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A comparative Life Cycle Assessment of external wall-compositions for cleaner construction solutions in buildings

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ABSTRACT

Application of Life Cycle Assessment (LCA) in buildings is usually performed at the envelope scale, mainly for comparison of several sample-solutions, and provides in-depth analyses of the related energy and environmental performances. In this way, it is possible to identify those solutions that perform best in energy and environmental terms, and that so are suitable for construction of sustainable buildings.

In this context, the study was aimed at carrying out energy and environmental assessments to compare four external-wall samples characterised by different rates of sophistication in terms of assembly technologies and component materials.

The samples considered were properly designed for development of the subsequent energy-environmental analysis. In particular, two “standard” wall compositions and two ventilated façades were considered, using rock-wool and recycled Polyethylene Terephthalate (R-PET) as insulating materials.

The study documented that, as regards both energy and environmental impacts, ventilated façades perform quite well compared to the ”standard“ wall compositions, especially when equipped with R-PET. It also confirmed that both solutions easy to be disassembled and recycled materials are key design choices for environmental sustainable and low energy demanding buildings along their whole life cycles.

Finally, the authors believe that the study provides helpful insights on the environmental sustainability of eco-friendly materials and technologies, and can contribute to less time and resources consuming LCAs at the building scale.

1. Introduction

The construction industry has worldwide significant environmental, social and economic impacts on the society: in this regard, a distinction can be made between the positive and the negative impacts related to construction activities. In particular, the first ones include: providing buildings and facilities so that they can satisfy human beings' requirements; providing employment opportunities directly or indirectly (through other industries related to the construction industry); and, contributing to national economy enhancement (Zuo and Zhao, 2014).

In the context of the negative impacts, it is worldwide recognised that construction practices are major contributors to environmental problems, particularly because of the use of non-renewable resources and energy (Bianchini and Hewage, 2012).

At the world level, construction of civil works and buildings requires a huge consumption of raw materials which, indeed, settles to an average of 60% of the whole amount extracted from the lithosphere: from this volume, buildings represent almost 40%, which means approximately 24% of the global extractions (Zabalza Bribián et al., 2011).

Additionally, the energy consumption associated with the life cycles of buildings accounts for around 40% of the global energy demands. This situation is reflected on average in the European context, where the energy required for building indoor heating and cooling represents the main share of the total energy consumed in buildings (Kaynakli, 2012; Batouli et al., 2014), as shown in Fig. 1 (European Commission, 2013).

For greater understanding, it should be observed that the total life cycle energy of a building includes both embodied and

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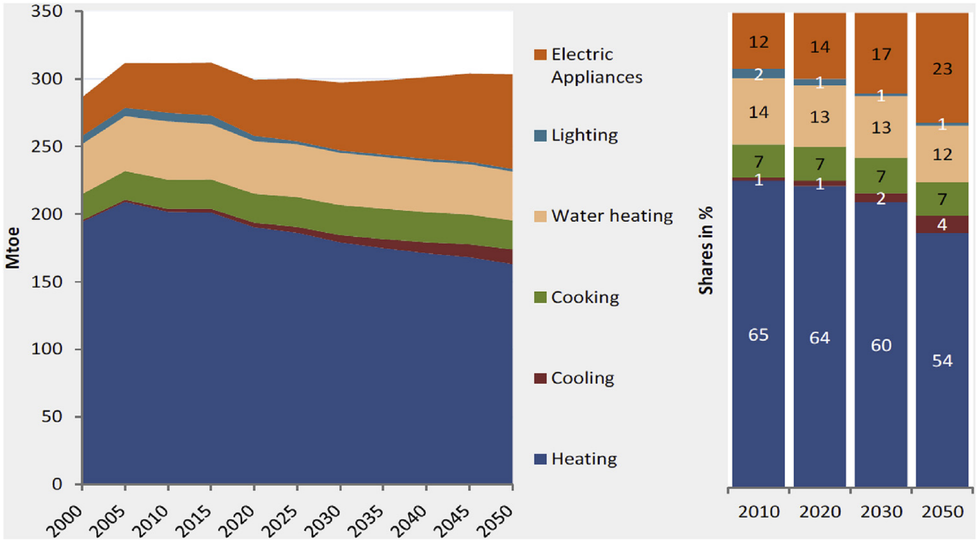


Fig. 1. European energy demand in the residential sector by energy use. Extrapolated from European Commission (2013).

operational energy. In this regard, Dixit et al. (2012) clarified that the embodied energy (generally expressed as primary energy) represents the energy sequestered in buildings and building materials during all processes of production, on-site construction, and final demolition and disposal. In this context, direct and indirect energy are the two primary components of the embodied energy. The first is used for construction, operation, renovation, and demolition of buildings, whilst the second is consumed for production of the material used for the construction of buildings and technical installations (Sartori and Hestnes, 2007; Cabeza et al., 2014). In this regard, Rauf and Crawford (2015) showed that variations in service lives of buildings can have significant effects upon the related annual and life cycle embodied energy demands. Therefore, according to the authors, there is evidence of the importance of integrating building service-life considerations into the initial design process and facilities management phase. In this way, it would be possible to enable selection of the most appropriate construction materials and methods to reduce energy demand over life cycles of buildings. In addition to the embodied energy, the operational energy should also be taken into account for building life cycle energy assessments. Based upon the definition provided by Dixit et al. (2012), operational energy is the energy spent to maintain the inside environment through various processes, such as heating and cooling, lighting and operating building appliances. Various studies showed that the operational energy can vary between 70% and 90% of the whole life cycle energy consumption of a building (Asdrubali et al., 2013).

All that stated, in order to face the challenges of energy consumption, climate change and resources depletion, the building sector development should be oriented towards solutions that are environmentally sustainable and enable to reduce consumption of both materials and energy (La Rosa et al., 2014).

For this purpose, it is needed to choose from the early stages of a building design appropriate technical solutions and materials to reduce environmental impacts, not only in the construction phase but, most of all, in the entire life cycle of a building. In this context, the Life Cycle Assessment (LCA) methodology can be used to orient the architectural design to the maximisation of buildings environmental sustainability and energy efficiency (Ingrao et al., 2014a).

Indeed, as Rebitzer et al. (2004) state according to ISO 14040:2006 (International Organisation for Standardization (ISO), 2006a) and 14044:2006 (International Organisation for Standardization (ISO), 2006b), this methodology examines life cycles of products enabling identification and analysis of the related environmental impacts from the compilation of both input and output flows.

LCA has been significantly improved during the past three decades in order to become more systematic and robust for both identification and quantification of the potential environmental impacts associated with a product in its life cycle (Jeswani et al., 2010). Currently, LCA is used in product/process selection, design and optimisation and can integrate with simulation techniques and design tools to help companies to be fully aware of the environmental consequences of their actions, both on- and off-site (Compagno et al., 2014). Hence, it can be considered as an invaluable decision-support tool for researchers, manufacturers, policy-makers and company owners (Ingrao et al., 2015a). With particular regard to the building sector, LCA enables evaluation of important aspects relating to buildings life cycles like, for instance, the energy use and the energy embodied in building materials, the transportation of those materials to the construction yards, as well as the associated emissions of Greenhouse Gases (GHGs) (Malmqvist et al., 2011).

When used as a support-tool for building design, LCA should be first applied, together with a detailed energy analysis, at the envelope scale. This should be done for the envelope components, namely the perimeter and the inside walls, the ground-floor, the halfway-floors (for multi-storey buildings only) and the roof, through life cycle evaluations of several solutions. The latter are generally represented by samples characterised by a one square-metre surface and a thickness which is strictly dependent upon the given composition. Comparison of the compositions hypothesised enable identification of those being most energy performing and environmentally sustainable: those selected are then used to model construction of the building by considering the related square metres installed.

In this context, the aim of the study was to perform energy and environmental life cycle comparative assessments of four external-wall samples characterised by different rates of sophistication in terms of assembly technologies and component materials utilised. An early stage of design of the samples considered was needed to be performed for the subsequent energy-environmental analysis, and so it was included within the study. In particular, each sample was equipped with a thermal insulation layer to obtain thermal transmittance values equalling, at least, the limits established by the related Italian regulations. Since the construction of environmentally sustainable buildings is increasingly being centred upon the usage of recycled-material based products, the authors decided to test the utilisation of cleaner insulating materials such as, for instance, the recycled Polyethylene Terephthalate (R-PET) panels whose production had been assessed from an environmental perspective by Ingrao et al. (2014b). The authors believe that studies like this are desirable to provide valuable insights regarding the environmental sustainability rates associated with the life cycles of such products compared to conventional ones.

2. A survey on recycled-materials in buildings: thermal insulation properties and environmental sustainability

Thermal insulation is acknowledged worldwide as one of the most effective ways to enable energy saving (Dylewski and Adamczyk, 2011; Tingley et al., 2015). Based upon Cabeza et al. (2010), thermal insulation systems are materials or combinations of them that are used primarily to provide resistance to heat flows thanks to their low values of thermal conductivity (λ). In this context, selecting the right materials and determining the optimum insulation thickness for building insulation applications is an important issue that, over the years, has been the objective of several research works in this field (Dylewski and Adamczyk, 2011).

External wall insulation systems are built up from different layers of which an insulation material usually represents the main component. The environmental impact of insulation is often considered as negligible due to the in-use savings that can be accrued after its installation. Therefore, LCA-based evaluations are desirable in order to support such a statement by estimating the environmental impacts across the whole life cycle (Tingley et al., 2015). In any case, it is recommended to use sustainable insulating materials in order to limit the global environmental impact associated with buildings in their life cycles. Asdrubali et al. (2012) stated that such materials are those usually made from natural or recycled materials and whose production requires small amounts of both energy and non-renewable resources, and so causes lower environmental impacts than conventional materials. In this regard, over the last fifteen years, especially in Europe and USA, there has been an upsurge of interest in those materials (Asdrubali et al., 2015), since they represent effective ways to reduce non-renewable resources depletion and the global environmental impact of disposal processes at the end-of-life of products (Melià et al., 2014). In particular, the production of recycled materials is an increasing phenomenon that can prevent the environmental pollution resulting from industrial and agricultural wastes management, allowing to avoid the environmental impacts associated with waste-to-energy (WTE) treatment or sanitary landfill disposal (Lertsutthiwong et al., 2008; Ingrao et al., 2015b).

In this context, numbers of papers have been published subsequently in order to deliver results from the research-works conducted in this field: those papers were briefly discussed in the following sections.

