Building and Environment 222 (2022) 109409

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Comparing flexible and conventional monolithic building design: Life cycle environmental impact and potential for material circulation

Hanna Kröhnert, René Itten, Matthias Stucki *

Zurich University of Applied Sciences (ZHAW), Life Sciences and Facility Management, Institute of Natural Resource Sciences, CH-8820, Wadenswil, Switzerland

ARTICLE INFO

Keywords:
Whole building LCA
WBLCA
Circular economy
Construction sector
Flexible building design
Comparative LCA

ABSTRACT

Due to severe sustainability problems caused by the built environment, calls for adopting circular economy principles in building design, such as flexibility and reversibility, are increasing. However, there is still a lack of quantitative studies on the corresponding environmental benefits in this regard. In the present study, a life cycle assessment of a multi-storey residential reference building is carried out, comparing a flexible, reversible building design using a load-bearing steel structure and wooden ceiling elements to a conventional, monolithic design based on reinforced concrete. The assessment is carried out on a whole building level, including construction, operation, maintenance, and the end-of-life phase. Both building designs show similar results for a regular life cycle of 60 years without major refurbishment (13 and 14.5 kg CO_2-eq/m^2 per operational year). When longer building lifetimes are considered, the environmental impact of the reference building per operational year decreases significantly. In this context, flexible building design is advantageous as it facilitates the refurbishment of buildings, while monolithic building design often leads to premature demolition due to low adaptability. Further advantages of reversible building design include the increased potential of materials to be recirculated at the end-of-life stage of a building and in the potential reuse of structural elements. This study shows that 14% of the embodied greenhouse gas emissions of the flexible building can be avoided if the foundation, load-bearing structure and ceiling elements are kept in place for a subsequent building. Such direct reuse leads to a substantially higher environmental value retention than recycling of the same materials.

1. Introduction

Buildings play a crucial role regarding sustainability efforts globally [1]. The construction and the operation of buildings are responsible for about 30% of total greenhouse gas (GHG) emissions and energy consumption worldwide [1]. At the same time, large quantities of waste are generated, mainly concrete and other mineral demolition waste [2]. In the European Union, for example, construction and demolition waste accounts for more than 35% of the total waste generated [3].

Up to about 2010, efforts to reduce the environmental impact of buildings focused on energy efficiency and emissions during the operational phase which represented the most relevant life phase with respect to climate change and energy, mainly due to heating systems using fossil fuels [4]. In Europe, regulations and certification programmes led to a promotion of low energy buildings and renewable energy sources for heating. With buildings becoming more energy efficient, their environmental burden slowly started to shift towards other life cycles phases, mainly the construction phase [5]. In parallel, extensive research was undertaken to consider the entire life cycle of buildings including the embodied impact of materials and components [4]. Certification systems and standards for sustainable buildings were enhanced by criteria concerning embodied impact, e.g., the Leadership in Energy and Environmental Design (LEED) [6], the German Sustainable Building Certification (*Deutsche Gesellschaft für Nachhaltiges Bauen*, DGNB) [7], and the Swiss Energy Efficiency Path (*Schweizerischer Ingenieur-und Architektenverein*, SIA 2040) [8].

An internationally accepted method to assess and optimise the environmental impact of buildings in a comprehensive way is the standardised Life Cycle Assessment (LCA) method, which considers resource use and emissions along the entire life cycle in a cradle-to-grave approach [4]. Scientific publications on building LCA have surged in recent years [5], exploring the relevance of functional unit and system boundaries, life cycle phases, materials, and impact categories, but also short-comings and future research possibilities, for example, [5,9–13].

A benchmark study by Lavagna et al. [13] of the European residential building stock showed that alongside the operational phase, the

---

* Corresponding author.

E-mail addresses: xkht@zhaw.ch (H. Kröhnert), rene.itten@zhaw.ch (R. Itten), matthias.stucki@zhaw.ch (M. Stucki).

https://doi.org/10.1016/j.buildenv.2022.109409
Received 22 February 2022; Received in revised form 30 June 2022; Accepted 12 July 2022
Available online 22 July 2022

production phase accounted for a significant share of the environmental impact (up to 40%). Among building materials, concrete and steel emerged as those relevant with high environmental impact [13,14]. In the European benchmark, about 50% of the embodied impact of buildings were related to load-bearing structures, which mainly contained concrete and steel [13]. Lavagna et al. [13] concluded that it was essential to consider refurbishment while maintaining at least the load-bearing structure of buildings instead of complete demolition in order to reduce environmental impacts of the building sector. Selective deconstruction and reuse of building structure were also pointed out as effective mitigation measures by Assefa et Ambler [15].

The maintenance phase, i.e., the replacement of components, was found to be another relevant life phase [16]. In this context, prolonging the lifetime of components as well as choosing materials with less embodied impact were pointed out as important mitigation measures [16]. The end-of-life (EoL) phase including waste management was found to be relevant as well, mainly due to the large amounts of solid waste [13,14]. Most published LCA studies on buildings have focused on energy demand and GHG emissions [5]. However, in order to avoid trade-offs, other environmental impact and emissions should also be considered, such as resource depletion, human toxicity, and use of land and water [4,13].

Despite the increased number of published LCA studies, a comparison between different materials and building concepts remains challenging [5]. System boundaries and reference units often vary [5]. Furthermore, buildings are typically standalone products and their design is highly individual [17]. LCA results depend on case-specific parameters, such as building type, regional energy mixes, regional climate, assumptions about energy consumption during the operational phase, and expected service life, to name a few [5]. All of this makes benchmarking results, i.e. deriving reference values for comparison, difficult [5,18]. In this context, there is still a need for whole building LCAs, taking into account regional characteristics [5].

While the LCA method is recognised as an important tool to mitigate the environmental burden of buildings, it also has its shortcomings: static whole building LCAs normally assume building lifetimes of between 40 and 60 years [4,19], while, in reality, numerous buildings experience premature demolition or major reconstruction before they reach their foreseen lifetime [20]. Another issue is that common indicators used in linear LCA do not provide information on material recirculation and material efficiency [21,22].

A concept which goes beyond linear cradle-to-grave thinking is the Circular Economy (CE) approach, which aims at decoupling economic activities from the consumption of finite resources [23]. Guiding principles of the CE approach can be summarised as eliminating waste and pollution, keeping materials at their highest values in the economic system, and using regenerative resources [23]. Over the last decade, CE concepts have gained increasing attention from industry, researchers and policy makers [24]. In Europe, the transition to a climate-neutral, resource-efficient and circular economy is laid down in the New Circular Economy Action Plan of the European Union [3] which forms part of the European Green Deal [25].

Applied to buildings, key instruments for the transition towards CE are extending service life and closing material cycles [26]. Currently, most buildings in Europe are designed as monolithic, static structures which show little adaptability [20]. Consequently, even though the possible physical lifespan of a building can be well over 100 years, numerous buildings tend to be demolished prematurely because replacements or refurbishment are either not possible at all or only at a too high cost [20]. Another consequence of premature deconstruction is the production of mixed, non-recovered demolition waste [20].

In contrast to the common monolithic design, flexible and reversible building design complies with CE principles [20]. Flexible design (also: Design for Change) aims mainly at extending building lifetime as it allows for transformation and adaptation to future changes in both users and needs [26]. Examples of flexible design are installations which are easily accessible or inner walls which are demountable. Reversible building design (also: Design for Disassembly) aims mainly at full recovery of components and materials at the EoL phase of the building, for example by using dry, mechanic connections such as bolts and screws instead of wet and chemical joints such as mortar or glue [26]. Reversible design is highly related to flexible design as it also allows for resource-efficient repairs, maintenance, and replacements [26].

Despite increasing attention towards the CE approach, in the built environment it is still in its infancy [27]. Guidelines for the implementation of CE solutions in building design, as well as choosing CE indicators to measure the level circularity, are in the early stages [28]. There is still a need for quantitative studies, especially comparative LCA, in order to prove that CE solutions effectively decrease the environmental burden of buildings [26,27,29,30]. In this context, Munaro et al. [27] specifically point out the need for comparative LCA studies between monolithic and flexible building structures.

The present study was designed to help close research gaps regarding quantitative whole building LCA as well as quantitative evaluations of the CE approach in the building sector. The concrete goal of the study was to assess the environmental performance of a flexible and reversible building design in comparison with a conventional, monolithic building design. The results of this study ultimately help decision makers, especially public building owners, to make informed choices regarding sustainability aspects.

2. Methods

The main part of this study was a comparative LCA of a reference building, following the LCA method standardised in ISO 14040 [31] and using the LCA software SimaPro v9 [32]. The Swiss norms SIA 2040 [33] and SIA 2032 [34] formed the basis for choosing system boundaries and considered processes. The SIA 2040 lays out a reduction path for the Swiss building sector in order to achieve the long-term goals of a 2000-Watt Society (primary energy use of 2000 Watt and GHG emissions of no more than 1000 kg CO_2-eq. per person and year). The related SIA 2032 specifies the required methodology to determine the embodied impact of buildings.

As one objective of reversible building design consists in enhanced material recovery at the EoL phase, a material flow analysis assuming current waste treatment practices was carried out for both building designs in order to compare mass-based CE indicators such as material recovery rates and amounts of unrecovered waste.

The considered reference building, the investigated building designs, data sources, system boundaries as well as analysis methods are described in the following sections (2.1–2.7).

2.1. Reference building

An eight-story residential building, as illustrated in Fig. 1, was used

Fig. 1. Illustration of the reference building (source: UNAS Technology SA).

as a reference building. The building was designed by UNAS Technology SA for urban areas in Switzerland and its design was available at a pre-project stage. In total, the reference building contained 122 apartment units, with a combined energy reference area (ERA) of 13601 m^2.

