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On the necessity of improving the environmental impacts of furniture and appliances in net-zero energy buildings

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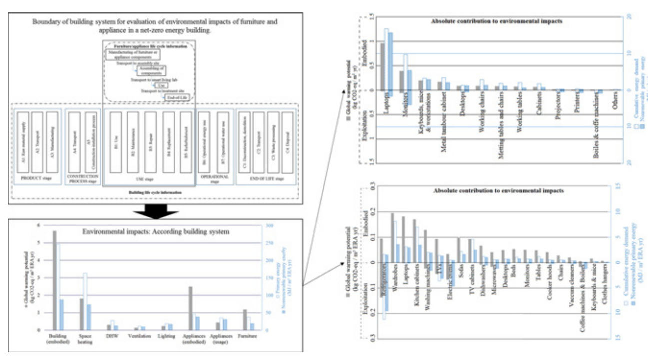
HIGHLIGHTS

- Assessment of the environmental impacts of furniture and appliances throughout the LCA of a nearly net-zero energy building.
- Furniture is responsible for around 10% and appliances for 25% of the building"s overall impacts.
- Embodied impacts dominate over the operational phase impacts.
- For offices, laptops have the greatest impacts the source being their production phase.
- For dwellings, refrigerators have the greatest impacts, the source being their operational phase.

GRAPHICAL ABSTRACT



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ABSTRACT

There is now clear evidence regarding the extensive use of furniture and appliances in daily human life, but there is less evidence of their impact on the environment. Responding to this gap in knowledge, this study focuses on an assessment of the environmental impacts of furniture and appliances as used in highly energy efficient buildings. Their primary energy, non-renewable energy and global warming potential indicators have been assessed by extending the boundaries of the Life Cycle Assessment (LCA) study beyond the building itself. In conclusion, we found that furniture and appliances were responsible for around 30% of greenhouse gas emissions and non-renewable energy consumption and 15% of primary energy consumption comparing to the overall impacts of the building. Since embodied impacts represent the largest values, the process for labelling the appliances' energy efficiency should encompass a life-cycle point of view, not just a usage point of view as the case currently. Among office appliances, computer equipment was ranked as the highest impacting element, especially laptops and monitors. As for domestic appliances, refrigerators and electric ovens had the biggest impacts. Concerning furniture, the greatest impacts were from office and kitchen cabinets.

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1. Introduction

The overexploitation of non-renewable resources and the damage being caused to the environment have compelled countries to use energy and raw materials more efficiently (Eurostat, 2016). To better contribute to a reduction in the emission of greenhouse gases, which are the major cause of climate change, several countries have proposed medium and long term objectives (MSDEFCC, 2015; European Commission, 2017). In Switzerland, to encourage the sustainable and equitable use of the world's natural resources the Federal Institute of Technology in Zurich promoted the "2000-watt per capita" society vision. The level of 2000 watts corresponds to the global average level of energy consumption per person. According to this vision, the current impact of primary energy, non-renewable energy and greenhouse gases associated with all human activity should be reduced by a factor of 2, 3 and 4 respectively by 2050 (Jochem et al., 2004; Morrow and Smith-Morrow, 2008; SIA-D0236, 2011; 2000-watt society, 2017). Buildings represent one of the major contributors (UNEP SBCI, 2009; Conejos and Langston, 2010) have significant potential for cost-effective emissions reduction (UNEP SBCI, 2009). In the European Union, the built environment is responsible for 36% of greenhouse gas emissions and 40% of total energy consumption (European Commission, 2016). For this reason, the scientific community has focused its efforts on this sector for more than 20 years, in an effort to minimise the environmental impacts (Cole and Kernan, 1996; Dincer, 2002; Thormark, 2006; Prasartkaew and Kumar, 2010; Pacheco-Torgal and Jalali, 2012; Cuce et al., 2014; Silvestre et al., 2013). Using a life cycle assessment (LCA) method, various appropriate solutions have been developed and proposed, leading to reductions in the impacts of buildings. These solutions have been found to be suitable especially for reducing the impacts at the operational phase through the minimisation of energy demand (Ramesh et al., 2010; Jankovic, 2012; Berggren et al., 2013; Grondzik and Kwok, 2014). The development of ultra-low energy buildings that require little energy for space heating, cooling or ventilation, led to net-zero energy building (NZEB) concept. For an NZEB the total energy produced on site is equal to or greater than the total amount of energy used by the building on an annual basis (Peterson et al., 2015). To motivate the development of NZEBs, the Council of the European Parliament has established a mandatory directive. This directive requires all new buildings to be NZEBs by the end of 2020, and all new public buildings to be net-zero energy by 2018 (European Commission, 2016). Although by 2020 all new buildings will be NZEBs, the problem of climate change will always be unresolved and embodied impacts will consequently become the next target for reducing the greenhouse gas emissions of the building sector. Different studies have aimed to identify the stratigraphy of building components with a small environmental footprint (Lopez-Mesa et al., 2009; Weiss et al., 2012; Iribarren et al., 2015; Fraile-Garcia et al., 2015; Fraile-Garcia et al., 2016). Among the different solutions, ground-breaking construction technologies were found to have very low embodied impacts even though they present barriers to easy implementation (Arora et al., 2014; Giesekam et al., 2016). The current development of low environmental footprint buildings introduces the challenge of evaluating the environmental impacts of furniture and appliances. Even if an increased production of these goods has been acknowledged, due to their extensive utility in daily life (European Commission, 2016; BIO Intelligence Service and ERA technology, 2011), few studies have assessed the impacts that they have on the environment.

The environmental impacts of appliances are widely treated in the literature. The impacts of refrigerators are treated by Xiao et al. (2015) and Xue et al. (2017), those of vacuum cleaners by Bobba et al. (2015) and Gallego-Schmid et al. (2016), those of washing machines by Bourrier et al. (2011) and Ardente and Mathieux (2014), those of dishwashers by Fulvio and Peiro (2015), those of televisions by Hischier and Baudin (2010), those of cooker hoods by Reale et al. (2015), those of ovens by Fulvio and Peiro (2015), and those of cooker hobs by Elduque et al. (2014).

Although few studies examining the environmental impacts of furniture can be found in the literature. Kitchen and TV cabinets have been treated by Garcia et al. (2011), office chairs by Gamage et al. (2008), and wardrobes by Iritani et al. (2015). In general, these studies emphasise the environmental impacts of specific furniture or appliances and aim to promote possible scenarios for decreasing their impacts on the environment. According to the literature review and own knowledge, none of the studies has exceeded the scope of LCAs for buildings by integrating an assessment of the environmental impacts of furniture and appliances. Motivated by this gap in knowledge and by the necessity to reduce primary (and especially non-renewable) energy demand and greenhouse gas emissions, this study aims to evaluate the environmental impacts of furniture and appliances throughout the LCA of a nearly net-zero energy building. The question is addressed for both offices and dwellings. For both destinations of use, our final purpose is to rank furniture and appliances according to their environmental impacts.

