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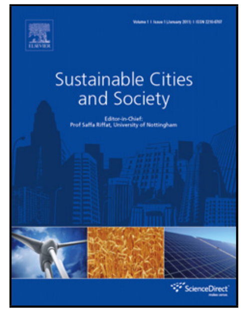

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The use of forest-based materials for the efficient energy of cities: environmental and economic implications of cork as insulation material

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Highlights

- · The current transformation of cork into finished products generates important environmental impacts that counteract the original advantages of a forest-based material.
- · Biogenic carbon has to be considered as the main advantage of the forest-based material, but eco-design strategies have to be implemented along their life cycle.
- · Cork insulation boards reach the market with the highest selling; being transformation costs the main significant.
- · Cork has a high potential of retrofit buildings, being a significant insulation material from an environmental approach.
- · Cork oak forests could improve their capacity of cork production by harvesting more available surface and applying more prioritization criteria.

Abstract

Cork is a very interesting forest-based material for many industrial sectors as a natural and renewable material with a high geographical concentration in the Iberian Peninsula. Currently stoppers for beverages are its most valuable application, but the properties of the cork are an excellent opportunity to eco-innovate. Natural materials are being studied as potential sustainable solutions for building sector to reduce environmental impact and energy use of cities. This study introduces and evaluates the environmental and economic implications of using cork insulation boards as a solution for retrofit buildings in Barcelona metropolitan area.

Results demonstrate a high potential of retrofit buildings with cork insulation boards from an environmental and economic perspective, therefore the present capacity of cork oak forest sector in Catalonia is not ready to absorb the potential demand that could be generated, as less than 50% of forests are not managed and harvested. This is also an opportunity for this sector to diversify its market and develop other products that can fit into many other sectors. The use of cork wastes and by-products to produce granulates would be a relevant circular economy strategy in order to substitute other non-renewable materials.

Keywords: Construction; cork sector; eco-innovation; environmental impact; Mediterranean

Nomenclature

CC	Climate Change
CED	Cumulative Energy Demand
CO_2	Carbon dioxide
EN	European norm
EPS	Expanded polystyrene
FDP	Fossil Depletion Potential
FEP	Freshwater Eutrophication Potential
FU	Functional unit
GW	Glass wool
HTP	Marine Eutrophication Potential
ISO	International Standardization Organization
LCA	Life cycle assessment
MDP	Water Depletion Potential
MEP	Marine Eutrophication Potential
NMVOC	non methanic volatile organic compounds
ODP	Ozone Depletion Potential
PCOP	Photochemical Oxidant Formation Potential
PU	Polyurethane
SO_2	Sulfur dioxide
SW	Stone wool
TAP	Terrestrial Acidification Potential
XPS	Extruded polystyrene

1. Introduction

Cork is a natural, renewable product typically harvested in Mediterranean Region, in particular the Iberian Peninsula, which is home to the majority of cork oak forests and where most of the cork extraction activity takes place. Cork is used to make many products, but the sector is mainly focused on the production of closures for wine and champagne bottles, which are products of high added value (Silva et al. 2005; Rives et al. 2011, 2012c, 2013). The rest of cork applications are manufactured using cork granulates, made from wastes generated in these manufacturing processes, and also from forestry wastes, as a circular economy strategy to optimize raw material use and minimise environmental impacts (Rives et al. 2012a).

Forestry wastes comprise different kinds of raw materials such as virgin cork, second cork, little pieces of reproduction cork, reproduction planks with defects, cork of tree branches, cork of fired trees etc. Whereas wastes from the natural industry comprises raw materials from the preparation of natural cork products, natural cork stopper production (pieces of cork resulting from the process of cutting into strips, pieces of punched strips, rejected stoppers, etc.), and natural disc production for the champagne stoppers' manufacturing (Rives et al. 2012a). Champagne stoppers use cork granulate and they come from cork wastes, their size is between 0.25 - 8 mm and their specific weights is around 55 - 75 $kg \cdot m^{-3}$ (Rives et al. 2012c).

<Figure 1>

The granulate industry can be divided into two types: white cork granulates and black cork granulates. White cork granulate by-products are mainly intended to alimentary uses such as stoppers for wines, champagnes and other alcoholic beverages, and for this reason a pre-treatment or preparation is required in order to clean the raw material before processing it to meet the health requirements of the final product. Otherwise, black cork granulate is intended to non-alimentary uses, especially for the construction sector such as insulators and floorings, and for design and decoration purposes. In these cases, the cleaning stage is not mandatory. Globally, products made of white cork granulate have a higher market price, and for this reason the production of these kind of goods has a larger market quote (Mestre and Gil 2011).