2.1. Assessments of both material and thermal properties

In recent years, several literature studies have dealt with the use of recycled materials in the building sector by testing and improving both material and thermal properties (i.e. thermal conductivity). For instance, Patnaik et al. (2015) studied the thermal behaviour of R-PET, waste wool and also of a two layer material consisting of waste wool fibres and recycled PET fibres in 50/50 proportions. The investigated samples were characterised by thermal conductivity values ranging between 0.030 and 0.038 W/m·K. Other studies investigated the thermal effect of mixing recycled plastics with conventional building materials. For instance, a mix of exhaust sheaths of electric wires and concrete to realise high performance screeds was studied by Asdrubali et al. (2011) and D'Alessandro et al. (2014) where encouraging results were shown. In particular, that author-team documented that the measured thermal conductivity was equal to 0.189 W/m·K, appreciably lower than the characteristic value of common screeds (0.800 W/m·K). In the field of plastic-waste recovery, Iucolano et al. (2013) mixed PET waste with polyolefin waste for production of artificial aggregates to be used for manufacturing of hydraulic mortars by partially replacing natural aggregates: the recycled plastic aggregate were characterised by values of thermal conductivity being five times lower than the silica sand. Moreover, Melo et al. (2012) studied the thermal performances of insulating materials as produced using scraps coming from several Brazilian footwear industries. In particular, they investigated an ethylene-vinyl acetate material produced from the cuttings of expanded sheets and the measured thermal conductivity was equal to 0.260 W/m·K. Also textile industry scraps seem to be suitable for the realisation of thermal insulation materials. In this regard, Valverde et al. (2013) focussed upon both preparation and characterisation of new materials made of textile industry waste (polyester and polyurethane). From evaluation of the thermal properties of those materials, the authors documented thermal conductivity values ranging between 0.041 and 0.053 W/m·K. Similar results regarding the utilisation of two different kind of acrylic textile waste were presented by Briga-Sá et al. (2013). Moving the attention to other materials, Ayadi et al. (2011) proved that, by means of foaming processes, glass wastes could be successfully used to realise recycled thermal insulation material. In particular, they realised a 450 kg/m^3 dense material characterised by thermal conductivity equal to 0.031 W/m·K. In addition, Van de Lindt et al. (2008) proposed a material constituted by fly ash from power plants (65%), water (26%) and scrap tires fibres (9%) with a thermal conductivity value that levelled out to 0.035 W/m·K. Sutcu and Akkurt (2009) investigated the use of recycled paper processing residues to make porous bricks with reduced thermal conductivity. As a matter of fact, a reduction up to 50% was observed by the two authors compared to bricks of the same composition, which is encouraging for higher energy saving potential in residential applications. Furthermore, throughout the years, several researchers have dealt with the use of agricultural biomass, also in combination with other types of wastes, in order to realise innovative building materials to be characterised in terms of thermal insulation properties. For instance, Lertsutthiwong et al. (2008) assessed a mixture of solid wastes from tissue paper manufacturing and corn peel. The investigated products revealed values of thermal conductivity that ranged between 0.139 and 0.250 W/m·K, based upon the mixture used. Sherely et al. (2008) studied the thermo-physical properties of banana fibre/polypropylene commingled composite materials by varying the quantity of the two components and performing different chemical and physical treatments. The most performing sample was a 980 kg/m^3 dense material with a thermal conductivity equal to 0.157 W/m·K. Binici et al. (2014) mixed textile waste with fibres of sunflower stalk and stubble so as to obtain a new insulation product with interesting thermal conductivity values. Khedari et al. (2003) carried out a study for evaluating the suitability of using durian peel and coconut coir as raw materials for production of particleboards for thermal insulation in buildings. They obtained fairly low values of thermal conductivity varying between 0.054 and 0.185 W/m·K. Finally, other authors (Paiva et al., 2012; Pinto et al., 2011) showed that corn's cob has the potential to be utilised as a sustainable material for building thermal insulation.

2.2. Environmental sustainability related assessments

In addition to those highlighted in Section 2.1, numerous studies have been developed along the years with the aim of assessing and enhancing both energy efficiency and environmental sustainability rates of recycled materials for building applications.

In the field of plastics, Intini and Kühtz (2011) and Ingrao et al. (2014b) applied LCA in order to environmentally assess the production of a polyester fibre mats for building thermal insulation, using fibres produced by processing flakes that were obtained from post-consumer PET bottles. Both studies highlighted, indeed, that the use of such a waste material allows for environmental gains that highly compensate the impacts coming from the most harmful processes involved, thus enabling minimisation of the damage associated with the analysed system. Environmental benefits in the field of recycled materials for application in buildings were also highlighted by Rincón et al. (2014) specifically for rubber obtained from recycling of out-use tires. As a matter of fact, the authors performed LCA and emphasised upon the potential of using this material to form drainage layer for extensive green roofs and compared results with conventional roof systems. It is clear that the use of an insulating system rather than another one influences upon the energy performance and environmental sustainability of the envelope and, as a result, of the whole building structure. Therefore, as also evidenced by the papers reviewed above, proper evaluations are needed in order to find sets of solutions that allow for enhanced energy saving and environmental sustainability in buildings, whilst preserving indoor air-quality and comfort. For instance, Chwieduk (2013) documented the feasibility of replacing the thick and heavy thermal mass external walls used in high latitude countries by thin and light thermal mass ones with phase change materials incorporated, without compromising the indoor comfort throughout the year. In addition, Baglivo et al. (2014) carried out a multi-criteria optimisation analysis aimed at identifying high energy efficiency (HEF) external walls for zero energy buildings in the Mediterranean climate, privileging eco-friendly materials such as those natural and recycled. In this regard, living walls can be considered as HEF walls. They are made of pre-vegetated panels, vertical modules, or planted blankets that are fixed vertically to a structural wall or frame. The panels and geotextile felts provide support to the plants and are generally made out of plastic, clay, metal, or concrete (Feng and Hewage, 2014). Finally, Breviglieri Pereira de Castro et al. (2014) evaluated the emissions of GHGs due to walls (with different material compositions) in their life cycles, including the phases of construction, use and maintenance, and end-of-life. Moreover, Mequignon et al. (2013) compared GHG-emissions produced by different wall-compositions (W-Cs) according to their life-spans for European building typologies and climate. In another study, in terms of global environmental impacts, Han et al. (2015) performed LCA to compare ceramic façade material to three other common ones, namely glass, marble and aluminium.

Therefore, based upon the findings of the studies reviewed, there is evidence that material production negatively affects the environmental sustainability associated with the life cycle of a wall and, as a result, of the building where it is installed. This is because building material production highly contributes to GHG-emissions and other environmental impacts like, for instance, abiotic resource stock depletion and non-renewable energy consumption. Therefore, improvements seeking more sustainable external building envelopes are desirable through development of better-integrated design solutions that includes selection of more sustainable and durable materials. In doing so, attention should be paid upon the construction practices and climates associated with a building location rather than another one.

Finally, Table 1 shows a summary of the studies reviewed here, indicating for each of them the materials investigated and the related thermal conductivity values. Moreover, in the Table the

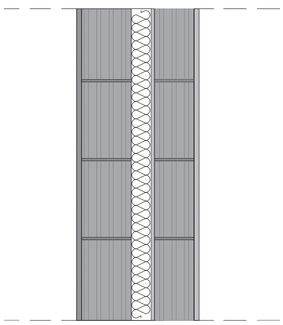
Table 1
Summary of materials investigated, thermal properties and environmental sustainability related assessments.

Reference(s)	Material(s) analysed	Thermal properties λ [W/m·K]	Sustainability assessment (Y/N, type)
Patnaik et al. (2015)	Recycled PET (R-PET), Waste Wool (WW), 50% R-PET/50% WW	0.030–0.038	N
Asdrubali et al. (2011), D'Alessandro et al. (2014)	Screeds (mix of exhaust sheaths of electric wires and concrete)	0.189	N
Iucolano et al. (2013)	Mixed PET waste with polyolefin waste	0.100–0.250	N
Melo et al. (2012)	Ethylene-vinyl acetate material from footwear industries craps	0.260	N
Valverde et al. (2013)	Textile industry waste (polyester and polyurethane)	0.041–0.053	N
Briga-Sá et al. (2013)	Textile waste	0.044	N
Ayadi et al. (2011)	Glass wastes	0.031	N
Van de Lindt et al. (2008)	Fly ash (from power plants)/water/scrap tires fibres material	0.035	N
Sutcu and Akkurt (2009)	Porous bricks with recycled paper	<0.4	N
Lertsutthiwong et al. (2008)	Tissue paper solid waste/corn peel material	0.139–0.250	N
Sherely et al. (2008)	Banana fibre/polypropylene commingled composite materials	0.157–0.182	N
Binici et al. (2014)	Mixed textile waste/sunflower stalk fibres/stubble fibres	0.164	N
Khedari et al. (2003)	Durian peel/coconut coir particleboards	0.054–0.185	N
Paiva et al. (2012), Pinto et al. (2011)	Corn's cob	0.101	N
Intini and Kühtz (2011)	Recycled PET	0.035[a]	Y, LCA
Ingrao et al. (2014b)	Recycled PET	0.036[a]	Y, LCA
Rincón et al. (2014)	Rubber from recycling of out-use tires	NA	Y, LCA
Han et al. (2015)	Ceramic, glass, marble and aluminium façade materials	NA	Y, LCA
Chwieduk (2013)	Wall compositions including PCMs	NA	Y, Energy saving
Baglivo et al. (2014)	NA	NA	Y, Multi-criteria analysis
Feng and Hewage (2014)	NA	NA	Y, LCA
Breviglieri Pereira de Castro et al. (2014)	NA	NA	Y, GHG emissions (LCA based)
Mequignon et al. (2013)	NA	NA	Y, GHG emissions (LCA based)

NA = Not Applicable.
[a] Value declared by the manufacturer.

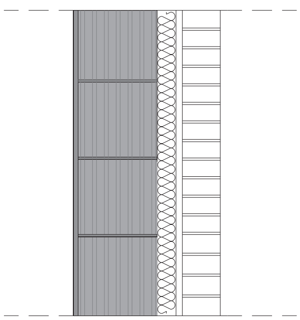
Table 2
Main characteristics of the studied walls: thickness, equivalent thermal conductivity and thermal transmittance.

Wall 1



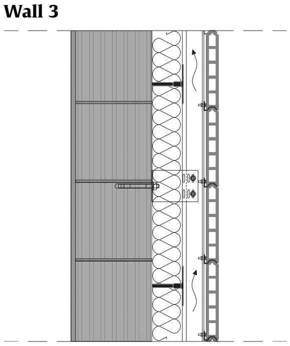
Plaster	1.5 cm
Thermal block $\lambda_{eq.} = 0.220$ W/m·K	15 cm
Thermal insulation $\lambda = 0.037$ W/m·K	6 cm
Mortar	1 cm
Thermal block $\lambda_{eq.} = 0.220$ W/m·K	12 cm
Plaster	1.5 cm
Total thickness	37 cm
Calculated transmittance	0.33 W/m^2·K

Wall 2



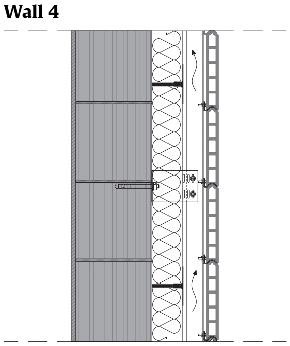
Plaster	1.5 cm
Thermal block $\lambda_{eq.} = 0.178$ W/m·K	25 cm
Thermal insulation $\lambda = 0.033$ W/m·K	6 cm
Air gap	2
Face brick $\lambda_{eq.} = 0.358$ W/m·K	12 cm
Total thickness	46.5 cm
Calculated transmittance	0.25 W/m^2·K

Wall 3



Plaster	1.5 cm
Thermal block $\lambda_{eq.} = 0.178$ W/m·K	25 cm
Thermal insulation $\lambda = 0.037$ W/m·K	10 cm
Ventilated cavity	7 cm
Cladding $\lambda_{eq.} = 0.300$ W/m·K	4 cm
Total thickness	47.5 cm
Calculated transmittance	0.23 W/m^2·K

Wall 4



Plaster	1.5 cm
Thermal block $\lambda_{eq.} = 0.178$ W/m·K	25 cm
Thermal insulation $\lambda = 0.036$ W/m·K	10 cm
Ventilated cavity	7 cm
Cladding $\lambda_{eq.} = 0.300$ W/m·K	4 cm
Total thickness	47.5 cm
Calculated transmittance	0.22 W/m^2·K

authors clarified if those studies included environmental sustainability related assessments and, in that case, of what type (i.e. LCA, GHG-emission estimation and so).