For this study, the reference building was designed twice: once in a conventional way and once in a flexible way.

The Universal Sustainable Architectural Structure Model (UNAS), which was developed by UNAS Technology SA, served as an example of a flexible building design. The core of the UNAS design consisted of a load-bearing steel structure. Based on the steel structure, walls and floors were planned in a modular, reversible way which would allow for future restructuring of building space without major demolition and without wet construction work. Ceilings in the UNAS design consisted of removable wooden cases which were filled with stone chippings as ballast. The floor was designed as a dry construction element on top of the wooden cases and was constructed from OSB board, compressed foam glass granulates and plaster board. Walls were also designed as drywall constructions, featuring plasterboards supported by steel profiles and filled with mineral wool functioning as insulation. Installations such as cables, water and heating pipes were planned to be embedded in a reversible way into the flooring and drywalls. Regarding building materials, priority was given to recycled or renewable materials (e.g., steel, wood, foam glass), which could be easily separated and recycled at the EoL phase of the building. Despite these guiding principles, certain amounts of lean concrete, bricks and reinforced concrete were implemented in the flexible design for foundation, basement and staircases due to structural and safety aspects.

The main features of the conventional, monolithic design consisted in a load-bearing structure made from reinforced concrete and a screed floor. Drywall constructions were also included in the conventional design, but only for non-load-bearing internal walls. All other building components, such as windows, flat rooves, facades, floor coverings, and technical installations were the same in both designs with exception of the heat dissipation system which was based on floor heating within the conventional design and based on radiators within the flexible design.

2.2. *Functional unit and investigated product system*

All emissions and resources were determined referring to one building life cycle, with the functional unit *Provision and operation of reference building over 60 years in Switzerland.* A lifetime of 60 years was assumed following the requirements of SIA 2040. The LCA was carried out in a cradle-to-grave approach as shown in the product system illustration in Fig. 2, including construction, maintenance, operation and EoL phase of the building.

The construction phase included the extraction of raw materials, manufacturing of building materials, and transportation to Switzerland, as well as direct land use and preparation work on site. The maintenance phase included the replacement of building components which had a life expectation of lower than 60 years. The EoL phase included the demolition of the building as well as waste processing and disposal of materials which were not recycled. The study focused on the embodied environmental impact related to materials and components of the building. For the sake of completeness, the operational phase was considered as well, including the energy demand for space heating and hot water provision, the electricity demands of auxiliary equipment, water demand and wastewater treatment.

2.3. *Data collection and life cycle inventory*

Foreground data concerning quantities of building materials and components were provided for both building designs through UNAS Technology SA in the form of bills of quantities (BoQ). The BoQ were derived based on structural calculations as well as on layout

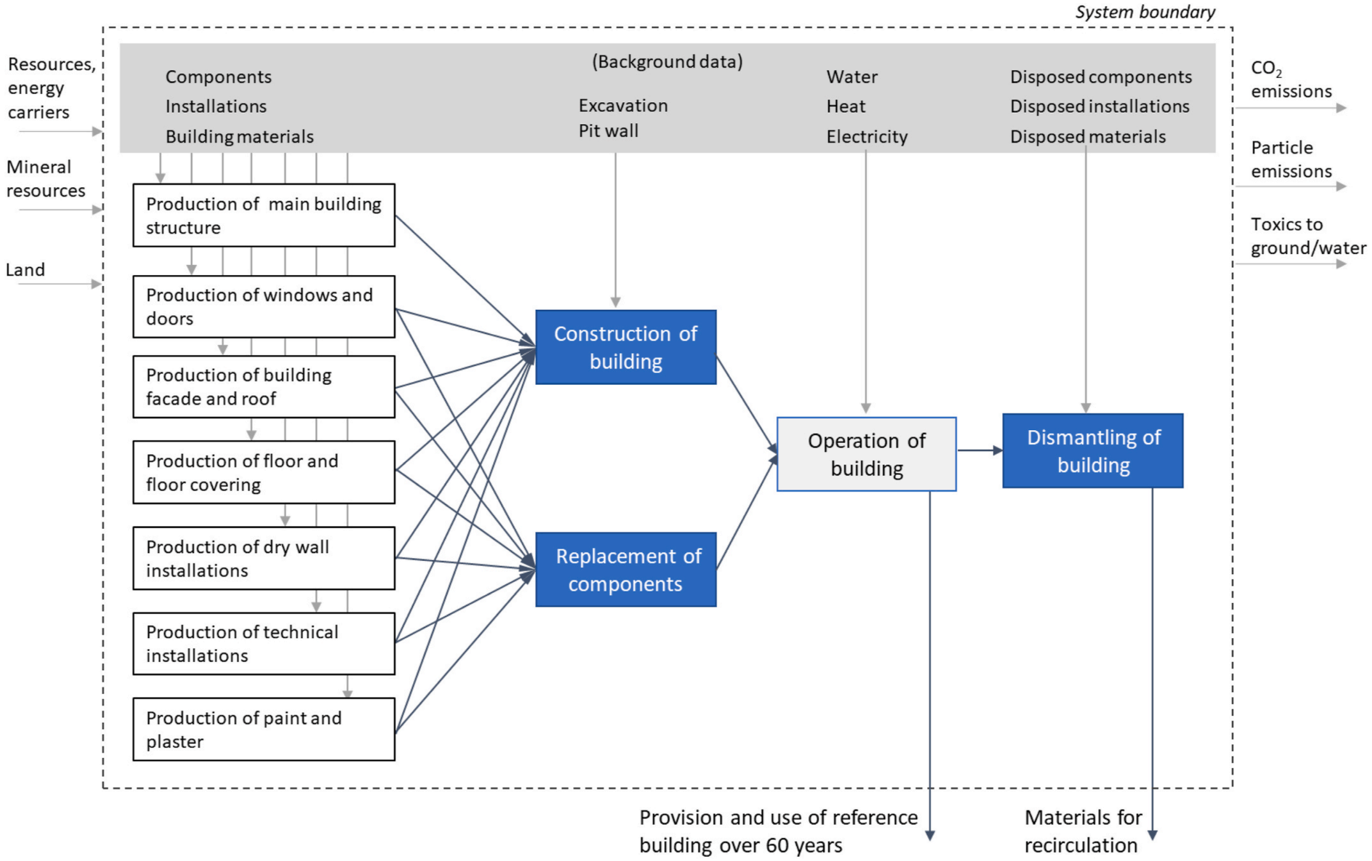

Fig. 2. System boundary and life stages which were included in the life cycle assessment of the reference building.

specifications concerning, for example, facades, walls, floors, windows, and flat rooves. The foreground data was linked to the Swiss KBOB database for the building sector [35] by the Swiss authorities for sustainable construction. The KBOB database contained generic LCA data for average building materials and products and relied on background inventory data from the ecoinvent-v2.2 database [36,37]. In Switzerland, the KBOB database is used within various national standards and certification systems, among them SIA 2040 and SIA 2032.

In this section, the life cycle inventory of each life stage is described. A comprehensive list of inventory data as well as corresponding KBOB datasets is given in the supplementary material of this paper (S1).

2.3.1. *Construction*

Quantities of building materials were derived from the BoQ. Relevant material quantities for construction are listed in Table 1.

Technical installations were not covered by the BoQ. Instead, most were modelled using generic KBOB datasets per square meter ERA. One kitchen per apartment was modelled using a generic dataset for kitchens. Space heating and hot water provision was assumed to be based on brine-water heat pumps. Heat pumps and borehole heat exchangers were modelled by upscaling the generic KBOB datasets by a factor of 10 to account for the building size.

2.3.2. *Operation*

Inventory data for the operational phase is also included in Table 1. Both building designs aimed at the same insulation standard and consequently, the thermal energy demand for space heating was assumed to be the same. The same efficiency was considered for heat pumps in both building designs, assuming that modern, low-temperature radiators were used within the flexible design which work at the same water flow temperature as floor heating systems, about 40 °C.

Table 1

Life cycle inventory of relevant building components (excluding replacements during maintenance) and operational phase in the conventional and the flexible design of the reference building.

Life cycle phase	Component	Material/Description	Conventional design		Flexible design	
			Value	Unit	Value	Unit
Construction	Direct land use		2025	m^2	2025	m^2
	Main structure	Concrete	17844	t	4254	t
		Reinforcing steel	797	t	183	t
		Steel profiles	–		995	t
		Lean concrete (foundation)	428	t	428	t
		Bricks	1837	t	206	t
		Wood (ceilings)	–		995	t
		Stone chippings in ceilings	–		1501	t
	Drywalls	Gypsum board	288	t	625	t
		Mineral wool	26	t	76	t
		Steel supports	10	t	30	t
	Floor	Screed/concrete floor	1832	t	90	t
		OSB board			135	t
		Foam glass granulate			508	t
		Gypsum board			317	t
	Floor covering	Parquet	9603	m^2	9603	m^2
		Ceramic tiles	80	t	80	t
		Artificial stone tiles	71	t	71	t
	Windows	22% frame, 78% glazing	5121	m^2	5121	m^2
		Aluminium blinds	4528	m^2	4528	m^2
	Doors	Inner doors (wood)	2019	m^2	2019	m^2
		Outer doors	58	m^2	58	m^2
	Facade	Wood	30	t	28	t
		Mineral wool	9.2	t	8.7	t
	Flat roof	Bitumen sealing	61	t	78	t
		Polyurethane rigid foam	18	t	16	t
	Tinsmith work	Copper sheets	2.9	t	3.2	t
		Steel sheets	38	t	0.7	t
	Balcony installations	Wood (side panels, floor grids)	60	t	60	t
		Steel railing	111	t	111	t
	Technical installations	Electrical system	13601	m^2	13601	m^2
		Sanatory system	13601	m^2	13601	m^2
		Ventilation system	13601	m^2	13601	m^2
		Heat distribution system	13601	m^2	13601	m^2
		Heat dissipation system	13601	m^2	13601	m^2
		Brine-water heat pumps (10 kW)	10	–	10	–
		Borehole heat exchanger	1500	m	1500	m
		Kitchens	122	–	122	–
Operation	Heat	Space heating	20779	MWh	20779	MWh
		Hot water provision	13710	MWh	13710	MWh
	Electricity	Heat pumps, auxiliary equipment	11.4	MWh	11.4	MWh
	Water	Tap water	715744	t	715744	t
		Wastewater	715744	t	715744	t

The energy demand was estimated based on SIA 2040 [33]. As an electricity product, the average Swiss consumers' mix from 2011 was used, as implemented in the KBOB database. The consumers' mix included national electricity production as well as imports but did not include the market share sold as certified electricity. An average daily water demand of 142 l tap water per person was assumed, which corresponded to the average water consumption in Swiss households for 2019 [38]. The number of inhabitants was estimated to be 230, assuming a standard living area per person of 60 m^2 [33]. Wastewater was assumed to be purified in a municipal wastewater treatment plant, and fermented sludge was assumed to be disposed via municipal incineration.

