Life cycle assessment methodology of ICB and the applications of cork powder in aroma elimination

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Abstract

This work was based on two research challenges suggested by an expanded cork agglomerated industry (insolation cork board - ICB) (Sofalca, Sociedade Central de Produtos de Cortiça, Lda.), namely: (i) ICB life cycle assessment; (ii) characterization of the characteristic aroma of ICB and the use of cork powder as a potential sorption material of that aroma.

The first part of this work aims to calculate the carbon footprint of the ICB produced by a Portuguese company and to compare it with other insulation materials available in the market. A Life Cycle Thinking approach and the ISO/TS 14067 requirements was followed in this work to perform a "cradle-to-gate" life cycle analysis. The inventory analysis mainly uses primary data collected from a Portuguese ICB producing company, complemented with secondary data from a commercial life cycle databases and literature concerning respectively, the external transportation of the cork raw-material and the emission factors of electricity and fuel production and use. Results of this study show for the ICB a carbon footprint of -116.229 kg CO_2 equivalent per m^3 of ICB. It is the only insulation material present in the market with a negative carbon footprint, which is mainly due to the utilization of cork, a renewable raw material, the proximity of its source to the factory, and the use of biomass for generating the steam needed for the process.

From the knowledge about the properties of cork it was decided to use a waste of cork, in particular the cork powder, to try to solve the burning smell. It was then tried to find the most natural cork powder (the powder obtained with the fewest possible changes) in order to be as accurate as possible in the analysis that would be subjected. The process that was used to analyze the adsorption capacity of the cork powder to adsorbed aroma compounds (2-methoxy-4-methylphenol and 4-ethylguaicol that were present in the ICB), was the gas chromatography method, as it would be the most appropriate process to obtained the desired results. After several analyzes and conducting a graph of seven samples, it was possible to generate the calibration line only for the aroma compound 2-methoxy-4-methylphenol. For the 4-ethylguaiacol was not possible because the aroma did not reach the saturation point. However, it could thus be concluded that on the basis of the tests performed on cork powder, it has an adsorption power of about 95 %.

Keywords*:* Carbon footprint; Cork; Greenhouse gas emissions; Global warming; Insulation cork board; Gas chromatography; Aromatic compounds; Adsorption capacity; Cork powder

Resumo

Esta Tese de Mestrado teve por base dois desafios colocados pela empresa de aglomerados expandidos da cortiça (insolation cork board - ICB) (Sofalca, Sociedade Central de Produtos de Cortiça, Lda.), nomeadamente: (i) a avaliação do ciclo de vida do ICB; (ii) a caracterização do aroma característico do ICB e o uso do pó de cortiça para remover esse aroma.

Numa primeira etapa considerou-se importante calcular a pegada de carbono do ICB, e compará-lo com outros materiais de isolamento disponíveis no mercado. Uma abordagem da metodologia “Ciclo de Vida” e os requisitos ISO / TS 14067 foi seguido neste trabalho para realizar uma análise "do berço ao portão”. A análise do inventário utiliza principalmente dados primários coletados a partir da empresa produtora de ICB, complementados com dados secundários a partir de uma base de dados de ciclo de vida comercial e literatura relativas, respetivamente, ao transporte externo da matéria-prima da cortiça e aos fatores de emissão de eletricidade e combustível, produção e utilização. Os resultados deste estudo mostram para o ICB uma pegada de carbono de -116,229 kg CO_2 equivalente por m^3 de ICB. É o único material de isolamento presente no mercado com uma pegada de carbono negativo, que é principalmente devido à utilização de cortiça, uma matéria-prima renovável, a proximidade da sua origem até à fábrica, e a utilização da biomassa para gerar o vapor necessário para o seu processo.

Na continuação da investigação, efetuou-se um estudo com o fundamento de se encontrar uma solução viável para este problema, o que levou a encontrar na origem do produto, a cortiça, uma resolução para a solução do mesmo. Partindo do conhecimento relativo às propriedades da cortiça decidiu-se utilizar um desperdício de cortiça, mais propriamente o pó de cortiça para tentar resolver o então designado aroma a queimado. Tentou-se então encontrar pó de cortiça o mais natural possível (a obtenção deste pó teve por base o menor número possível de transformações) com o objetivo de ser o mais preciso nas análises a que iria ser sujeitado. O processo que foi utilizado para a análise de capacidade de adsorção pelo pó de cortiça para adsorver compostos aromáticos (2-methoxy-4-methylphenol e 4-ethylguaicol que estavam presentes no ICB) foi a cromatografia gasosa, visto que seria o processo mais adequado para a obtenção dos resultados pretendidos. Após várias analises e da realização de um gráfico