3. Description of the designed walls

Four external wall compositions being compliant with the thermal transmittance limits established by a set of Italian regulations were selected as samples for the comparative analysis (Table 2). In particular, two wall compositions commonly used for applications in the climatic zone chosen for the study (Wall 1 and Wall 2), and two more technically advanced – but not so diffused – samples (Wall 3 and Wall 4) were selected. The first wall sample has a basic stratigraphy that consists of two thermal blocks with plaster surface finishing and an intermediate layer of conventional insulating material (15 kg/m^3 dense expanded polystyrene). The second sample, instead, is more performing and is constituted by a thermal block, an insulation layer consisting of expanded polystyrene panels (35 kg/m^3), an air gap, and face bricks as exterior surface. The third sample is a ventilated façade consisting of a

Table 3
Characteristics of the recycled-PET panel.

Composition	Polyester staple fibre polyester staple fibre with thermo-bonding function
Main parameters	Fire reaction class: 1 Dimensions: 500 × 1000 mm Operating temperature range: 40 ÷ 110 °C Density(ρ): 30 kg/m^3 Thermal conductivity (λ): 0.036 W/m·K

thermal block, a layer of rock-wool (40 kg/m^3), a ventilated cavity and a finishing cladding (hollow tiles), with a supporting structure constituted by extruded aluminium profiles. The fourth sample is an analogous façade, except for the insulating layer, which is made up of recycled-PET panels whose main features are shown below in Table 3.

Starting from the stratigraphy of each wall analysed (from the internal to the external surface, left to right), the corresponding thermal transmittance was calculated following the ISO 6946 (2007): the obtained values were reported in Table 2. Regarding the ventilated façades, following the approach of ISO 6946, the thermal transmittance was evaluated neglecting the thermal resistance of the air cavity and of all the layers between that and the external environment, considering for the external surface resistance the value related to still air. This approach is commonly adopted for a rough modelling of ventilated façades, and it is clearly precautionary since it does not account for their positive contribution during the summer period. The values of thermal conductivity (for homogeneous layers) and equivalent conductivity (for non-homogeneous layers) used for the calculation and reported in Table 2 were declared by the manufacturer of each component material.

When data for a specific layer were lacking, the thermal properties suggested by the Italian reference standard (ISO 8990, 1994) were used.

Finally, the LCA analyses were carried out assuming that the four walls will serve a building to be installed in the Italian Climatic Zone 'E' (ICZ-E). It was done so because, based upon the

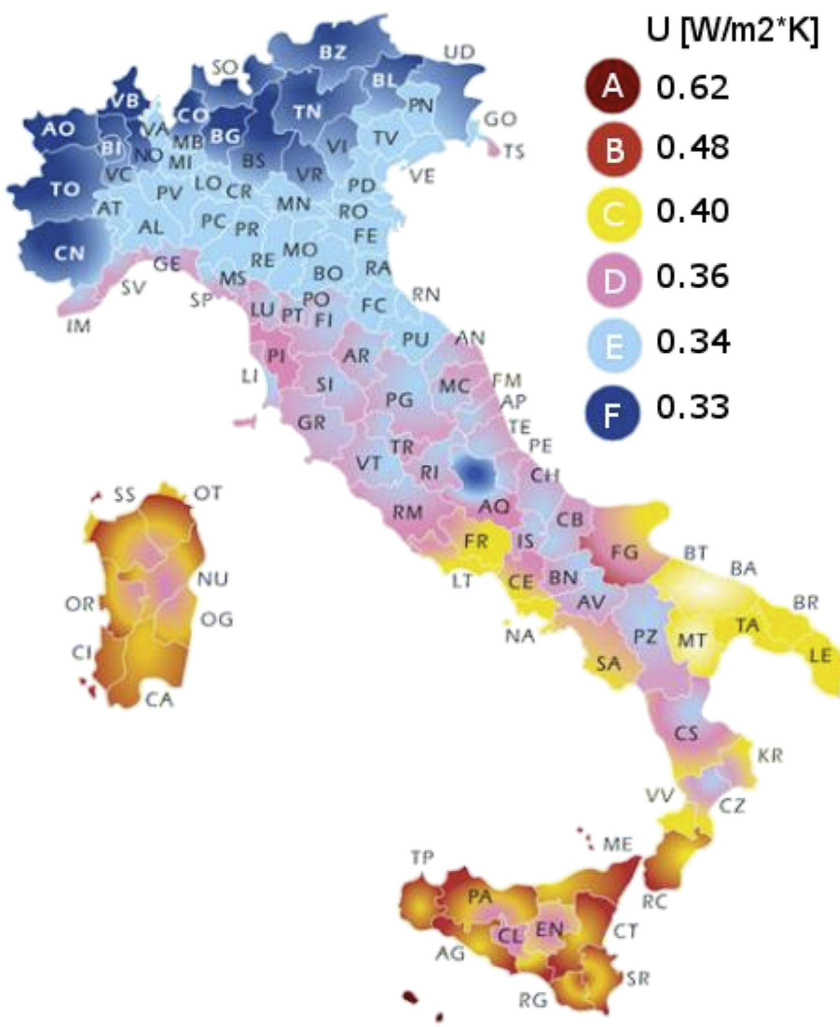


Fig. 2. Italian climatic zones and related thermal transmittance limits for external walls.
Source: Italian Encyclopaedia "Treccani". Available at http://www.treccani.it/scuola/lezioni/fisica/calore.html.

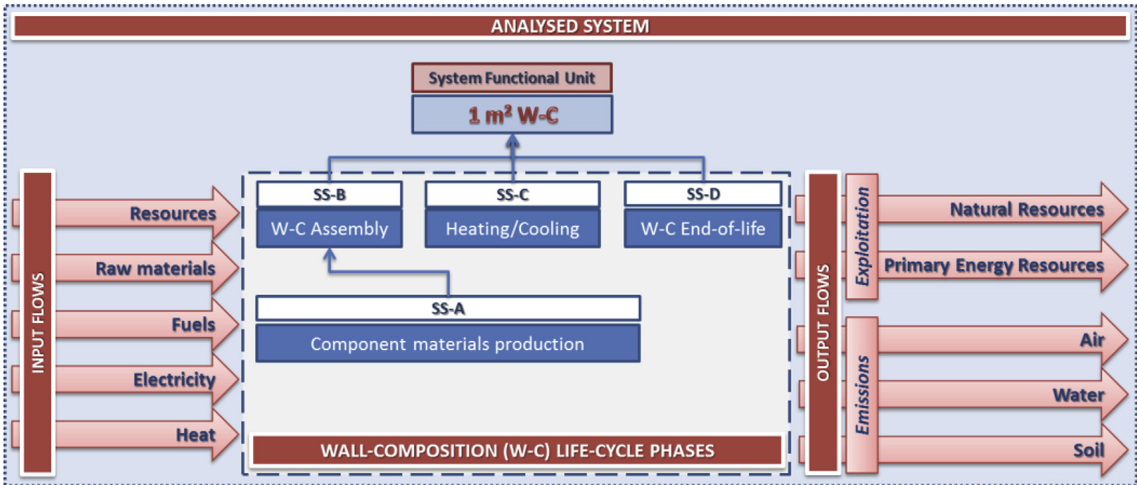


Fig. 3. Boundaries of the analysed system.
Source: Personal elaboration.

Annex A of the Italian Republic President's Decree (26th August 1993) n. 412 (DPR 412, 1993), it was documented that 52.7% of the Italian municipalities are currently located in that zone: so, the latter can be considered as the most representative of the Italian territory.

In this context, each sample's thermal transmittance was calculated from the related value of thermal conductivity reported in Table 2 and resulted as compliant with the limit established for the ICZ- E, namely 0.34 $W/m^2 \cdot K$ (Fig. 2).

4. Material and method

4.1. LCA development criterion

In the study here-presented, attributional LCA was applied with the aim of assessing the environmental impacts along the life cycles of several W-Cs. The study was set up according to the requirements established by the ISO standards 14040:2006 and 14044:2006 and, therefore, was divided into the following phases: 1) Goal and scope definition; 2) Life Cycle Inventory (LCI) analysis; 3) Life Cycle Impact Assessment (LCIA); 4) Life Cycle Interpretation. In particular, all data collected and used for the LCI were loaded into SimaPro v.7.3.3 (SimaPro, 2006) accessing the Ecoinvent v.2.2 database (Ecoinvent, 2010). Then, in agreement with De Benedetto and Klemeš (2009), the LCIA was performed by aggregating the output flows quantified in the inventory analysis into a limited set of impact categories. For this purpose, the classification/characterisation scheme provided by Impact 2002+ (Joillet et al., 2003) was accessed, and so this method was utilised to carry out the LCIA phase. This was done using both a mid-point and an end-point approach, thereby including also the phases of '*normalisation*' and '*weighing*' into the assessment. The mid-point approach was used to compare the analysed wall samples based upon specific characterisation values expressed as equivalent indicators (kg CO_2 for '*Global Warming*', kg $PM_{2.5.}$ for '*Respiratory Inorganics*', kg C_2H_3Cl for '*Carcinogens*', just to name a few). Then, the comparison was extended to the end-point approach, using the results obtained from the '*weighing*' phase. Those results were estimated by means of equivalent numerical parameters ("*weighing points*" or "*damage points*" or "*eco-points*") to make it possible to represent quantitatively the environmental effects of the analysed systems. In the light of this, the analysed compositions were compared in terms of total damage so as to highlight the most environmentally sustainable and less energy demanding option in its life cycle. Then, the comparison of the W-Cs under study was extended to the impact categories (ICs) and the damage categories (DCs), based upon the distinction provided by the method (Jolliet et al., 2003). In particular, for greater understanding it is clarified that, according to http://www.sciencedirect.com/science/article/pii/S0048969714008778Joillet et al., 2003, the:

- ICs represent the negative effects to the environment through which the damage (due to an emitted substance or an used resource) occurs;
- DCs are obtained by grouping the impact categories into major ones and represents the environmental compartments suffering the damage.

Finally, for greater understanding, it is underscored that the total damage is associated with the life cycle of the single wall investigated. It can be calculated by summing up the contributions of the processes and materials falling within the system border or of the damage and impact categories or even of all substances emitted and resources used (Ingrao et al., 2014b).

4.2. Goal and scope definition

As De Benedetto and Klemeš (2009) state, this is the phase in which it is needed to identify the objectives of the study and the system boundaries in order to avoid omitting relevant parts of the system to be investigated. Moreover, at this stage of the assessment, the Functional Unit (FU) is required to be chosen to enable the link of input and output flows to environmental impacts and also the comparability of results (ISO, 2006a). In this context, the aim of this research was to perform a comparative LCA of the four W-Cs shown in Table 2, highlighting both the inventory flows and the environmental impacts related to their life cycles. In particular, the study was conducted for comparison between "conventional" and "unconventional" W-Cs, and so for highlighting the environmental impacts resulting from the usage of more sophisticated assembly technologies and component materials, as those of the two ventilated façades considered ("unconventional" W-Cs). Moreover, the study will enable identification of the W-C to be recommended for construction of more environmentally sustainable and less energy demanding buildings and, hence, can be considered as the starting point for application of LCAs at the building scale. In particular, the obtained results will enable making those LCAs less time and resource consuming, thereby avoiding performing the life cycle analysis of the building every time something is changed in the envelope composition.