2.3.3. Maintenance

The maintenance phase considered replacements of components during the use of the building. Lifetimes of components were assumed following SIA 2032, as summarised in Table 2. For a building life cycle of 60 years, this implied that components with a lifetime of 20 years were replaced twice, while components with a lifetime of between 30 and 40 years were replaced only once. Following the specifications in SIA 2032, only 100% replacements were considered, which meant that components and installations were assumed to be entirely replaced when reaching their maximum lifetime.

2.3.4. End-of-life

The EoL phase included the dismantling and disposal of all materials and components. For each dataset used to model construction and maintenance, the corresponding disposal dataset within the KBOB database was used [39]. The KBOB disposal datasets included dismantling and handling, as well as average waste treatment and recycling scenarios in Switzerland.

The current KBOB database did not include a disposal inventory for steel, as a 100% recycling rate was assumed for this material. Accordingly, steel profiles and reinforcing steel did not make any contribution to the EoL phase in this study. Within the KBOB database, concrete was assumed to be demolished and crushed, and then 90% recycled and 10% disposed of in landfills. Wood components were assumed to be 45% recycled and 55% disposed of via municipal incineration. For most of the remaining building materials, either municipal incineration or disposal in landfill was considered within the KBOB database.

2.4. Allocation and recycling processes

The product system as shown in Fig. 2 did not contain any multi-product processes which required an allocation of resources and emissions.

The system model *allocation, recycled content cut-off* was used within the ecoinvent background database. In this system mode, an attributional LCA approach is followed, and the subdivision of multi-product activities was carried out by allocation based on physical properties, economic revenue, mass or other properties. As far as building materials are concerned, the cut-off system model meant that the use of recycled material, such as steel, did not lead to any environmental burden connected to the primary extraction of raw materials. Accordingly, no environmental credit was granted for material recovery and thermal energy recovery through incineration at the EoL stage of the building.

2.5. Impact assessment

The life cycle impact assessment (LCIA) was carried out using the six impact categories on midpoint level. The LCIA methods were selected because of their prominence in recent literature within the building sector [13] as well as the recommendation for LCIA methods for the Product Environmental Footprint by the European Commission [40]. For all midpoint indicators, long-term emissions were excluded from the LCIA due to the related high level of uncertainty.

The impact categories are as follows:

- **GHG emissions** on a 100a horizon [41], expressed in kg CO_2-eq.
- **Cumulative energy demand** (CED), non-renewable and renewable, as implemented in ecoinvent-v2.2 [42], considering direct energy use as well as embodied energy based on higher heating values of raw materials.
- **Particulate matter** (PM), as implemented in the Environmental Footprint (EF) method [43], expressed as number of lethal disease incidences due to emissions of particles with diameters smaller than 2.5 µm (deaths/kgPM2.5emitted).
- **Resource use of minerals and metals**, as implemented in the EF method [44], expressed in kg Sb-eq using a depletion model based on a use-to-availability ratio.
- **Land use**, as implemented in the EF method [45], expressed as dimensionless soil quality index aggregating the impact categories erosion resistance, mechanical filtration, groundwater regeneration, and biotic production.
- **Freshwater ecotoxicity**, as implemented in the USEtox method [46], using both recommended and interim characterisation factors, expressed as comparative toxic units for ecosystems (CTUe) which describe the fraction of species potentially affected per kg emitted substance over a year.

Table 2
Lifetimes of building components used to model the maintenance phase of the reference building.

	20 years	30 years	40 years	60 years
Main structure:				bearing structure foundation ceilings brick walls floor
Installations:	heat pumps	electrical system heat distribution system heat dissipation system ventilation system sanitary facilities	borehole heat exchanger	
Exteriors:		flat rooves windows outer doors	facade balcony installations: wood	tinsmith work balcony installations: steel
Interiors:	kitchens	drywall constructions inner doors floor covering wall panelling/covering ceiling panelling/covering		

In addition to the midpoint indicators, the overall environmental impact on endpoint level was assessed since this represents a common impact indicator used for buildings in Switzerland and provides an aggregated result covering a multitude of environmental impacts.

- **Overall environmental impact** according to the ecological scarcity method (ESM) [47] including long-term emissions, expressed in eco-points, aggregating 19 environmental impact categories to a single indicator using weighting factors on a distance-to-target principle. In the Swiss version of the ESM, weighting factors compare current emissions to national emission targets as well as to international targets supported by Switzerland.

2.6. *Evaluation of flexibility as design concept*

Two different approaches were used to quantify potential environmental benefits of flexible building design. In an initial approach, it was assumed that the expected lifetime of the reference building created with flexible design could be extended thanks to its ability to adapt to future needs. In a corresponding sensitivity study, the environmental impact of the flexible reference building was determined assuming lifetimes of 80 years and 100 years. Absolute impact from the maintenance and operational phase were scaled up proportionally to the lifetime, while the absolute impact of the construction phase stayed unchanged.

In a second approach regarding reversibility, it was assumed that the main structure of the flexible building was stripped bare after a 60-year lifespan, and that foundation, wooden ceiling elements and load-bearing steel structures were directly reused for a subsequent building. In this approach, the corresponding avoided burden, i.e., the embodied impact of the reused structural elements, was granted as a credit to the environmental impact during the first building life cycle. For both approaches, relative GHG emissions of the flexible building per operational year and m^2 ERA were determined and compared to the base case of 60-year lifetimes.

2.7. *Circular economy indicators based on mass flows*

A material flow analysis of demolition waste was conducted for both building designs to derive total material recovery rates, recycling rates, downcycling rates, and amounts of waste sent to landfill. In this study, the term *recovery rate* referred to any kind of material reutilisation, while *recycling rate* was only used for converting material into material of roughly the same value. Accordingly, the term *downcycling rate* was used for conversion of material into material with a lower value.

The recycling rate of the reference building was derived according to Eq. (1), where M refers to the mass of all materials in a material group i, $TC_{REC,i}$ is the mass transfer coefficient to recycling, and n is the number of the material group:

$$recycling\ rate = \frac{\sum_{i=1}^{n} M_i \bullet TC_{REC,i}}{\sum_{i=1}^{n} M_i} \tag{1}$$

The downcycling rate was derived in the same way as the recycling rate, replacing the transfer coefficient TC_{REC} with the transfer coefficient TC_{DC} for downcycling. As no upcycling was assumed for building materials, the recovery rate in this study was equal to the sum of recycling rate and downcycling rate. The amount of waste sent to landfill was determined as absolute mass using the corresponding transfer coefficient TC_{LF} to landfill:

$$waste\ to\ landfills = \sum_{i=1}^{n} M_i \bullet TC_{LF,i} \tag{2}$$

Table 3 summarizes the material groups which were used in this study and the corresponding transfer coefficients, including the transfer coefficient to incineration for the sake of completeness. The classification of building materials into material groups and the values for transfer coefficients to material recovery, waste to landfill sites and incineration were taken from Klingler et al. [48], which comprised an analysis of current waste management practices in the Swiss building sector. For this study, the material recovery of steel, reinforcing steel and non-iron metals was counted as recycling, while the material recovery of all other material groups was counted as downcycling, considering current recycling processes in Switzerland. Recycling of concrete in the sense of closed loop recycling exists, but this is rare which was why it was neglected in the present study. The same applied to gypsum materials. Stone chippings used as ballast within wooden ceiling elements in the flexible design were the only material which fell into the material group *gravel, stone*. As the stone chippings were not mixed with any other material and therefore could be easily reused after dismantling without any further treatment, 100% recycling was assumed for this material group.

Table 3
Material groups and corresponding mass transfer coefficients used to determine recycling rate, downcycling rate and amount of disposed waste connected to the investigated reference building [48].

Material group	Recycling TC_{REC}	Downcycling TC_{DC}	Waste to landfill TC_{LF}	Incineration TC_{INC}
Reinforcing steel	1.000	0	0	0
Concrete	0	0.672	0.328	0
Seal sheeting	0	0	0.024	0.976
Plate glass	0.158	0	0.782	0.056
Gypsum materials	0	0.175	0.695	0.130
Wood and wood materials	0	0.297	0.003	0.700
Gravel, sand	1.000	0	0	0
Adhesives, sealers and coatings	0	0.247	0.680	0.073
Synthetic resin flooring	0	0	1.000	0
Plastics	0	0	0.045	0.955
Mineral thermal insulation	0	0	0.350	0.650
Mortar, plaster	0	0.528	0.472	0
Non-iron metals	0.825	0	0.175	0
Organic thermal insulation	0	0	0.035	0.965
Steel	0.980	0	0.020	0
Unspecified mineral building materials	0	0.528	0.472	0

Materials and masses of most building components could be derived directly from the BoQ of the conventional and flexible building design. Average compositions of doors and windows were taken from Klingler et al. [48]. Material compositions of technical installations, such as electrical systems, sanitary facilities, borehole heat exchangers and heat distribution systems, were derived from inventory data within the generic KBOB datasets. Kitchens, heat pumps, heat distribution systems and ventilation system were not considered within the mass flow analysis, which was justifiable since their contributions to the total mass of the building were estimated to be negligible.