Despite the fact that cork is not widely introduced in the building sector, it is one of the natural materials with an important presence in architectural projects. Traditionally, different types of thermal insulation materials with an non-renewable origin have been used in buildings over the years, including expanded polystyrene, extruded polystyrene, phenolic foam, rockwool, fibre glass and mineral wool, all of which are inorganic (Papadopoulos 2005; Pfundstein et al. 2012). But due to the current strategy of increasing the sustainability of buildings, some natural materials have been introduced as constructive solutions. A significant number of thermal insulation materials produced with natural resources are appearing in the market: these materials are primarily based on biological materials, forest residues and straws, and they also known as biomaterials, with some of the most well-known are sheep wool, cotton, cork, hemp, linen and kenaf fibres (Liu et al. 2017). Apart from their properties for thermal and acoustic insulation, most of these materials have a high carbon storage capacity, acquired during its cultivation (Pervaiz and Sain 2003). In the case of cork, this occurs because long-lived species increase the potential to hold carbon reserves.

A wide number of papers about the introduction of natural materials for thermal insulation in buildings have been published; among them, some discuss the properties of corn, hemp, coconut, agro-waste (rice, sunflower), cellulose fibre and flax (Kymäläinen and Sjöberg 2008; Binici et al. 2014; Ingrao et al. 2015; Wei et al. 2015; Lopez Hurtado et al. 2016). Interest in these materials has been recently increasing in the building field, and the majority of studies are related to properties description, the evaluation of thermal performance or the investigation about functionalities. But a highlighted topic of these materials is their environmental performance during their extraction, manufacturing, installation, usage and end of life management. Cork is one of the most widespread natural material and recently different studies have analysed its environmental sustainability from different points of view (de Brito et al. 2010; Pargana et al. 2014; Silvestre et al. 2016; Sierra-Pérez et al. 2016a; Demertzi et al. 2017). These studies have focused mainly in Portugal and Spain, analysing different types of insulation products with different boundaries systems. In general, there is a need for investigation of natural materials from an environmental perspective, as there are very few comparable studies.

This article presents one of these cork insulation products from a comprehensive approach:

1) Defining its manufacturing process from the forest to the building site;
2) Evaluating the environmental and economic implications of its manufacturing;
3) Comparing the cork product and the most common insulation competitors in the market;
4) Presenting the implications of the use of cork as insulation material for the energy retrofit in an urban scenario.

2. Material and methods

This section describes the methods used to reach the objectives established above.

2.1. The product under study

The product studied in this article was an agglomerated cork board used as thermal insulation in buildings, both in façades and roofs. This product is manufactured in Spain, in the region of Catalonia, and it is produced in one of the few Spanish factories, of that region which is not focused in the production of wine stoppers.

This study collects and presents the information related to the transformation process in which the forest cork waste was used to produce a thermal insulation product. Thus, a field research was done by visiting the analysed company and interviewing its production manager. In order to collect the needs of energy and resources during the manufacturing, a questionnaire was designed to keep record of the requirements of each stage of manufacturing. These data were used to evaluate the product from an environmental and economic approach.

2.2. Assessment of the environmental and economic implications of the manufacturing of the white agglomerate board

The product analysed is used as thermal insulation, so the assessment of its environmental and economic implications had to be done under the consideration of its thermal resistance. In this regard, it could be subsequently compared with other insulation materials with the same function.

Consequently, the functional unit used in this environmental assessment was the quantity of product to insulate one square meter providing a thermal resistance R-value of 1 m^2 K/W, according to EN 15804:2014 (European Committee for Standardization 2014a). The methodology used for the environmental analysis was Life Cycle Assessment (LCA) (ISO/EN 14040 2006), and evaluated the environmental burdens associated with a product, process, or activity. The first step was identifying and quantifying energy and materials used and wastes released to the environment, and then the impact of those energy and materials used and releases to the environment was assessed.

This study applied the hierarchical approach of ReCiPe 2008 (Goedkoop et al. 2013). The selected midpoint indicators were Climate Change (CC, kg CO_2 eq.), Ozone Depletion Potential (ODP, kg CFC-11 eq.), Terrestrial Acidification Potential (TAP, kg SO_2 eq.), Freshwater Eutrophication Potential (FEP, kg P eq.), Marine Eutrophication Potential (MEP, kg N eq.), Human Toxicity Potential (HTP, kg 1,4-DB eq.), Photochemical Oxidant Formation Potential (PCOP, kg NMVOC), Water Depletion Potential (WDP, m^3), Metal Depletion Potential (MDP, kg Fe eq.) and Fossil Depletion Potential (FDP, kg oil eq.). In addition, Cumulative Energy Demand (CED, MJ) is also included due to the importance of the energy consumption in the insulation materials

(Hischier et al. 2010). The system boundaries considered in this study began in the forest where the raw cork is extracted, and ended when the product is produced and packed ready to distribute at production plant. Simapro (PRé Consultants 2010) was the software used in this study, using Ecoinvent 3.1 database (Ecoinvent 2009) to obtain the environmental information related to the inputs in Table 1.

<Table 1>

2.3. Economic analysis

The economic analysis involved two steps: the first one was the evaluation of all the costs associated with the manufacturing process, from forest to the building site, and the second was a price comparison of the market value of different insulating products used in Spain. The analysis was referred to the same unit of reference used in the environmental analysis.