2. Method

The methodology used to assess the weight of the impacts from the furniture and appliances used in a building is structured around three steps. First, the environmental impacts of the furniture and appliances are evaluated by applying guidelines ISO 14040 and ISO 14044 (ISO, 2006a; ISO, 2006b). Then the environmental impacts of the building, including its furniture and appliances, are assessed. The impacts of the building assessed according to the CEN standard (EN-15978, 2011), which breaks down the life-cycle into different stages: production, construction, use and end of life. In the end, a sensitivity analysis ranks the furniture and appliances according to their aggregated impacts. The methodology and the boundary of the study are presented in Fig. 1.

The smart living lab (smart living lab, 2015), which will be built by 2020 in Fribourg, Switzerland, has been chosen as the most appropriate case study. Various factors make this specific building an interesting choice for the purposes of this study.

The smart living lab aims to reach the 2050 goals as defined in the 2000-watt society vision. For this reason, the weight ascribed to the environmental impacts of the furniture and appliances should become more important, highlighting the necessity to improve these in an NZEB. NZEBs are considered to be a solution with very low environmental impacts and to represent the trend of future construction (European Commission, 2016). In considering the furniture and appliances in this building LCA projects will indicate where scientists need to concentrate their efforts on the environmental impacts of buildings.

Furthermore, the smart living lab is multi-functional, which makes it possible to identify which parts of its construction are more important regarding its two different destinations of use. The smart living lab has a complex structure, and can be presented as unique within the LCA of the building presented in the literature thus far. The complexity of the structure comes from the experimental hall, where a beam of 21 m in the experimental ceiling has to support four levels. The structure complexity increases the impacts of the building if an optimal solution is not found (Bielser, 2016). The main materials in this structure are wood, concrete and steel. Reinforced concrete is used in the foundations and slab; wood is used for most part in the beams, columns, internal floors; and steel is used for the beams of the experimental part of the building. Wood is also used in the external and internal walls. The external envelope of the smart living lab has a thermal transmittance equal to 0.1 $W/m^2 \cdot K$. The slab is insulated with the help of polyurethane material; the external walls and roof are insulated using cellulose fibre. The windows are double-glazed with a wood frame. The building's architectural feasibility scenario is presented in Fig. 2.

For the calculation of the environmental impacts, we have assumed a 60 year reference study period for the building, and the functional unit used is square meter energy floor area per year (m^2 ERA/yr). The functional unit of m^2 ERA/yr, the 60 year of reference study period and the

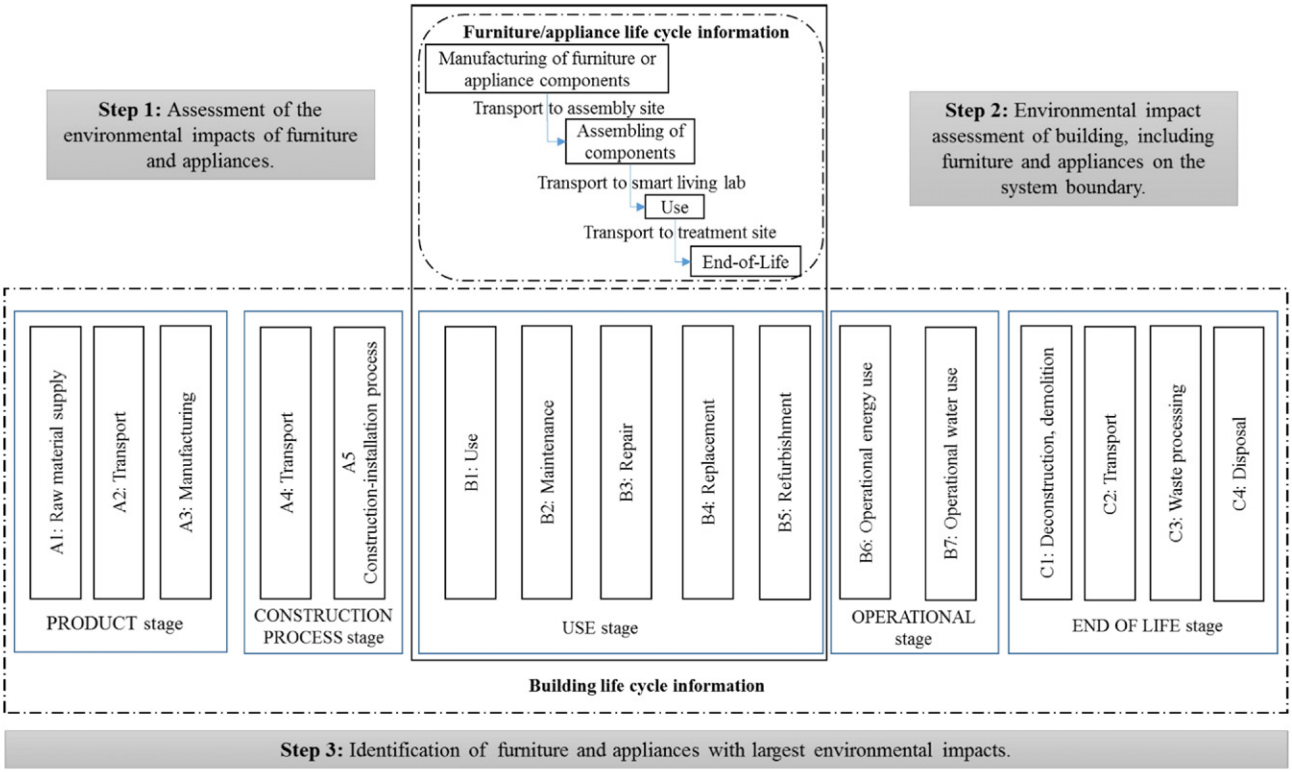


Fig. 1. Methodology used to assess the environmental impacts of furniture and appliances throughout the LCA of a nearly net-zero energy building.

evaluation of the energy reference area of the smart living lab are based on various Swiss standards (SIA-2040, 2011; SIA-2032, 2010; SIA-416/1, 2007). In this study only the cumulative energy demand, non-renewable energy and global warming indicators are considered. According to the 2000-watt society vision, these environmental indicators are considered the most pertinent for the Swiss context and must be assessed in all LCA studies. We have used the KBOB database (KBOB, 2014) to evaluate the environmental impacts of building elements and components. KBOB contains information about the environmental impacts of building materials and components, which are evaluated in accordance with the CEN standard (EN-15804, 2012). This relies largely on the ecoinvent database (Frischknecht et al., 2013). In the KBOB database, cumulative energy demand (renewable and non-renewable) indicators are calculated according to the impact assessment method described by Bösch et al. (2007) and Frischknecht et al. (2007) and the global warming potential is calculated according to the impact assessment method described in IPCC (2007). For the evaluation of the environmental impacts of furniture and appliances, we have used the ecoinvent database (Kellenberger et al., 2007) and the impact assessment methods are the same as those used for the KBOB database (KBOB, 2014). The database and the methods used to evaluate the impacts of furniture, appliances and building elements are fully compatible.

