Building and Environment 95 (2016) 145–159

Contents lists available at ScienceDirect

Building and Environment

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

Experimental and numerical characterization of innovative cardboard based panels: Thermal and acoustic performance analysis and life cycle assessment

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ARTICLE INFO

Article history:
Received 7 July 2015
Received in revised form
26 August 2015
Accepted 5 September 2015
Available online 5 September 2015

Keywords:
Cardboard panels
Thermal insulation panels
Recycled materials
Innovative panels
Corrugated cardboard
Sound insulation
Life cycle assessment

ABSTRACT

Efficient thermal insulating materials can significantly reduce energy consumption for both heating and cooling of buildings. When selecting an insulation material, however, it is important to consider other important aspects, such as acoustic performance, environmental impacts, effects on human health and costs of production. That is the reason why key research developments are recently achieved in the field of sustainable, highly efficient materials. Within this context, this paper deals with the thermal and acoustic performance and the environmental impact analysis of two kinds of corrugated multi-layer cardboard panels, usually applied in the packaging industry. Thermal analyses were conducted in order to measure the thermal conductivity by means of both an experimental campaign and numerical methods. The acoustic absorption coefficient and the transmission loss were experimentally determined by means of an impedance tube. Finally a Life Cycle Assessment of the considered panels was implemented and compared to the performance of other commonly used insulation materials. The main results of the study show that the cardboard-made panels usually applied for low-cost packaging present promising performance in terms of both acoustic and thermal insulation potential, i.e. of the same order of magnitude than high-performance commercialized products. The environmental impact evaluation also reveals an interesting behavior of the corrugated cardboard panels, which can by any means be considered as a promising recycled insulation material.

1. Introduction

In Europe 25% of the industrial production is due to the construction sector which accounts for 42% of the overall energy used in the continent and about 30% of carbon dioxide emissions [1]. For this reason the European Directive 2010/31/EU [2] requests to reach nearly zero energy buildings by the year 2020, thus recognizing that green building strategies can be extremely efficient in fossil fuel savings and greenhouse gas reduction. Thermal insulation is acknowledged as one of the most effective way to ensure energy savings [3,4], nevertheless a competitive insulation material should not only fulfill good thermal performances, but also present good acoustic characteristics in terms of sound insulation and a low environmental impact and production cost [5–9]. In this context, the increasing attention that recently has been focused on sustainable and natural materials is easily understandable [10,11]. Researches that enhance recyclability and develop eco-friendly materials as alternatives to many currently used ones are very up-to-date [12], especially in order to minimize the use of non-sustainable or harmful materials, *e.g.* mineral wools, which have good performances and low cost but whose fibers can cause irritation [13], or expanded products, such as EPS, which are derived from petrol and present a high amount of embodied energy [14].

In this panorama, natural fibers have gained increasing attention because of their internal structure, which can generally

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http://dx.doi.org/10.1016/j.buildenv.2015.09.003
0360-1323/

guarantee high porosity. Among these fibers, cellulose is the most representative biopolymer and it is widely used for producing paper and cardboard. Therefore, different insulation materials with cellulose as the main raw material have been recently developed [15]. Acoustic performance was investigated in natural fibers panels by Berardi et al. [16]. An insulation material made from waste newspapers and magazines with heat insulation and sound absorbing properties was also developed by Yeon et al. [17]. Physical and mechanical properties of cardboard panels made from used beverage carton with veneer overlay were examined by Ayrilmis et al. [18]. The simultaneous heat and mass transport in paper sheets during moisture sorption from humid air was evaluated by Foss et al. [19]. Furthermore, the International Organization for Standardization (ISO) has also published different standards to be applied as reference models for the numerical validation of experimentally obtained data, like the ISO 10077-2 standard [20], which can be used for the calculation of windows, doors and shutters thermal transmittance. Additionally, in recent years, numerical simulations have also been flanked to standard-based analytical evaluations to verify experimental results or, if developed before the experimental procedure, select specific experiments to be run, thus leading to huge time and money savings.

For example a simulation methodology was developed by Arambakam et al. [21] to study the role of microscale geometry of a fibrous material on its performance as an insulation medium and a one dimensional transient model for coupled heat and mass transfer (HAM) in porous materials was developed by Steeman et al. [22].

When considering the environmental problem related to the production of a building or of building materials, on the other hand, the most acknowledged method to be used is the Life Cycle Assessment (LCA), regulated by ISO 14040 [23], which considers the principles and framework for an LCA, and ISO 14044 [24], which specifies the requirements and guidelines for carrying out an LCA study. This methodology was applied by Ardente et al. to the case study of kenaf-fibers insulation board [25] and by Asdrubali et al. for the environmental impact evaluation of buildings [14].

Within this context, the main purpose of this work is to investigate the thermal and acoustic properties and the environmental impact of corrugated cardboard panels, made of waste paper, usually applied in the packaging industry, and completely recyclable in their turn. Because they are made of very widespread and common wastes, these panels are very cost effective with respect to typical insulation panels and the absence of any raw material in the panel development also suggests promising performance in terms of life cycle environmental impact. Furthermore, the characteristic internal geometry of the panels can guarantee a very low density with respect to packed cardboard panels, and a reliable resistance to be compact and self-supporting. Nevertheless, the presence of still air inside the flutes and the stiffness guaranteed by the internal structure allow to reach promising air cavity structure, improving thermal and acoustic performance.

2. Materials and methods

2.1. Description of the cardboard panels

The investigated panels were prepared by overlapping a variable number of single (double-faced) boards, consisting of two facings (liners), adhered to one inner fluted medium which can have different standardized heights. Two types of flutes (C-flute and E-flute), respectively 4.1 and 1.9 mm thick, were considered (Fig. 1). Table 1 reports all the analyzed samples and while Fig. 2 shows all the tested configurations. The unique geometry of the cardboard allowed to investigate the behavior of different samples prepared by changing the total thickness of the panel, the relative orientation of the single boards, and the thickness of the flute.

The different analyses carried out on the considered corrugated cardboard samples are resumed in Fig. 3.

2.2. Methods for assessing thermal properties

The thermal characterization of the samples was carried out by means of the guarded hot plate apparatus (Fig. 4), by defining their thermal conductivity (λ) in monodimensional heat flux conditions, thus considering the simplified version of the Fourier's law (2):

$$\phi = (\lambda/d)A\Delta T \quad (1)$$

where ϕ is the heat quantity transferred through the total area of the sample A, d is the total thickness of the material and ΔT is the temperature difference in the specific direction considered. The thermal conductivity is thus determined from the heat flow rate at steady state conditions and the temperature difference between the hot and cold surfaces of the samples, according to the ISO 8302 [26], EN 12664 [27] and EN 12667 [28] standards.

Additionally a numerical validation of the obtained values was reached both applying weighted average of the air and cardboard thermal conductivities, with respect to their superficial area in an orthogonal section of the panel, and defining a computational model by means of a Finite Element Method software.

2.3. Methods for assessing acoustic properties

For the acoustic characterization of the samples, both sound absorption and sound insulation properties were investigated in an impedance tube (Fig. 5), measuring the normal incidence absorption coefficient (α) and the Transmission Loss (TL) of the panels.

The first parameter indicates the part of acoustical energy of the incident wave that is not absorbed by the tested sample and it is experimentally determined, according to the ISO 10534-2 standard [29], by measuring the sound pressures in two fixed positions. Then the transfer function between them is defined, allowing to obtain the reflection coefficient of the sample and its absorption coefficient [30]. Transmission Loss on the other hand, is a key factor for the quantification of the insulation properties of acoustic materials. It is related to the sound transmission coefficient (τ) by the law presented in Equation (2):

$$TL = 10 \cdot \log(1/\tau) \quad (2)$$

It is measured by means of the 'two-load' transfer function method [31,32], acquiring the sound pressure in four fixed microphone positions and repeating the measurements with two configurations of the termination, anechoic and rigid.

3. Acoustic and thermal analysis

3.1. Experimental campaign for acoustic characterization

The acoustic characterization in terms of absorption coefficient and Transmission Loss was carried out with an impedance tube (Brüel & Kjær, model 4260), using a two (α) and a four microphones method (TL) respectively. For the absorption coefficient measurements several steps were performed. First of all, the environmental parameters of the room i.e. atmospheric pressure, air temperature, and relative humidity, were defined. Microphones calibration was accomplished. Then, after the sample positioning, the evaluation of the signal-to-noise ratio was made and finally the transfer function calibration for the channels phase displacements was evaluated.

Fig. 1. Images of the considered samples: (a) E-flute; (b) C-flute; (c, d, e, f) parallel, orthogonal 1 × 1 and 2 × 2, and sandwich (4E-10C-4E) samples.

Table 1
Considered samples and carried out measurements.