2.3.1. Analysis of the production costs

The production costs included labour costs, machinery costs, other expenses and general expenses, following a full-cost accounting approach (Gluch and Baumann 2004). The labour cost and input prices were taken directly from the enterprises involved in the study and referred to the year 2017.

The *labour cost* considered for the raw material extraction phase was an opportunity cost (Jenkins 1995) of 8 € h^{-1}, communicated by the Catalan Cork Institute; while the labour cost referred to the manufacturing phase, which was of 16,76 € h^{-1}, was referred to the collective labour agreement of the wood industry sector for the province of Girona, area where the company is located.

The *machinery costs* were calculated using a model that includes both fixed costs (capital recovery, interest and depreciation, taxes and insurance) and variable costs (fuel, electricity, lubricant, repair and maintenance costs). A cost of 0.67 € l^{-1} is assumed for Spanish diesel fuel and a cost of 0.092 € kWh^{-1} for electricity.

The item *other expenses* included goods acquisition (fungicide, polyurethane and polyethylene film) and service contracts.

The *general expenses*, such as supervisory and the operating costs and expenses associated with the administration of the companies, were also computed applying a percentage of 10% to the other costs.

The costs incurred for the production of cork boards were divided into four stages:

(a) cork extraction;

(b) transport from the forest to the manufacturer;

(c) granulates manufacturing;

(d) board manufacturing.

Both in the cork extraction stage and in the manufacturing stages 3 workers were involved. The transport of raw material was a service contract and was considered for an average distance of 100 km between the forest and the manufacturing plant.

Moreover, each stage included different production processes (Table 1) that involve the use of machineries and inputs.

Allocation

The cork extracted is used both in the stopper manufacturing process (main product) and in the board manufacturing process (co-product). Thus, it is necessary to perform an allocation procedure to identify which costs referred to the cork extraction stage correspond to the main product and which one to the co-product (Demertzi et al. 2017). In the study case a mass allocation was performed and in accordance with the information provided by forest company, the allocation factors considered were 86% for the main product and 14% for the co-product.

Manufacturing production yield

A 76% of the raw material that enters the manufacturing process is rejected, both in the manufacture of granules and in the classification of the granules. Moreover in this factory the cork dust is separated and not used, hence only 24% of the raw material is used in boards.

Price comparison analysis

The price comparison analysis was carried out through the investigation of market prices of different insulating materials commonly used as thermal insulation in buildings. The data used were the market prices recorded in Spain in the first half of 2017 (CYPE Ingenieros 2017), normalized to the functional unit.

This analysis compares the market prices of the common insulating materials with respect to the cork market price, considering the weight of an FU, expressed in kg, as the comparison unit.

2.4. Extrapolation to urban scale

The objective of this section is to confirm the importance of the potential energy savings in an urban scale through the use of cork from local cork oak forests, evaluating their capacity in a future scenario of energy renovation. For this research, the Barcelona metropolitan area was selected as a case study because it is the biggest functional area close to Catalan cork oak forests. Thus, the analysed product could improve their environmental and social implications due to its proximity and its location in rural areas. Moreover, there is a high potential of building retrofitting into this functional area. A recent atlas of the Spanish building stock (Ministerio de Fomento 2016) accounts for more than 75% of buildings requiring urgent energy renovation measures, because they had been built before any regulations about thermal insulation entered into force (IDAE 2012).

To extrapolate the studied product to an urban scale, in first place it was needed to obtain the potential surface of building envelope (m^2) to retrofit in the metropolitan area. At this level, a geospatial model was developed according to recent studies (Mastrucci et al.

2015; García-Pérez et al. 2017a), using Spanish cadastral dataset and Geographical Information System (GIS). This approximation considered façade and roof surfaces of all residential buildings, on which the year of building construction helps to characterize the retrofit requirements: buildings built before 1981, when no thermal regulations were approved, built between 1981 to 2007, when first thermal regulations were adopted and built between 2007-2015, when Spanish Technical Building Code came into force (IDAE 2012). The retrofit standard was defined in the recent version of Spanish Technical Building Code (Ministerio de Fomento 2013). At the same time, the study considered previous research which characterize the environmental impacts of more typical retrofit constructive solution, including cork as insulation material (Sierra-Pérez et al. 2016b; García-Pérez et al. 2017b). Knowing these environmental implications, according to the functional unit described above, these results were extrapolated to the resulted surface envelope by constructive solution. Finally these results allowed us to establish the potential of cork as insulation material at urban scale.

Cork may be an interesting insulation material from an environmental approach, but it is important to consider the real capacity of cork oak forests to produce agglomerated cork boards. For that, the period and rate of retrofitting helps to characterize both the existence of raw material and the market share. In this scenario, it was possible to calculate both rates: firstly, obtaining the quantity of cork required to the retrofit buildings built in Barcelona; secondly, the literature review helped to obtain a characterization of Catalan cork oak forests capacity. Results will be expressed in quantity of cork versus time. Once both of them were obtained it was possible to calculate in this scenario the retrofit period (total number of years), and the retrofit rate (average envelope surface/year).