representativo de sete amostras, conseguiu-se realizar a reta de calibração para o composto aromático 2-methoxy-4-methylphenol. Para o composto aromático 4-ethylguaicol não foi possível realizar a reta visto que o aroma não conseguiu alcançar o ponto de saturação. No entanto, pode-se concluir com base nos testes efetuados de que o pó de cortiça tem um poder de adsorção na ordem dos 95 %.

Palavras-chave: Pegada de carbono, Cortiça, Gases de efeito de estufa, Aquecimento Global, Aglomerado Negro de Cortiça; Cromatografia gasosa; Compostos aromáticos; Capacidade de adsorção; Pó de cortiça

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List of abbreviations

APCOR - Association Portuguese Cork

CFCs – Chlorofluorocarbons

EPD – Environmental Product Declaration

EU – European Union

GC – Gas Chromatography

GHE – Greenhouse Effect

GHG – Greenhouse Gases

GW – Glass Wool

GW – Global Warning

HFCs – Hydrofluorocarbons

ICB – Insulation Cork Board

IPCC – Intergorvernmental Panel of Climate Change

LCA – Life-Cycle Assessment

LDPE – Low Density Polyethylene

LECA – Light Expanded Clay Aggregates

PAHs – Polycyclic Aromatic Hydrocarbons

PFCs – Perfluorocarbons

PU – Polyurethane

SW – Stone Wool

TCA – Trichloroanisole

XDS – Extruded Polystyrene

Chapter 1 - Introduction

The aim of this project is to analyse a building insulation material, ICB (insulation cork board), which has as a raw material, cork. In the process of preparing this material, it's used oak branches of the pruning of the oak tree and the corks that do not have the necessary conditions for the manufacture of the noblest product, the cork stoppers. During the preparation of the process of manufacture of the ICB, the materials are subjected to high temperatures, to allow the cork to agglomerate. Because of the use of the extracts of the oak branches, the extracts (cork fragments) combust, which causes the finished product to acquire an aroma of burning wood. Due to this problem, came the challenge, presented by the SOFALCA company, of trying to solve or present alternative resolutions for this aroma. The basis of this thesis holds up in the attempt to inhibit this aroma.

SOFALCA is a century old company that has a main business the manufacture of expanded cork agglomerate, commonly known as black agglomerated cork. This product, a result of the agglutination of the beads of the raw material that only takes place as a result of volumetric expansion and exudation of natural cork resins, by the action of temperature transmitted by a thermal fluid (steam). It is then produced an agglomerate, that in its constitution there isn't any glues or additives, solely made of cork, which is why also is known as pure agglomerated cork. Internationally and in current technical documentation, expanded cork agglomerate is often referred to by the acronym ICB, Insulation Cork Board (DAP 001, 2015). During the process of manufacture, the company is faced with a problem: due to the high temperatures at which the cork is subjected, the material combusts (due to the presence of small fragments of wood) resulting in a consequent aroma of burnt cork. This factor is problematic since the aroma resides, has this product is used in closed environments.

Therefore, this thesis is based on this problem posed by the company SOFALCA, with the aim of using an ecological method as a solution.

It was proposed for the solution of this problem the use of a so-called cork waste, more specifically cork powder. In particular the idea came from the knowledge of the use of cork powder to absorb the excessive aroma of "aroma bags".

SOFALCA also requested to calculate the carbon footprint of the ICB. And, since SOFALCA has an environmental product declaration (EPD) for the ICB, that report was a source of valuable information and real industrial data used to calculate the ICB's carbon footprint, analysing this way if the product meets all requirements to be considered a green product or not.

The so-called carbon footprint is a common indicator used by companies to assess and account for direct and indirect emissions of greenhouse gases (GHGs), during the life cycle of their products. It is expressed in kilograms of carbon dioxide equivalent per cubic meter of inventory life cycle (kg CO^2 eq/m^3 ILC) and the emissions can be calculated using mass balance or stoichiometric calculations (Amorim, 2013).

The carbon footprint is an increasingly consensual indicator, which can be calculated based on the life-cycle assessment methodology and following the ISO/TS 14067 requirements.