Type of layer	Number of layers	Average thickness (mm)	Orientation	Thermal analysis	Acoustic analysis (α)	Acoustic analysis (TL)
C-flute	8	33	Parallel	×		×
			Orthogonal (1 × 1)			×
			Orthogonal (2 × 2)			×
	12	50	Parallel	×		×
			Orthogonal (1 × 1)	×		×
			Orthogonal (2 × 2)			×
	16	67	Parallel			×
			Orthogonal (1 × 1)			×
			Orthogonal (2 × 2)			×
	18	75	Parallel	×	×	
			Orthogonal (1 × 1)		×	
			Orthogonal (2 × 2)		×	
	22	95	Parallel		×	
			Orthogonal (1 × 1)		×	
			Orthogonal (2 × 2)		×	
	26	112	Parallel		×	
			Orthogonal (1 × 1)		×	
			Orthogonal (2 × 2)		×	
E-flute	16	39	Parallel	×		×
			Orthogonal (1 × 1)			×
			Orthogonal (2 × 2)			×
	26	51	Parallel	×		×
			Orthogonal (1 × 1)	×		×
			Orthogonal (2 × 2)			×
	32	64	Parallel			×
			Orthogonal (1 × 1)			×
			Orthogonal (2 × 2)			×
	40	76	Parallel	×	×	
			Orthogonal (1 × 1)		×	
			Orthogonal (2 × 2)		×	
	46	87	Parallel		×	
			Orthogonal (1 × 1)		×	
			Orthogonal (2 × 2)		×	
	52	99	Parallel		×	
			Orthogonal (1 × 1)		×	
			Orthogonal (2 × 2)		×	
Sandwich	10 internal C-flutes	51	2E-10C-2E		×	×
		60	4E-10C-4E	×	×	×
		68	6E-10C-6E		×	×
	10 external C-flutes	51	5C-4E-5C		×	×
		60	5C-8E-5C	×	×	×
		68	5C-12E-5C		×	×

Fig. 2. Examples of layers orientation in the considered samples.

The measurements of the Transmission Loss were carried out with the two-load method, which consisted of these main steps: first of all, as for the absorption measurement the environmental settings were defined and the microphones were calibrated. Then the background noise calibration measurement was performed with an anechoic and a rigid termination of the tube. Finally, after the

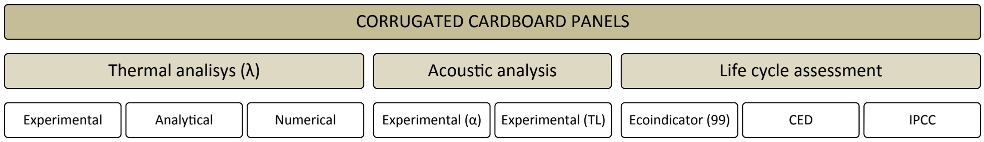

Fig. 3. Schematic of the different analyses carried out on the considered C and E-flute samples.

Fig. 4. Guarded hot plate apparatus.

insertion of the sample, signal measurements were done with again the anechoic and the empty end of the tube as before. All the measures to determine the absorption coefficient and the Transmission Loss were carried out using the large tube (sample diameter 100 mm) in order to cover the range of frequencies between 50 and 1600 Hz for all the considered samples.

3.2. Experimental campaign for thermal characterization

The thermal characterization was carried out by means of a guarded hot plate facility which required a single sample in the form of a square slab with size 500 × 500 mm. The apparatus was constituted by:

1. A main heater split into a square element of 250 × 250 mm (the central heater), supplied with an assigned power rate, and a frame element with a total thickness of 125 mm (the guard heater), kept at the same temperature of the previous one by a closed-loop control system, and both realized in aluminum with a thickness of 30 mm and internally heated by heating cartridges fed with direct current;
2. A second guarded hot plate placed beneath the main heater and sandwiched between two panels of an insulator 40 mm thick (of 500 × 500 mm plan dimension), also kept at the same temperature of the main heater as to prevent a downward heat flux;
3. A cooling system (cold plate) (500 × 500 mm), constituted by a stainless steel container with an internal spiral circuit in which a liquid refrigerator (water) can flow;
4. A chiller to chill the liquid;
5. An acquisition and control system and a software developed in a LabView environment for both temperature regulation and data acquisition.

The temperature monitoring was carried out by means of 26 screened J-type thermocouples placed inside the apparatus, which can be divided in two kinds of sensors: 16 thermocouples were addressed in monitoring the thermal balance between the measure zone and the guard zone, while 10 thermocouples were used to detect the average temperatures on the cold and hot sides of the sample. During the measurements a fixed heat rate was delivered by the electric heater at the bottom of the apparatus, producing a heat flow through the sample towards the upper plate chilled by the liquid cooling system. Once the steady state conditions were reached, the power supplied to the measure zone and the average temperature gradient between the two sides of the sample were acquired respectively every 0.1 s and 5 s.

Thermal analyses were all conducted at a temperature around 23 °C. The experimental campaign was developed in two different phases. First of all, the samples were investigated without altering the environmental conditions, thus at a relative humidity (RH) equal to 30%. Then, the most representative samples were selected and further investigated after conditioning their relative humidity to 0% in a climatic chamber. The samples considered, chosen as to be representative of the different configurations tested and to guarantee the optimum sample thickness for the guarded hot plate facility to work correctly, were:

1. 12Cp, constituted by 12 parallel C-flutes;
2. 27Ep, constituted by 27 parallel E-flutes;
3. 4E-10C-4E, sandwich prepared with 4 external E-flute layers per side, and 10 internal C-flute layers;
4. 5C-8E-5C, sandwich prepared with 5 external C-flute layers per side, and 8 internal E-flute layers.

3.3. Thermal behavior of cardboard panels: analytical evaluation

The samples analyzed in this work can be considered as composite materials. They all present, in fact, cardboard layers and air cavities which are the inner parts of the insulation panel. For this

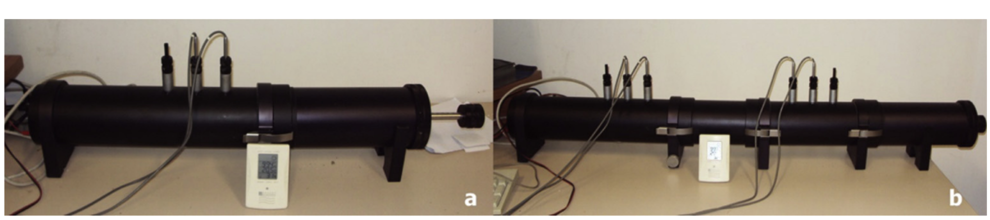

Fig. 5. Impedance tube configuration for the absorption coefficient (a) and the transmission loss (b) measurement.

reason, a weighted average of the two materials thermal conductivities, with respect to their superficial area in an orthogonal section of the panel, was considered. The nominal value for the cardboard thermal conductivity ranges in literature between 0.14 and 0.23 W/mK. For this reason three different values of this property were considered in the numerical method: 0.14, 0.19 and 0.23 W/mK. The value of equivalent thermal conductivity of the air cavities, on the other hand, was defined according to the ISO 10077-2 standard [20].

3.4. Thermal behavior of cardboard panels: numerical analysis

Numerical finite element method within COMSOL Multiphysics environment was used to (i) create two and three-dimensional models, (ii) simulate a gradient of temperature applied to these models, and (iii) analyze the associated heat transfer in steady-state conditions. Because of the symmetry of the samples and of the specific kind of heat flux considered, which was mono-dimensional, only two flutes wave lengths were considered for the 2-D models. For these models, a parallel disposition of the different panels was exclusively considered. Simulations were carried out considering alternatively:

1. 2 C-flute layers;
2. 2 E-flute layers;
3. 8 C-flutes and 16 E-flutes, for a total thickness of the 2-D model of about 30 mm;
4. 12 C-flutes and 26 E-flutes, for a total thickness of the 2-D model of about 50 mm;
5. 18 C-flutes and 40 E-flutes for a total thickness of the 2-D model of about 75 mm;
6. 4E-10C-4E and 5C-8E-5C sandwich configurations for a total thickness of the 2-D model of about 56 mm.

Three-dimensional models were considered in order to investigate the change in the thermal conductivity of the panels with respect to the reciprocal orientation of the single layers. For this reason two 3-D models were drawn for both the E and the C-flutes, by considering 2 overlapped layers. In order to reduce the computational time, only half wave length was drawn in the 3-D models and all the air layers were treated as solid domains, using the equivalent thermal conductivity defined following the ISO 10077-2 standard [20]. The considered 2-D and 3-D models were discretized by means of a free triangular and a free tetrahedral mesh, respectively, taking care to make it more refined and thicker on the cardboard layers, and on the bordering portion of the air domains. An example of a two and a three-dimensional mesh setting can be seen in Fig. 6.

For all the considered models, at the bottom cardboard layer, a temperature of 10 °C was applied, while a temperature of 30 °C was associated to the upper cardboard layer. Furthermore, adiabatic conditions were associated to all the lateral boundaries of the geometry, in order to prevent an external heat flux in those directions. An iterative procedure was applied in order to define the more accurate air equivalent thermal conductivity for every cardboard layer of each model.