3. Results

According to the life cycle assessment carried out in this study, a 60-year life cycle of the investigated reference building, if built using conventional design, is connected to GHG emissions of 1.14 10^7 kg CO_2-eq and a cumulative non-renewable energy demand equivalent to 3.09 10^8 MJ. The corresponding results for the flexible building design are 1.05 10^7 kg CO_2-eq and 3.11 10^8 MJ, respectively. When referring to operational years and ERA, these results translate into GHG emissions of

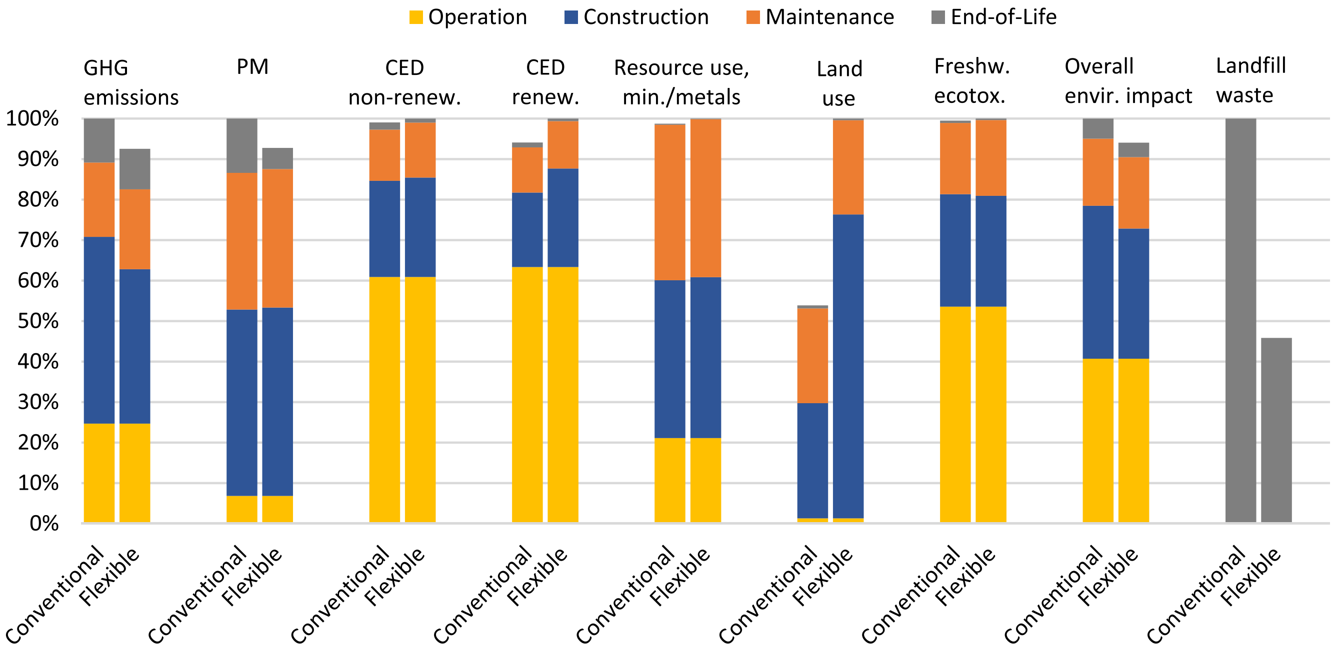

Fig. 3. Relative comparison of environmental impact between conventional and flexible building design for GHG emissions according to IPCC 2013 100a; CED as implemented in ecoinvent; PM, resource use of minerals and metals and land use assessed with the EF method; freshwater ecotoxicity according to the USEtox method, overall environmental impact according to ESM, and the amount of waste sent to landfill based on mass flows at EoL.

13–14.5 kg CO_2-eq/m^2a and a non-renewable CED of 380–390 MJ/m^2a for both designs.

Fig. 3 gives an overview of the relative comparison between the two building designs for all considered LCA indicators as well as for the total amount of landfill waste, showing relative contributions from different building life stages.

For most LCA impact categories, the two designs show similar total impacts with a difference of less than 10%. Land use is an exception, where flexible design leads to an increase in results of approximately 50% when compared to conventional design. The differences between the two designs are entirely caused by differences in the embodied impact related to construction, maintenance and EoL, since the impact of the operational phase is the same. For both designs, the embodied impact shows higher contributions than the operational phase with respect to GHG emissions, PM, resource use of minerals and metals, land use, as well as for the overall environmental impact. The operational phase emerges as the dominant life cycle phase with respect to non-renewable cumulative energy demand (due to electricity based on nuclear power), renewable cumulative energy demand (due to geothermal energy and electricity based on hydropower), as well as freshwater ecotoxicity (due to wastewater treatment and electricity based on coal). For flexible design, the total amount of waste deposited in landfills is

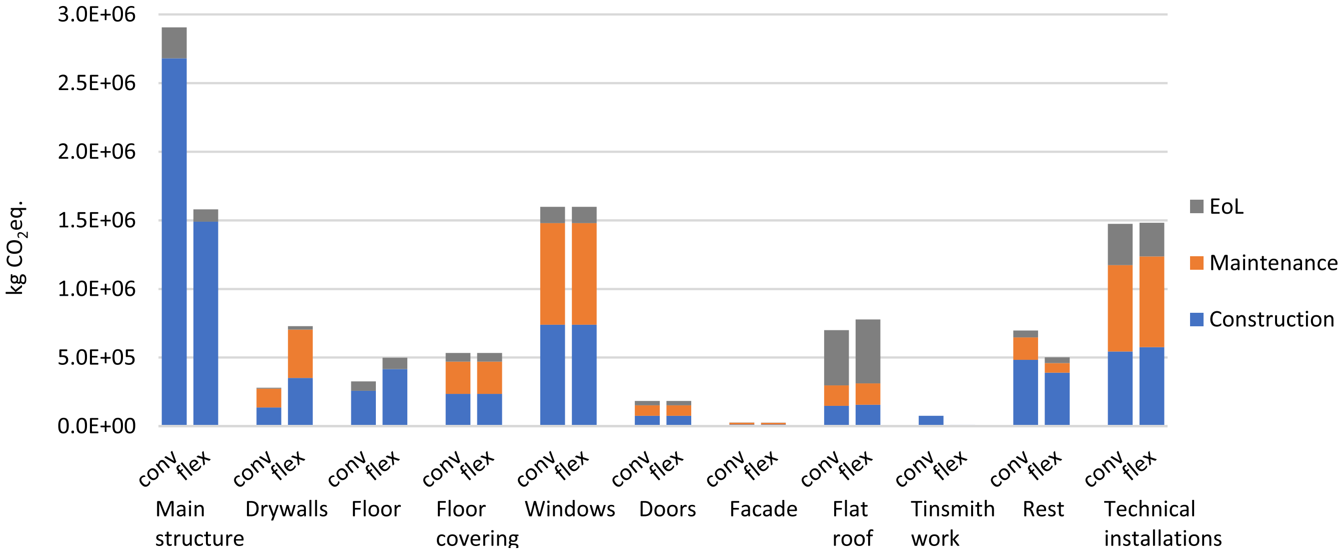

Fig. 4. Absolute contribution to embodied GHG emissions (IPCC, 100a) from components of the reference building comparing conventional building design and flexible building design; given values refer to a building life cycle of 60 years.

about half the amount found for conventional design.

The results for the embodied impact are described in more detail in the following section, while a detailed description of main drivers and relevant processes regarding operational phase is included in the supplementary material (S2).

3.1. Embodied impact of reference building

Individual contributions to the embodied GHG emissions from construction, maintenance and EoL for different components of flexible and conventional design are compared in Fig. 4. Corresponding figures regarding the other impact categories are given in the supplementary material (S3). Table 4 summarizes the absolute results for the embodied impact of the reference building in flexible design and highlights the most relevant components for each impact category.

In flexible building design, main structure, windows and technical installations are the most relevant components regarding embodied GHG emissions, with a contribution of about 15% each. The contribution of the main structure is dominated by steel (9%) and concrete (7%). The embodied GHG emissions of windows are mainly caused by the production of glazing, metal-wood frames, and aluminium blinds. Among the technical installations, the electrical system, sanitary facilities, and the ventilation system show the highest contributions. In total, the embodied GHG emissions of conventional design are about 10% higher than for flexible design. This difference is primarily due to the larger amount of concrete used in the main structure of the conventional design.

Regarding the embodied impact of PM, floor covering emerges as most dominant component for both building designs. This contribution is almost entirely attributed to particle emissions within the production process of ceramic tiles. Compared to flexible building design, the main structure of the conventional building shows an increase of 8% in terms of contribution to the embodied impact of PM due to particle emissions connected to the demolition of concrete in the main structure.

The total embodied non-renewable CED is about 80% related to fossil fuels used for machinery and production processes, and 20% related to electricity based on nuclear energy. For both designs, main structure, windows and technical installations are the most relevant components for the total embodied non-renewable CED.

The renewable CED as implemented in ecoinvent represents the total *harvested* energy which makes wood as a building material with high heating value being the main driver of this impact category. Consequently, wooding ceiling elements in the main structure of the flexible building design represent the major contributor to the embodied renewable CED. In comparison, the main structure of the conventional building does not contain wood at all, leading in total to an embodied renewable CED which is about 50% lower.