It will be important indeed to make a brief explanation of the cork manufacturing process based on a better understanding of the derivation of cork powder, as it is with this product that it was tried to solve the problem that has been posed by SOFALCA.

This thesis is introduced by two distinctive chapters, one to explain the process of the calculation of the carbon footprint of the ICB, and the other to explain the process of analyses of the cork powder as an aroma removal. They are represented this way because both are in format of an article. The article of the carbon footprint is already submitted to the scientific journal “Journal of Clean Production” and in a revision process, and the article of cork powder as an aroma removal is to further submit.

1.1. Objectives of this work

This work has the following objectives: i) use of life-cycle assessment methodology to calculate the carbon footprint of ICB; ii) compare the ICB with other insulation materials used in construction; iii) detection and identification of the aroma compounds present in the ICB; iv) analyse the adsorption of the aroma compounds present in the ICB by cork powder.

Chapter 2 - Literature review

2.1. Cork industry

2.1.1. The origin of cork

Cork comes from the oak tree, whose scientific name is *Quercus Suber L*., which is a kind of oak, dicotyledonous and angiosperm belonging to the genre *Quercus* and *Fagaceae* family (Silva, 2007). Ordinarily, cork is known as the bark of the oak tree.

The extraction of the cork of the oak tree is called "tiradira" or stripping, and is held manually by skilled operators. There are already stripping machines but they're still in the implementation phase, not being used in practice (Silva, 2007). Manual extraction is carried out with the aid of an axe and the cork is obtained in the form of curve and rectangular plates. The first extraction of cork, by law, can only be performed when the cork has 70 cm of perimeter at a height of 1.30 m from the ground, being these features available after approximately 25 years (Gil, 1998). The first cork obtained is called "virgin cork" and has a very uneven surface. The second stripping occurs past nine years and the cork obtained is called the "secundeira" (second) cork, with fewer irregularities than the virgin cork. The main product, where it is gathered the best characteristics for use, appears after the third stripping, and the product from then on is called "amadia" cork. Also, in this selection process, it is briefly review the diseases present on the board, such as spots. The spots can be yellow or blue. The yellow spot is supposed to be a lack of nutrients in the tree, although it was still not found a scientific evidence that can prove this theory. The blue spots represent excess of water near the area where the oak tree resides (Fortes et al., 2006).

The harvests are defined by law and must have a minimum of nine years between each one, and may be an exception of 7 or 8 years. DL nº 155/2004 of June 30th defines the rules for the protection of oak and holm oak. The time of stripping usually occurs between May and August (Silva, 2007).

34 % of the world area of oaks is located in Portugal, and more than 80 % is located in Alentejo. Figure 1 allows to check the global distribution and the national area distribution of the oak tree (APCOR, 2015).

ÁREA DE MONTADO DE SOBRO CORK OAK FOREST AREA

PAÍS COUNTRY	ÁREA AREA (HECTARES - HA)*	PERCENTAGEM PERCENTAGE
PORTUGAL	736.775	34%
ESPANHA SPAIN	574.248	27%
MARROCOS MOROCCO	383.120	18%
ARGÉLIA ALGERIA	230.000	11%
TUNÍSIA TUNISIA	85.771	4%
FRANÇA FRANCE	65.228	3%
ITÁLIA ITALY	64.800	3%
TOTAL	2.139.942	100%