4. Life cycle assessment of the cardboard panels

4.1. Goal and scope definition

According to the international standards of the ISO 14040 series, the Life Cycle Assessment (LCA) of the corrugated cardboard panels was carried out [23,24]. The primary objective of this LCA study was to determine and evaluate the environmental impacts associated to these panels, when their application field is set to thermal and acoustic insulation. The secondary objective of the LCA study was to compare these innovative panels in terms of energy consumption and potential environmental impacts, with conventional insulation materials.

Considering the innovativeness of this application, a cradle-to-gate LCA approach was proposed, since no actual data would have been available about their direct use in a real building.

The following life-cycle steps were analyzed:

1. Base paper production;
2. Manufacturing of the corrugated cardboard;
3. Transports along all phases.

According to ISO 14040 standard, a specific functional unit (f.u.) has to be defined. It is the reference unit through which a system performance is quantified in a LCA. The functional unit (f.u.) of the present LCA study has been defined, according to a proposal of the Council for European Producers of Materials for Construction [7,33] as the mass in kg of insulating panel that involves a thermal resistance R equal to 1 m^2 K/W:

$$f.u. = R \cdot \lambda \cdot \rho \cdot A (\text{kg}) \tag{3}$$

where R is the thermal resistance equal to 1 m^2 K/W; λ is the thermal conductivity of the panel in W/mK; ρ is the density of the panel in kg/m^3; A is the area equal to 1 m^2. This functional unit gives information about the amount of insulation material required to obtain a specific thermal resistance during the insulation lifetime of the panel. It is particularly appropriate since the environmental impacts associated to the panels have been investigated with regard to a reference insulation capacity.

In this work, the acoustic properties of the corrugated cardboard panels were investigated as well. Nevertheless, no specific functional unit has been introduced until now in this field. For this reason, it seemed appropriate to consider the f.u. introduced for thermal insulation materials. Both the C-flute and the E-flute panels with a parallel orientation of the layers were considered for LCA analysis. The thermal conductivity of the C-flute panels measured during the tests was 0.053 W/m K, while the density ρ was about 132 kg/m^3. Therefore the f.u. for the C-flute insulation panel is 7.0 kg. Considering the E-flute panels, the thermal conductivity measured during the tests was 0.058 W/m K, while the density ρ was about 276 kg/m^3. Therefore the f.u. for the E-flute insulation panel is 16 kg.

Six traditional insulation materials were also considered in this study, for comparative purpose. The functional unit associated to these materials was defined by means of literature densities and thermal conductivities. The obtained results are resumed in Table 2.

This work gives the inputs and outputs from the paper mill and the corrugated board plant separately, since in the considered production chain, they actually are two distinct factories. In order to make a complete LCA study supplementary data are also needed, such as environmental impacts of pre-combustion, electricity consumption and production for the public grid, and waste treatment. In this context, a specific flowchart of the cradle-to-gate LCA for the corrugated cardboard panels has been defined (Fig. 7). In the flowchart six arrows are marked with the letter T and a number from 1 to 6 and represent a specific transport phase.

4.2. Preliminary assumptions and limitations

It is important to further point out one specific assumption regarding the LCA study carried out in this work: because of a lack of information, the use phase (application of the panel in the

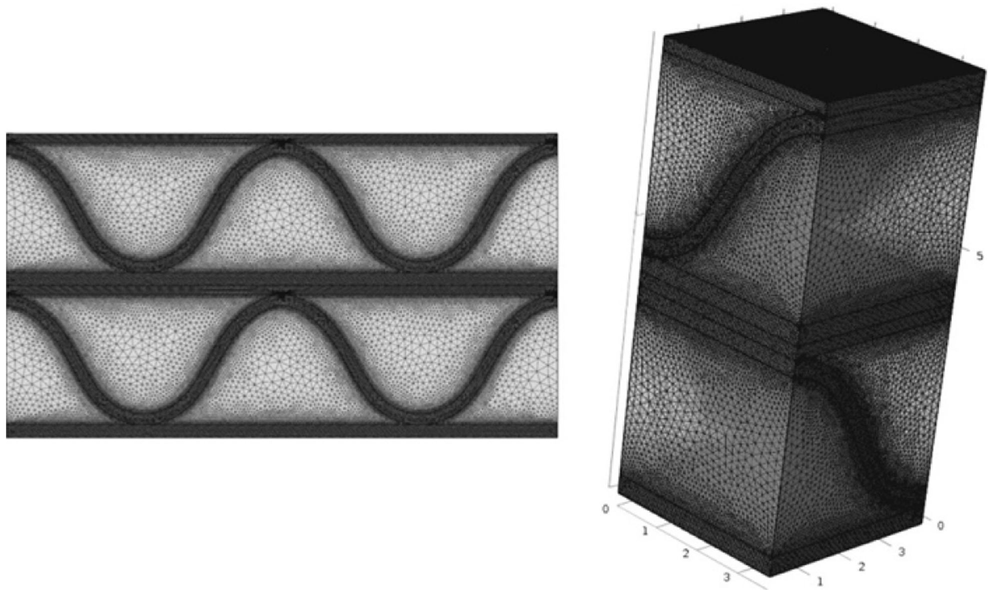

Fig. 6. (Left) Example of a two-dimensional mesh (2 C-flute parallel layers). (Right) Example of a three-dimensional mesh (2 C-flute orthogonal layers).

Table 2
Functional unit (f.u.) of the different materials considered.

Material	λ (W/mK)	ρ (kg/m^3)	F.u. (kg)
C-flute	0.053	132	7.0
E-flute	0.058	276	16.
Glass wool	0.038	58	2.2
Rock wool	0.039	105	4.1
Expanded polystyrene (EPS)	0.032	50	1.6
Extruded polystyrene (XPS)	0.035	34	1.2
Cellulose	0.040	120	4.8
Cork slab	0.046	105	4.8

building envelope) is not included in the system boundaries. The related environmental impacts have hence been neglected, considering a cradle to gate approach. Some further assumptions for the LCA study are the following:

1. The data used for the inventory phase, due to confidential reasons, were not based on questionnaires answered by the manufacturer of the cardboard panels but were taken from databases available in SimaPro 7.3.3. Since these databases were implemented considering a large number of European corrugated cardboard plants, they can be taken as an acceptable reference value for this study.
2. The study is limited to the system boundaries defined above.
3. The environmental impact assessment is limited to the environmental impact categories associated to three life cycle impact assessment methods: the Eco-Indicator 99 method, the Cumulative Energy Demand method (CED) and the Intergovernmental Panel on Climate Change method (IPCC) [34].
4. The LCAs carried out for some traditional insulation materials for comparison purposes were implemented considering average values of thermal conductivity and density, available in literature.

4.3. Life cycle inventory analysis (LCI)

As previously said, two kinds of corrugated cardboard panels were investigated: the E-flute and the C-flute panels. Three different types of cardboard typologies, for both the investigated panels, were considered:

1. One panel constituted by kraftliner and semichemical fluting base paper (high percentage of virgin fibers);
2. One panel constituted by kraftliner, medium fluting (wellenstof) and testliner base paper (medium percentage of virgin fibers);
3. One panel constituted by testliner and medium fluting (wellenstof) base paper (low percentage of virgin fibers).

The inventory phase was carried out by means of the SimaPro software, version 7.3.3. and its internal databases. In this work, the Ecoinvent database version 2.2 was used. As it has been said, three different models were considered for every flute-type panel (E and C-flute). Each of these models was implemented by adapting three processes taken from the Ecoinvent database for paper and board [35], included within the software itself:

1. Corrugated cardboard, fresh fiber, single wall, at plant/RER U;
2. Corrugated cardboard, mixed fiber, single wall, at plant/RER U;
3. Corrugated cardboard, recycling fiber, single wall, at plant/RER U.

These modules include the production of corrugated board out of corrugated base papers. The following steps are clearly included: energy production, corrugated board production itself, waste water treatment. Furthermore, the base paper included in the process is associated to its own production process. It is noteworthy that the data considered in SimaPro databases, including the energy mix, are an estimation based on average data from European producers, collected from FEFCO (European Federation of Corrugated Board Manufacturers) [35]. They can thus be taken as acceptable reference values for the investigated panels, once they are adapted to the specific functional unit of the panel, i.e. f.u. = 7.0 kg and f.u. = 16 kg for the C-flute and the E-flute panels, respectively.