2.1. Environmental impacts of furniture and appliances

To enable an assessment the environmental impacts of furniture and appliance, we have referred to the articles and documents published in the literature, since no database is available. Through an extensive literature review, we have identified the studies presenting the most complete LCA. The studies found are quite variable as regards the LCA method. They generally differ from each other in terms of their boundaries, the database used for calculation, and the indicator(s) calculated. To increase the reliability of the LCA results, all the studies have been homogenised by adding the missing LCA phases or contextualising them for our study. The environmental impacts of the furniture and appliances have been assessed in accordance with the guidelines contained in ISO 14040–14044 (ISO, 2006a; ISO, 2006b). The functional unit for each element is defined as an item of furniture/appliance during its corresponding reference study period. The boundary of the study includes all stages: the extraction of raw material from the earth, manufacturing, transport and end of life. The information about the

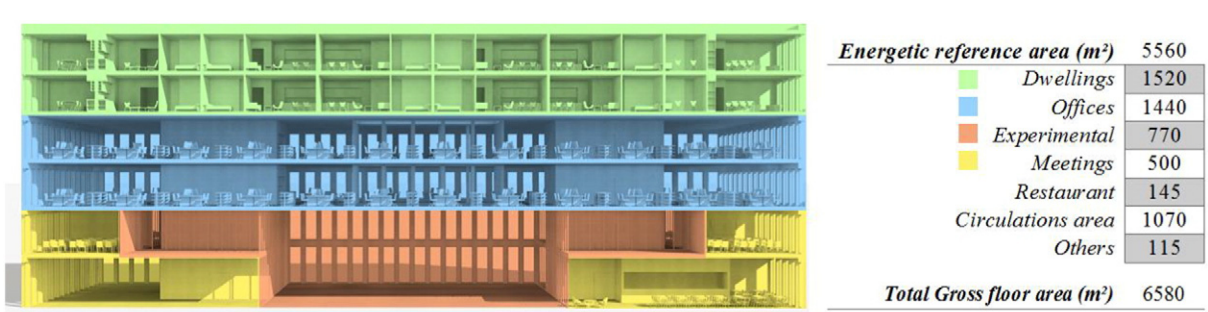


Fig. 2. Architectural feasibility design of the smart living lab building and its main characteristics.

inventory of materials and the manufacture of furniture and appliances has been extracted from the studies found in the literature. However, the literature does not contain any information for some types of furniture. In the case of furniture with missing information we assessed its impacts based on an inventory of its materials, the quantity of which is measured to an accuracy of 1 g. A detailed list of furniture materials and elements is presented in Tables 1 and 2.

Assuming that furniture is mainly produced in Europe and appliances in China, their transport to the smart living lab is undertaken by road for furniture and partly by sea and partly by road for appliances.

The energy consumed by appliances during their usage phase is calculated from the information provided in Duke Energy (2016) and Bobba et al. (2015) for appliances used in dwellings, and in SIA-2040, (2006) and ADEME (2005), for those used in offices. The end-of-life phase is taken into account by considering the waste scenario of Switzerland as proposed in the Ecoinvent database (Kellenberger et al., 2007). The environmental impacts according to the cumulative energy demand (CED), non-renewable energy (NRE) and global warming potential (GWP) indicators are assessed using SimpaPro V8 software (Goedkoop and Oele, 2004). The full results of the embodied environmental impacts of unit process for furniture and appliances are presented in Supplementary materials 1.

2.2. Environmental impacts of smart living lab

The global inventory data required to assess the smart living lab environmental impacts, have been collected and presented according to the design and construction phases as proposed in CEN standard EN-15978, (2011).

Table 1
Inventory data for some domestic furniture elements.

Component	Material	Unit	Quantity
Double bed	MDF	m3	0.083618
	Steel	kg	12.01
	Textiles	kg	1.01
	Polyurethane	kg	4.19
	Polyethylene film	kg	0.27
	ABS	kg	0.2
	Paper	kg	0.007
	Polystyrene foam slab	kg	0.04
	Extrude polystyrene	kg	0.03
	Cardboard	kg	1.25
	Wood wool	kg	1
Boiler	Steel	kg	0.074
	Cable	m	1
	ABS	kg	0.672
	Carton	kg	0.181
	Polyethylene	kg	0.007
Sofa table	Steel	kg	5.266
	Glass	kg	22.241
	ABS	kg	0.032
	Textiles	kg	0.144
	Polyurethane	kg	0.43
	MDF	m3	0.035648
	Lead	kg	0.451
	Polystyrene foam slab	kg	0.157
	Extrude polystyrene	kg	0.068
	Polyethylene film	kg	0.047
	Carton	kg	2.566
	Alkyd paint	kg	0.847665
Sofa	MDF	m3	0.1027
	Hardwood	m3	0.007264
	Polyurethane	kg	16.054
	Steel	kg	3.438
	Polyester	kg	6.4428
	Cotton	kg	3.4692
	Sealant	kg	0.63
	Polyethylene film	kg	0.628
	Cardboard	kg	6.853

Table 2
Inventory data for some office furniture elements.

Component	Material	Unit	Quantity
Clothes hanger	Steel	kg	4.78
	ABS	kg	0.96
	Acrylic binder	kg	0.011
Office table	Steel	kg	8.62
	PVC	kg	0.38
	Alkyd paint	kg	0.031
	Hardwood	m3	0.02
Working table	Steel	kg	13.9
	Hardwood	m3	0.032
	Alkyd paint	kg	0.074
	Sealant	kg	0.068
	Polyvinylchloride	kg	0.29
Meeting chair	ABS	kg	1.94
	Steel	kg	3.2
	Textile	kg	0.32

2.2.1. A1–A3: Production phase

All processes of raw material extraction from the earth as well as transportation to the factory and the production of the building's components and systems are included in this module. Table 3 summarises

Table 3
Inventory data used for the calculation of impacts (lifetime of materials and systems extracted from the KBOB database, (2014) and Hoxha et al. (2014)*. LB-Lifetime of building.

Inventory data	Quantity	Transport (km)	Lifetime (years)	KBOB code
Mass excavation	1276 m^3		60*	62.001
Poor concrete	137,025 kg		60*	01.005
Reinforcing steel	25,410 kg		60*	06.003
Concrete for foundations	424 m^3		60*	01.011
Steel profiles	4000 kg		60*	06.012
Structural wood	968,618 kg		60*	07.006
Gravel	129,384 kg		30*	03.012
Rockwool	6434 kg		30*	10.008
Polyurethane	7308 kg		30*	10.006
Cellulose fibre	93,215 kg		30*	10.010
Wood	50,503 kg		30*	07.013
Polyethylene	5062 kg		30*	09.007
Bituminous waterproofing	11,540 kg		30*	09.003
Parquet	985 kg		30*	11.018
Mineral plaster	143,511 kg		30*	04.001
Double glazing	740 m^2		30*	05.002
Wood frame	130 m^2	300	30*	05.005
Doors	252 m^2		30*	12.001
Electrical equipment (dwellings)	2025 m^2 ERA		25	34.001
Electrical equipment (office, experimentation)	3531 m^2 ERA		25	34.002
Ventilation equipment (office, experimentation)	2355 m^2 ERA		25	32.011
Air exhaust kitchen and bathroom	193 m^2 ERA		25	32.003
Heating equipment (warm air heating)	5560 m^2 ERA		25	31.015
HVAC (Air-water pump 8 KW)	1 unit		25	31.019
Sanitary equipment (office, experimentation)	425 m^2 ERA		25	33.003
Sanitary equipment dwellings	193 m^2 ERA		25	33.001
Solar panels	100 m^2		25	31.009
Photovoltaic panels on roof	26 kWp		25	34.025
Photovoltaic panels on façade	168kWp		25	34.027
Space heating	72.5 MJ/m^2 ERA			
Domestic hot water (DHW)	26 MJ/m^2 ERA	-	In function of lifetime of building	-
Electricity for ventilation	14 MJ/m^2 ERA			
Electricity for lighting	24.5 MJ/m^2 ERA			

the quantity of materials and components that are expected to be used for the construction of the smart living lab.