3. Results and discussion

3.1. Technical description of the cork insulation product

The product under evaluation is an insulation board made mainly from raw cork with a thermal conductivity (λ) of 0.042 W/m K, a density of 171 kg/m^3 and a total weight of 7.2 kg.

The manufacturing process of the agglomerated board is composed of three main stages (Figure 2). This process begins in the cork oak forests, where the extraction process takes place. This process generates forestry waste, which is the raw material for the board production. The extraction stage not only includes the cork extraction but also the maintenance of roads and the activities of the forest regeneration that implies the use of different resources and means of transport. Subsequently, the raw cork is transported to the factory where the board is produced. In this case, the 80% of the raw cork used is local and the 20% comes from Portugal. Once the raw cork is introduced in the manufacturing stage, the first process is the granulation, where the raw material is crushed with mechanical machinery. After that, the board is conformed through the joint action of compression, temperature and polyurethane as agglutinating agent. Finally, boards are cut and packed for their distribution.

<Figure 2>

In order to evaluate the environmental and economic performance of the board it was necessary to collect the inventory data for each manufacturing stage. Table 2 presents all inputs by Functional Unit describing the activities carried out during the process.

<Table 2>

3.2. Environmental assessment of the production of cork insulation boards

The manufacturing of the studied product implies environmental impacts due to the use of different energy sources, materials, machinery and means of transports. Table 3 contains the results of the life cycle assessment, and it could be seen that during the production of the insulation board 12.2 kg of CO_2 -eq. were emitted and 213 MJ eq. were used. Moreover, other impact categories had been evaluated to obtain a broader view.

<Table 3>

The manufacturing process described above has different environmental impacts along their stages. Figure 3 presents the distribution of the impacts by manufacturing stage. It can be noted that the manufacturing stage (granulation and board manufacturing) concentrated the majority of the environmental impacts, except for HTP and MDP. During the granulation stage the use of electricity was an important input, so its source had a high influence in the final results. The agglomeration process implied a high quantity of energy to reach the temperature required for the board conformation. In the case under study, the thermal energy was obtained from a diesel boiler with a low technical development, so the environmental performance was significant.

<Figure 3>

Figure 3 also includes an additional column expressing Climate Change (CC) that includes the biogenic carbon contained in the board. One of the main advantages of the forest-based materials was their capacity of carbon storage, because part of the carbon fixed in cork oak trees was transferred to cork material. This capacity of cork helps to mitigate the climate change implications of others elements in the same constructive system. Besides its capacity of carbon storage, the sustainability of cork also comes from the bark extraction process, since it is an ecological process that does not damage the tree, allowing the new bark to regrow for subsequent extractions.

The established functional unit contained 7.2 kg of cork, so this quantity of material included a total of 15 kg of biogenic carbon (European Committee for Standardization 2014b). Regarding the system considered, which is the cradle to gate approach, the production of the product emitted 12.2 kg of CO_2 –eq. Thus, the final balance in global warming terms was -2.88 kg of CO_2 –eq. In this case, the forest-based origin of this material helps to mitigate the emission of CO_2 during the manufacturing process. However, also the use of this product allows mitigating the impact of other materials less sustainable in the building.

Table 4 compares the results obtained for cork with respect to the reference insulation materials from different studies, which use the same FU and the same standard for the LCA. As it can be seen, the manufacturing of cork boards had higher environmental implications than the rest of insulation materials. Nevertheless, if biogenic carbon was taken into account, the advantages of using forest-based materials were clear. Therefore, it is also important to maintain this advantage by improving the manufacturing of cork products from an environmental approach.

<Table 4>

3.3. Economic results

3.3.1. Production cost analysis results

The economic results show the distribution of costs from the forest to the building site with respect to the expenditure items considered.

As shown in the Table 5, in this context the production cost of a functional unit was 14.87 €. Granulate manufacturing was the stage that had greater impact in the results (58% of the costs); if adding the board manufacturing stage, the costs went up to almost 85% of the total costs. The cork extraction stage represented 14% of costs, while the transport was almost irrelevant (1%).

Moving to the individual cost items, machineries determined the greatest impact, which summed 48% of all costs, followed by labour, 34%. The other expenses item was concentrated in the board manufacturing phase and refers to the use of polyurethane as additive and polyethylene film for packaging, and it accounted for 9%.

<Table 5>

This result was, of course, an average value that is subject to large variability. First of all, in the board production a natural material was used; consequently, the cork does not always present the same physical and morphological characteristics. Therefore, the manufacturing costs can vary considerably if the factory needs to get supplies from very distant extraction sites or if the raw material has a poor quality, thus resulting in a lower manufacturing production yield.

3.3.2. Price comparison analysis results

The European market of insulation materials is still dominated by non-renewable products like mineral or inorganic fibrous materials, glass wool (GW) and stone wool

(SW), and organic foamy materials, expanded polystyrene (EPS), extruded polystyrene (XPS) and the polyurethane (PU) (Papadopoulos 2005; Pfundstein et al. 2012).