Finally, the study is addressed to LCA practitioners, designers, builders and company owners, so that they could learn about the methodology to be used for similar studies and also about the inventory flows and the environmental impacts associated with the investigated walls. Doing so could allow them to understand the important role that a correct use of LCA plays for enhancement of both environmental sustainability and energy efficiency of buildings.

4.2.1. Functional unit

In this study, the FU was represented by 1 m^2 of wall (sample) as a reference for both inventory flows and environmental impacts. Each wall sample tested will be utilised for construction of a building located in the province of Perugia (Italy), so operating in one of the Italian “E” climatic zones shown in Fig. 2. This choice for the FU facilitates the comparison amongst the four compositions tested enabling, in turn, a better interpretation of the results gained. As previously done by other authors such as, for instance, Pulselli et al. (2009) and Rossi et al. (2012), a service life of 50 years was considered for the aforementioned building and, so, for the four W-Cs analysed.

4.2.2. System boundaries

The system boundaries were divided into the following subsystems (SS): production of the component materials (SS-A); and, W-C assembly (SS-B), use (SS-C) and, end-of-life (SS-D). The system boundaries thus defined were shown in Fig. 3 also indicating, in qualitative terms, the main categories of input and output flows related to the system. In particular, it should be observed that SS-A encompasses resources extraction and processing for production of the component materials. SS-B was defined as including all the main activities involved in the installation of such materials, whilst SS-C is about the electricity consumption (per square metre of W-C) for indoor heating and cooling during the 50 year service life of the building. In addition, SS-D contains the activities of wall dismantling and treating, based upon both the material types and the assembly technologies considered.

Finally, all transports involved, such as those of the component materials to the construction yard for W-C assembly and then to the disposal treatment plants when the W-C end-of-life is reached, were accounted for.

4.3. Life cycle inventory analysis

All elaboration phases, as listed in section 4.1, play important roles in LCA studies but, amongst them, the inventory analysis is acknowledged worldwide as the most important one (Ingrao et al., 2015a). This is mainly because all the activities involved in the product's life-cycle must be analysed and modelled, and all data related to the environmental impacts must be compiled and calculated (Zhang et al., 2015). Additionally, the LCI analysis represents the foundation for the subsequent LCIA (Suh and Huppes, 2005): hence, it needs to be performed to avoid data uncertainties that can heavily affect the LCIA results and so can compromise the value and reliability of the study conducted.

An LCI analysis mainly involves data compilation (Zhang et al., 2015): indeed, in this study, all input and output flows were analysed starting from performing data collection and calculation. In particular, since particularly specialised systems were assessed, priority was given to using primary data resulting from W-C design in terms of input material typologies and amounts used. Additionally, secondary data were taken from international databases like Ecoinvent v.2.2, such as the extraction of resources, and the production of materials and energies, as well as the life cycles of the means used for input material transport. It was done so because, as also concluded by Siracusa et al. (2014), this database is acknowledged worldwide to be a reliable background data source and, according to Frischknecht and Rebitzer (2005), to accommodate most of the background materials and processes often required in LCA studies. Data collection and elaboration were performed for each phase falling within the system boundaries defined and discussed above, namely: production of the component materials, as well as of assembly, use and disposal of W-Cs. Moreover, data collection was carried out continuously accessing Ecoinvent v.2.2 in order to verify what processes and raw materials were necessary to be created since not already present in the database. From the analysis, it was resulted that all supportive data needed were already included within Ecoinvent, thereby avoiding creating new items or making assumptions and hypothesis for using background data within the database. Finally, to enable greater understanding, the following sections were dedicated to a detailed discussion of the data and methodological approach used for the inventory analysis development.

Table 4
Input data to W-C production – Wall 1.

Wall 1						
Material	Thickness	Description	Dimensions (cm)	Weight per piece (kg)	kg/m^2	Pieces/m^2
Plaster	1.5 cm	–	–	–	2.25	–
Thermal block $\lambda_{eq.} = 0.220$ W/m × K	15 cm	Block for double-walled or single-layer compositions. Rectangular horizontal holes. Installation with mortar between elements, horizontal and vertical joints thickness varying between 5 and 15 mm	15 × 25 × 25	5.9	91	15.4
Thermal insulation $\lambda = 0.037$ W/m × K	6 cm	Expanded polystyrene panels (15 kg/m3)	50 × 100 × 6	0.45	0.9	2
Mortar	1 cm	–	–	–	2	–
Thermal block $\lambda_{eq.} = 0.220$ W/m × K	12 cm	Block for double-walled or single-layer compositions. Rectangular horizontal holes. Installation with mortar between elements, horizontal and vertical joints thickness varying between 5 and 15 mm	12 × 25 × 25	4	61.6	15.4
Plaster	1.5 cm	–	–	–	2.25	–
				Total weight	187.00[a]	kg/m^2

[a] It includes 27 kg/m^2 of plaster for installation of the thermal blocks.

Table 5
Input data to W-C production – Wall 2.

Wall 2						
Material	Thickness	Description	Dimensions (cm)	Weight per piece (kg)	kg/m^2	Pieces/m^2
Plaster	1.5 cm	–	–	–	2.25	–
Thermal block $\lambda_{eq.} = 0.178$ W/m × K	25 cm	Block for double-walled or single-layer compositions. Rectangular horizontal holes. Installation with mortar between elements, horizontal and vertical joints thickness varying between 5 and 15 mm	25 × 25 × 25	8.7	134	15.4
Thermal insulation $\lambda = 0.033$ W/m × K	6 cm	Expanded polystyrene panels (35 kg/m3)	50 × 100 × 6	1.05	2.1	2
Air gap	2 cm	–	–	–	–	–
Face brick $\lambda_{eq.} = 0.358$ W/m × K	12 cm	Facing brick with rectangular vertical holes (percentage ≤ 45%). Installation with mortar between elements, horizontal and vertical joints thickness varying between 5 and 15 mm	12 × 25 × 6	2	110	55
				Total weight	306.85[a]	kg/m^2

[a] It includes 58.5 kg/m^2 of plaster for installation of the thermal blocks.

Table 6
Input data to W-C production – Wall 3.

Wall 3						
Material	Thickness	Description	Dimensions (cm)	Weight per piece (kg)	kg/m^2	Pieces/m^2
Plaster	1.5 cm	–	–	–	2.25	–
Thermal block $\lambda_{eq.} = 0.178$ W/m × K	25 cm	Block for double-walled or single-layer compositions. Rectangular horizontal holes. Installation with mortar between elements, horizontal and vertical joints thickness varying between 5 and 15 mm	25 × 25 × 25	8.7	134	15.4
Thermal insulation $\lambda = 0.037$ W/m × K	10 cm	Semi-rigid non-coated rock-wool panels (40 kg/m3)	60 × 120 × 10	2.88	4	1.39
Ventilated cavity	7 cm	–	–	–	–	–
Cladding $\lambda_{eq.} = 0.300$ W/m × K	4 cm	Hollow tiles	25 × 100 × 4	7.5	30	4
				Total weight	185.75[a]	kg/m^2

[a] It includes 13.5 kg/m^2 of plaster for installation of the thermal blocks and 2 kg/m^2 of aluminium structure as support of the hollow tiles.

4.3.1. SS-B: W-C assembly

In this research, W-C assembly was set-up to include production of the component materials (SS-A) shown in Table 2. Therefore, it was modelled considering 1 m^2 of W-C as FU and accounting for each of the aforementioned component materials produced, based upon both surface mass (kg/m^2) and transportation from the manufacturer to the Building Construction Yard (BCY) for installation. All the elaborated data were listed in Tables 4–7.

Finally, modelling of the W-C assembly phase included also estimation of the energy consumption related to the on-site installation activities (electricity and fuel use by different construction equipment). In this regard, from review of several specialised papers in this field it was possible for the authors to observe that this value generally ranges between 1% and 4% of the total embodied energy of the construction materials utilised (Utama and Gheewala, 2008, 2009; Asdrubali et al., 2013; Devi and Palaniappan, 2014; Biswas, 2014). Therefore, based upon the W-Cs considered and the operations generally involved for their assembly, it seemed to the authors as reasonable to assume an average value equal to 2%. The obtained values, expressed as consumption of both electricity and fossil fuel (diesel), were recorded in Table 8. Walls 1 and 2 are those with the lowest and highest consumption rates, whilst similar values of both electricity and diesel were found for walls 3 and 4. It is clear that such evidences are strictly dependent upon the asset and the component materials characterising each wall considered.

4.3.2. SS-C: use

This phase was modelled as the amount of electricity consumed for indoor heating and cooling, based upon heat losses and gains through the analysed W-Cs in winter and summer. As it is known, heat is transferred by conduction through the building envelope walls. In this context, the following wall parameters can be found as affecting this process: thermal resistance, thermal mass and solar absorptance. A certain influence is also exerted by the coefficient of convection and heat transfer, and the thermal emittance. Massive walls are able to store heat and to delay heat transmission, with benefit both in winter (reduction of heat losses) and summer (reduction of cooling load due to the delaying of internal surface temperatures rise). Ventilated façades with appropriate thermal mass and insulation could provide suitable internal heat retention during winter and, moreover, increase the benefits in summertime. This is because a significant part of the heat transferred from the covering material to the air cavity is eliminated by the ventilation (caused by temperature differences between the inside air and the outside air in the air cavity itself). A complete thermo-fluid dynamic analysis of the thermal behaviour of wall compositions requires the knowledge of different parameters (heat transfer coefficients, friction factors, thermophysical properties of the materials, etc.) that are not so easy to be evaluated, and for which quite uncertain values are often used. Moreover, the uncertainty affecting those parameters can reduce the reliability of using complex calculation methods, such as computational fluid dynamics based

Table 7
Input data to W-C production – Wall 4.

Wall 4						
Material	Thickness	Description	Dimensions (cm)	Weight per piece (kg)	kg/m^2	Pieces/m^2
Plaster	1.5 cm	–	–	–	2.25	–
Thermal block $\lambda_{eq.} = 0.178$ W/m × K	25 cm	Block for double-walled or single-layer compositions. Rectangular horizontal holes. Installation with mortar between elements, horizontal and vertical joints thickness varying between 5 and 15 mm	25 × 25 × 25	8.7	134	15.4
Thermal insulation $\lambda = 0.036$ W/m × K	10 cm	Polyester fibre mat produced from flakes that are obtained from post-consumer Polyethylene Terephthalate (PET) bottles	50 × 100 × 10	1.5	3	2
Ventilated cavity	7 cm	–	–	–	–	–
Cladding $\lambda_{eq.} = 0.300$ W/m × K	4 cm	Hollow tiles	25 × 100 × 4	7.5	30	4
				Total weight	184.75[a]	kg/m^2

[a] It includes 13.5 kg/m^2 of plaster for installation of the thermal blocks and 2 kg/m^2 of aluminium structure as support of the hollow tiles.

Table 8
Electricity and fuel consumption for W-C assembly.