The impact indicator *resource use of minerals and metals* expresses abiotic resource depletion based on a use-to-availability ratio [44]. Therefore, main drivers regarding the reference building are not sand or iron, which are used in high quantities, but additives with high characterisation factors such as gold, zinc, tellurium and silver. Copper is the only non-additive metal which is among the main drivers for resource use of minerals and metals. For both building designs, technical installations and windows are the dominant component, with respective contributions of about 60% and 30% to the total embodied resource use of minerals and metals.

The embodied impact due to land use is mainly connected to wood as a building material. Consequently, relative contributions from components are comparable to those for the embodied renewable CED in both building designs.

Zinc and copper are the main drivers for freshwater ecotoxicity. The corresponding relevant processes are sulfidic tailings connected to copper mining and blasting processes for copper and zinc mining. Another driver is electricity based on nuclear power and coal due to pollution connected to uranium and lignite mining. For both building designs, technical installations show the highest contributions to freshwater ecotoxicity due to contributions from copper cables in the electrical system, as well as from brass and steel components of sanitary facilities and heating systems.

The embodied overall environmental impact for both building designs is mainly attributed to GHG emissions (27%), main air pollutants and PM (~20%), heavy metals into air (~16%), heavy metal into water (~10%), and mineral resources (~6%). The corresponding components which are most relevant are main structure, windows and technical installations. In total, the embodied overall environmental impact of the conventional design is about 10% higher than for the flexible design due to the use of more concrete in the main structure.

Table 4
Absolute results for the embodied environmental impact of the reference building with flexible design and identification of relevant components for each impact category; given values refer to a building life cycle of 60 years including construction, maintenance and EoL.

	GHG emissions kg CO_2-eq	PM dis. incid.	CED non-renew. MJ	CED renewable MJ	Resource use min./metals kg Sb-eq	Land use -	Freshw. Ecotox. CTUe	Overall envir. impact eco-points
Main structure	1.58E+06	1.38E-01	2.25E+07	2.52E+07	1.50E+00	1.57E+08	2.17E+08	2.75E+09
Drywalls	7.29E+05	1.85E-02	1.15E+07	4.68E+05	4.15E-01	1.35E+06	1.14E+08	8.16E+08
Floor	4.99E+05	1.38E-02	1.03E+07	4.84E+06	4.73E-01	2.96E+07	5.59E+07	5.77E+08
Floor covering	5.34E+05	3.92E-01	8.60E+06	1.06E+07	3.11E+00	6.50E+07	5.19E+07	9.84E+08
Windows	1.60E+06	8.94E-02	2.48E+07	7.36E+06	2.98E+01	3.47E+07	4.83E+08	2.62E+09
Doors	1.85E+05	1.90E-02	2.99E+06	4.26E+06	6.09E-01	1.62E+07	2.98E+07	2.60E+08
Facade	2.56E+04	1.11E-03	5.98E+05	1.28E+06	9.32E-03	9.91E+06	5.59E+05	5.06E+07
Flat roof	7.78E+05	1.94E-02	1.10E+07	3.20E+05	9.48E-01	1.10E+06	3.63E+07	6.50E+08
Tinsmith work	9.46E+03	2.06E-03	1.47E+05	2.18E+04	3.95E+00	6.64E+04	6.04E+07	1.80E+08
Balcony installations	1.28E+05	1.54E-02	2.45E+06	3.55E+06	1.62E-01	3.15E+07	2.17E+07	2.37E+08
Rest	3.75E+05	1.98E-02	5.13E+06	7.77E+05	7.16E-01	3.78E+06	5.26E+07	4.97E+08
Direct land use	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.40E+07	0.00E+00	3.63E+07
Technical installations	1.48E+06	1.32E-01	2.32E+07	4.78E+06	6.92E+01	1.55E+07	7.52E+08	3.55E+09
Total	7.92E+06	8.60E-01	1.23E+08	6.34E+07	1.11E+02	3.80E+08	1.87E+09	1.32E+10

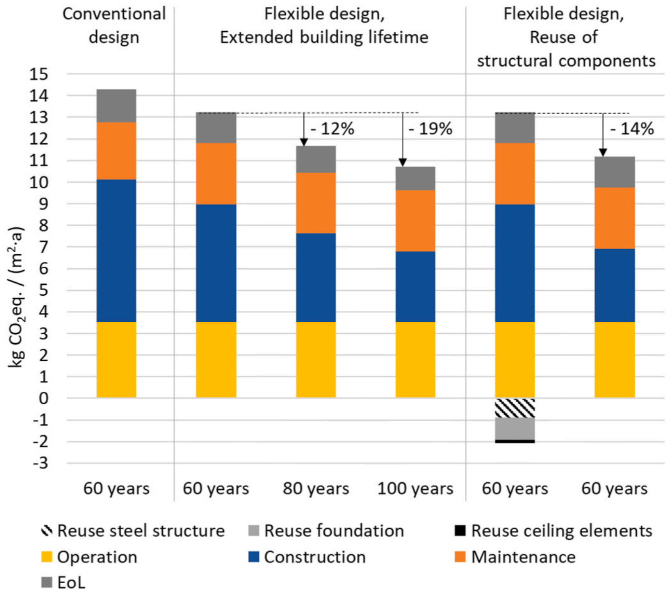

Fig. 5. Effect of extended lifetimes and of reuse of structural elements on the on GHG emissions of flexible building design compared to the conventional building; results are given as relative GHG emissions per year and per square meter ERA.

3.2. *Environmental benefit of extended building lifetime and reuse of structural elements*

The determined reductions of GHG emission per operational year due to extended building lifetime and due to direct reuse of structural components of the flexible building are shown in Fig. 5, which compares relative results for each life stage per operational year and square meter ERA.

Extending the lifetime of the flexible building from 60 to 100 years means that the GHG emissions per year related to the construction phase decrease by 40%, leading to a reduction in total GHG emissions per year of about 19%. As far as a building with a lifetime of 100 years is concerned, construction phase and maintenance phase reach comparable contributions to GHG emissions.

Regarding reuse, the avoided burden on the foundation, load-bearing steel structure and wooden ceiling elements is shown as negative emissions for the flexible building in Fig. 5. In addition, the resulting net GHG emissions are shown. The avoided GHG emissions from reuse are in total 1.11 10^6 kg CO_2-eq, which are 14% of the total GHG emissions of the flexible building. The highest avoided burden results from the reuse of the steel structure with 7.27 10^5 kg CO_2-eq. (~9% of the total GHG emissions).

Comparing the reduction of environmental impact due to lifetime extension and reuse of structural components, Fig. 5 shows that reuse of structural components leads to a slightly higher impact reduction than a lifetime extension of 20 years, but to a smaller impact reduction than a lifetime extension of 40 years.

3.3. *Material flows at building end-of-life and circular economy indicators*

The total mass of building materials used for construction and maintenance of the reference building is 2.74 10^7 kg for conventional design and 1.43 10^7 kg for flexible design. Relative mass flows from different material groups regarding recycling, downcycling, landfill and incineration at EoL are illustrated in Fig. 6 for both building designs. To enhance clarity, the mass flow of steel in Fig. 6 refers to the sum of the material groups *steel* and *reinforcing steel*. With regard to mass, the conventional design relies predominantly on mineral materials: concrete constitutes 70% of the total building mass, while unspecified mineral building materials, including brick and screed, constitute about 15%. Steel, which is mainly reinforcing steel, contributes about 5%. Material groups such as wood, gypsum materials and mineral thermal insulation (i.e., mineral wool) account only for minor parts of the building mass.

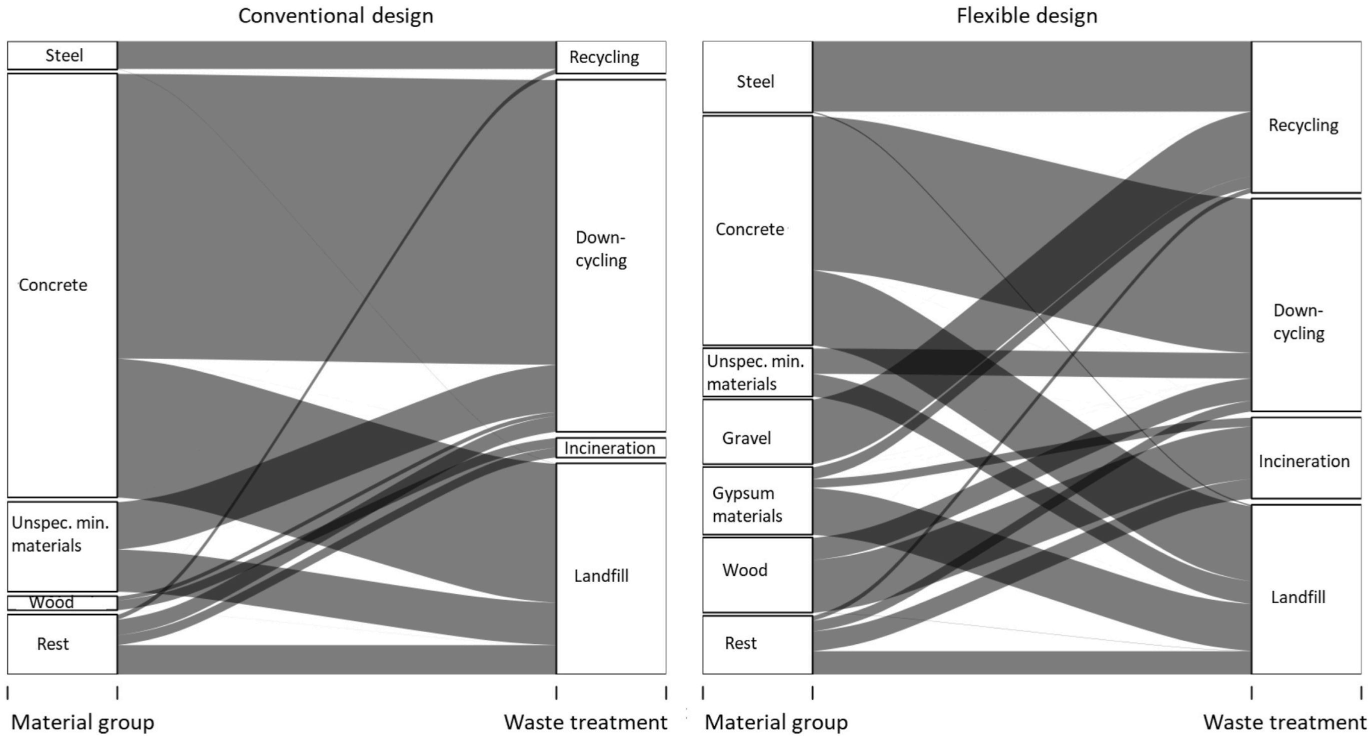

Fig. 6. Relative mass flows of building material groups with respect to waste treatment at end-of-life for conventional (left) and flexible (right) design of the reference building; results shown in the graph include materials from construction and maintenance phase.

