A1-A3	A1-A3	A1-A3	A1-A3	A1-A3		Ground slab, roof	Roof	Roof Windows	Roof	Roof, windows		ESU-CO-og Okeneventure database	
[34]	2010		Colombia	Brick concrete and steel	2	New-build	140	1 m2	50	A1-A5, B1-B5				A1-A5, B1-B5		Concrete, Steel						Ecoinvent v 2.2	CML 2
[35]	2012		UK	Traditional build, brick and block	2	New-build	90	Whole building	50	A1-A3	A1-A3	A1-A3	A1-A3	A1-A3		Materials with bricks	Bricks	Bricks	Bricks	Bricks		Ecoinvent	CML 2001
[36]	2015		Flemish/Belgium	Masonry brick walls	2	New-build	117	Whole building	60						A1-A3							Ecoinvent 3.1	ReCiPe Endpoint int [H]
[37]	2013		UK	Brick solid wall	3	new-build	144	1 m2	50	A1-A3						Concrete precast elements						Ecoinvent	ReCiPe Midpoint int and Endpoint int
[35]	2012		UK	Brick and block	2	New-build	130	Whole building	50	A1-A3	A1-A3	A1-A3	A1-A3	A1-A3		Materials with bricks	Bricks	Bricks	Bricks	Bricks		Ecoinvent	CML 2001
[35]	2012		UK	Brick and block	2	New-build	60	Whole building	50	A1-A3	A1-A3	A1-A3	A1-A3	A1-A3		Materials with bricks	Bricks	Bricks	Bricks	Bricks		Ecoinvent	CML 2001
[34]	2010		Spain	Brick concrete and steel	2	New-build	160	1 m2	50	A1-A3, B1-B5				A1-A3, B1-B5		Concrete						Ecoinvent v 2.1	CML 2
[26]	2013	2002	Italy	Reinforced concrete & bricks	3	New-build	443	1 m2, yr	50	A1-A5, B1-B5						Envelope ext., structural elements						Ecoinvent	Eco-indicator 99, IPCC 2007

Apartments

Single family houses

Office	[38]	2018		Italy	Concrete structure	3	New-build	790	Whole building	100	A1-A3						Structure							Database from SimaPro	IPCC 2007
	[39]	2004	1998-2001	Finland	Beam-column system, prefab concrete	4	New-build	17,300	1 m2	50	A1-A3	A1-A3, BI-B5	A1-A3, BI-B5				Structural frame	Structural frame, Ext. external envelope	HVAC services, roof elements, surfaces (int)	Surfaces (int), Structural frame, Ext. external envelope				SimaPro Database	Eco-Indicator 95
	[9]	2017	2015	Denmark	Sandwich construction, concrete and curtain walls	4 + basement	new-build	11,500	1 m2,yr	80	A1-A3			B4			Slabs, windows, ext. Envelope						Okobau database	DK-GBC LCA	
	[9]	2017	2015	Denmark	Brick facade, reinforced concrete	6 + basement	New-build	6,200	1m2,yr	80	A1-A3			AI-A3			Slabs, inner walls						Okobau database	DK-GBC LCA	
	[40]	2017		Brazil	Reinforced concrete floors, masonry brick walls	4	New-build (hypothetical)	2730	Whole building	50	A1-A3	A1-A3	AI-A3				Curtain wall multi-ions, walls	Floors	Walls	Walls, Curtain wall multi-ions			GABI database	Tally application in Revit	
	[40]	2017		Brazil	Reinforced concrete floors, masonry brick walls	4	New-build (hypothetical)	2730	Whole building	50	A1-A3	A1-A3	AI-A3				Walls	Floors		Floors	Walls		GABI database	Tally application in Revit	
	[33]	2015		Denmark	Reinforced concrete, wood envelope	4 + basement	new-build	3283	1 m2,yr	80	A1-A3	A1-A3	AI-A3	AI-A3			Slabs	Slabs, windows	Slabs	Slabs			ESU-CO2g Okobau-database		
	[26]	2013	2009	Italy	Reinforced concrete structure, bricks	5	New-build	3353	1 m2,yr	50	AI-A5, BI-B5						Envelope ext.						Ecoinvent	Eco-indicator 99, IPCC 2009	
	[39]	2004	1998-2001	Finland	In-situ concrete	5	New-build	15,600	1 m2	50	A1-A3		AI-A3, BI-B5	AI-A3, BI-B5	AI-A3, BI-B5			Structural frame	Structural frame, External envelope	External envelope, structural frame, roof element, HVAC services	Structural frame, External envelope			SimaPro Database	Eco-Indicator 95
	[39]	2004	1998-2001	Finland	Prefab reinforced concrete	9	New-build	24,000	1 m2	50	A1-A3		AI-A3, BI-B5	AI-A3, BI-B5	AI-A3, BI-B5			Structural frame	Structural frame	Surfaces (int), Structural frame, HVAC services	Structural frame, External envelope			SimaPro Database	Eco-Indicator 95
Multi storey offices	[41]	2016		UK	RC, structural frame and flat slab construction, brick facade	11	New-build	15590	Whole building	100	A1-A3						Floors/slabs				Floors/slabs		the GreenGuide Book (BRE)	IMPACT	
	[42]	2008		Thailand	Concrete, brick & curtain wall combination	38	New-build	60,000	Whole building	50	A1-A3		AI-A3	AI-A3			Cement, concrete		Cement, concrete	Cement, concrete			Thailand government databases		
	[43]	2015		Canada	Brick/block building	2	New-build	2100	Whole building	30	A1-A3												Aurodesk Green Building Studio (GBS)	Athens Impact Estimator (IE)	
	[44]	2013	2009	Spain	Reinforced concrete	2	New-build	1743	Whole building	50	A1-A3						Concrete, cement						Ecoinvent 2.0	IPPC 2007	
	[45]	2011		U.S.	Steel frame	3	New-build	3190	whole building	50	A1-A3						Steel						BEDEC database (CCT 2009)		
	[46]	2003		U.S.	Reinforced concrete, bricks, Steel	6	new-build	7300	Whole building	75	A1-A3			AI-A3	AI-A3									DEAM(TM) database	
Other	[47]	2017	1865	U.S.		4	Existing	2137	Whole building	75													IE4B, Athens	EPA TRACI	