Other materials, including renewable ones, compose the rest of the market: kenaf-fibres, cotton, jute, flax, hemp and cork, among others.

Table 6 shows the price comparison between the market prices of common insulator materials compared with the market price of cork. The selling price of cork boards (29,33 € UF^{-1}) was about twice the cost of production, but in our analysis costs incurred for distribution, end-user sales and transaction costs had not been computed.

Cork boards reached the market with the highest selling price compared to products that perform the same function. The price went from double, compared with the stone wool boards up to about 6 times more than the common extruded polystyrene boards.

<Table 6>

Results showed that the cork used as a thermal insulator was a valid way to valorise both the waste of the main production and the raw material of low quality that is not used in the stopper production. This situation is typical of Catalan cork, highly appreciated to produce cork stoppers; however, most of the annual raw cork in Catalonia does not meet current standards of quality to produce natural cork stoppers, forcing to use about 60% of cork production to granulate (Mundet et al. 2017).

Furthermore, the Spanish market absorbs much of the national production, while the rest is exported. Economic results show the high potential of cork in the thermal insulation market, although it could refer to a niche market as production is still limited and tied to raw material resources. These restrictive conditions guarantee, at the same time, high prices and the presence of a constant demand, as the market is not saturated and does not compete with traditional products.

Cork can have high potentials in the building sector, in fact it is a forest-based material with interesting aesthetic aspects, Therefore, it is incomparable respect to others insulation materials, for it does not only perform a technical function, but has environmental and decorative aspects that can justify higher sales prices.

3.4. Extrapolation to urban scale

3.4.1. Environmental interest

First of all, it was important to determine if the use of agglomerated cork boards was interesting from an urban scale approach. Previous studies had obtained the environmental implications of diverse constructive solutions and insulation materials (García-Pérez et al. 2017b). According to this research, if GWP biogenic was considered, there was an absolute difference between the more and least recommended façade-roof combination of 3.690.000 tonnes of CO_2 eq. To better understand the magnitude of these possible savings, it was possible to compare them with the CO_2 production of Catalonia (Spain). During 2012, the energy sector produced in this region 32.631 millions of tonnes of CO_2 eq. (Oficina Catalana del Canvi Climàtic 2014). The savings reached up to 11% of this annual production of CO_2. This amount could justify the strategy to use cork as insulation material from an urban scale approach. Even more, when the European Union wants to achieve a goal of reducing CO_2 emissions by 20%, considering the retrofit of buildings as one of the main actions (European Comission 2011).

3.4.2. Real capacity of cork oak forest

A recent study conducted by Rives et al. (2012b) characterized the raw cork extraction in cork oak forest in southern Europe. Moreover, Sierra-Pérez et al. (2015), carried out an economic characterization of cork sector, accounting that up to 7,600 tonnes of raw material extracted from the cork forests in Catalonia (Spain) are potentially usable. According to J.M. Tusell (2008), at present Catalan cork oak forests are not fully used, at an estimated rate of 50%.

The proposed scenario considered that the manufacture of cork insulation products was carried out with this 50% of potentially usable forest. However, this amount could increase because agglomerated cork board should also be obtained from waste material from the cork stoppers production (Sierra-Pérez et al. 2016a).

Considering 7,600 tonnes as quantity of annual extraction, and knowing, on the one hand, the number of square meters of envelope surface needed for retrofit, and on the other hand, the corresponding quantity per functional unit, it was possible to calculate both the retrofit period and the retrofit rate. Buildings were classified according to their energy performance in three sorts: before 1981, between 1981 to 2007, and 2007-2015. Table 7 shows that a huge amount of buildings was constructed before thermal regulations were enforced, which their retrofitting with cork go on for more than 220 years. If the retrofitting of the entire building stock to was considered with current requirements, the amount reached 310 years. Logically, the retrofit rate was reduced as energy requirements decrease. On the one hand, the quantity per functional unit decreased because of the new more exigent regulations. On the other hand, the total amount of envelope surface decreased.

<Table 7>

To better understand this capacity, a map of the potential of retrofit residential buildings using local cork oak forest was used. The map showed all residential buildings built before 1981, which needed priority intervention. Using Plaza Cataluña, one of the main centres of the metropolitan area, as epicentre of retrofitting, each colour used in Figure 4 represents a period of time of 10 years. The geolocated results helped to visualize the amount of buildings of each period.

<Figure 4>

The results obtained in this urban scale scenario showed a very long period of retrofitting and also a high rate. Whereas on the one hand, they indicated a high potential of retrofit buildings, on the other hand, the current capacity of Catalan cork oak forest was not ready to satisfy this demand in a reasonable period of time. At this level, it is possible to apply more criteria to prioritize retrofit actions, such as vulnerability indicators (Ministerio de Fomento 2015), energy poverty approaches (Pachauri and Spreng 2011; Nussbaumer et al. 2012) or other urban sustainability criteria (Braulio-Gonzalo et al. 2015). On the other hand, there is a need of improving the capacity of Catalan cork oak forest, through the improvement of the artificial regeneration that increases the level of Catalan cork oak forests exploitation (Zapata 2002). Moreover, it is also necessary to increase the efficiency of manufacturing processes of the cork product to optimise the use of raw cork.