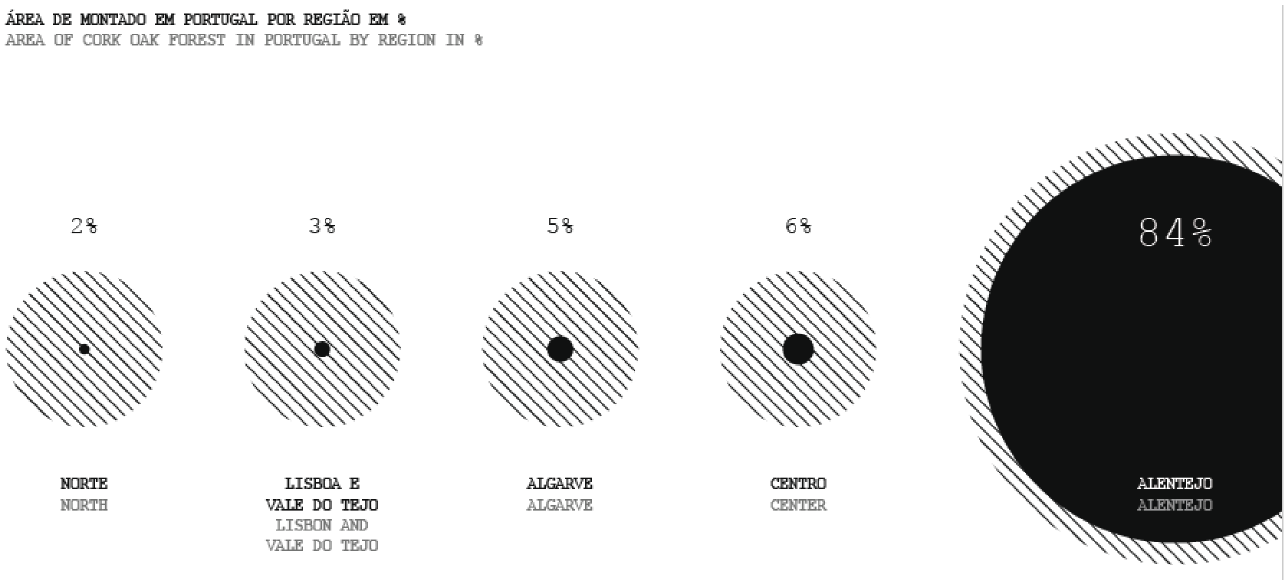
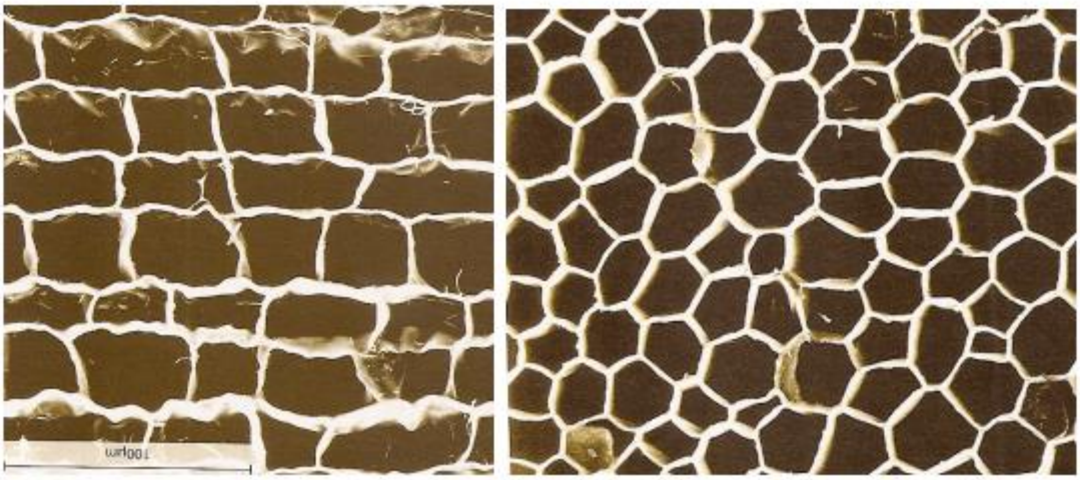


Figure 1 - Area of oak tree in the world and in Portugal by region in % (source: APCOR)

2.1.2. Chemical properties of cork

Cork exhibits some unique properties, due to its cellular structure and chemical composition (Conde et al., 1998), such as high coefficient of friction, resilience, imperviousness to liquids, low thermal conductivity, low density, high energy absorption, excellent insulation properties and resistance to fire, among others (Fernandes et al., 2010).

Cork is constituted of cells arranged compactly without free spaces and a regular form, and the cell wall consists of five layers. Both innermost layers are composed with suberine, that confer impermeability to cork, the intermediate layer is formed with lignin and it gives rigidifying and structure to cork and the two exterior layers form the cellular cavities (Gil, 1998). The cells have a form of pentagonal prism, and hexagonal sometimes. Its dimensions are 30 to 40 μm wide and between 35 and 45 μm height (Figure 2) (Pereira et al, 1987).



A B

Figure 2 – Cork's cellule; A – transversal cut; B – tangential cut (source: Pereira et al, 1987)

The structure of the cells constituting the cork is decisive for explaining the behaviour of the material. The cell wall consists of structural compounds which are not soluble in water. The main compounds of structural found are suberine, lignin and polysaccharides. Other substances are found in significant amounts, for example, pectins, terpenes, phenolics and lipids (Pereira, 2007).