## References

- [1] United Nations Environmental Programme, Protocol for Measuring Energy Use and Reporting Greenhouse Gas Emissions from Building Operations, Sustain. Build. Clim. Initiat. (2008).
- [2] United Nations, World Economic Situation and Prospects 2018, 2018. doi:10.1007/BF02929547.
- [3] L.C.M. Eberhardt, H. Birgisdóttir, M. Birkved, Life cycle assessment of a Danish office building designed for disassembly, Build. Res. Inf. 0 (2018) 1–15. doi:10.1080/09613218.2018.1517458.
- [4] M. Hauschild, R.K. Rosenbaum, S.I. Olsen, E. Al., Life Cycle Assessment - Theory and Practice, 2018. doi:10.1007/978-3-319-56475-3.
- [5] ISO, DS/EN ISO 14044, Miljøledelse – Livscyklusvurdering – Krav og vejledning, Environmental management – Life cycle assessment – Requirements and guidelines, (2008).
- [6] ISO, DS/EN ISO 14040, Miljøledelse - Livscyklusvurdering - Principper og struktur, Environmental management - Life cycle assessment - Principles and framework, (2008) 20.
- [7] M. Paelari, M. Lavagna, A. Campioli, The assessment of the relevance of building components and life phases for the environmental profile of nearly zero-energy buildings: life cycle assessment of a multifamily building in Italy, Int. J. Life Cycle Assess. 21 (2016) 1667–1690. doi:10.1007/s11367-016-1133-6.
- [8] V. John, Derivation of reliable simplification strategies for yje comparative LCA of individual and “typical” newly built Swiss apartment buildings, (2012).
- [9] H. Birgisdóttir, S.S. Madsen, Bygningers indlejrede energi og miljøpåvirkninger, vurderet for hele bygningens livscyklus, 2017.
- [10] R. Sathre, S. González-García, Life cycle assessment (LCA) of wood-based building materials, Eco-Efficient Constr. Build. Mater. Life Cycle Assess. (LCA), Eco-Labeling Case Stud. (2013) 311–337. doi:10.1533/9780857097729.2.311.
- [11] C. Okoli, K. Schabram, A Guide to Conducting a Systematic Literature Review of Information Systems Research, Work. Pap. Inf. Syst. 10 (2010) 1–51. doi:10.2139/ssrn.1954824.
- [12] S. Editor, K.H. Rosen, An INTRODUCTION to DGNB, Green Build. Counc. Denmark. (2007).
- [13] DS Dansk Standard, DS/EN 15978 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method, (2012) 64.
- [14] F.N. Rasmussen, T. Malmqvist, A. Moncaster, A.H. Wiberg, H. Birgisdóttir, Analysing methodological choices in calculations of embodied energy and GHG emissions from buildings, Energy Build. 158 (2018) 1487–1498. doi:10.1016/j.enbuild.2017.11.013.
- [15] M.U. Hossain, S.T. Ng, Critical consideration of buildings’ environmental impact assessment towards adoption of circular economy: An analytical review, J. Clean. Prod. 205 (2018) 763–780. doi:https://doi.org/10.1016/j.jclepro.2018.09.120.
- [16] Italian Ministry for the Environment Land and Sea, Voluntary National Review of Italy: National Sustainable Development Strategy, (2017) 98.
- [17] E. Macarthur Foundation, Circularity in the built environment: Case studies, (2016) 1–72. <https://www.ellenmacarthurfoundation.org/assets/downloads/Built-Env-Co.Project.pdf>.
- [18] The Danish Government, Vejen til et styrket byggeri i Danmark - regeringens byggepolitiske strategi, Copenhagen, 2014.
- [19] The Danish Government, Miljø- og Fødevareministeriet, Erhvervsministeriet, Strategi for cirkulær økonomi, (2018).
- [20] R. Marsh, Building lifespan: effect on the environmental impact of building components in a Danish perspective, Archit. Eng. Des. Manag. 13 (2017) 80–100. doi:10.1080/17452007.2016.1205471.