Conclusions

Data obtained in the paper allowed an objective analysis of the environmental impacts generated during the production of cork insulators boards, an analysis of the production costs of the product and a broad view of the potential of the product for retrofitting in local or regional buildings in the Barcelona metropolitan area.

The current transformation of cork into finished products generates important environmental impacts that counteract the original advantages of a forest-based material. For that reason, at this time cork cannot be a competitor to other non-renewable insulation materials from an environmental perspective. The biogenic carbon has to be considered as the main advantage of the forest-based material, but further research should be done in this field. Besides, regarding the economic results, there is a great opportunity to improve the product from an eco-design perspective, including the environmental considerations into the design of products and services, to innovate into products and processes, because currently is a very traditional product. Moreover, from an economic perspective and compared with other solutions with the same function, cork insulation boards reach the market with the highest selling price (from 2 to 6 times more), the costs in the transformation of the product are the main significant (85%). The application of eco-design strategies could also a) contribute to increase the opportunities of cork through the improvement of forest management, b) increase the efficiency of manufacturing processes and c) stimulate the establishment of manufacturing companies.

Moreover, cork is a forest-based material that can be considered from a circular economy approach, in fact, the cork board at the end-of-life can be recycled and used almost entirely for the manufacture of new products.

At the urban scale, results based on the proposed scenario indicated a high potential of retrofit buildings, where cork as insulation material is very interesting from an environmental approach. By contrast, the current capacity of Catalan cork oak forests is not used enough because local cork companies are too focused on the production of cork stoppers. Both improving their capacity by harvesting more available surface and applying more prioritization criteria could be deeply explored in future research.

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Table 1. Summary of all processes, machines and materials involved for each stage

	Stage	Machinery	Input
a	**Material extraction**		
	Transport workers	all-terrain vehicle	
	Stripping	manual	
	Plant protection	manual	fungicide
	Cork movement from tree to the road	manual	
	Cork movement from the road to a meeting point in the forest	forestry tractor	
	Classification and piling up of raw cork	manual	
	Lorry loading	manual	
b	**Transport**	lorry	
c	**Granulates manufacturing**		
	Displacement of the crushing cork to hopper	excavator shovel	
	Cork crushing and non-usable parts removal	trituration machine	
	Displacement of crushed cork to grading	industrial vacuum cleaner	
	Classification of granulates	vibrating sifter	
	Displacement of granulation and rejection to packaging	industrial vacuum cleaner	
	Granulate packaging	Silo	
d	**Board manufacturing**		
	Displacement of granules to mixing	dispenser	
	Granulates mixing	mixer	
	Displacement mixing to boards agglomeration	proportioning hopper	

Board agglomeration	press, oil boiler, vacuum cleaner vapours,	polyurethane
Boards cutting	saws, grinder, conveyor belt	
Displacement of boards to packaging	Hand Pallet Truck	
Packaging	Thermoretractable laminator	polyethylene film
Displacement of packed boards to storage	Hand Pallet Truck	

Table 2. Inventory data to produce the FU of cork insulation boards (R=1 m^2 K/W)

Inputs	**Unit**	**Quantity**
Raw material extraction		
Materials		
Water	m^3	3.62E-03
Fungicide (Thiophanate-methyl 45%)	kg	3.03E-03
Transport		
Workers	km	3.07E+00
Forestry tractor	km	5.42E+01
Distribution of auxiliary materials	km	1.00E+02
Transport to the manufacturer		
From the forest	km	2.40E+02
Manufacturing		
Granulation		
Diesel for internal displacements	MJ	7.63E+00
Board agglomeration		
Electricity	kWh	5.85E+00
Diesel boiler	MJ	4.24E+01
Polyurethane (PU)	kg	1.68E-01
Transport (PU)	km	2.00E+01
HPDE	kg	4.55E-02

Table 3. Environmental impact assessment of the production of the FU of cork insulation boards (R= 1 m^2 K/W)

Impact category		**Unit**	
Climate Change	**CC**	kg CO_2-eq	**1.22E+01**
Ozone Depletion Potential	**ODP**	kg CFC_{-11}-eq	**1.93E-06**
Terrestrial Acidification Potential	**TAP100**	kg SO_2-eq	**4.96E-02**
Freshwater eutrophication Potential	**FEP**	kg P-eq	**1.28E-03**
Marine Eutrophication Potential	**MEP**	kg N-eq	**2.26E-02**
Human Toxicity Potential	**HTPinf**	kg 1,4-DCB-eq	**2.12E+00**
Photochemical Oxidant Formation Potential	**POFP**	kg NMVOC	**4.84E-02**
Water Depletion Potential	**WDP**	m^3	**2.81E-02**
Metal Depletion Potential	**MDP**	kg Fe-eq	**4.66E-01**
Fossil Depletion Potential	**FDP**	kg oil-eq	**4.31E+00**
Cumulative Energy Demand	**CED**	MJ	**2.13E+02**