Suberine is the main constituent of cork, corresponding to approximately half of its entire constituent material, being responsible for many of its features. Its monomer composition consists of fatty acids, fatty alcohols and glycerol (Pereira, 2007).

Lignin is the second most important structural compound in the cork (20 to 25 %). Due to its chemical structure, lignin is a hard, rigid polymer, which is responsible for the rigidity of the cell wall. It is hydrophobic and so the water absorption is very low (Pereira, 2007).

The polysaccharides account for approximately 20 % of the cork structure and are mainly cellulose, hemicellulose and pectins (Pereira, 2007).

Recently there have been new ideas for the use of cork as adsorbent. This particular feature could lead to its use in the extraction of compounds or in the adsorption of pollutants (Olivella et al., 2010).

Table 1 - Distribution of cork companies in Portugal in % (source: APCOR)

LOCALIZAÇÃO DAS EMPRESAS GEOGRAPHIC DISTRIBUTION OF THE COMPANIES

AVEIRO	ÉVORA	SETÚBAL	FARO	LISBOA	SANTARÉM	OUTROS | OTHER	TOTAL
220	16	13	7	5	2	5	268
82,09%	5,97%	4,85%	2,61%	1,87%	0,75%	1,87%	100,00%

2.1.3. The Manufacturing Industry

Nearly 75 % of the mounted area is situated in the south of the country, but about 82 % of the manufacturing is located in the North Central region, more specifically in the district of Aveiro. These data were obtained from the 2015 annual Association Portuguese Cork (APCOR) and refers only to their 270 associated companies. However, there are almost 650 companies on the cork industry in Portugal. Table 1 allows to view the distribution companies across the country (APCOR 2015).

2.1.4. Manufacturing Sectors

As already mentioned, the stripping should be conducted according to the DL nº 155/2004 of June 30th. After the harvest, the boards are stacked to ensure the stabilization of the cork, this being done according with the rules set by the International Code of Cork Stopper Manufacturing Practice (Cork Information Bureau, 2008).

According to this code, among other restrictions, the piles of cork shouldn't be in direct contact with the ground or with other materials that may contaminate the cork. The piles must be outdoors, to facilitate air circulation, and an inclined space, to allow the flow of water, and the rest time must be at least 6 months, advising the Code that the cork planks stabilize until the following winter of the “tiradia” campaign (Confédération Européene du Liège, 1999).

After the stabilization period, the cork planks undergo a process of cooking which aims to clean the cork, to extract water-soluble substances, increase thickness, reduce the density of cork and make it more soft and elastic. This one cooking process is carried out in water with a temperature of around 100 °C and a minimum period of one hour (Confédération Européene du Liège, 1999).

After the baking process, the planks have a further period stabilization, which should be between two and four weeks, and has an aim of flatten the planks and allow them to rest. After this process, it is considered that the cork already has the consistency required to be made into cork stoppers (Cork Information Bureau, 2008).

Finally, the cork planks are selected according to specific corks stoppers that are intended to produce.

After this preparation process, in addition to processing the boards, is obtained cooking scraps, shavings and waste, the latter two being used in the production of granulates (Forum Projecto, 2005).

2.1.5. Production of natural cork stoppers

The production process of cork stoppers consists essentially of the following processes - (Cork Information Bureau, 2008, Confédération Européene du Liège, 1999, Figueiredo, 2001):

- Rabaneação: process where the cork planks are cut with a width greater than the length of the stoppers manufacturing;
- Brocagem: Drilling process of cork strips made through a tube with dimensions slightly superior to the diameter of the stopper to be manufactured;
- Pre-drying: this process is to ensure the dimensional stability of stoppers before the rectification of their size;
- Rectification: process in which is obtained the specified dimensions and allows regularizing the surface of the stopper
- Selection: the process by which the stoppers are selected according to their quality ranging from Extra, Superior, 1st to 6th quality;

- Cleaning and drying: processes which involves the final cleaning operations, the drying process is also important to prevent a possible excess of moisture which makes the cork stopper more susceptible to microbiological contamination;
- Colmatagem: process of sealing the pores of the surface of the stopper;
- Marking: process in which the stopper is printed with a logo or other marking desired;
- Packing: process in which the stoppers are packed in plastic bags filled with SO_2, a microbiological proliferation gas.