2.2.2. A4 & A5: Construction phase

For reasons of simplification, we have assumed that the transportation distance from the factory to the construction site is the same for all the building materials and components. The distance is assumed to be 300 km which corresponds to the average distance from places of manufacture to construction sites in Switzerland.

The construction of the building has been taken into consideration by increasing by 5% the amount of materials and components needed at the production phase of the building. These hypotheses will probably not significantly affect the reliability of the final results, since other studies have shown that the construction phase accounts for at most 5% of the overall building impacts (Lasvaux, 2010; Hoxha et al., 2016).

2.2.3. B1–B5: Use phase

In this phase we consider the goods and services used during the use phase of the building. This includes the construction elements as well as the furniture and appliances. The processes of maintenance, repair, replacement and refurbishment are included within this stage. Based on the lifetime of a building's components and systems as presented in Table 3, maintenance requirements and the number of replacements are calculated according to CEN standard EN-15978, (2011). The repair process is considered to take place every 50 years. Here, we acknowledge that 10% of materials and components with a lifetime equal to that of the building will be repaired.

The figures for the furniture and appliances are calculated based on the architectural feasibility of the smart living lab, the plan of which can be found in Supplementary materials 2. The inventory data needed for assessing the environmental impacts of the furniture and appliances are summarised in Tables 4 and 5.

2.2.4. B6 & B7 operational phase

In this module, we have included the environmental impacts of the energy and water consumed during the use phase of the building for heating, ventilation, hot water, lighting and appliances. The building's heating needs are completely provided by a district heating system, while the domestic hot water requirements are provided partly by solar panels and partly by electricity. The district heating was also found by Gustavsson et al. (2010) to be the most environmentally friendly solution compared with other heating systems. Since ventilation is responsible for a large share of the environmental impacts during the operational phase (Heiselberg et al., 2009), we have considered for the purposes of this study that the building will be naturally ventilated. There are integrated mechanical ventilation systems in the meeting rooms and the restaurant only. In addition, no cooling systems will be provided. Ventilation and air conditioning have not been employed in previous real projects, and this choice has been shown not to have any influence on the comfort of the building (baumschlager aberle architekten, 2017).

Heiselberg et al. (2009) found that the design parameter with second most significant impacts during the operational phase was light control. As such, we have considered that only the working areas will be fully lit (lighting area of 25%) with automatic switch off. For the other areas (75%) the intensity of light will be 50%. To cover the requirement for electricity with low environmental impact, photovoltaic panels have been integrated on the roof and on the east, west and south façades of the smart living lab. The integration of photovoltaic panels on the roof and on the east, west and south façades is justified by the fact that the environmental impact of the energy produced by the panels is lower than the impact of electricity from the Swiss grid (Jusselme et al., 2015). The absolute amount of electricity produced by the photovoltaic panels is around 90% of the needs of the building in a one-year time period, which shows that the smart living lab can be considered as a net-zero energy building. The largest amount of electricity is produced during the summer period, when the needs of the building are lower than what is produced by photovoltaics. When this is the case, the extra electricity is transferred to the Swiss electricity grid, and if production is lower than what is required, the difference is covered by the grid. The environmental impacts of the surplus energy produced by the photovoltaic panels are allocated to Swiss electricity grid. No benefits from the transfer of low-impact electricity to the grid are considered, as was proposed by previous studies (Sartori et al., 2012; Georges et al., 2015).

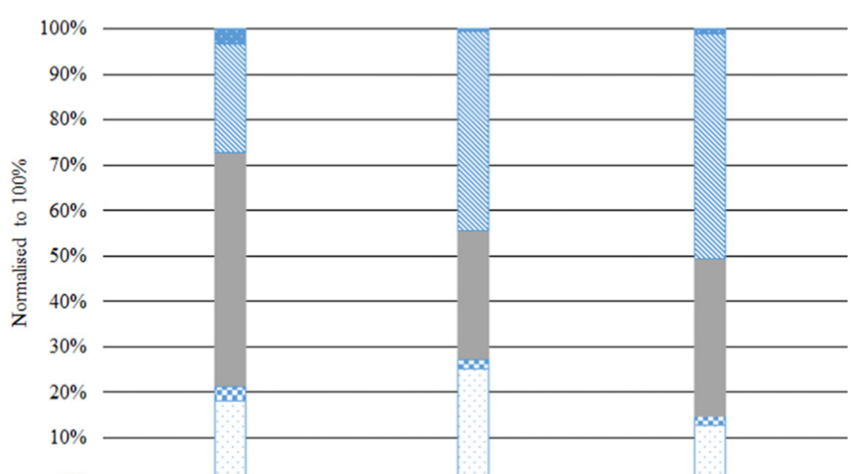
Table 4
Inventory data for furniture and appliances in office areas of the smart living lab. Expected lifetime (Home Inspection (2010)[1]; ADEME, (2012)[2], American Hospital Association (1998)[3]; EPA, (2014)[4]; our hypothesis [n/a][5]}. Energy consumption {(SIA 2024, 2006) *; (ADEME, 2005) **}.

Offices						
Component	Qty (unit)	Lfm* (yrs)	Unit process reference	Trans (km) [type]	Energy consumption in the use phase** (MJ/yr)	Unit process End of life
Laptops	180	5 [4]	Computer, laptop {GLO} Kellenberger et al., 2007		92*	
LCD Monitors	180	6 [2]	Bhakar et al. (2015)		213*	
Desktops	12	5 [3]	Computer, desktop without screen {GLO} Kellenberger et al., 2007		395*	
Docking station	180	5 [5]	McCorkell (2008)			
Keyboards	180	5 [4]	Keyboard {GLO} Kellenberger et al., 2007			
Mouse	180	5 [4]	Pointing device, optical mouse, with cable {GLO} Kellenberger et al., 2007	13,000/2000 [sea/road]	-	
Printers	6	5 [2]	Printer, laser, colour {GLO} Kellenberger et al., 2007		962**	
Projectors	6	10 [3]	Nishiguchi (2008)		623**	
Boilers	12	10 [1]	Our data		395**	
Coffee machines	8	10 [1]	Brommer et al. (2011)		395**	
Working tables	180	20 [3]	Our data		–	
Working chairs	180	15 [3]	Gamage and Boyle (2008)			
Meeting tables	46	15 [3]	Our data			Curb side collection (CH)
Meeting chairs	104	15 [3]	Our data			(Kellenberger et al., 2007)
Metal tambour cabinets	180	20 [3]	Techo Royal Ahred (2011)			
Cabinets	180	15 [3]	Techo Royal Ahred (2011)			
Whiteboards (m^2)	74	15 [5]	Cui et al. (2011)	2000 [road]		
Clothes hangers	40	15 [5]	Our data			

Table 5
Inventory data for furniture and appliances in dwelling areas of the smart living lab. Expected lifetime (Home Inspection (2010)[1]; ADEME (2012)[2]; EPA (2014)[3]; *; Bobba et al. (2015)[4]). Energy consumption (Duke Energy (2016) *; Bobba et al. (2015) **).