Table 5
Results for CE indicators based on material flows at EoL of the reference building; the results refer to materials used for construction as well as for replacements during maintenance.

	Total material recovery rate	Recycling rate	Downcycling rate	Waste to landfills	
				absolute value	mass rate
Conventional design	62%	5%	57%	$9.41 \cdot 10^6$ kg	34%
Flexible design	60%	25%	35%	$3.94 \cdot 10^6$ kg	28%

Compared to the conventional design, the material composition of the flexible building design is more diverse, although mineral materials are still in the majority. Concrete accounts for 37% of the total building mass. Steel, wood, gypsum materials, gravel and stone, and unspecified mineral materials have contributions of around 10% each.

The corresponding results for the CE indicators considered (material recovery rate, recycling rate, downcycling rate, waste to landfills) are summarised in Table 5. Both building designs reach total material recovery rates of around 60%. However, material recovery for conventional design mainly consists in downcycling of concrete and other mineral materials. For flexible design, the recycling rate of 25% consists of equal shares in closed loop recycling of steel and assumed reuse of stone chippings.

For both building designs, roughly one third of the building waste is disposed in landfills. The absolute amount of deposited waste for conventional design is more than twice as high as for flexible design due to the higher total mass of the conventional building. For flexible design, gypsum materials used for drywalls and floors account for about 30% of the waste sent to landfills.

Roughly 10% of the waste from flexible building design is disposed via incineration, which constitutes a rate which is about four times higher than for conventional design. The main reason for this higher rate is wood and wooden materials in the flexible design.

4. Interpretation and discussion

In the following sections, the results of the LCA as well as the material flow analysis for the reference building are integrated and put into context. Following a discussion of data quality and consistency, the environmental performance of flexible building design is examined. Results found in this study are compared to published results from other studies, and recommendations for further research are given.

4.1. Data quality, data consistency and limitations

The present study was based on a rather exceptional data collection both in terms of comprehensiveness and quality. For a specific reference building, BoQ on a whole-building level were available for conventional design as well as for flexible design. The BoQ were derived based on designer specifications, taking into account static calculations, actual building geometry and specific material solutions. The foreground data from the BoQ was linked to the Swiss LCA catalogue for construction (KBOB). KBOB datasets follow a consistent methodology and they fulfil the same quality requirements as ecoinvent-v2.2 datasets which served as background data. In this sense, the comparison between conventional and flexible building design in the study was carried out using consistent, high quality foreground data linked to consistent, high quality background data. Nonetheless, there are limitations and uncertainties which should be considered.

When this study was carried out, the design of the reference building existed on a pre-project level. In case that the reference building were actually to be built, material quantities could differ by up to 10% from the pre-project BoQ. Material quantities used for technical installations could differ even more from the assumed values, since only generic datasets were used in this study for installations.

In general, a high level of uncertainty is expected due to the prospective character of the study. Maintenance, demolition and disposal of building materials will take place only decades after construction. Potential future developments regarding technologies, materials and energy mixes were not considered in this study. In the same way, the results of CE indicators such as recycling rate and disposed waste are also subject to uncertainties. Current transfer coefficients for material recovery and final disposal were used, but clearly these might change in the decades to come.

Life expectations for component groups were taken from the Swiss norm SIA 2032 [34], which regulates the assessment of embodied impact of buildings. Following the norm, no partial replacements but only 100% replacements of components were modelled. This is clearly a very conservative assumption which may lead to a certain overestimation of the actual embodied impact of the maintenance phase.

In summary, even though this study was carried out using a well-founded database, care should be taken to not overinterpret the results in absolute terms.

4.2. Environmental performance of flexible building design

Assuming a regular 60-year building life cycle including replacement of components but without major refurbishment, the LCA of the reference building showed comparable results for most impact indicators on a midpoint level for both flexible and conventional design. Flexible design led to GHG emissions which were about 7% lower, corresponding to an absolute difference of 870 t CO_2-eq. Land use for flexible design was found to be about 50% higher than for conventional design due to higher use of wood. There is a scientific discussion about how to derive and how to weight the impact of land use for buildings [49]. Within the ecological scarcity method, lower weight is given to land use than to GHG emissions and heavy metal emissions. Consequently, the overall environmental impact of flexible design was 6% lower than for conventional design.

In short, neither major advantages nor major disadvantages emerged for flexible design from the LCA of a regular building life cycle of 60 years. If anything, the results showed that flexible building design does not lead *per se* to a lower environmental impact than monolithic design. Like any building design, flexible design should also undergo an optimisation process to minimise the building's environmental impact. Special care should be taken to avoid trade-offs between flexibility and environmental impact. For example, the use of gypsum boards for drywall constructions and floors have proven to make a considerable contribution to the embodied impact of the building. Here, panels based on clay or straw might be more eco-friendly alternatives.

An environmental benefit of flexible building design is expected when refurbishment is needed during the building lifetime as is often the case in commercial or public buildings in urban areas which have a fluctuation of tenants, and which undergo changes in use. In such cases, flexibility as a design criterion can extend the service lifetime of the building as it allows for easier refurbishment which can ultimately prevent premature demolition. From an LCA perspective, it is extremely challenging to analyse potential refurbishments of buildings on a pre-project level since these are not normally planned at the beginning of the building life cycle. Nonetheless, a sensitivity study carried out in the present study showed that extending building lifetime represents a very effective measure to reduce the relative embodied impact of buildings per operation year, considering the high contribution of the construction phase to the total impact of the whole building life cycle. This is particularly important as the embodied impact of the construction is set once and for all at the beginning of the building lifetime, while the actual impact of maintenance, operation and dismantling still have the potential to decrease due to future technological developments.

Alongside environmental benefits regarding refurbishment, decision-makers should also consider time and cost aspects. Refurbishment of the considered flexible building design, including changes in installations, consists of dry construction work, while refurbishment of monolithic buildings involves demolition of reinforced concrete components and wet construction work to rebuild them. Consequently, the refurbishment process of the flexible building is expected to be considerably shorter as no drying time is needed. In addition, noise and particle emissions are lower for dry construction work, which is another relevant aspect in densely used urban areas.

With respect to CE aspects for waste treatment, the steel structure used in the investigated flexible design showed clear advantages compared to the reinforced concrete structure of the conventional design. Similar material recovery rates were found for both building designs. However, flexible design led to a much higher closed loop recycling rate as building steel is almost fully recovered in closed loop recycling processes in Switzerland. In contrast, material recovery of concrete mainly consists of downcycling, which helps to save mineral resources but which is connected to only low retention of GHG emissions and energy demand. Furthermore, only two thirds of building concrete is recovered, while the remaining third is disposed of in landfills. The analysis of disposal processes in Switzerland revealed that there is not yet an established recycling market for other relevant building materials such as gypsum and mineral wool, which are still predominantly disposed of via incineration and landfills even if they were neatly separated at EoL. Consequently, it would be necessary that all stakeholders, i.e., also the production and disposal industry, evolved in the CE direction to fully profit from the reversibility of flexible building design in terms of material recovery.

Finally, another advantage of flexible and reversible building design consists in the continued use of structural elements. The flexible building investigated is designed in such a way that the main structure can be stripped bare at EoL and then reused for a second building life cycle - a scenario which could also be labelled as an extreme case of refurbishment. The analysis of direct reuse showed that 14% of the embodied GHG emissions of the building could be avoided when reusing the foundation, wooden ceiling elements and load-bearing steel structure for a subsequent second building. Compared to recycling, this direct reuse has a clear environmental advantage as it leads to almost complete value retention. The reuse of the steel structure and wooden ceiling elements is not limited to the same location but can also take place at another site. This paves the way for more reuse potential which at present simply does not exist for monolithic buildings.

4.3. *Comparison to literature*

The GHG emissions (embodied and operational) of the flexible reference building are compared to published LCA results for apartment buildings and single-family homes in Fig. 7. Only European studies are considered in the comparison, and the results cover average benchmarks [13,50–52] as well as specific case studies [11,12,53,54].

The GHG emissions per square meter floor area and operational year of the reference building were below all published results. This difference is mainly due to the operational phase, as published LCA with higher GHG emissions included high contributions from the operational phase of more than 70% [13,54], while a contribution of only 25% was found for the reference building in this study.

In general, the studies considered for the comparison differ in many relevant parameters, such as climate zone, energy source for heating, insulation standard, electricity mix, building type and size, system boundaries as well as used background data. The high number of relevant parameters makes a comparison among case studies generally challenging.