Table 4. Comparison of environmental implication between cork and reference insulation materials

Insulation material	Ref.	CC	CC*	CED
Cork		1.22E+01	-2.86E00	2.13E+02
EPS	(1)	3.25E00	-	7.44E+01
XPS	(1)	5.21E00	-	9.81E+01
PU	(1)	3.33E00	-	8.59E+01
SW	(2)	3.6E00	-	6.33E+01

* Included the biogenic carbon content in FU.
(1) (Pargana et al. 2014)
(2) (Zabalza Bribián et al. 2011)

Table 5. Production costs of cork insulator boards

€ FU^{-1}	labour	machinery	other expenses	general expenses	total
Cork extraction	1.43	0.46	0.03	0.19	2.11
Transport			0.13		0.13
Granulates manufacturing	2.62	5.19		0.78	8.60
Board manufacturing	1.03	1.43	1.21	0.37	4.04
Total	5.08	7.09	1.36	1.34	14.87

Table 6. Price comparison between the market price of cork and other insulator materials

	FU	Price	Comparative analysis
	kg	€ FU^{-1}	% (price of insulator material / price of cork)
Cork	7.18	29.33	-
SW (Stone wool)	4.94	15.48	53%

EPS (Expanded polystyrene)	1.33	6.45	22%
PU (Polyurethane)	0.78	6.25	21%
GW (Glass wool)	0.76	5.18	18%
XPS (Extruded polystyrene)	0.72	4.80	16%

Table 7. Retrofit period and rate of residential buildings of Barcelona metropolitan area, considering real capacity of Catalan cork oak forest.

	Before 1981	1981-2007	2007-2015
Envelope surface (m^2)	70,381,024.12	27649370.02	2,793,374.73
Functional unit. (kg / m^2)	24.09	22.42	14.07
Total kg	1,695,712,887.50	619,962,213.62	39,299,411.34
Retrofit period (years)	223.12	81.57	5.17
Retrofit rate (m^2/year)	315,440.06	338,948.42	540,202.70

Figure captions

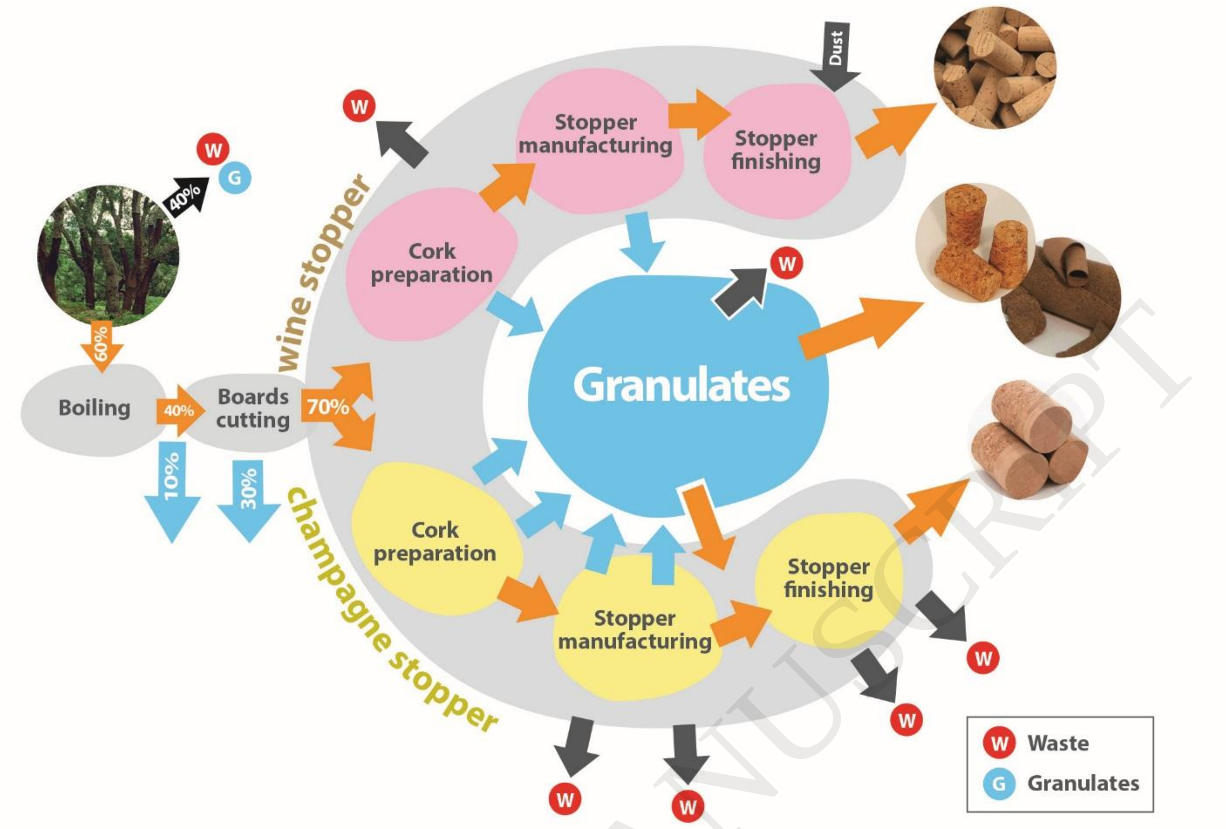
Figure 1. Diagram of the cork flows in the manufacturing of wine and champagne stoppers