Wall	Electricity (kWh/m$^2_{W\text{-}C}$)	Diesel (kg/m$^2_{W\text{-}C}$)
1	1.23	0.11
2	2.43	0.22
3	1.95	0.17
4	1.91	0.17

analyses (Ciampi et al., 2003). Furthermore, for a comparative analysis of life cycle impacts a very detailed calculation of the energy consumption is not necessary, since its influence upon the evidences of the comparison is not relevant. Therefore, a simplified calculation approach (with an acceptable level of uncertainty) is used to model the use phase. In particular, regarding the summer period, calculation was performed under a variable regime, considering facing position of the analysed walls to sunlight. Solar radiation is, indeed, absorbed by the wall structure that accumulates the heat contained in that radiation and, subsequently, returns it to the indoor environment after a certain period of time. For this reason, it would be needed to estimate the hourly temperature-trend on the inner face of the wall to determine, hour by hour, the heat flow transmitted by adduction between the inner face of the wall itself and the indoor air. In the light of the complexity resulting from such a calculation, it was assumed that the indoor temperature in summertime remains almost constant (26 ± 1 °C), whilst the outdoor temperature varies with a sinusoidal manner. Therefore, according to Stewart (1948), the heat flow through the envelope from the outside to the inside environment was calculated using the following equation:

$$\mathbf{Qt(gained)} = \boldsymbol{U} \times \boldsymbol{A} \times \Delta \boldsymbol{teq} \tag{1}$$

in which:

- $Q_{t(gained)}$ indicates the heat gains from the outside and is expressed as W per square metre of wall;
- U is the thermal transmittance associated with the given wall and measured as W/m^{2}K;
- A is the wall surface assumed as equal to 1 m^2;
- Δt_{eq} is the equivalent difference of temperature between the outdoor and the indoor environment. It is defined as a fictitious thermal gradient that, in the absence of irradiation, would give rise to a heat flow through the wall structure equal to that occurring in real conditions of both irradiation and thermal gradient between outside and inside air.

In the particular case, Δt_{eq} was extrapolated from Pizzetti (1986) in which Δt_{eq} values are associated with the daily hours, and with both surface mass and facing position of the given wall, and are referred to the following thermal conditions:

- 40° North latitude;
- Daily Temperature Range (DTR), represented as $T_{out(max)} - T_{out(min)}$, equal to 11 K;
- difference between the outdoor and the indoor design temperatures ($\Delta T_d = T_{d(out)} - T_{d(in)}$) equal to 8 K;
- average absorption coefficient of the radiated surfaces equal to: 0.5; 0.7; and, 0.9 for light, medium and dark colour, respectively.

For $Q_{t(gained)}$ calculation, the worst condition was taken into consideration (neglecting the effects of shading and, for the ventilated façades, also the effects of ventilation), and so the highest value of Δt_{eq} was extrapolated for each wall analysed. Then, the so calculated amounts of ΔT_{eq} were needed to be referred to the climatic conditions specifically related to the BCY location that was taken into account for the study development. For this purpose, a correction factor was used, as extrapolated from Pizzetti (1986) based upon both the DTR and ΔT_d values of the BCY location considered (Perugia, Italy). According to the UNI 10349 (1994), those values are 10 K for DTR and 2.6 K for ΔT_d, whilst the local latitude (43° 06′ 00″) can be considered as quite close to the standard value of 40° indicated above. The correction factor obtained resulted in −3.92.

For greater understanding, the values of surface mass, of ΔT_{eq}, and of the ΔT_{eq} corrected as clarified above (ΔT^c_{eq}), were listed in Table 9.

Therefore, $Q_{t(gained)}$ was calculated from U and ΔT^c_{eq} using equation (1) and then converted into thermal energy ($E_{t(gained)}$) via multiplication by the indoor air-cooling time (T) in the life cycle of the wall. In particular, T was estimated considering for each year of the life time of the walls a mean use of the air conditioning system

Table 9
Surface mass, ΔT_{eq} and ΔT^c_{eq} for each W-C analysed.

Wall	Surface mass (kg/m^2)	ΔT_{eq} (K)	ΔT^c_{eq} (K)
1	187.00	15.29	11.37
2	306.85	5.53	1.61
3	185.75	15.24	11.32
4	184.75	15.20	11.28

in a standard cooling season for the reference climatic zone, according to equation (2):

$$\boldsymbol{T} = \boldsymbol{N}(\boldsymbol{h}) \times \boldsymbol{N}(\boldsymbol{d}) \times \boldsymbol{N}(\boldsymbol{m}) \times \boldsymbol{N}(\boldsymbol{y}) \quad (2)$$

assuming.

- N(h) (number of hours per day) = 6;
- N(d) (number of days per month) = 30;
- N(m) (number of months per year) = 4;
- N(y) (number of years characterising the W-C lifetime) = 50.

From application of equation (2), T resulted in 36,000 h and then the values of $E_{t(gained)}$ was calculated accordingly.

For completeness reasons the calculated values of $Q_{t(gained)}$ and $E_{t(gained)}$ were listed in Table 10 for the wall samples tested.

In order to quantify the electricity required for subtracting those amounts of thermal energy from the indoor environment, it was hypothesised to use a high-efficiency heat pump, working also as air conditioner. For this reason, the calculated values of $E_{t(gained)}$ were divided by the typical coefficient-of-performance of a refrigeration machine (COP_{RM}), like the air conditioner that was assumed to be utilised. The related value was calculated from the coefficient-of-performance of a heat pump (COP_{HP}) considering that $COP(RM) = COP(HP) - 1$: in particular, assuming $COP(HP) = 3.5$, COP_{RM} resulted in 2.5. So, the electricity consumption for indoor cooling ($E_{E(cooling)}$) was calculated.

For what concerns to the winter period, calculation of the energy losses through the wall was done in stationary regime following equation (3):

$$\mathbf{Qt}(\mathbf{lost}) = \boldsymbol{U} \times \boldsymbol{A} \times \Delta \boldsymbol{t} \quad (3)$$

in which:

- $Q_{t(lost)}$ indicates the thermal power lost from the indoor environment and is expressed as W per square metre of wall;
- U is the thermal transmittance associated with the given wall and measured as (W/m^2K);
- A is the wall surface assumed as equal to 1 m^2;
- Δt is the gradient between the indoor (20 °C) and outdoor (5 °C) environment temperatures.

Then, $Q_{t(lost)}$ was used to calculate $E_{t(lost)}$ through equation (2), considering a yearly mean use of the heating system in a standard heating season for the reference climatic zone, during the whole 50 years life time: 6 months per year (from 15th October to 15th April), 30 days per month and 4 h per day (i.e. 36,000 h in total) (DPR 412, 1993). The calculated values of both $Q_{t(lost)}$ and $E_{t(lost)}$ were shown in Table 11.

For calculation of the electricity consumption for indoor heating ($E_{E(heating)}$), $E_{t(lost)}$ was divided by the $COP_{(HP)}$ already provided above and equal to 3.5.

Table 10
$Q_{t(gained)}$ and $E_{t(gained)}$: thermal power and energy flown through the envelope sample into the hypothetical indoor environment – Values per single W-C.

Wall	$Q_{t(gained)}$ ($W/m^2{}_{W\text{-}C}$)	$E_{t(gained)}$ ($kWh/m^2{}_{W\text{-}C}$)
1	3.75	135.00
2	0.40	14.47
3	2.60	93.78
4	2.48	89.39

Table 11
$Q_{t(lost)}$ and $E_{t(lost)}$: Thermal power and energy flown out from the hypothetical indoor environment through the envelope sample into the outdoor environment – Values per single W-C.

Wall	$Q_{t(lost)}$ ($W/m^2{}_{W\text{-}C}$)	$E_{t(lost)}$ ($kWh/m^2{}_{W\text{-}C}$)
1	4.95	178.20
2	3.75	135.00
3	3.45	124.20
4	3.30	118.80

Table 12
Electricity consumption for indoor heating and cooling during the life cycle of each wall: values per square metre of W-C.

Wall	$E_{E(cooling)}$	$E_{E(heating)}$	$E_{E(Tot)}$
	$kWh/m^2{}_{W\text{-}C}$		
1	54.00	50.91	**104.91**
2	5.79	38.57	**44.36**
3	37.51	35.49	**73.00**
4	35.76	33.94	**69.70**

To enable greater understanding of the study conducted, the electricity consumption amounts for both heating and cooling were reported in Table 12 together with the related totals.

From Table 12, there is evidence that wall 1 is the most electricity demanding one for indoor heating and cooling, thus showing the worst behaviour in both winter and summer. Wall 2 presents the greatest rate of energy efficiency during summer due to the high surface mass (almost 307 kg/m^2) that results in increased thermal inertia compared to the other compositions. Such an aspect positively affects the summertime behaviour of the wall in terms of its capacity of reducing the thermal fluctuations occurring within the indoor environment due to the cyclic variations of the external temperature. Walls 3 and 4 show similar behaviours in winter and summer due to the same stratigraphy asset, and to the usage of insulating materials characterised by quite close thermal conductivity values, as shown in Table 3. In particular, wall 4 is the best of the two and, by the way, the one with the best energy performance in winter: in fact, electricity requirements are the lowest with respect to the other walls. Additionally, in wintertime, energy performance rates quite comparable to those of walls 3 and 4 were recorded for wall 2.

Finally, comparing the total amounts of electricity consumed ($E_{E(Tot)}$), wall 2, thanks to the best behaviour in summer and also to the good behaviour in winter, results to be the most energy performing wall amongst those analysed and so would appear as the most preferable solution. However, the location of the building where these W-Cs were assumed to be installed does not usually undergo hot summer periods. Therefore, according to the authors, there would be no need for W-Cs that are characterised by high energy performance rates in summer, and so enable highly reduced consumption of electricity for indoor cooling. This emphasises upon wall 4 as a considerable alternative to the other walls tested, because it presents the best thermal insulation behaviour in winter and, a part from wall 2, also in summer.

4.3.3. SS-D: end-of-life

Due to the difficulty of collecting data on site, this phase was modelled based upon the composition of each wall analysed, using background data entirely extrapolated from the Ecoinvent database system. In particular, it was assumed that, after dismantling, the waste material is transported to a recovery plant where it is regenerated through a crushing process, thus making it reusable as filling material for roadbeds realisation. Such a disposal treatment was considered for the waste material resulting from demolition of:

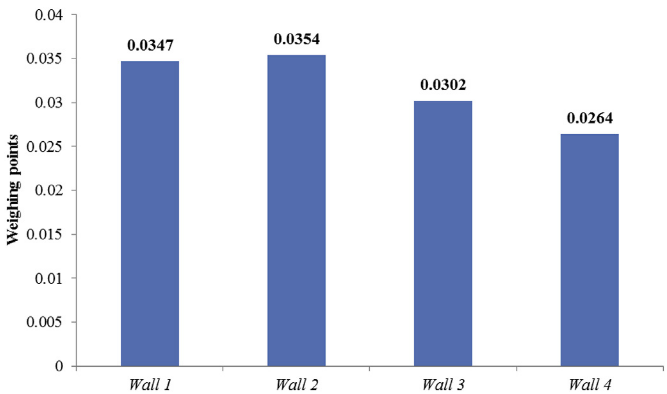


Fig. 4. Comparative environmental assessment of the W-Cs analysed based upon the related damage points. Personal elaboration of LCIA results obtained from the LCIA performed according to Impact 2002+.