On a qualitative level, the results of this study confirm the observed ongoing shift of environmental impact from the operational phase towards the embodied impact of buildings, due to an increased move towards energy efficient buildings as well as a move away from fossil-based heating systems [13]. Furthermore, the results are in line with the conclusion of Lavagna et al. [13] who show that upgrading existing buildings rather than demolishing and rebuilding them is important in order reduce environmental impacts. Alongside construction, the maintenance phase has relevant contributions for the embodied impact of the reference building. This confirms Thomark's [16] conclusion that maintenance should not be neglected within building LCA and that prolonging the lifetime of components and choosing materials with less embodied impact are additional important measures to mitigate the environmental impact of buildings.

Discrepancies between previously published conclusions exist concerning resource depletion. In their review of LCA of buildings, Sharma et al. [19] concluded that resource depletion was particularly important with respect to the construction of the main structure due to high demand for stone, sand and gravel. In this study, resource depletion of minerals and metals is dominated by metals like copper, zinc, silver, and gold, mainly used for technical installations and windows. This difference highlights the relevance of the choice of impact assessment methods. In this study, resource use of minerals and metals was evaluated as it was implemented in the EF method, which weighted resource

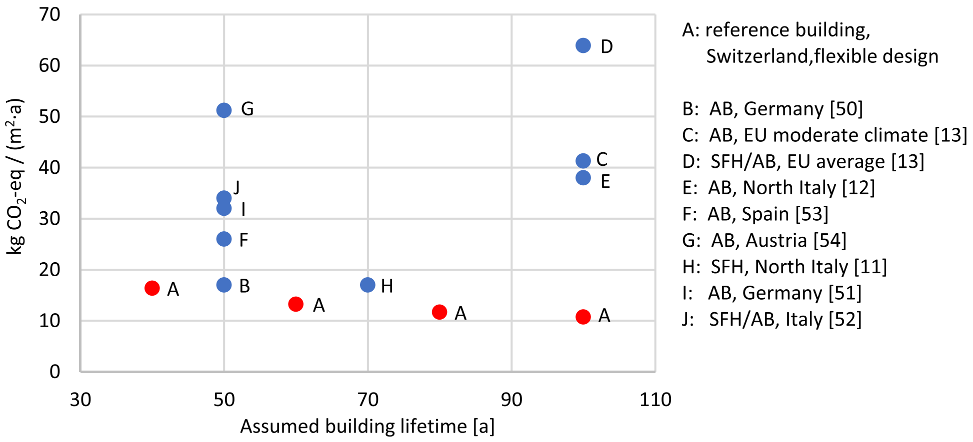

Fig. 7. Comparison of GHG emissions of European single-family homes (SFH) and apartment buildings (AB) per operational year and m^2 floor area. Red dots refer to results for the reference building with flexible design; blue dots refer to results from literature. The values for GHG emissions include the operational phase and the embodied impact of the buildings. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

depletion on a use-to-availability ratio [44] and consequently gave little weight to the depletion of sand and gravel.

4.4. Research recommendations

An existing research gap which could not be covered by this study was the need for a quantitative life cycle assessment of refurbishment scenarios in comparison to demolition and rebuilding to assess the environmental value of flexible building designs. Such analyses would require data for a specific refurbishment scenario. This remains challenging for new buildings with innovative design as the exact needs for future refurbishment are typically not known when a building is constructed. In this context, the study highlighted the shortcoming of standardised LCA methodologies for the comparison between conventional and flexible building designs. The norm SIA 2032, which was used to determine the embodied impact of the reference building, only considered a static building life cycle of 60 years without any refurbishment and did not cover the functionality of building flexibility. Furthermore, a comprehensive analysis would ideally include cost and time aspects along with environmental aspects.

5. Conclusions

The environmental performance of a flexible and reversible building design based on a load-bearing steel structure combined with wooden ceiling elements and drywall constructions was analysed in comparison to a conventional, monolithic design based on reinforced concrete.

The study revealed that a major environmental advantage of flexible building design lies in the possibility to adapt building space to future needs, which can ultimately prevent premature demolition and extend the building lifetime. The results show that extending the lifetime of a building significantly decreases its embodied impact due to the high contribution of the construction phase in general and the high impact of steel and concrete as structural materials.

Furthermore, a flexible and reversible building design decreases the amount of mixed demolition waste and increases material recirculation as components and materials can be neatly separated after decommissioning. Actual recycling rates could be further increased if material recovery processes for relevant materials such as mineral wool and gypsum were expanded.

Finally, a further advantage of a flexible and reversible building design consists in the continued use of components for subsequent building life cycles. Direct reuse of structural components can also take place in different locations and leads to a much higher impact retention than recycling of materials alone. However, reuse practices in the built environment still need to be established to profit fully from this advantage.

From an LCA perspective, the study revealed that a quantitative comparison between conventional and flexible building designs remains challenging as it is difficult to consider the functionality of building flexibility on a pre-project level.

To conclude, the present study confirms that a flexible and reversible design can be an effective measure to mitigate the environmental impact of buildings. At the same time, the study also makes clear that building designers alone cannot solve the sustainability problem of the building sector. Upstream and downstream actors must also play their part, e.g., by adopting cleaner production processes, increasing the durability of components, and expanding recycling and reuse practices.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or non-profit sectors.

CRediT authorship contribution statement

Hanna Kröhnert: Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **René Itten:** Writing – review & editing, Supervision. **Matthias Stucki:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is made available in the supplementary material.

Acknowledgements

This research paper was made possible thanks to collaboration with UNAS Technology SA (Zurich, Switzerland) and their project partners from raumlabor.ch, ARCHIPART AG, Nüesch Development AG (all Zurich, Switzerland), mawi SA (Lausanne, Switzerland), and ArcelorMittal SA (Esch/Alzette, Luxembourg). The authors gratefully acknowledge all stakeholders who were involved in the design and the technical layout of the buildings and who supported the research with their expertise.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2022.109409.

References

[1] UN, 2020 Global Status Report for Buildings and Construction: towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector, United Nations Environment Programme, Nairobi, Kenya, 2020.
[2] European Commission, Deloitte, BRE, ICEDD., VTT, RPS, FCT, Resource Efficient Use of Mixed Wastes Improving Management of Construction and Demolition Waste: Final Report, 2017. https://data.europa.eu/doi/10.2779/99903. (Accessed 16 May 2022).
[3] European Commission, A New Circular Economy Action Plan - for a Cleaner and More Competitive Europe, COM, 2020, 98 final, (2020), https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN. (Accessed 1 January 2022).
[4] M. Buyle, J. Braet, A. Audenaert, Life cycle assessment in the construction sector: a review, Renew. Sustain. Energy Rev. 26 (2013) 379–388, https://doi.org/10.1016/j.rser.2013.05.001.
[5] C.K. Anand, B. Amor, Recent developments, future challenges and new research directions in LCA of buildings: a critical review, Renew. Sustain. Energy Rev. 67 (2017) 408–416, https://doi.org/10.1016/j.rser.2016.09.058.
[6] U.S. Green Building Council (Ed.), LEED Reference Guide for Building Design and Construction, 2013 edition, U.S. Green Building Council, Washington, DC, 2013. https://www.usgbc.org/leed. (Accessed 16 May 2022). accessed.
[7] DGNB System Version 2020 International, 2019. https://www.dgnb-system.de. (Accessed 15 May 2022).
[8] SIA, Norm SIA 2040: SIA-Effizienzpfad Energie (SIA Energy Efficiency Path), The Swiss Society of Engineers and Architects (SIA), Zurich, Switzerland, Zurich, Switzerland, 2017.
[9] H.H. de Simone Souza, P.P. de Abreu Evangelista, D.L. Medeiros, J. Albertí, P. Fullana-i-Palmer, M.Á. Boncz, A. Kiperstok, J.P. Gonçalves, Functional unit influence on building life cycle assessment, Int. J. Life Cycle Assess. 26 (2021) 435–454, https://doi.org/10.1007/s11367-020-01854-1.
[10] S. Xing, Z. Xu, G. Jun, Inventory analysis of LCA on steel- and concrete-construction office buildings, Energy Build. 40 (2008) 1188–1193, https://doi.org/10.1016/j.enbuild.2007.10.016.
[11] G.A. Blengini, T. Di Carlo, The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings, Energy Build. 42 (2010) 869–880, https://doi.org/10.1016/j.enbuild.2009.12.009.
[12] M. Paleari, 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, https://doi.org/10.1007/s11367-016-1133-6.

[13] M. Lavagna, C. Baldassarri, A. Campioli, S. Giorgi, A. Dalla Valle, V. Castellani, S. Sala, Benchmarks for environmental impact of housing in Europe: definition of archetypes and LCA of the residential building stock, Build, Environ. Times 145 (2018) 260–275, https://doi.org/10.1016/j.buildenv.2018.09.008.

[14] E. Hoxha, G. Habert, S. Lasvaux, J. Chevalier, R. Le Roy, Influence of construction material uncertainties on residential building LCA reliability, J. Clean. Prod. 144 (2017) 33–47, https://doi.org/10.1016/j.jclepro.2016.12.068.

[15] G. Assefa, C. Ambler, To demolish or not to demolish: life cycle consideration of repurposing buildings, Sustain. Cities Soc. 28 (2017) 146–153, https://doi.org/10.1016/j.scs.2016.09.011.

[16] C. Thormark, The effect of material choice on the total energy need and recycling potential of a building, Build. Environ. 41 (2006) 1019–1026, https://doi.org/10.1016/j.buildenv.2005.04.026.

[17] F. Pomponi, A. Moncaster, Circular economy for the built environment: a research framework, J. Clean. Prod. 143 (2017) 710–718, https://doi.org/10.1016/j.jclepro.2016.12.055.