Dwellings						
Component	Qty (unity)	Lfm (yr)	Unit process reference	Transport (km) [type]	Energy consumptions in use phase** (MJ/yr)	Unit process End of life
LCD television	26	12 [3]	Hischier and Baudin (2010)		1167*	
Laptops	34	5 [3]	Computer, laptop {GLO} Kellenberger et al., 2007		39*	
Desktops	14	10 [3]	Computer, desktop, without screen {GLO} Kellenberger et al., 2007		170*	
LCD Monitors	14	6 [2]	Bhakar et al. (2015)		90*	
Keyboards	14	5 [3]	Keyboard {GLO} Kellenberger et al., 2007			
Mouse	38	5 [3]	Pointing device, optical mouse{GLO} Kellenberger et al., 2007		-	
Kitchen ovens	30	18 [3]	Fulvio and Peiro (2015), Amienyo et al. (2016)	13,000/2000	1515* (7 days' use)	
Microwaves	22	12 [1]	Truttmann and Rechberger (2006)	[sea/road]	518*	
Cooker hoods	30	8 [4]	Reale et al. (2015)		65*	
Refrigerators medium size	30	18 [3]	Xiao et al. (2015)		3105*	
Dishwashers	30	13 [3]	Fulvio and Peiro (2015)		178*	
Boilers	26	10 [1]	Our data		125*	
Coffee machines	26	10 [1]	Brommer et al. (2011)		324*	
Washing machines	30	10 [1]	Bourrier et al. (2011)		518*	
Vacuum cleaners	30	5 [4]	Duke Energy (2016)		65**	Curb side collection (CH)
TV cabinets	26	15 [3]	Garcia et al. (2011)			Kellenberger et al., 2007
Kitchen cabinets	160	15 [3]	Garcia et al. (2011)			
Wardrobes	38	15 [3]	Iritani et al. (2015)			
Sofas	20	15 [3]	Our data			
Armchairs	42	15 [3]	Assumption			
Dining tables	32	15 [3]	Assumption			
Computer tables	14	15 [3]	Assumption			
Tables	28	15 [3]	Assumption			
Chair	132	15 [3]	Assumption			
Double bed	20	15 [3]	Our data			
Single bed	16	15 [3]	Assumption	2000 [road]		
					-	
Clothes hangers	34	15 [3]	Our data			

A dynamic monthly time step is used for calculation of the electricity produced by the photovoltaic panels, as this was found to be reliable previously (Maurizio et al., 2015). Taking into consideration this scenario and hypothesis, the energy consumed in the operational phase is simulated in a dynamic regime using Lesosai software (E4tech, 2008). The results obtained are presented in Table 1.



	GWP (kg CO2-eq/m² ERA yr)	CED (MJ/m² ERA yr)	CEDnr (MJ/m² ERA yr)
C1-C4: End of life	0.40 (3%)	3.22 (1%)	3.04 (1%)
B6-B7: Exploitation phase	2.94 (24%)	257.10 (44%)	142.49 (50%)
B1-B5: Use phase	6.36 (52%)	165.18 (28%)	98.56 (34%)
A4-A5: Construction	0.38 (3%)	11.49 (2%)	5.88 (2%)
A1-A3: Production	2.22 (18%)	148.06 (25%)	36.80 (13%)
Total	12.31 (100%)	585.05 (100%)	286.78 (100%)

Fig. 3. Environmental impacts of the smart living lab according to its life-cycle.

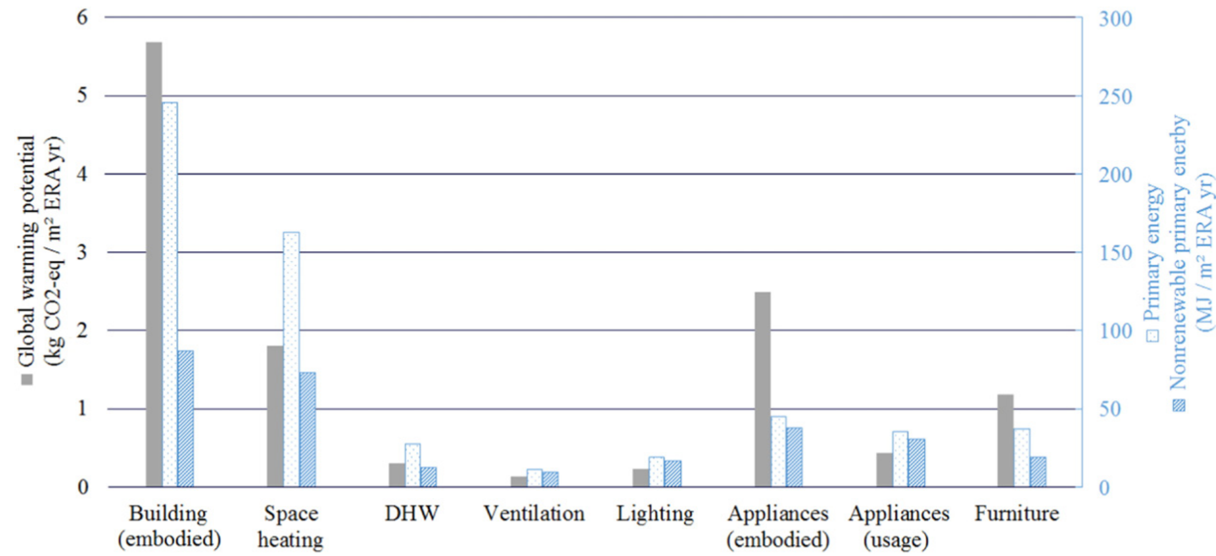


Fig. 4. Environmental impacts of the smart living lab according to its systems.

2.2.5. C1–C4 end of life

Based on the KBOB database (KBOB, 2014), the whole end-of-life process of the building (demolition of building, transportation of materials to recycling site, treatment or elimination of materials) is included in the study.