Figure 2. Scheme of the manufacturing process of the cork insulation board under study

Figure 3. Distribution of environmental impact during the production of cork insulation boards by manufacturing stages

Figure 4. Representation of the capacity of local cork oak forest for the thermal retrofit of Barcelona

Figr-1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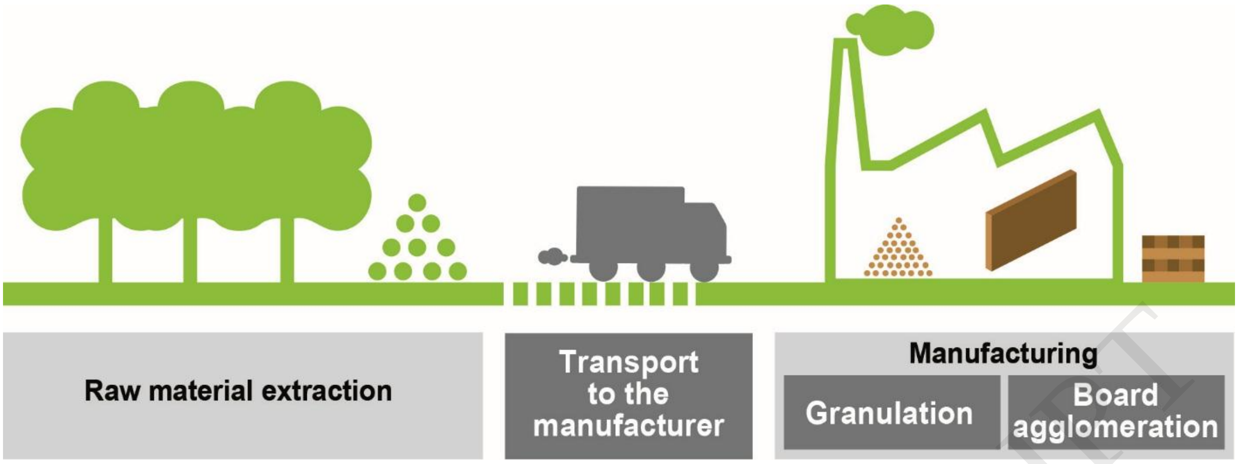
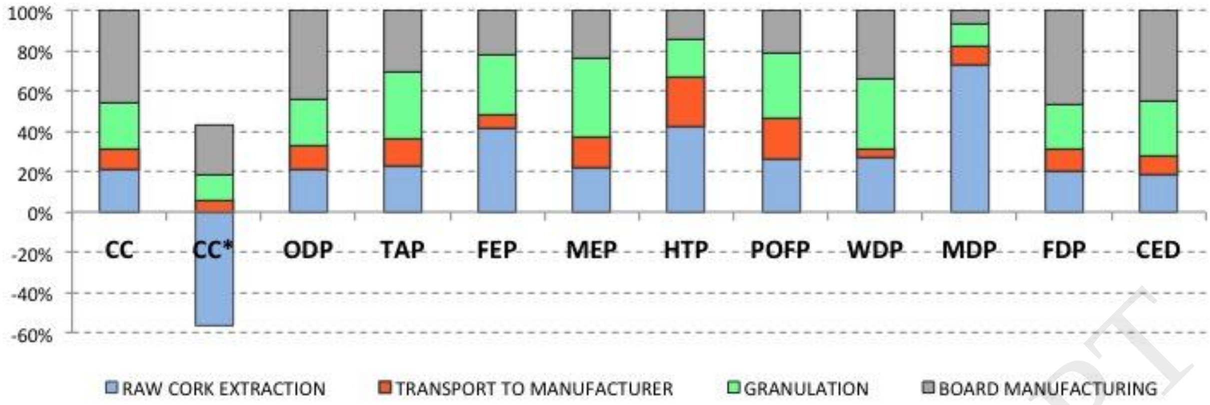
G Granulates

Figr-2


Raw material extraction
Transport to the manufacturer
Manufacturing
Granulation
Board agglomeration

Figr-3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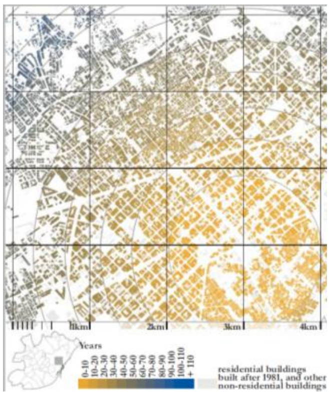
BOARD MANUFACTURING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residential buildings
built after 1981, and other
non-residential buildings