[18] D. Trigaux, K. Allacker, W. Debacker, Environmental benchmarks for buildings: a critical literature review, Int. J. Life Cycle Assess. 26 (2021) 1–21, https://doi.org/10.1007/s11367-020-01840-7.

[19] A. Sharma, A. Saxena, M. Sethi, V. Shree, Varun, Life cycle assessment of buildings: a review, Renew. Sustain. Energy Rev. 15 (2011) 871–875, https://doi.org/10.1016/j.rser.2010.09.008.

[20] W. Debacker, S. Manshoven, Key Barriers and Opportunities for Materials Passports and Reversible Building Design in the Current System, Buildings As Material Banks (BAMB), 2016. http://www.bamb2020.eu/wp-content/uploads/2016/03. (Accessed 30 January 2021).

[21] Ellen MacArthur Foundation, Life Cycle Assessment for the Circular Economy, 2022 (accessed June 29, 2022), https://ellenmacarthurfoundation.org/life-cycle-assessment-for-the-circular-economy.

[22] A. van Stijn, L.C. Malabi Eberhardt, B. Wouterszoon Jansen, A. Meijer, A circular economy life cycle assessment (CE-LCA) model for building components, Resour. Conserv. Recycl. 174 (2021), 105683, https://doi.org/10.1016/j.resconrec.2021.105683.

[23] Ellen MacArthur Foundation, What Is a Circular Economy?, 2022. https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview. (Accessed 19 May 2022).

[24] M. Geissdoerfer, P. Savaget, N.M.P. Bocken, E.J. Hultink, The Circular Economy - a new sustainability paradigm? J. Clean. Prod. 143 (2017) 757–768, https://doi.org/10.1016/j.jclepro.2016.12.048.

[25] European Commission, The European Green Deal, COM, 2019, 640 final, (2019), https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX:52019DC0640. (Accessed 2 March 2021).

[26] E. Antonini, A. Boeri, M. Lauria, F. Giglio, Reversibility and durability as potential indicators for circular building technologies, Sustainability 12 (2020) 7659, https://doi.org/10.3390/su12187659.

[27] M.R. Munaro, S.F. Tavares, L. Bragança, Towards circular and more sustainable buildings: a systematic literature review on the circular economy in the built environment, J. Clean. Prod. 260 (2020), 121134, https://doi.org/10.1016/j.jclepro.2020.121134.

[28] A. Stephan, A. Athanassiadis, Quantifying and mapping embodied environmental requirements of urban building stocks, Build. Environ. 114 (2017) 187–202, https://doi.org/10.1016/j.buildenv.2016.11.043.

[29] P. Mhatre, V. Gedam, S. Unnikrishnan, S. Verma, Circular economy in built environment - literature review and theory development, J. Build. Eng. (2020), 101995, https://doi.org/10.1016/j.jobe.2020.101995.

[30] P. Ghisellini, M. Ripa, S. Ulgiati, Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review, J. Clean. Prod. 178 (2018) 618–643, https://doi.org/10.1016/j.jclepro.2017.11.207.

[31] ISO 14040:2006, Environmental Management - Life Cycle Assessment - Principles and Framework, International Organization for Standardization, Geneva, Switzerland, 2009.

[32] PRéConsultants, SimaPro v9. https://simapro.com/, 2020. (Accessed 13 June 2020).

[33] SIA, Norm SIA 2040: SIA-Effizienzpfad Energie (SIA Energy Efficiency Path), The Swiss Society of Engineers and Architects (SIA), Zurich, Switzerland, 2017.

[34] SIA, Norm SIA 2032: Graue Energie - ökobilanzierung für die Erstellung von Gebäuden (grey energy - life cycle assessment of buildings), The Swiss Society of Engineers and Architects (SIA), Zurich, Switzerland, 2010.

[35] KBOB, Liste Oekobilanzdaten im Baubereich 2009-1-2016-gerundet-kW (LCA data for the construction sector), Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren (KBOB), Switzerland. https://www.kbob.admin.ch/kbob/de/home/themen-leistungen/nachhaltiges-bauen/oekobilanzdaten_baubereich.html, 2016. (Accessed 18 January 2021).

[36] R. Frischknecht, N. Jungbluth, H.J. Althaus, G. Doka, R. Dones, T. Heck, S. Hellweg, R. Hischier, T. Nemecek, G. Rebitzer, M. Spielmann, The ecoinvent database: overview and methodological framework, Int. J. Life Cycle Assess. 10 (2005) 3–9, https://doi.org/10.1065/lca2004.10.181.1.

[37] R. Hischier, H.-J. Althaus, C. Bauer, G. Doka, R. Frischknecht, T. Nemecek, A. Simons, M. Stucki, J. Sutter, M. Tuchschmid, Documentation of Changes Implemented in Ecoinvent Data v2.1 and v2.2; Ecoinvent Report No. 16, Ecoinvent Centre, St. Gallen, Switzerland, St. Gallen, Switzerland, 2010.

[38] SVGE, Haushaltsverbrauch in der Schweiz (Household consumption in Switzerland), Fachverband für Wasser-, Gas- und Fernwärmeversorger, SVGW, 2021. http://wasserqualitaet.svgw.ch/index.php?id=874. (Accessed 24 May 2021). assessed 05/24/2021.

[39] P. Stolz, R. Frischknecht, Hintergrundbericht zur Aktualisierung der Sachbilanzen von Baumaterialien (Background report on updates for the inventory of building materials), Koordinationskonferenz der Bau- und Liegenschaftsorgane der Öffentlichen Bauherren KBOB, Switzerland, 2017.

[40] S. Fazio, V. Castellani, S. Sala, E.M. Schau, M. Secchi, L. Zampori, E. Diaconu, Supporting Information to the Characterisation Factors of Recommended EF Life Cycle Impact Assessment Method, European Commission, Ispra, 2018.

[41] IPCC, Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2013.

[42] R. Frischknecht, N. Jungbluth, H.-J. Althaus, R. Hischier, G. Doka, C. Bauer, R. Dones, T. Nemecek, S. Hellweg, S. Humbert, Implementation of Life Cycle Impact Assessment Methods. Data V2. 0 (2007). Ecoinvent Report No. 3, Ecoinvent Centre, Switzerland, 2007.

[43] P. Fantke, J.R. Evans, N. Hodas, J.S. Apte, M.J. Jantunen, O. Jolliet, T.E. McKone, Health impacts of fine particulate matter, in: Glob. Guid. Life Cycle Impact Assess. Indic, vol. 1, UNEP/SETAC Life Cycle Initiative, Paris, 2016, pp. 76–99.

[44] L. Van Oers, A. De Koning, J.B. Guinée, G. Huppes, Abiotic resource depletion in LCA, Road Hydraul. Eng. Inst. Minist. Transp. Water Amst. (2002).

[45] U. Bos, R. Horn, T. Beck, J.P. Lindner, M. Fischer, LANCA®-characterization Factors for Life Cycle Impact Assessment: Version 2.0, Fraunhofer Verlag, 2016.

[46] R.K. Rosenbaum, T.M. Bachmann, L.S. Gold, M.A.J. Huijbregts, O. Jolliet, R. Juraske, A. Koehler, H.F. Larsen, M. MacLeod, M. Margni, T.E. McKone, J. Payet, M. Schuhmacher, D. van de Meent, M.Z. Hauschild, USEtox - the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment, Int. J. Life Cycle Assess. 13 (2008) 532–546, https://doi.org/10.1007/s11367-008-0038-4.

[47] R. Frischknecht, S. Büsser Knöpfel, K. Flury, M. Stucki, M. Ahmadi, Swiss Eco-Factors 2013 According to the Ecological Scarcity Method, Federal Office for the Environment (FOEN), Bern, Switzerland, 2013.

[48] M. Klingler, D. Savi, G. Doka, Harmonisierte Ökobilanzen der Entsorgung von Baustoffen, Für die Liste der Ökobilanzdaten im Baubereich, Büro für Umweltchemie, Zurich, Switzerland, 2019. https://www.bafu.admin.ch/bafu/de/home/suche.html#Harmonisierte%20%C3%96kobilanzen%20der%20Entsorgung%20von%20Baustoffen. (Accessed 2 April 2021).

[49] K. Allacker, D.M. de Souza, S. Sala, Land use impact assessment in the construction sector: an analysis of LCIA models and case study application, Int. J. Life Cycle Assess. 19 (2014) 1799–1809, https://doi.org/10.1007/s11367-014-0781-7.

[50] H. König, M.L. De Cristofaro, Benchmarks for life cycle costs and life cycle assessment of residential buildings, Build. Res. Inf. 40 (2012) 558–580, https://doi.org/10.1080/09613218.2012.702017.

[51] F. Schlegl, J. Gantner, R. Traunspurger, S. Albrecht, P. Leistner, LCA of buildings in Germany: proposal for a future benchmark based on existing databases, Energy Build. 194 (2019) 342–350, https://doi.org/10.1016/j.enbuild.2019.04.038.

[52] R. Moschetti, L. Mazzarella, N. Nord, An overall methodology to define reference values for building sustainability parameters, Energy Build. 88 (2015) 413–427, https://doi.org/10.1016/j.enbuild.2014.11.071.

[53] I.Z. Bribián, A.A. Usón, S. Scarpellini, Life cycle assessment in buildings: state-of-the-art and simplified LCA methodology as a complement for building certification, Build. Environ. 44 (2009) 2510–2520.

[54] A. Passer, H. Kreiner, P. Maydl, Assessment of the environmental performance of buildings: a critical evaluation of the influence of technical building equipment on residential buildings, Int. J. Life Cycle Assess. 17 (2012) 1116–1130, https://doi.org/10.1007/s11367-012-0435-6.