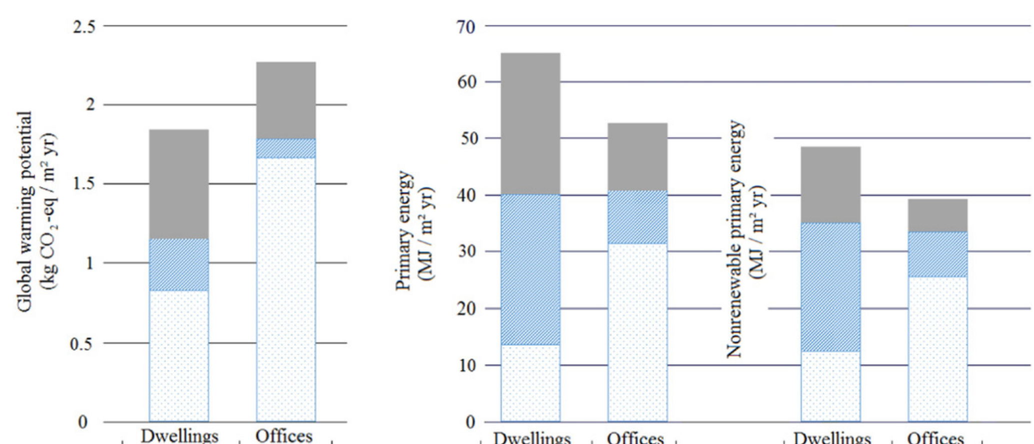
3. Results

The results of the smart living lab's life-cycle analysis for the global warming potential (GWP), cumulative energy demand (CED) and non-renewable energy (CEDnr) indicators are presented in Fig. 3. Splitting the impacts in this way highlights the weight of the embodied impacts (A1-A5 & B1-B5) compared with the operational phase. The embodied impacts account for around 70%, 55% and 50% of the impacts in terms of GWP, CED and CEDnr respectively.

A more detailed analysis of the results in Fig. 3 highlights that, for the GWP indicator, the use phase (B1-B5), which is responsible for 52%, can be ranked as the main factor of the impacts, followed by the operational phase (B6-B7 24%) and the production phase (A1-A5 18%). However, for the CED and CEDnr indicators, the operational phase (B6-B7), which is responsible for 44% and 50% of the respective impacts, represents the highest impacts compared with other life-cycle phases, followed by the use phase (B1-B5). Based on these results, the construction and end–of-life phases can be considered to have negligible impacts even in highly energy-performing buildings, since their relative contribution to the overall impacts is less than 2%.

To allow us to better understand the smart living lab's principal sources of environmental impacts, Fig. 4 presents these impacts according to its different systems. A general observation for all indicators is that the embodied impacts of the building's construction present the highest values and can be ranked as the primary source of environmental impacts in highly performing buildings.

Energy consumed for heating appears as the second key factor accounting for the consumption of primary and non-renewable energy, and is third for the GWP indicator. The embodied impacts of appliances are ranked as second according to the GWP indicator, and third for the CED and CEDnr indicators. With an influence of more than 5% of the overall impacts, furniture and the operational phase of appliances are considered as having a significant environmental impact. Based on the



	Dwellings	Offices	Dwellings	Offices	Dwellings	Offices
Furniture	38%	21%	38%	23%	27%	15%
Appliances (usage)	18%	5%	41%	17%	47%	20%
Appliances (embodied)	45%	74%	21%	60%	26%	65%

Fig. 5. Environmental impacts of dwellings and offices elements in the smart living lab.

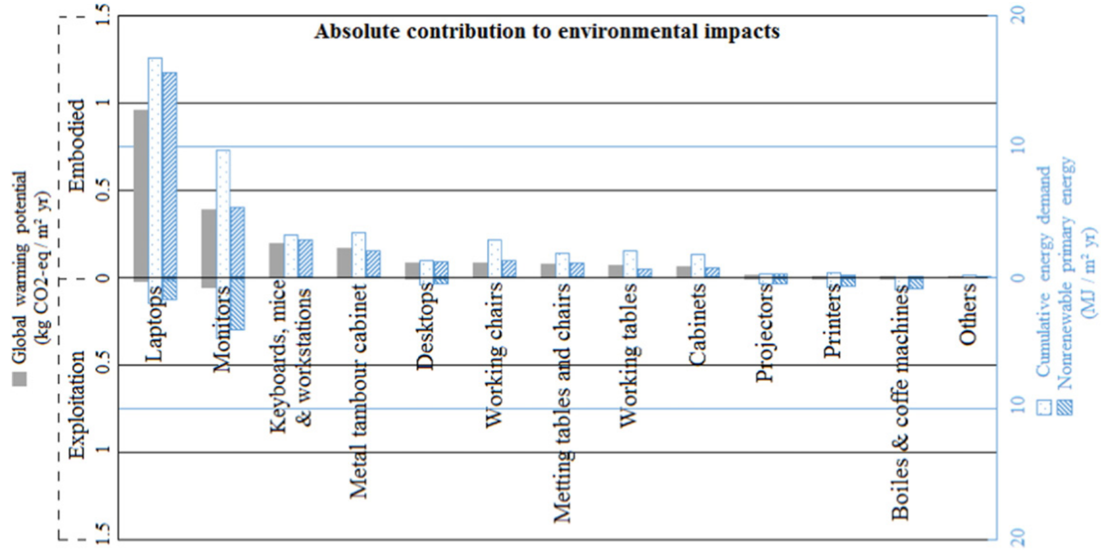


Fig. 6. Absolute environmental impacts of office furniture and appliances.

results of the smart living lab, domestic hot water (DHW), ventilation and lighting present second order impacts.

This analysis highlights the importance of environmental impact assessments for furniture and appliances in future building projects and the necessity of improving these elements and components by reducing their impacts.

Fig. 5 presents the environmental impacts of the furniture and appliances according to their destination of use in the smart living lab. According to the CED and CEDnr indicators the overall impacts of the domestic furniture and appliances are higher than those of the office furniture and appliances. For the GWP indicator, on the other hand the overall impacts of the office furniture and appliances are higher than those for the furniture and appliances used in the dwellings. A more detailed analysis shows that the embodied impacts of appliances used in the offices are higher than those for the appliances used in the dwellings. On the other hand, the energy used during the operational phase of domestic appliances has a larger impact compared with the office appliances. However, in considering all life-cycle phases, the office appliances have higher impacts according to GWP indicator and almost the same weight for the CED and CEDnr indicators compared with the domestic appliances. Since the embodied impacts of appliances are significant in the labelling process, the whole life-cycle phases must be considered and not just energy consumption in the operational phase, as is currently done by all manufacturers.

For furniture, the results obtained show that those used in residential buildings have higher impacts than those used in offices.

The relative and absolute contributions, based on a sensitivity analysis of the environmental impacts of office furniture and appliances, are presented in Figs. 6 and 7. Due to the strong correlation between indicators (minimum correlation coefficient = 0.86), the conclusions for