- the entire walls 1 and 2, due to the very low amounts of insulating material utilised compared to the thermal blocks and the face bricks, and also to the assembly technology adopted that makes it difficult to separate the component layers. Both aspects make removal of the insulating material worthless;
- the thermal blocks and the hollow tiles (plus the plaster used for their installation) utilised in walls 3 and 4.

On the contrary, a recycling treatment for the insulating materials (R-PET and mineral wool) and the aluminium support structure used for walls 3 and 4 assembly was considered, thus attempting to maximise the benefits resulting from the usage of those W-Cs compared to the others. For recycling of both PET-based and rock-wool panels, it was assumed that at most 10% of the insulating material is contaminated during removal and handling operations and so it is disposed of in Inert Material Landfills (IMLs). The end-of-life data and modelling evidences were summarised in Table 13.

5. Results and discussion

The LCIA phase highlighted that, despite being the one to perform best as regards the total consumption of electricity for indoor heating and cooling, wall 2 is the one with the worst behaviour in terms of the environmental sustainability associated with its entire life cycle. This can be seen in Fig. 4 where results from the comparative assessment performed were graphically represented per W-C square metre.

On the contrary, wall 4 results as the one to cause the lowest environmental impact, mainly due to the environmental gains coming from:

1. recycling of the post-use bottles for production of the R-PET insulating mats used, as documented by Ingrao et al. (2014b);
2. recycling of that R-PET insulating mat at the end-of-life of the wall.

Table 13
Wall end-of-life modelling outcomes.

Walls and wall component(s)	Amount (kg/m^2)	Waste treatment scenario
Walls 1 and 2 + thermal blocks and hollow tiles of walls 3 and 4	853.35	Regeneration for production of the filling material used for roadbeds realisation
PET-based mats	4.00	10%: IML; 90%: Recycling
Rock-wool mats	3.00	
Aluminium support structure	4.00	100%: Recycling

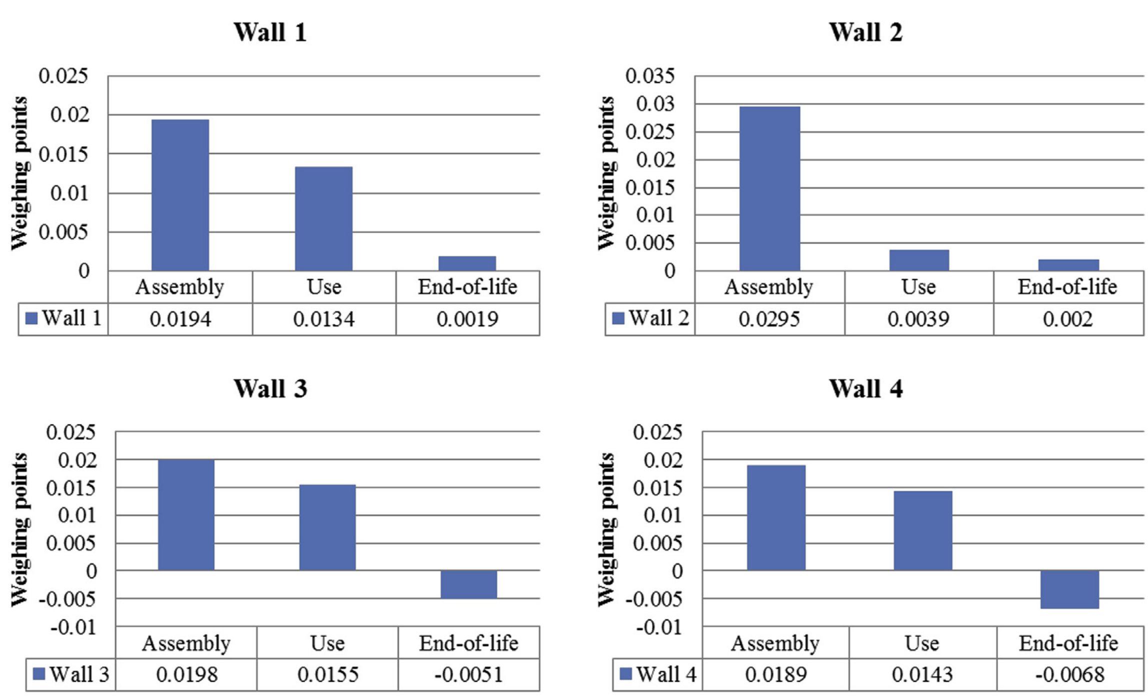


Fig. 5. A comparative environmental assessment of the W-C life cycles is depicted in this figure. Personal elaboration from Impact 2002+ using the LCIA-results related to the FU life cycle.

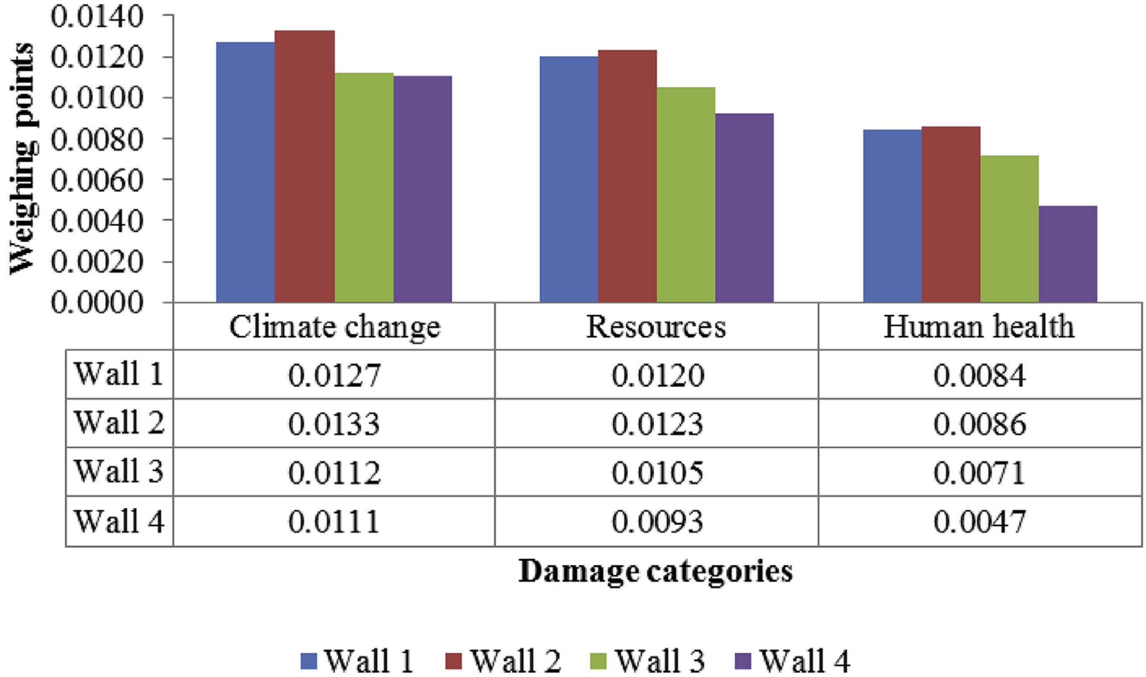


Fig. 6. Most affected DCs for single wall considered: A comparison based upon LCIA-results from Impact 2002+. The values indicated are, indeed, expressed as weighing points per square metre of wall (FU of the study).

Table 14
"Damages assessment" values for the three (up to four) most affected ICs (midpoint approach).[a]

DC	Unit of measurement	Wall 1	Wall 2	Wall 3	Wall 4
Climate change	kg CO_{2eq}	1.26E+02	1.32E+02	1.11E+02	1.10E+02
Resources	MJ primary	1.82E+03	1.87E+03	1.60E+03	1.41E+03
Human health	DALY	5.98E-05	6.10E-05	5.06E-05	3.34E-05

DALY (Disability-Adjusted Life Year): a measure of the overall severity of a disease, expressed as the number of years lost due to illness, disability or premature death.
PDF (Potential Damage Fraction): the fraction of species that have a high probability of not surviving in the affected area due to unfavourable living conditions.
[a] Personal elaboration of LCIA-results from Impact 2002+.

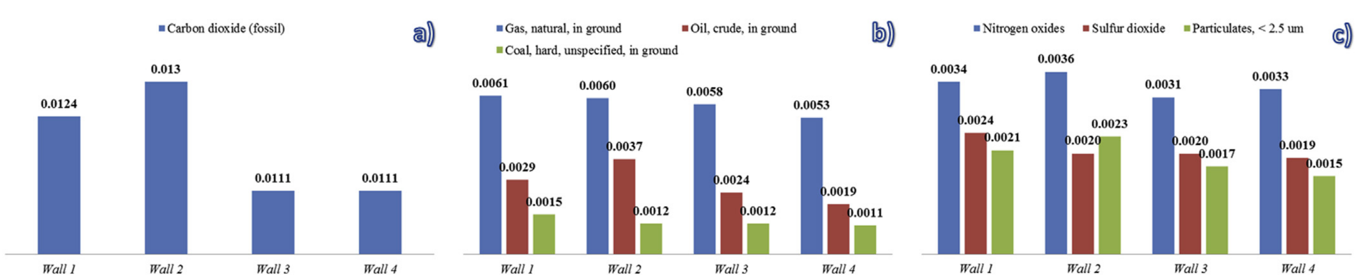


Fig. 7. Substance emitted and primary-energy resources used most affecting: a) Climate change; b) Resources; c) Human health. Results were expressed as damage points per square metre of W-C. Personal elaboration of LCIA-results from Impact 2002+.

Both aspects lead to avoided emission of aromatic hydrocarbons in the total amount of 1.54 g per square metre of wall (38% from 1, 62% from 2), thus positively influencing the environmental sustainability associated with the life cycle of the wall. Furthermore, from Fig. 5 there is evidence that wall 4 is the one with the lowest impacts in the phases of assembly (including component material production) and use, as well as with the highest environmental gains in the end-of-life thanks to the use of the R-PET mat.

Considering that wall 4 is also characterised by a quite good insulation performance in both winter and summer times, it could be considered as the most preferable option and so potentially usable for construction of a building.

For greater understanding of the study conducted, the comparative analysis was detailed by providing, for all walls tested, results on DCs and ICs, and also on the most impacting substances emitted and resources consumed. In doing so, the authors focussed upon both the mid- and endpoint approach. In particular, from Fig. 6 and Table 14 there is evidence that, though to varying degrees, for all walls the most affected DCs are: *Climate change*, *Resources* and *Human health*.

For a greater rank of detail, in Fig. 7 the most impacting substances and resources were shown for each W-C considered with the corresponding values of damage caused (damage points).

As a matter of fact, if the damages of all substances and resources considered were summed up per single wall analysed, a value quite close to that shown in Fig. 4 would be obtained.

Doing so would, indeed, result in:

- 0.0308 pt up to 0.0347 pt for wall 1 (−11.24%);
- 0.0318 pt up to 0.0354 pt for wall 2 (−10.17%);
- 0.0273 pt up to 0.0302 pt for wall 3 (−9.6%);
- 0.0261 pt up to 0.0264 pt for wall 4 (−1.14%).

Those missing percentages are represented by all the other substances and resources that were neglected due to the very minor single contributions that they make.

To enable greater understanding of the study carried out, the comparison shown in Fig. 7 was extended to the amounts of those substances emitted and resources used, extrapolated from Ecoinvent as output flows (Fig. 8).