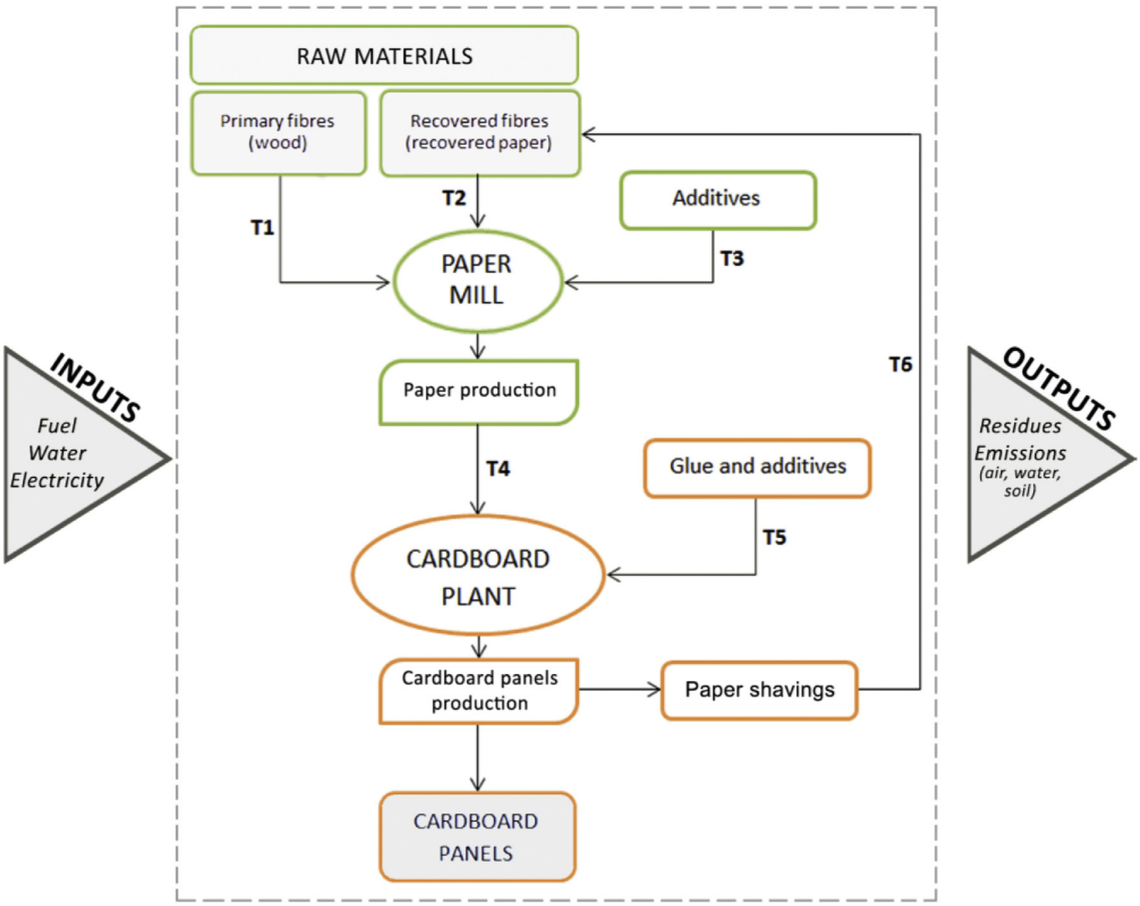

Fig. 7. Schematic life cycle (cradle-to-gate) of the cardboard panels.

5. Results

5.1. Acoustic analysis

As far as acoustic absorption, cardboard panels cannot be considered as porous materials. Unlike thermal insulators, porous absorbers require high values of open porosity, *i.e.* air moving inside open and interconnected pores. The highest the open porosity, the strongest the interactions between the solid frame and the interstitial fluid, leading to sound energy attenuation, due to friction and thermal loss at the boundary layer. In cardboard panels air is enclosed inside the flutes and the aforementioned phenomena are limited.

Cardboard panels could be better treated like membrane absorbers, *i.e.* sheets of elastic, non-porous material secured to a frame at a certain distance from the wall, to form an air gap of variable thickness. The acoustic field vibrates the plate and the vibration energy is transferred to the air, which act as a spring in a mass-spring system.

Several equations try to correlate the acoustic properties of membrane absorbers with the mechanical properties of the plate, for instance Young's modulus or Poisson's ratio. Unfortunately all these formulations are inadequate since in real applications acoustic properties depend on the mechanical damping of the structure, which, in turn, depends on the way the panel is installed. Thus sound absorption coefficient of membrane absorbers evaluated with an impedance tube is deeply affected by boundary effects and cannot be considered fully representative of the real performance of the panel. Fig. 8 reports the sound absorption trends of several tested configurations of cardboard panels. As expected, all the tested samples do not show a particularly interesting sound absorption behavior. Anyhow it can be noticed that in every tested configuration, the absorption coefficient increases as the thickness of the panel increases. Furthermore, the C-flute samples always exhibit a higher absorption coefficient with respect to the E-flute ones.

Considering Transmission Loss (TL) measurements, as already stated for the acoustic absorption, boundary effects deeply affect these measurements leading to overestimated values of transmission loss (Fig. 9). An overestimation of sound attenuation evaluated by means of an impedance tube was also found in other papers [36]. Thus these results should not considered as absolute values to be compared with those obtained in diffuse field (using ISO 10140-2 standard [37]), but they provide useful information about comparative analysis between the different cardboard configurations.

As far as samples constituted by the only C-flutes, in all the investigated configurations (parallel, orthogonal 1 × 1, and orthogonal 2 × 2 orientation), it is possible to notice a general increasing value of TL as the thickness of the samples grows. Furthermore, the orientation itself clearly produces significant changes in its trend. In fact, in the parallel orientation samples a significantly better insulation behavior is detected in the range between 100 and 600 Hz (peak of 70 dB of TL at 400 Hz, for the maximum thickness analyzed of 66 mm). For higher frequencies the insulation behavior steadies at lower values. In both the orthogonal 1 × 1 and 2 × 2 configurations (having a consistent trend of TL), a significant improvement on the TL is reached in the

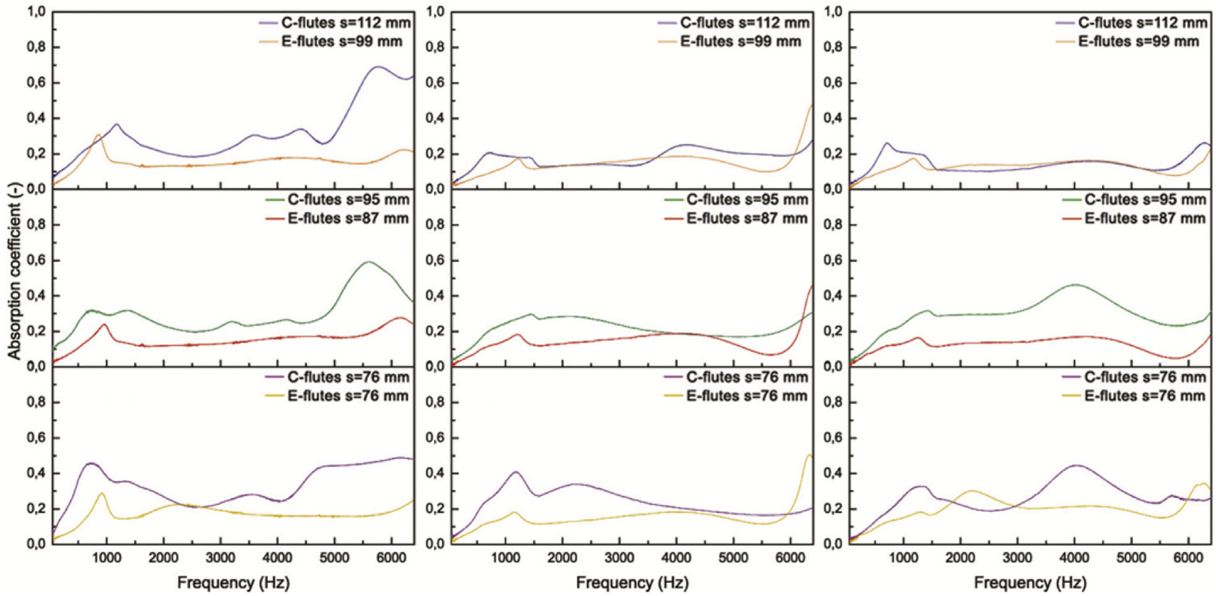

Fig. 8. Absorption coefficient of the three different configurations considered for the C-flute and E-flute samples with a variable total thickness.