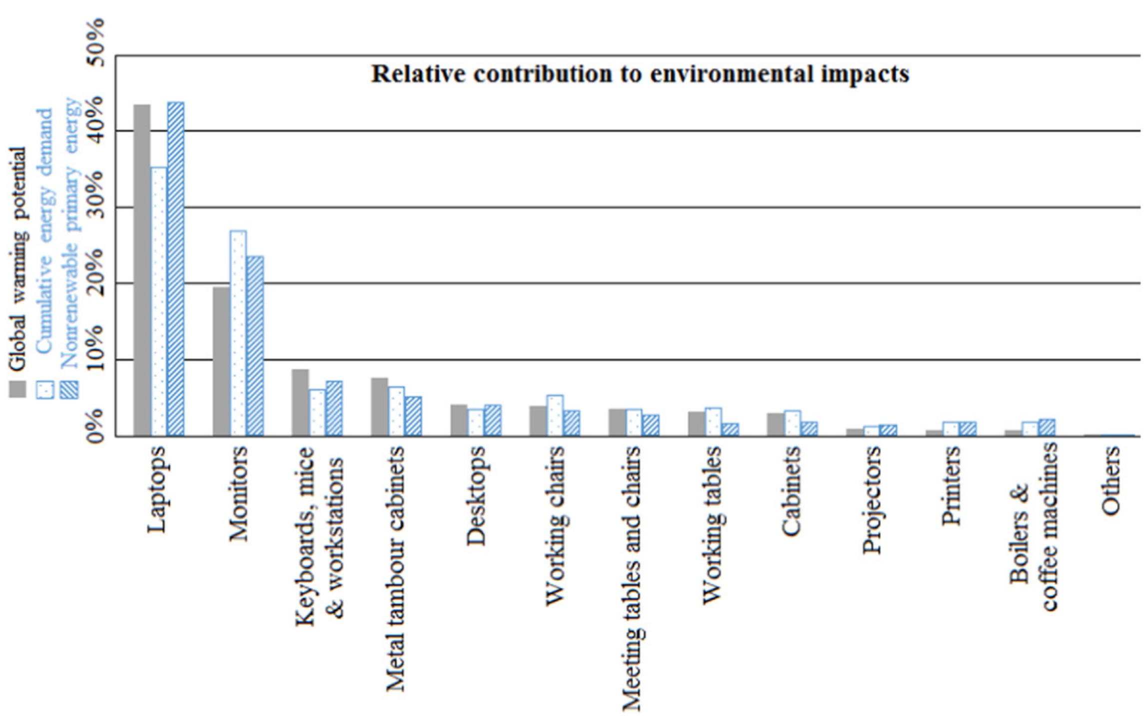


Fig. 7. Relative contribution of office furniture and appliances according to aggregated impacts.

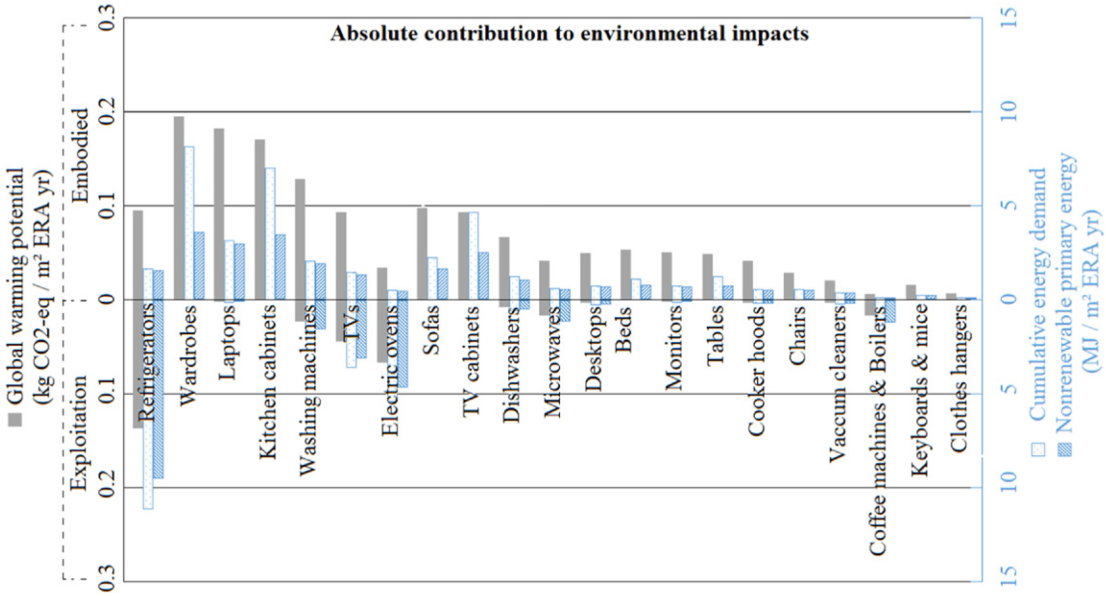


Fig. 8. Absolute environmental impacts of domestic furniture and appliances.

the furniture and appliances are the same for the GWP indicator, with small variations. Based on the absolute and relative contribution of furniture and appliances for all indicators, the embodied impacts make the biggest contribution. Computer equipment makes the largest impact. Taking a cut-off of 10%, laptops alone are responsible for 40% and monitors for around 25% of the overall impact. As far as furniture is concerned, the metal tambour cabinets present significant environmental impacts.

For domestic furniture and appliances, the results are presented in Figs. 8 and 9. Even in this case, all indicators are strongly correlated and the results are presented according to the weight of furniture and appliances for the GWP indicator. Unlike for office appliances the operational phase of domestic appliances such are refrigerators, TVs, washing machines and electric ovens, has higher impacts than their embodied phase. For other furniture and appliances, the impacts of the operational phase are insignificant. Based on the results shown in Fig. 6, and taking into account both the operational and embodied impacts, refrigerators are ranked as the appliances responsible for the most impacts, with an absolute contribution to GWP, CED and CEDnr of 12%, 20% and 22% respectively, followed by wardrobes, laptops, kitchen cabinets, etc.

4. Discussion

The results obtained in this study classify the impacts of the building's construction phase (A4-A5) as insignificant compared with the impacts of other phases, even though we have considered the hypothesis of transporting the building's elements and components to the construction site, as well as the hypothesis of the environmental impacts of the construction phase influencing the increment of the impacts.

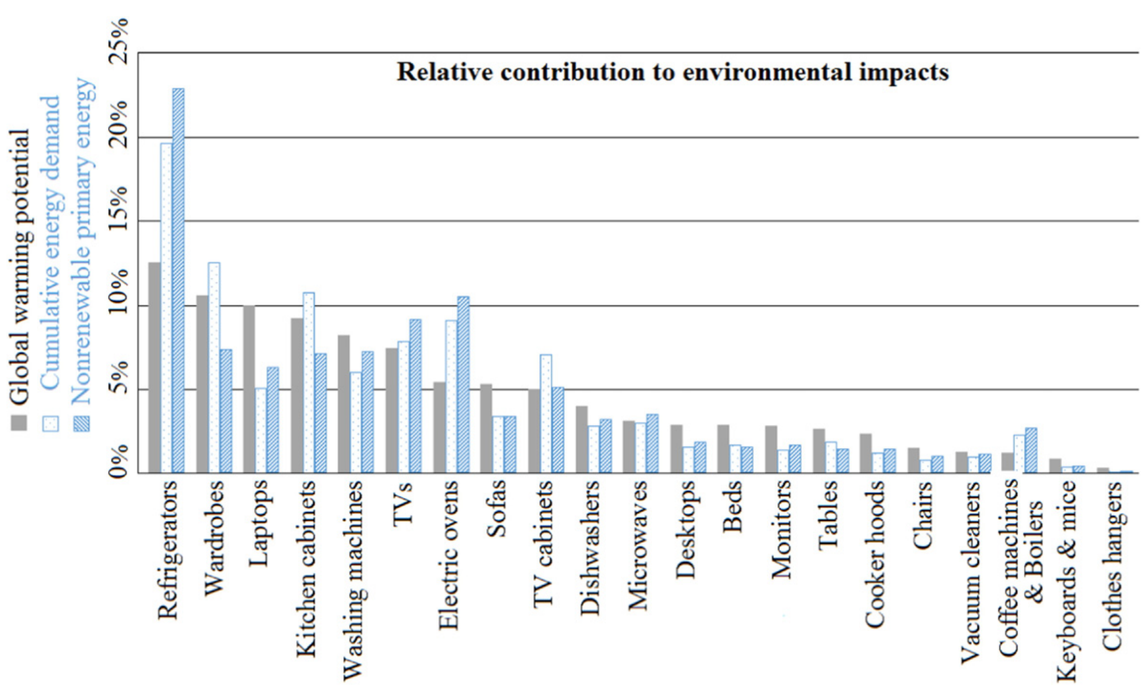


Fig. 9. Relative contribution of domestic furniture and appliances according to aggregated impacts.