By way of example, it can be asserted that wall 2 is responsible for the emission in air of 128 kg of fossil carbon dioxide corresponding to a damage value of 0.013 pt, thereby affecting *Climate change* for 97.74% and representing almost 37% of the damage

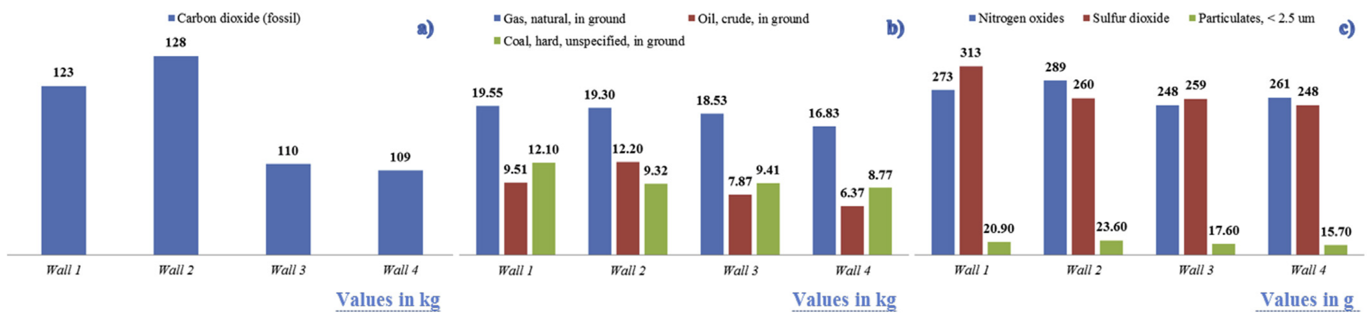


Fig. 8. Amounts of substance emitted and primary-energy resources used most affecting: a) Climate change; b) Resources; c) Human health. Personal elaboration of LCIA-results from Impact 2002+.

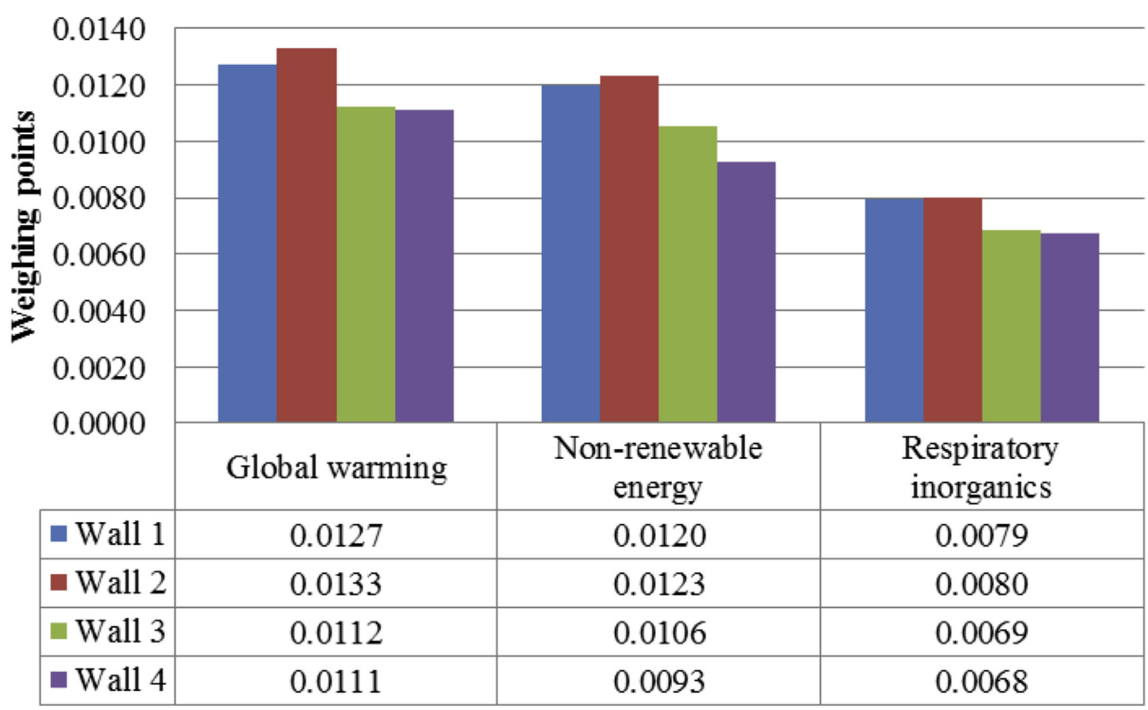


Fig. 9. Most impactful ICs per single wall considered: A comparison based upon LCIA-results from Impact 2002+ . The weighing points shown are, indeed, referred to the FU of the study.

Table 15
"Characterisation" values for the most impactful ICs (midpoint approach).

IC	Unit of measurement	Wall 1	Wall 2	Wall 3	Wall 4
Global warming	kg CO_{2eq}	1.26E+02	1.32E+02	1.11E+02	1.10E+02
Non-renewable energy	MJ primary	1.82E+03	1.87E+03	1.60E+03	1.41E+03
Respiratory inorganics	kg $PM_{2.5eq}$	8.02E-02	8.08E-02	6.97E-02	6.85E-02

caused by the wall in its life cycle (0.0354 pt). Wall 3 implies consumption of 18.53 kg of natural gas with a damage equal to 0.0058 pt, thus contributing for almost 55% to the damage occurring to *Resources* (0.0105 pt) and for nearly 20% to that associated with the wall in its life cycle (0.0302 pt). Similar considerations can be made per single wall regarding the other substances and resources considered.

As per the ICs, those with the highest impacts were shown in Fig. 9 and Table 15, based upon the findings from application of the mid- and endpoint approach: they resulted as to be *Global warming*, *Non-renewable energy* and *Respiratory Inorganics*.

All that stated, it can be concluded that, thanks to the type of stratigraphic composition utilised for walls 3 and 4, the latter perform quite well in both energy and environmental terms. Thus, they can be considered as good candidates for the design of environmental sustainable and low energy demand buildings. In addition, the usage of R-PET mats makes wall 4 the one with the highest rates of energy efficiency and environmental sustainability. In this regard, it performs best for all DCs and ICs, as well as for almost all the substances and resources considered causing, indeed, largely lower impact values than the other options: hence, it represents the most preferable solution.

6. Conclusions

Worldwide, the construction industry is characterised by a huge consumption of raw materials (on average, about 60% of the whole amount extracted from the lithosphere) and also by a high energy consumption (life cycles of buildings accounts for around 40% of the global energy demand). It is therefore crucial to direct the development of the building sector towards environmentally-friendly solutions, in order to face the challenges of energy consumption, climate change and resources depletion. For this purpose, appropriate choices about the entire life cycle of a building (and not only the construction phase) are needed from the early stages of a building design, and the LCA methodology is fully recognised as a valid tool in this regard.

The aim of this paper was to compare four external-wall solutions, constituted by different materials and characterised by different technologies, through an LCA approach, in order to identify the best solution from both the energy and the environmental point of view. The functional unit selected was 1 m^2 of wall, and all the wall samples were considered to be installed and operating in a building located in Italy (in particular, in an "E" climatic zone).

For all the considered walls the damage categories with the highest impacts were Climate Change, Resources and Human Health whilst, in terms of impact categories, those resulted to be most affected were Global Warming, Non-renewable Energy and Respiratory Inorganics.

Results showed also that ventilated façades perform quite well, as far as both energy and environmental impacts, compared to "standard" wall compositions. Comparing a ventilated façade with conventional insulating material (wall 3) to standard wall compositions (wall 1 and 2), the impact reduction varied between 12% and 17% in terms of damage categories, and between 12% and 16% in terms of impact categories. This is essentially due to the low impacts in the phases of assembly and use, and also to the highest environmental gains at the end-of-life, which are linked to an easy disassembly-recycle-reuse of construction materials. Moreover, the use of recycled materials (in particular, R-PET) for the thermal insulation layer resulted as a key aspect to obtain the highest rates of energy efficiency and environmental sustainability. In particular, comparing the ventilated façade with R-PET (wall 4) to standard wall compositions (wall 1 and 2), the impact reduction varied between 13% and 45% in terms of damage categories, and between 13% and 25% in terms of impact categories. Moreover, from comparison of the two ventilated façades, it emerged that the environmental advantages related to the use of R-PET were up to 34% in terms of damage categories, and up to 12% in terms of impact categories.

Finally, the study highlighted that the usage of recycled materials and easy-disassembly compositions are cleaner construction solutions that can be considered as key design choices for environmental sustainable and low energy demanding buildings along their life cycles.

References

Asdrubali, F., D'Alessandro, F., Schiavoni, S., Baldinelli, G., 2011. Lightweight screeds made of concrete and recycled polymers: acoustic, thermal, mechanical and chemical characterisation. In: Proceedings of 6th Forum Acusticum, Aalborg, Denmark.

Asdrubali, F., Schiavoni, S., Horoshenkov, K.V., 2012. A review of sustainable materials for acoustic applications. J. Build. Acoust. 19, 283–312.

Asdrubali, F., Baldassari, C., Fthenakis, V., 2013. Life cycle analysis in the construction sector: guiding the optimization of conventional Italian buildings. Energy Build. 64, 73–89.

Asdrubali, F., D'Alessandro, F., Schiavoni, S., 2015. A review of unconventional sustainable building insulation materials. Sust. Mater. Technol. 4, 1–17.

Ayadi, A., Stiti, N., Boumchedda, K., Rennai, H., Lerari, Y., 2011. Elaboration and characterisation of porous granules based on waste glass. Powder Technol. 208, 423–426.

Baglivo, C., Congedo, P.M., Fazio, A., 2014. Multi-criteria optimization analysis of external walls according to ITACA protocol for zero energy buildings in the mediterranean climate. Build. Environ. 82, 467–480.

Batouli, S.M., Zhu, Y., Nar, M., D'Souza, N.A., 2014. Environmental performance of kenaf-fibre reinforced polyurethane: a life cycle assessment approach. J. Clean. Prod. 66, 164–173.

Bianchini, F., Hewage, K., 2012. How "green" are the green roofs? Life cycle analysis of green roof materials. Build. Environ. 48, 57–65.

Binici, H., Eken, M., Dolaz, M., Aksogan, O., Kara, M., 2014. An environmentally friendly thermal insulation material from sunflower stalk, textile waste and stubble fibres. Constr. Build. Mater 51, 24–33.

Biswas, W.K., 2014. Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia. Int. J. Sust. Built. Environ. 3, 179–186.

Breviglieri Pereira de Castro, E., Mequignon, M., Adolphe, L., Koptschitz, P., 2014. Impact of the lifespan of different external walls of buildings on GHG emissions under tropical climate conditions. Energy Build. 76, 228–237.

Briga-Sá, A., Nascimento, D., Teixeira, N., Pinto, J., Caldeira, F., Varum, H., Paiva, A., 2013. Textile waste as an alternative thermal insulation building material solution. Constr. Build. Mater 38, 155–160.

Cabeza, L.F., Castell, A., Medrano, M., Martorell, I., Pérez, G., Fernández, I., 2010. Experimental study on the performance of insulation materials in Mediterranean construction. Energy Build. 47, 630–636.

Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G., Castell, A., 2014. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review. Renew. Sust. Energy Rev. 29, 394–416.

Chwieduk, D.A., 2013. Dynamics of external wall structures with a PCM (phase change materials) in high latitude countries. Energy 59, 301–313.