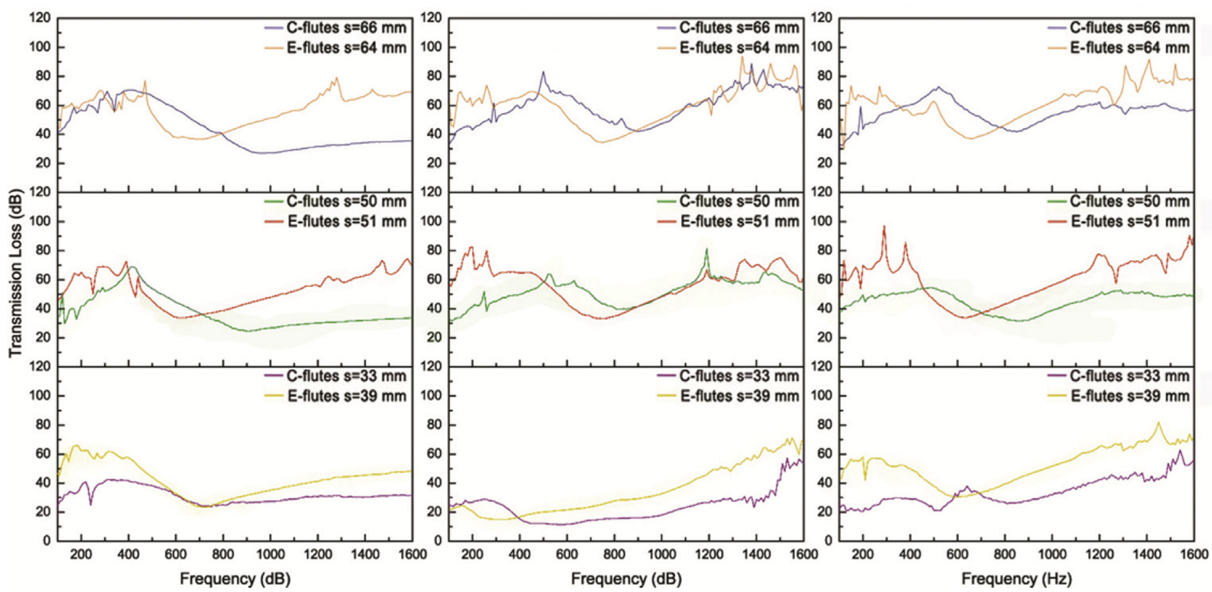

Fig. 9. Transmission loss of the three different configurations considered for the C-flute and E-flute samples with a variable total thickness.

range 800 ÷ 1600 Hz, and a peak of 80 dB is reached at 1400 Hz, for the thickness of 66 mm in the 1 × 1 configuration.

By comparing the same configuration of panels made by C or E-flute layers, in general, the E-flute panels present a better behavior at frequencies 900 ÷ 1600 Hz than the C-flute panels, especially in the parallel orientation samples, where they reach values of 60 dB against the about 30 dB of the C-flute. This effect can be explained by the higher area density of the E-flute panels that positively influences the transmission loss.

The sandwich configurations composed by considering an internal fixed layer of 10 C-flutes and two external fixed layers of 5 C-flutes, present a similar transmission loss trend for all the three investigated samples. At low frequencies the transmission loss presents a highly irregular trend, with sharp peaks and troughs ranging around a value of about 40 dB in the 4E-flute layers sample, and 60 dB in the 8E and 12E layers samples. Then, in the frequency range 700 ÷ 900 Hz, the minimum insulation power *i.e*. around 20, 30 and 35 dB in the 4E, 8E and 12E layers samples, respectively, is reached. At this point, the transmission loss starts to increase with a quasi-regular slope, which increases as the E-flutes layer number increases (Fig. 10).

5.2. Thermal characterization by means of experimental procedures

5.2.1. Relative humidity RH = 30%

The experimental results of the guarded hot plate apparatus analyses, carried out at a relative humidity of 30% are plotted in Fig. 11. C-flute parallel samples prepared considering 12 and 18 layers, present an identical value of thermal conductivity, i.e. 0.0530 W/mK. The sample prepared with 8 parallel C-flute layers,

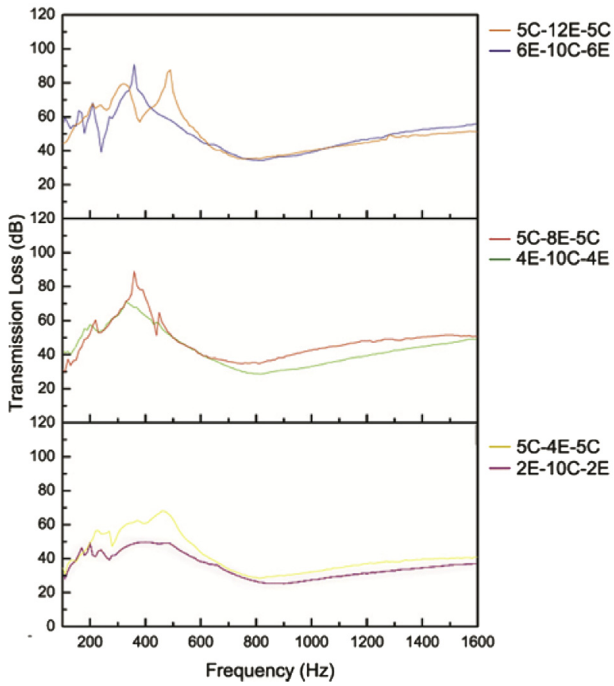

Fig. 10. Transmission loss of the six different sandwich configurations.

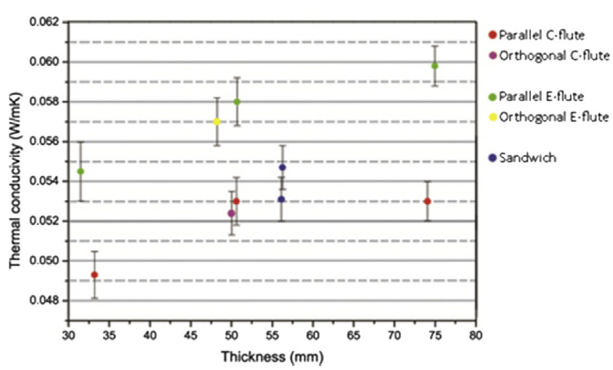

Fig. 11. Experimentally defined thermal conductivities (RH = 30%).

on the other hand, shows a lower λ value, *i.e.* 0.0493 ± 0.0012 W/mK. When considering the sample prepared with the orthogonal 1 × 1 orientation of 12 C-flute layers, a thermal conductivity of 0.0524 ± 0.0010 W/mK, thus lower than the previous ones, can be noticed. However this value is equal within the error to those of the samples constituted by 12 and 18 parallel C-flute layers. Four E-flute samples, three with a parallel orientation, and one with an orthogonal 1 × 1 orientation of the cardboard layers, have also been tested. In this case all of the three panels constituted by parallel layers (17, 27 and 40, with a total thickness of 31.5, 50.7 and 75.0 mm, respectively), show a different thermal conductivity, i.e. 0.0545 ± 0.0015, 0.0580 ± 0.0012, 0.0598 ± 0.0010 W/mK, respectively, but only the values of the two thicker ones are equal within the error. If the sample prepared with an orthogonal 1 × 1 orientation of 26 E-flute layers is considered, a thermal conductivity of 0.0570 ± 0.0012 W/mK, can be noticed. This value is, as on the case of the C-flute samples, lower than that of the parallel orientation E-flute panels. Furthermore, it is also equal within the error, to that of the sample prepared with 27 parallel E-flute layers.

Lastly, if the sandwich configurations are considered, it can be seen that the 4E-10C-4E sample shows the highest thermal conductivity, *i.e.* 0.0547 ± 0.0011 W/mK, versus the 0.0531 ± 0.0011 W/mK of the 5C-8E-5C sandwich configuration. Once again the thermal performance of the investigated samples results equal within the errors.

5.2.2. *Relative humidity RH = 0%*

The obtained experimental results, at a relative humidity of 0% are summarized in Table 3. All the considered samples present a lower thermal conductivity then those previously tested at a RH = 30%. The first sample, *i.e.* 12Cp, shows a λ value equal to 0.0490 ± 0.0011 W/mK. The main thermal conductivity is thus 0.0400 W/mK lower than that of the corresponding unconditioned sample. The same difference can be noticed between the thermal conductivity of the 26Ep sample, *i.e.* 0.0540 ± 0.0012, and its corresponding unconditioned one. When considering the two sandwich configurations, a different behavior can be noticed. The 4E-10C-4E sample, with a thermal conductivity of 0.0505 ± 0.0010 W/mK, shows even a higher difference in comparison with the corresponding unconditioned sample, *i.e.* 0.00420 W/mK, than the two single-flute specimens. The 5C-8E-5C sample, on the other hand, presents a λ value of 0.0508 ± 0.0011 W/mK, thus, only 0.0024 W/mK lower than the corresponding sample tested at a relative humidity of 30%.

5.3. *Thermal characterization by means of analytical procedures*

As it can be seen in Fig. 12, the analytical value of the investigated samples' thermal conductivity, defined as weighted average of the thermal conductivity of the cardboard and air cavities (by means of standard procedure), is highly influenced by the considered cardboard thermal conductivity (alternatively equal to 0.14, 0.19 and 0.23 W/mK). In fact, the C and E-flute samples and both the sandwich configurations present λ values that significantly grow from about 0.060 to 0.080, 0.090 to 0.140, and 0.065–0.090 W/mK, respectively.

It is noteworthy that considering the analytical procedure, which defines an overall thermal conductivity for each investigated sample by considering the number of each flute-layer composing every configuration and its associated theoretical thickness, it is not possible to discriminate between parallel and orthogonal configurations.