- [21] E. Davidson, Defining the trend: Cement consumption versus Gross Domestic Product, *Glob. Cem. Mag.* (2014) 8–14. doi:10.1146/annurev-orgpsych-041015-062429.
- [22] A. Laurent, S.I. Olsen, M.Z. Hauschild, Limitations of carbon footprint as indicator of environmental sustainability, *Environ. Sci. Technol.* 46 (2012) 4100–4108. doi:10.1021/es204163f.
- [23] A. Atmaca, Life-cycle assessment and cost analysis of residential buildings in South East of Turkey: part 2—a case study, *Int. J. Life Cycle Assess.* 21 (2016) 925–942. doi:10.1007/s11367-016-1051-7.
- [24] C. Liljenström, T. Malmqvist, M. Erlandsson, J. Fredén, I. Adolfsson, G. Larsson, M. Brogren, Byggandets klimatpåverkan - Livscykelberäkning av klimatpåverkan och energianvändning för ett nyproducerat energieffektivt flerbostadshus i betong, 2015.
- [25] S. Hrabovszky-Horváth, Z. Szalay, Environmental assessment of a precast concrete building stock in a time perspective, *Environ. Eng. Manag. J.* 13 (2014) 2797–2804. <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84930221636&partnerID=40&md5=094f8c56319bff0c38da7aa9a8de95f2>.
- [26] F. Asdrubali, C. Baldassarri, V. Fthenakis, Life cycle analysis in the construction sector: Guiding the optimization of conventional Italian buildings, *Energy Build.* 64 (2013) 73–89. doi:10.1016/j.enbuild.2013.04.018.
- [27] G.A. Blengini, Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy, *Build. Environ.* 44 (2009) 319–330. doi:10.1016/j.buildenv.2008.03.007.
- [28] X. Zhang, F. Wang, Analysis of embodied carbon in the building life cycle considering the temporal perspectives of emissions: A case study in China, *Energy Build.* 155 (2017) 404–413. doi:10.1016/j.enbuild.2017.09.049.
- [29] A.T. Balasbaneh, A.K. Bin Marsono, S.J. Khaleghi, Sustainability choice of different hybrid timber structure for low medium cost single-story residential building: Environmental, economic and social assessment, *J. Build. Eng.* 20 (2018) 235–247. doi:10.1016/j.job.2018.07.006.
- [30] C. Colli, A. Bataille, E. Antczak, F. Buyle-Bodin, Life Cycle Assessment of a French Single-Family House Refurbishment: The “bat-Eco2” Case Study, *Procedia CIRP.* 69 (2018) 160–165. doi:10.1016/j.procir.2017.11.043.
- [31] G.A. Blengini, T. Di Carlo, Energy-saving policies and low-energy residential buildings: An LCA case study to support decision makers in piedmont (Italy), *Int. J. Life Cycle Assess.* 15 (2010) 652–665. doi:10.1007/s11367-010-0190-5.
- [32] S. Citherlet, T. Defaux, Energy and environmental comparison of three variants of a family house during its whole life span, *Build. Environ.* 42 (2007) 591–598. doi:10.1016/j.buildenv.2005.09.025.
- [33] F.N. Rasmussen, H. Birgisdottir, Bygningens Livscyklus: Identifikation af væsentlige bygningsdele, materialegrupper og faser i en miljømæssig vurdering., 1. udg., Statens Byggeforskningsinstitut, Aalborg Universitet, 2015.
- [34] O. Ortiz-Rodríguez, F. Castells, G. Sonnemann, Life cycle assessment of two dwellings: One in Spain, a developed country, and one in Colombia, a country under development, *Sci. Total Environ.* 408 (2010) 2435–2443. doi:10.1016/j.scitotenv.2010.02.021.
- [35] R.M. Cuéllar-Franca, A. Azapagic, Environmental impacts of the UK residential sector: Life cycle assessment of houses, *Build. Environ.* 54 (2012) 86–99. doi:10.1016/j.buildenv.2012.02.005.
- [36] M. Buyle, A. Audenaert, J. Braet, W. Debacker, Towards a More Sustainable Building Stock: Optimizing a Flemish Dwelling Using a Life Cycle Approach, *Buildings.* 5 (2015) 424–448. doi:10.3390/buildings5020424.
- [37] T.M. Grath, S. Nanukuttan, K. Owens, M. Basheer, P. Keig, Retrofit versus new-build house