Ciampi, M., Leccese, F., Tuoni, G., 2003. Ventilated façades energy performance in summer cooling of buildings. Sol. Energy 75, 491–502.

Compagno, L., Ingrao, C., Latora, A.G., Trapani, N., 2014. Life cycle assessment of CRT lead recovery process. Int. J. Lifecycle Product. Manage 7, 201–213.

D'Alessandro, F., Asdrubali, F., Baldinelli, G., 2014. Multi-parametric characterization of a sustainable lightweight concrete containing polymers derived from electric wires. Constr. Build. Mater 68, 277–284.

De Benedetto, L., Klemeš, J., 2009. The Environmental Performance Strategy Map: an integrated LCA approach to support the strategic decision-making process. J. Clean. Prod. 17, 900–906.

Devi, L.P., Palaniappan, S., 2014. A case study on life cycle energy use of residential building in Southern India. Energy Build. 80, 247–259.

Dixit, M.K., Fernández-Solís, J.L., Lavy, S., Culp, C.H., 2012. Need for an embodied energy measurement protocol for buildings: a review paper. Renew. Sust. Energy Rev. 16, 3730–3743.

DPR 412, 1993. Decreto del Presidente della Repubblica Italiana, 26 Agosto 1993, n. 412: 'Regolamento recante norme per la progettazione, l'installazione, l'esercizio e la manutenzione degli impianti termici degli edifici ai fini del contenimento dei consumi di energia' (Italian Republic President's Decree, 26th August 1993, n. 412: 'Regulation for the design, installation, operation and maintenance of heating systems in buildings to reduce energy consumption') (in Italian).

Dylewski, R., Adamczyk, J., 2011. Economic and environmental benefits of thermal insulation of building external walls. Build. Environ. 46, 2615–2623.

Ecoinvent, 2010. The Swiss Centre for Life Cycle Inventories. Ecoinvent v2.2.

Ente nazionale italiano di unificazione (UNI), 1994. Riscaldamento e raffrescamento degli edifici – Dati climatici, UNI 10349 (Heating and cooling of buildings – Climatic data, UNI 10349). Italian Organisation for Standardisation (in Italian).
European Commission, 2013. EU Energy, Transport and GHG Emissions, Trends to 2050. Reference Scenario.
Feng, H., Hewage, K., 2014. Life cycle assessment of living walls: air purification and energy performance. J. Clean. Prod. 69, 91–99.
Frischknecht, R., Rebitzer, G., 2005. The ecoinvent database system: a comprehensive web-based LCA database. J. Clean. Prod. 13, 1337–1343.
Han, B., Wang, R., Yao, L., Liu, H., Wang, Z., 2015. Life cycle assessment of ceramic façade material and its comparative analysis with three other common façade materials. J. Clean. Prod. 99, 86–93.
Ingrao, C., Lo Giudice, A., Mbohwa, C., Clasadonte, M.T., 2014a. Life cycle Inventory of a precast reinforced concrete shed for goods storage. J. Clean. Prod. 79, 152–167.
Ingrao, C., Lo Giudice, A., Tricase, C., Rana, R., Mbohwa, C., Siracusa, V., 2014b. Recycled-PET fibre based panels for building thermal insulation: environmental impact and improvement potential assessment for a greener production. Sci. Total Environ. 493, 914–929.
Ingrao, C., Matarazzo, A., Tricase, C., Clasadonte, M.T., Huisingh, D., 2015a. Life cycle Assessment for highlighting environmental hotspots in Sicilian peach production systems. J. Clean. Prod. 92, 109–120.
Ingrao, C., Lo Giudice, A., Bacenetti, J., Tricase, C., Dotelli, G., Fiala, M., Siracusa, V., Mbohwa, C., 2015b. Energy and environmental assessment of industrial hemp for building applications: a review. Renew. Sust. Energy Rev. 51, 29–42.
Intini, F., Kühtz, S., 2011. Recycling in buildings: an LCA case study of a thermal insulation panel made of polyester fiber, recycled from post-consumer PET bottles. Int. J. Life Cycle Assess. 16, 306–315.
International Organization for Standardization (ISO), 1994. Thermal insulation: Determination of Steady-state Thermal Transmission Properties: Calibrated and Guarded Hot Box. ISO 8990.
International Organization for Standardization (ISO), 2006a. Environmental Management – Life Cycle Assessment – Principles and Framework. ISO 14040.
International Organization for Standardization (ISO), 2006b. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. ISO 14044.
International Organization for Standardization (ISO), 2007. Building Components and Building Elements: Thermal Resistance and Thermal Transmittance: Calculation Method. ISO 6946.
Iucolano, F., Liguori, B., Caputo, D., Colangelo, F., Cioffi, R., 2013. Recycled plastic aggregate in mortars composition: effect on physical and mechanical properties. Mater. Des. 52, 916–922.
Jeswani, H.K., Azapagic, A., Schepelmann, P., Ritthoff, M., 2010. Options for broadening and deepening the LCA approaches. J. Clean. Prod. 12, 120–127.
Joillet, O., Manuele, M., Raphael, C., Sébastian, H., Jérome, P., Gerald, R., Rosenbaum, R., 2003. IMPACT 2002+: a new life cycle impact assessment methodology. Int. J. Life Cycle Assess. 8, 324–330.
Kaynakli, O., 2012. A review of the economical and optimum thermal insulation thickness for building applications. Renew. Sust. Energy Rev. 2012 (16), 415–425.
Khedari, J., Charoenvai, S., Hirunlabh, J., 2003. New insulating particleboards from durian and coconut coir. Build. Environ. 38, 435–441.
La Rosa, A.D., Recca, A., Gagliano, A., Summerscales, J., Latteri, A., Cozzo, G., Cicala, G., 2014. Environmental impacts and thermal innovation performance of innovative composite solutions for building applications. Constr. Build. Mater 55, 406–414.
Lertsutthiwong, P., Khunthon, S., Siralertmukul, K., Noomun, K., Chandrkrachang, S., 2008. New insulating particleboards prepared from mixture of solid wastes from tissue paper manufacturing and corn peel. Bioresour. Technol. 99, 4841–4845.
Malmqvist, T., Glaumann, M., Scarpellini, S., Zabalza, I., Aranda, A., Llera, E., Díaz, S., 2011. Life cycle assessment in buildings: the ENSLIC simplified method and guidelines. Energy 36, 1900–1907.
Melià, P., Ruggieri, G., Sabbadini, S., Dotelli, G., 2014. Environmental impacts of natural and conventional building materials: a case study on earth plasters. J. Clean. Prod. 80, 179–186.
Melo, M.O.B.C., Da Silva, L.B., Coutinho, A.S., Sousa, V., Perazzo, N., 2012. Energy efficiency in building installations using thermal insulating materials in northeast Brazil. Energy Build. 47, 35–43.
Mequignon, M., Adolphe, L., Thellier, F., Haddou, H.A., 2013. Impact of the lifespan of building external walls on greenhouse gas index. Build. Environ. 59, 654–661.
Paiva, A., Pereira, S., Sá, A., Cruz, D., Varum, H., Pinto, J., 2012. A contribution to the thermal insulation performance characterization of corn cob particleboards. Energy Build. 45, 274–279.
Patnaik, A., Mvubu, M., Muniyasamy, S., Botha, A., Anandjiwala, R.D., 2015. Thermal and sound insulation materials from waste wool and recycled polyester fibres and their biodegradation studies. Energy Build. 92, 161–169.
Pinto, J., Paiva, A., Varum, H., Costa, A., Cruz, D., Pereira, S., Fernandes, L., Tavares, P., Agarwal, J., 2011. Corn's cob as a potential ecological thermal insulation material. Energy Build. 43, 1985–1990.
Pizzetti, C., 1986. Condizionamento dell'aria e refrigerazione. Teoria e calcolo degli impianti. Editore CEA, ISBN 9788808083838.
Pulselli, R.M., Simoncini, E., Marchettini, N., 2009. Energy and energy based cost-benefit evaluation of building envelopes relative to geographical location and climate. Build. Environ. 44, 920–928.
Rauf, A., Crawford, R.H., 2015. Building service life and its effect on the life cycle embodied energy of buildings. Energy 79, 140–148.
Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.P., Suh, S., Weidema, B.P., Pennington, D.W., 2004. Life cycle assessment: Part 1: framework, goal and scope definition, inventory analysis, and applications. Environ. Int. 30, 701–720.
Rincón, L., Coma, J., Pérez, G., Castell, A., Boer, D., Cabeza, L.F., 2014. Environmental performance of recycled rubber as drainage layer in extensive green roofs. A comparative Life cycle Assessment. Build. Environ. 74, 22–30.
Rossi, B., Marique, A.F., Glaumann, M., Reiter, S., 2012. Life cycle assessment of residential buildings in three different European locations, basic tool. Build. Environ. 51, 4012–4407.
Sartori, I., Hestnes, A.G., 2007. Energy use in the life cycle of conventional and low-energy buildings: a review article. Energy Build. 39, 249–257.
Sherely, A.P., Boudenne, A., Ibos, L., Candau, Y., Kuruvilla, J., Sabu, T., 2008. Effect of fibre loading and chemical treatments on thermophysical properties of banana fibre/polypropylene commingled composite materials. Compos. Part A-Appl. S 39, 1582–1588.
SimaPro, 2006. LCA Software and Database Manual. Prè Consultants BV, Amersfoort, The Netherlands.
Siracusa, V., Ingrao, C., Lo Giudice, A., Mbohwa, C., Dalla Rosa, M., 2014. Environmental assessment of a multiplayer polymer bag for food packaging and preservation: an LCA approach. Food Res. Int. 62, 151–161.
Stewart, J.P., 1948. Solar heat gain through walls and roofs for cooling load calculations. ASHVE Trans. 54, 361–389.
Suh, S., Huppes, G., 2005. Methods for life cycle inventory of a product. J. Clean. Prod. 13, 687–697.
Sutcu, M., Akkurt, S., 2009. The use of recycled paper processing residues in makinorous brick with reduced thermal conductivity. Ceram. Int. 35, 2625–2631.
Tingley, D., Hathway, A., Davison, B., 2015. An environmental impact comparison of external wall insulation types. Build. Environ. 85, 182–189.
Utama, A., Gheewala, S.H., 2008. Life cycle energy of single landed houses in Indonesia. Energy Build. 40, 1911–1916.
Utama, A., Gheewala, S.H., 2009. Indonesian residential high rise buildings: a life cycle energy assessment. Energy Build. 41, 1263–1268.
Valverde, I.C., Castilla, L.H., Nuñez, D.F., Rodriguez-Senín, E., De la Mano Ferreira, R., 2013. Development of new insulation panels based on textile recycled fibres. Waste Biomass Valor 4, 139–146.
Van de Lindt, J.W., Carraro, J.A.H., Heyliger, P.R., Choi, C., 2008. Application and feasibility of coal fly ash and scrap tire fibre as wood wall insulation supplements in residential buildings. Resour. Conserv. Recycl. 52, 1235–1240.
Zabalza Bribián, I., Capilla, A.V., Aranda Usón, A., 2011. Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build. Environ. 46, 1133–1140.
Zhang, Y., Luo, X., Buis, J.J., Sutherland, J.W., 2015. LCA-oriented semantic representation for the product life cycle. J. Clean. Prod. 86, 146–162.
Zuo, J., Zhao, Z.Y., 2014. Green building research-current status and future agenda: a review. Renew. Sust. Energy Rev. 30, 271–281.