5.4. *Thermal analysis by means of numerical method*

As it has been said, the thermal conductivity of the samples was also evaluated by means of computer simulations and the obtained results are plotted in Fig. 13. Also in this case, a decrease of the overall thermal insulation power of the samples can be seen, with changing the thermal conductivity of the cardboard. The difference between the λ values, however, is way less important than in the previously described analytical results, varying from 0.0460 to 0.0525 W/mK for the C-flutes, from 0.0575 to 0.0710 W/mK for the E-flutes and from 0.0490 to 0.0560 W/mK for the sandwich configurations.

Finally, by means of 3D numerical simulations it is also possible to appreciate the slight difference between a parallel and an orthogonal configuration of the samples (Table 4). Simulations seem to suggest a better insulation performance of the parallel orientation samples, with respect to the orthogonal ones, for both C and E-flute panels (Fig. 14).

Table 3
Experimentally defined thermal conductivities (RH = 0%, s = thickness, w = weight).

Sample	s (mm)	w (kg)	λ (W/mK)	Percentage error (%)	Description
12Cp	49.720	1.555	0.0490 ± 0.0011	2.3	12 parallel C-flutes
26Ep	50.690	3.375	0.0540 ± 0.0012	2.2	26 parallel E-flutes
4E-10C-4E	56.260	2.295	0.0505 ± 0.0010	2.12	Sandwich
5C-8E-5C	56.050	2.295	0.0508 ± 0.0011	2.11	Sandwich

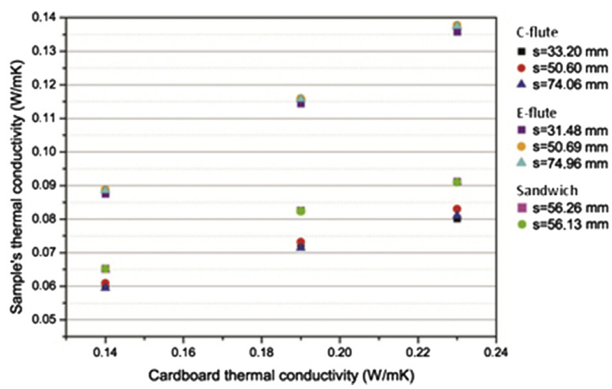

Fig. 12. Analytically defined thermal conductivities with varying the cardboard thermal conductivity: λ_{cb} = 0.14, 0.19, 0.23 W/mK (s = thickness).

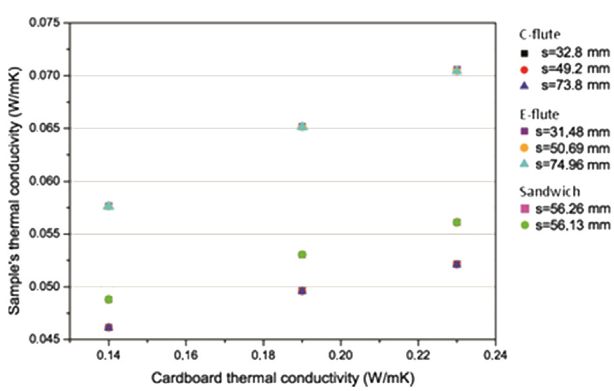

Fig. 13. Numerically defined thermal conductivities with varying the cardboard thermal conductivity: λ_{cb} = 0.14, 0.19, 0.23 W/mK (s = thickness).

Table 4
Numerically defined thermal conductivities (s = thickness, w = weight).

Sample	λ_{SIM} (W/mK)			Description
	λ_{cb} = 0.14	λ_{cb} = 0.19	λ_{cb} = 0.23	
2Cp	0.0464	0.0500	0.0527	2 parallel C-flutes
2Co	0.0465	0.0502	0.0530	2 orthogonal (1 × 1) C-flutes
8Cp	0.0462	0.0496	0.0522	8 parallel C-flutes
12Cp	0.0461	0.0496	0.0521	12 parallel C-flutes
18Cp	0.0461	0.0496	0.0521	18 parallel C-flutes
2Ep	0.0583	0.0662	0.0719	2 parallel E-flutes
2Eo	0.0584	0.0664	0.0722	2 orthogonal (1 × 1) E-flutes
16Ep	0.0577	0.0652	0.0705	16 parallel E-flutes
26Ep	0.0576	0.0651	0.0705	26 parallel E-flutes
40Ep	0.0576	0.0651	0.0705	40 parallel E-flutes
4E-10C-4E	0.0488	0.0530	0.0561	Sandwich
5C-8E-5C	0.0488	0.0531	0.0562	Sandwich

5.5. Life cycle impact assessment (LCIA)

5.5.1. Eco-indicator 99 (H)

Fig. 15 presents the results of the comparative LCA analysis of C–flute and E-flute cardboard panels together with some conventional thermal insulating materials. It can be seen that both C and E-flute panels present a general decrease of their overall impact, with the increasing percentage of recycled fibers. In fact, considering the E-flute panels, it can be seen that the fresh fiber configuration is associated to a total score of about 2447 mPt, the mixed fiber configuration to 1884 mPt and the recycled fiber configuration to 1585 mPt. If the C-flute panels are considered, the histogram shows for the fresh fiber configuration a total score of about 1069 mPt, for the mixed fiber configuration of 823 mPt and for the recycled fiber configuration of 693 mPt.

5.5.2. Cumulative energy demand (CED)

When the primary energy consumption is considered (Fig. 16) it can also be seen a decrease in the overall impact of both the investigated panels (C and E-flute), with increasing the recycled fibers percentage. In fact, the C-flute fresh fiber configuration is associated to an overall CED indicator of about 317.699 MJ, the mixed fiber configuration to 176.503 MJ and the recycled fiber one to 110.703 MJ. If the E-flute panels are considered, the histogram shows for the fresh fiber configuration an overall CED indicator of about 726.948 MJ, the E-flute mixed fiber panel to 403.868100 MJ and the E-flute recycled fiber panel to 253.306 MJ.

5.5.3. Intergovernmental panel on climate change (IPCC)

In this work the climate change factors of IPCC were investigated with respect to a time-frame of 100 years (GWP 100a method). The results in Fig. 17 do not show a significant difference between the three GWPs investigated for both the C and E-flute panels. As in previous methodologies, the highest impacts are mainly related to the base paper materials, which for both C and E-flute panels range between 85.38% (recycled fiber panel) and 84.64% (mixed fiber panel) of the overall impact associated to the specific case, corresponding to 5.884 and 5.549 kg_{CO2eq} for the C-flute, and to 13.463 and 12.698 kg_{CO2eq} for the E-flute panels, respectively.

6. Discussion of the results

6.1. Acoustic performances

Generally speaking, the investigated samples do not show a competitive behavior with respect to the commonly used absorbing materials, which, as shown in Table 5, can also reach an absorption coefficient of 1 for specific frequencies.

The explanation for their poor absorbing performance lies in their limited porosity. Good absorbers, in fact, have high open porosity, because a higher quantity of air molecules leads to a higher effect of friction and viscosity resistance. The corrugated cardboard panels, because of their manufacturing process, do not present interconnected voids. For this reason, even though a high percentage of air is included inside these panels (within the fluting medium and the liners), it is not easily reached by the sound, which

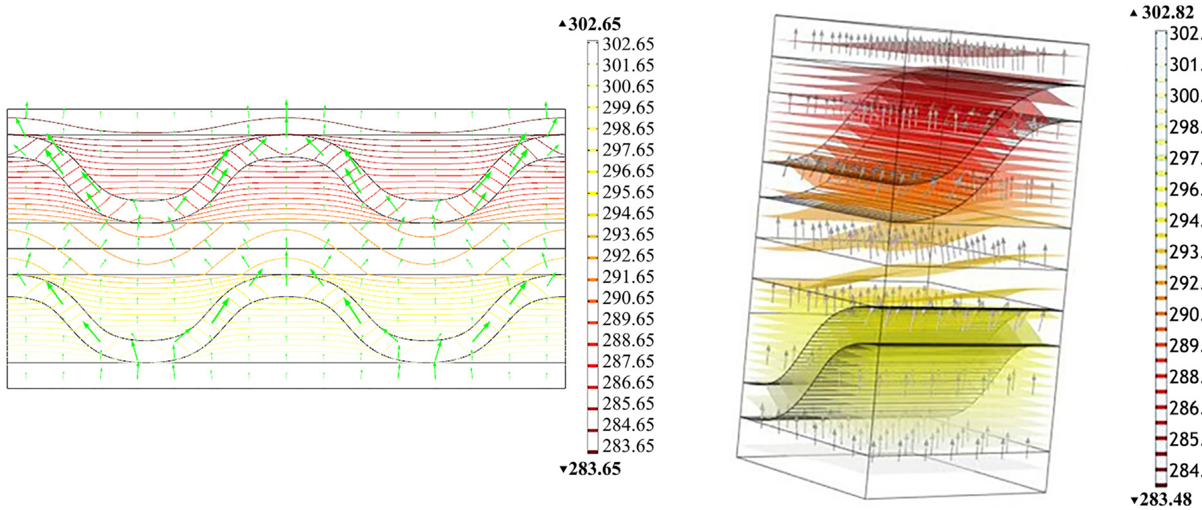

Fig. 14. Examples of 2D and 3D simulated models isothermal contours and surfaces.