- using life-cycle assessment, *Proc. Inst. Civ. Eng. - Eng. Sustain.* 166 (2013) 122–137. doi:10.1680/ensu.11.00026.
- [38] M. Lamperti Tornaghi, A. Loli, P. Negro, Balanced Evaluation of Structural and Environmental Performances in Building Design, *Buildings*. 8 (2018) 52. doi:10.3390/buildings8040052.
- [39] S. Junnila, The environmental impact of an office building throughout its life cycle, 2004. <http://lib.tkk.fi/Diss/2004/isbn9512272857/>.
- [40] M. Najjar, K. Figueiredo, M. Palumbo, A. Haddad, Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building, *J. Build. Eng.* 14 (2017) 115–126. doi:10.1016/j.jobbe.2017.10.005.
- [41] A. Azzouz, M. Borchers, J. Moreira, A. Mavrogianni, Life cycle assessment of energy conservation measures during early stage office building design: A case study in London, UK, *Energy Build.* 139 (2017) 547–568. doi:10.1016/j.enbuild.2016.12.089.
- [42] O.F. Kofoworola, S.H. Gheewala, Environmental life cycle assessment of a commercial office building in Thailand, *Int. J. Life Cycle Assess.* 13 (2008) 498–511. doi:10.1007/s11367-008-0012-1.
- [43] S.O. Ajayi, L.O. Oyedele, B. Ceranic, M. Gallanagh, K.O. Kadiri, Life cycle environmental performance of material specification: a BIM-enhanced comparative assessment, *Int. J. Sustain. Build. Technol. Urban Dev.* 6 (2015) 14–24. doi:10.1080/2093761X.2015.1006708.
- [44] I. Zabalza, A. Valero, A. Aranda, E. Llera, Methodological aspects and design implications to achieve life cycle low emission buildings. A case study: LCA of a new university building, *Strojarstvo*. 55 (2013) 87–102. <http://www.scopus.com/inward/record.url?eid=2-s2.0-84884891488&partnerID=tZOtx3y1>.
- [45] E. Wang, Z. Shen, C. Berryman, A Building LCA Case Study Using Autodesk Ecotect and BIM Model, *ASC Annu. Int. Conf. Proc.* 47th (2011). <http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1005&context=constructionmgmt&sei-redir=1&referer=http://scholar.google.dk/scholar?hl=da&q=Building+LCA+Case+Study+Using+Autodesk+Ecotect+and+BIM+Model&btnG=#search=%22Building+LCA+Case+Study+Using>.
- [46] C. Scheuer, G.A. Keoleian, P. Reppe, Life cycle energy and environmental performance of a new university building: Modeling challenges and design implications, *Energy Build.* 35 (2003) 1049–1064. doi:10.1016/S0378-7788(03)00066-5.
- [47] M. Hu, Balance between energy conservation and environmental impact: Life-cycle energy analysis and life-cycle environmental impact analysis, *Energy Build.* 140 (2017) 131–139. doi:10.1016/j.enbuild.2017.01.076.