Similar results were obtained in previous studies, which also concluded that the building's construction phase has lower impacts (Lasvaux, 2010; Hoxha et al., 2016).

In this study, we have found that the embodied impacts of appliances and furniture are the biggest contributors to the GWP indicator, and they are almost equally responsible for the primary and non-renewable energy demand in the operational phase. In NZEBs or buildings with ultra-low energy demand, the primary energy required for construction is equal to the energy required during the operational phase. This has also been shown in Swiss standard SIA-2040, (2011) which sets out guidelines and target values the operational phase and construction of very efficient buildings. For the global warming potential indicator, the construction of the building accounts for around 70% of the overall impact, while the operational phase represents 30%. The building's environmental impact results in this study correspond exactly to the targets defined in Swiss standard SIA-2040, (2011). The achievement of the 2050 targets, demonstrates that the smart living lab represents very high-performance construction. The embodied impacts are responsible for around 70% of the global warming potential indicator and 50% of the non-renewable and cumulative energy demand indicators, contrary to the previous building, where it was found to be responsible for 20% of the indicators (Berggren et al., 2013; Wyss et al., 2014). Furthermore, the smart living lab meets the requirement of the European directives for future buildings, which must be net-zero energy (European Commission, 2016). In addition, the impacts of the smart living lab are lower than those of the best-performing buildings among the buildings presented in (Thiers and Peuportier, 2012, Georges et al., 2015; Paleari et al., 2016; Hoxha et al., 2017).

The results presented in this paper are a function of the building's architecture and of the type of furniture and appliances considered in the study. Even though the type of furniture and appliances considered in the study has an influence on the results, according to the present study it seems necessary to include them within the scope of a building's LCA. The energy consumption of appliances during their operational phase requires a deeper investigation. The actual standards and the database (ADEME, 2005; Duke Energy, 2016; SIA-2040, 2011) provide general information about the energy used by appliances without considering the number of inhabitants and the number and type of appliances used in dwellings and offices. A dynamic investigation of the electricity consumption by each appliance in different destinations may be necessary for the future. In present study, the final results are considered to be reliable, since the environmental impacts of the appliances the in the operational phase were very low, and a deeper analysis of the electricity consumption of appliances would not change the results.

The lifetime of furniture and appliances is another parameter that needs a more detailed investigation. Different studies in the literature (Seiders et al., 2007; Home Inspection, 2010; InterNACHI, 2016; Inland Revenue, 2016) provide different values for the lifetime of furniture and appliances. This is due to the fact that the effective service life is influenced by many factors which can be classified between failure, dissatisfaction and change in consumer needs (Cooper, 2004). Conditions of use such as humidity and temperature are the main factors that influence failure related to the degradation of building elements. Dissatisfaction, on the other hand, is mostly associated with style changes and fashion trends. Finally, occupant needs change over time and depend on the number of persons per family and the presence of children (Potting and Blok, 1995; Ashworth, 1996). In this study, we have considered high lifetime values. Even with very long lifetimes, the furniture and appliances make significant environmental impacts, highlighting once again the necessity to consider them within the building's LCA.

Different scenarios can be envisioned in order to reduce the impacts of furniture and appliances. As a computer stations give rise to the largest impacts in offices, it is possible to reduce the number of appliances. Instead of a computer station composed of a laptop, docking station, monitor, keyboard and mouse, it can instead comprise a laptop with a bigger screen, a separate keyboard and a mouse. In this scenario, we eliminate the monitor and docking station without reducing the level of workplace comfort. According to BakkerElkhuizen (2017), the comfort of working with laptops is lower due to the fact that the screen and keyboard are in a single unit. This forces users to work in an uncomfortable position, which significantly decreases productivity and has a negative influence on the health of users. For safe and productive computer use, a 19 in. laptop is recommended, which can be adjusted to the user's eye level with the help of a notebook stand and a separate keyboard. This scenario, as recommended by BakkerElkhuizen (2017), is considered safe and meets the legal requirement that a workplace must meet when using laptops.

Another scenario involves the implementation of a virtual desktop infrastructure (VDI). Such scenarios should be investigated in further work.

5. Conclusion

This work is the first in which a building's LCA study includes an assessment of the environmental impacts of furniture and appliances. Results show that for a net-zero energy building, furniture is responsible for around 10% and appliances for 25% of the building's overall impacts in terms of both the global warming and non-renewable energy indicators. As a final conclusion, we state that an assessment of the environmental impacts of furniture and appliances must be included in building design.

For the global warming potential indicator, office furniture and appliances have greater impacts than those of dwellings, but for the primary energy and non-renewable energy indicators, domestic furniture and appliances present bigger impacts than those of offices.

For all indicators, appliances present greater environmental impacts than furniture in both offices and dwellings. The operational phase of appliances used in dwellings accounts for the greatest amount of primary and non-renewable energy for those used in offices results have shown the opposite. For the global warming indicator, the embodied impacts dominate the overall results, in both dwellings and offices. In general, we conclude that the embodied impacts dominate over the operational phase impacts which indicates the necessity of including whole life-cycle phases in the labelling process for appliances not just energy consumption.

A more detailed analysis of the environmental impacts of office furniture and appliances ranked laptops as the most highly impacting elements, responsible for 40%, noting in particular the impacts linked with their production phase. Monitors, which were responsible for 20% of the impacts of furniture and appliances, also have a highly significant impact, of which half is due to their operational phase and half to their manufacture. Concerning furniture, metal tambour cabinets (responsible for 8% of impacts) and chairs (responsible for 5%) are identified as higher impacting elements.

For dwellings, refrigerators have the greatest impacts, the source being their operational phase. Their contributions to the impacts from domestic furniture and appliances are 12%, 20% and 22% respectively according to the global warming, cumulative energy demand and non-renewable energy indicators. Laptops, washing machines, televisions and electric ovens also presented very significant impacts. Wardrobes, with a relative contribution of 10% and kitchen cabinets at 8%, have the highest impacts for furniture elements used in dwellings.

Further research is needed, especially for the creation of a database containing information about impacts from appliances and furniture. In addition, potential solutions to the impacts from these elements require to be developed.

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