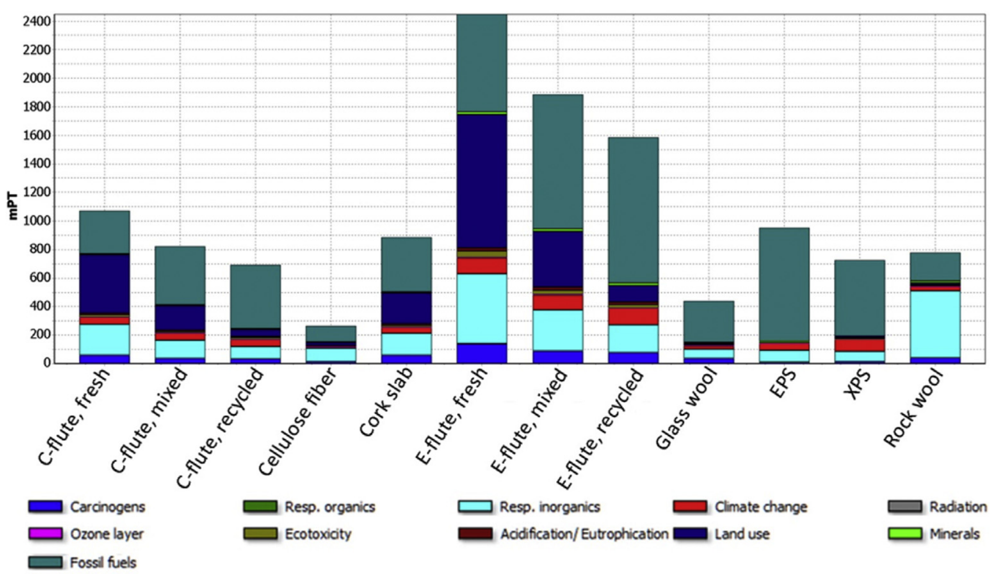

Fig. 15. LCA results with respect to the 11 Eco-Indicator impact categories, regarding the manufacturing stages of the different insulation materials.

on the contrary is mostly reflected by the first encountered liner. Anyhow it can be noticed that in every tested configuration, the absorption coefficient increases as the thickness of the panel increases All things considered, this material is more similar to a membrane absorber than to a porous one, and its acoustic performance is highly better in terms of insulation capacity than of the absorbing one.

All the cardboard panels in fact exhibit interesting properties in terms of transmission loss, even if in this case impedance tube measurements seem to overestimate the insulating performance. Furthermore, their acoustic performance always increases together with the thickness of the samples. Considering the C-flute samples, it is clear that the orientation itself also produces significant changes in the insulation trend. In fact, in the parallel orientation samples a significantly better insulation behavior is detected in the range between 100 and 600 Hz, while for higher frequencies the transmission loss steadies at lower values. In both the orthogonal 1×1 and 2×2 configurations, on the other hand, a significant improvement on the TL value is reached in the range $800 \div 1600$ Hz. This sensible change on the insulation properties of the samples can be explained in consideration of the reciprocal orientation of the different layers. In fact, the single parallel orientation panels, when impinged by a sound wave, tend to oscillate simultaneously while in the orthogonal configuration the flutes of two subsequent layers creating a 90° angle creates a stiffer system. If the E-flute samples are considered, it is also possible to appreciate the increase of TL together with their thickness, but the significant difference between the parallel and the orthogonal configurations is not that important as on the previous case. This is probably imputable to the geometry of the single panel: the rigidity of the single E-flute is much higher than that of the C-flute. Therefore the change on the reciprocal orientation does not affect appreciably the system. Moreover E-flute panels tend to perform better that C-flute ones because of their higher area density.

Finally, since all the sandwich configurations were prepared by considering the only parallel flutes layers, and consist of a large number of C-flute panels, the system is not allowed to reach a significant rigidity. For this reason, the behavior of the sandwich

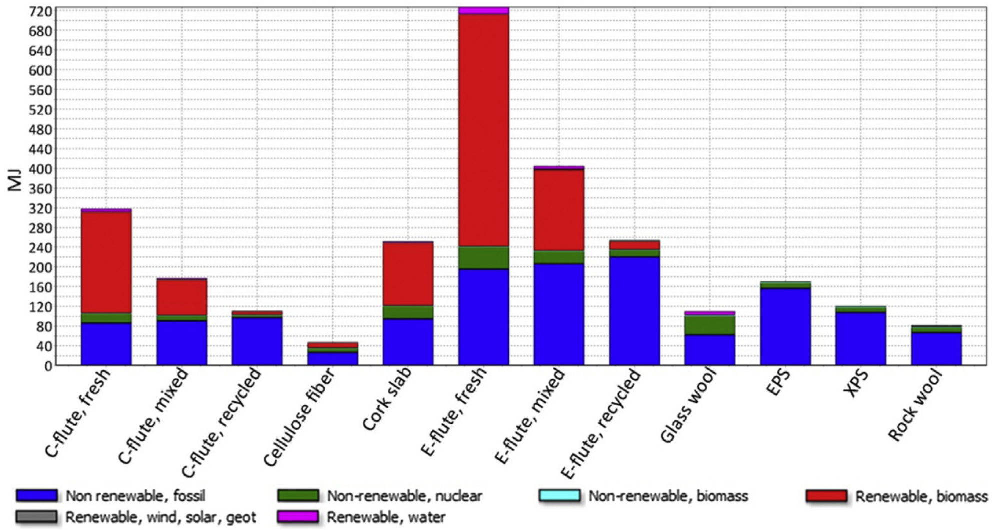

Fig. 16. LCA results with respect to the 6 CED impact categories, regarding the manufacturing stages of the different insulation materials.

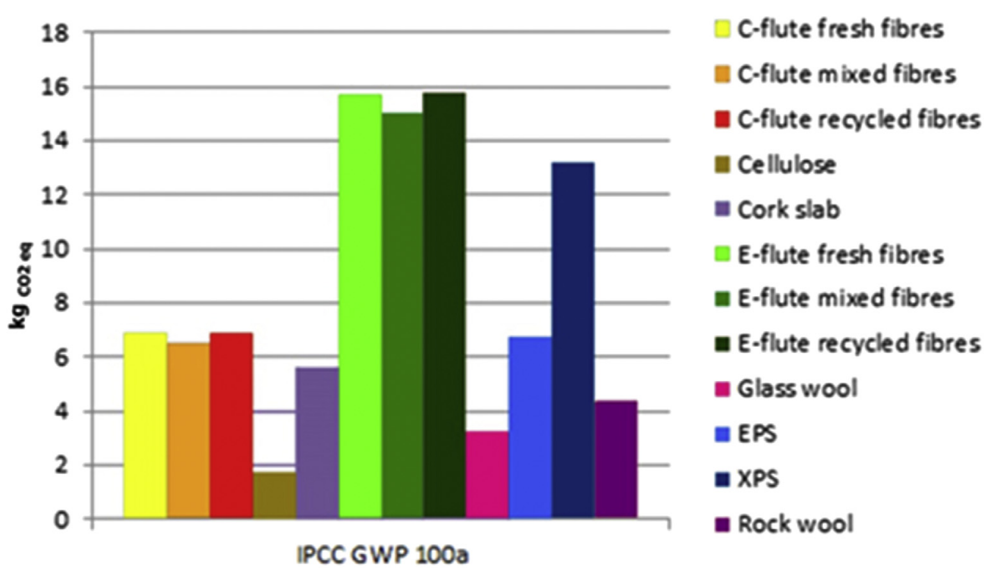

Fig. 17. LCA results with respect to the IPCC method, of the different insulation materials.

Table 5
Acoustic properties of some traditional and natural insulation materials [12].

Material	Thickness (cm)	Absorption coefficient at 500 Hz (–)	Thermal conductivity λ (W/mK)
Glass wool	5.0	1.00	0.050
Cellulose flocks (panels)	6.0	1.00	0.039
Rock wool	5.0	0.90	0.040
Expanded polyurethane	5.0	0.61	0.030
Expanded polystyrene	4.0	0.50	0.040
Cork (panels)	4.0	0.39	0.050
Hemp	30.0	0.60	0.050

samples is generally comparable to that of the C-flutes samples with a parallel orientation of the layers, and only a slight increase of the TL level is detectable, because of the presence of the E-flutes.

6.2. Thermal performances

The thermal conductivity of the considered samples was investigated by means of an experimental campaign, an analytical methodology based on ISO 10077-2 and computer simulations. The obtained results are summarized for the C-flute panels in Fig. 18. Considering this one and Fig. 11, it is possible to make some considerations. First of all, it is noteworthy that in all the considered thicknesses, the C-flute panels always present a lower λ value, with respect to the E-flute ones. This result was easily predictable, considering the high density of the second kind of samples, but the difference is not as important as it could be thought; rather the two values are very close to each other. This evidence can only be explained considering the effect of conductive and radiative phenomena inside the air cavities. In fact, the equivalent thermal conductivity of air cavities, defined according to the ISO 10077-2, gives the values of 0.034 and 0.028 W/mK for the C and the E-flute, respectively. It is clear that the larger dimension of air cavities inside the C-flute panels allows the development of much significant convective flows within these layers, with respect to the E-flute's ones. This phenomenon explains why, despite the significant difference in the percentage of cardboard volume between the two flutes (24% for the C-flute and 55% for the E-flute), their thermal conductivity is still comparable.

The guarded hot plate apparatus defines a λ value of about 0.053 and 0.058 W/mK for the C and the E-flute samples, respectively. Which are higher than those of commonly used high performance insulation materials, but still comparable to those of natural fibers such as cork and hemp (Table 5).

The analytical procedure shows an overall thermal conductivity of the samples that increases together with that of cardboard, but the obtained results seem too high if compared to those of the guarded hot plate (see Fig. 18). The thermal conductivities obtained by means of numerical simulations, on the other hand, are very similar to those experimentally defined. In light of a cardboard thermal conductivity of alternatively 0.23 and 0.14 W/mK, in fact, the results of the simulations are equal within the error to those of the experimentally tested C and E-flute panels, respectively. Simulation results seem to give a highly better approximation of the samples thermal insulation behavior, and this is probably due to their ability to consider the actual geometry of the system.

Finally, as it has been said, computer simulations suggest a slight increase of the λ value when an orthogonal configuration of the samples is considered, with respect to an identical parallel orientation sample. This result seems to conflict with the experimental evidence, which on the contrary, suggests a better behavior of the orthogonal samples. Anyhow, it is important to point out that the actual difference between these results is very small, and that the thermal conductivities obtained by means of the guarded hot plate apparatus are still equal within the experimental error of the facility, and are necessarily influenced by the imperfections associated to the manufacturing process of the corrugated cardboard panels.

6.3. Life cycle interpretation

First of all, it possible to point out that both the configurations considered (C and E-flute) show a high sensitivity to the base paper manufacturing process, which always represents the highest contribution to the overall environmental impact. Furthermore, the percentage of recycled material used in the preparation of the base paper represents an interesting value to consider. In both the Eco-Indicator 99 (H) and the CED methods, in fact, a higher percentage of virgin material always leads to a higher resulting impact. This trend cannot be found in the IPCC method, which, on the other hand, shows a comparable behavior of the different panels (of the same flute-type), in terms of global warming potential. Considering the obtained results, it appears clear that two are the main factors affecting the corrugated cardboard life cycle: the biomass consumption or land use (which decreases together with the virgin fiber percentage), and the fossil fuels consumption (which decreases together with the recycled fiber percentage).

It could thus be interesting to find the percentage of virgin fiber that optimizes the LCA results, or to introduce some alternatives to the fossil fuels in order to enable a higher recycling percentage, with lower global warming potential and fossil fuels consumptions. As it has been said, the LCA has been performed through different methods (Eco-Indicator 99(H), CED and IPCC) and in all of them a general better behavior of the C-flute panels is noticeable. The E-flute panels, in fact, always present at least twice the environmental impacts associated to the respective configuration of the previous ones. This high difference can be related to the huge discrepancy between the functional unit of the E and C-flute panels, *i.e.* 16 and 7.0 kg, respectively, that highly influences the environmental behavior of the investigated product.

When the investigated panels are compared to the traditional insulation materials, it is clear that the E-flute configurations do not present an interesting environmental behavior, since they generally produce higher impacts in comparison to the others. C-flute panels, on the other hand, especially in the high percentage of recycled fiber configuration, are associated to lower environmental impacts if compared to some of the other insulation materials considered.

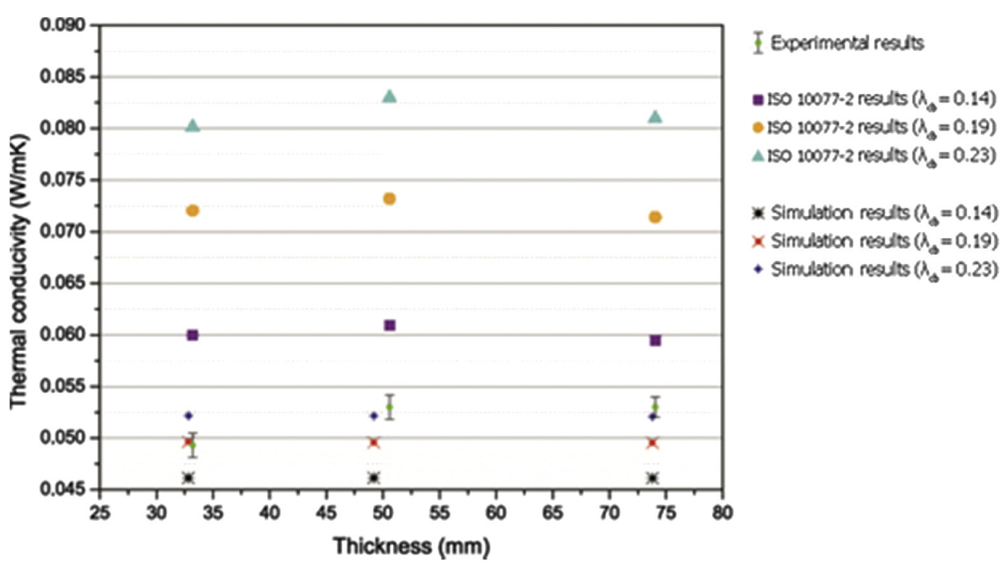

Fig. 18. Thermal conductivities obtained with three considered methods.

This result is highly encouraging since with a cradle-to-gate approach, which is the one applied in this thesis work, it is not possible to take into account an important factor: the possibility to recycle the panel itself. Most of the traditional insulation materials, in fact, are not easily recyclable, while these panels can easily be treated and re-utilized, thus reducing both wastes impact, and raw materials consumption.

7. Conclusions and future developments

In this work, innovative, thermal-acoustic insulation panels made by promising corrugated cardboard were experimentally, analytically and numerically studied, furthermore their environmental impact was defined by means of a Life Cycle Assessment analysis. In particular, cardboard layers typically used in packaging industry were optimized in terms of geometry and stratigraphy design to be ready for sustainable constructions' market. The acoustic analysis showed that, even though the absorption behavior of the investigated panels is not particularly notable, their sound insulation properties are quite remarkable, in particular if the heaviest E-flutes are used or the orthogonal configuration is employed in case of C-flutes. The thermal conductivity analysis showed that these panels do not reach the thermal insulation capability of high-performance commercialized products. Nevertheless, the thermal conductivity value achieves 0.0524 W/mK, and it can still be considered as acceptable to be considered as thermal insulation panels.

Comparing the obtained thermal insulation results, it is very interesting to notice how an analytical standard-based procedure seems to overestimate the thermal conductivity of the panels, while numerical simulations, which consider the actual geometry of the samples, give more accurate results of this parameter. In conclusion, the sound and thermal insulation properties of the considered panels, make them suitable to be used as light insulation solutions in the building sector, especially in internal partitions. Their use can also be extended to the acoustic control of open plan offices and temporary exhibition areas.

As for the environmental impact assessment, in all the different methods enforced, a general better behavior of the C-flute panels is noticeable. This is probably due to the higher density of the E-flute panels that leads to a functional unit almost three times that of the C-flute ones. In both cases, however, it is quite clear that the land use and fossil fuels consumption are the main contributors to the overall impact associated to the panels. When compared to other commonly used insulation materials, E-flute configurations do not present an interesting environmental performance, while C-flute panels are in some cases associated to lower environmental impacts. This result is highly encouraging since a cradle-to-gate approach does not take into account the use phase and the waste treatment. The corrugated cardboard panels are completely recyclable and do not present any hazard to human health in the use phase, unlike most of the traditional insulation materials. For this reason, it could be interesting to perform a further LCA by means of a cradle to gate approach, considering the actual data made available by the manufacturer of the cardboards and a numerical method that could take into account the use phase, and the recycling chain.

As a future development of this work, the thermal conductivity of full-scale panel integrated within a real wall stratigraphy by means of a hot box apparatus will be tested [38]. Furthermore, it could be interesting to develop a virtual reference model considering an experimentally defined cardboard thermal conductivity, and a numerical reference model for the performed acoustic analyses.

Acknowledgments

The authors would like to thank Mauro Benedetti S.p.A. for providing the samples and actively cooperate under the framework of this research. A.L. Pisello's acknowledgments are also due to the "CIRIAF program for UNESCO" in the framework of the UNESCO Chair "Water Resources Management and Culture", for supporting her research.

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