2.1.6. Production of granulates

Granulates are made from virgin cork, bits, scrap, waste of other processing operations and “falca”, a mixed of virgin cork, inner bark and wood - the granulates can also be obtained by grinding or recycled stoppers (Figueiredo, 2001), (Chiebao, 2011).

The granulation process aims to produce granulates for marketing and as a product necessary for the production of agglomerates.

2.1.7. Production of pure agglomerate

The pure agglomerate or the black agglomerate is obtained by the assemblage cork with less quality as in the form of granulates. The agglutination occurs via volumetric expansion and the natural cork resin by the action of a heat transfer fluid that is usually water vapour in a temperature above 300 °C. In this type of agglomerate, it is not used any types of adhesives and / or additives, which means that this type of agglomerate is also called pure agglomerated cork (Chiebao, 2011).

2.1.8. Cork products

The main target sector of cork products is the wine industry which accounts for 70.1 % of what is produced, followed by the construction sector with 26.3 % - including floors, insulation and coverings, blocks, plates, sheets, strips and other cork products such as home and office decoration, raw material (3.6 %) (APCOR, 2015).

The cork stoppers are classified according to their quality, ranging from Extra, Super, 1st to 6th, and may be of natural cork or of agglomerated cork. The natural cork stoppers are obtained directly from natural cork board by drilling, and the stoppers agglomerated cork are obtained by agglomeration of waste from the production of natural cork stoppers (Forum Projecto, 2005).

The cork agglomerates are the second most important product in cork industry and can generally be divided into two groups: pure or black agglomerate and the agglomerate compound.

2.2. Climate change

In recent years there has been an increase in global temperature, compared to other phases of the Earth in the past. It is known that global warming is due to natural and anthropogenic causes, but recent studies show that the greatest influence on global warming that follows, comes from the emissions of greenhouse gas (GHG) emissions of anthropogenic origin (EEA, 2009).

Climate change is one of the current threats to sustainable development, calling into question not only the natural balance, but also the security of most of the population.

The main causes of climate change are caused from the increasing of a set of concentrations of gases emitted by human activity, that interfere with normal patterns of radiation energy exchange between Earth and space, a phenomenon called "greenhouse effect".

Over the years, many scientific studies have demonstrated that the human action has changed atmospheric concentrations, spatial distribution and life cycles of the greenhouse gas effect. Despite some uncertainties, there are facts undeniable: carbon dioxide levels in the atmosphere is increasing exponentially and reached never before so high values (Borrego et al, 2010).

Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. The period from 1983 to 2012 was likely the warmest 30-year period of the last 1400 years in the Northern Hemisphere, where such assessment is possible. The globally averaged combined land and ocean surface temperature data, as calculated by a linear trend, show a warming of 0.85 [0.65 to 1.06] °C, over the period between 1880 to 2012 (IPCC, 2015).

2.2.1. Climate

Earth's climate is determined by the constant flow of energy between the sun and the planet's surface. The sun emits electromagnetic radiation like a black body, at a temperature of about 5726.850 °C according to Planck's Law, and about 99 % of the radiation emitted corresponds to wavelengths between 0.15 to 4 μm with maximum intensity in the visible region (Peixoto, 1981).

The atmosphere weakens the solar beam by absorption, scattering and reflection. About 30 % of solar radiation is immediately reflected back into space. The remaining power enters the atmosphere and is differentially absorbed. A fraction of ultraviolet (UV) radiation of short-wavelength (less than 0.29 μm), is partially filtered in the stratosphere, due to the presence of ozone, so the radiation reaching the Earth's surface is predominantly visible. The solar energy that reaches the Earth's surface is absorbed into the soil, water and air, being converted into heat by increasing surface temperature or evaporation/evapotranspiration, or converted into mechanical, electrical or chemical energy (Alexandra et al, 2004).

A part of the absorbed energy is, however, transferred into space, but with the temperature Earth's surface fluctuate between 6.85 to 26.85 °C, this issue is made mainly in the form of long-wave radiation, or infrared. By crossing through the atmosphere, as it does not behave as a black body radiation, infrared is partially absorbed by the gases existing in the atmosphere. Carbon dioxide (CO_2) and steam (H_2O) are the major absorptive gases, however being transparent to radiation in the range from 8 to 13 μm. While other air pollutants also absorb infrared radiation emitted by the Earth, part of the energy escapes to the atmosphere through the "window" of 8 to 13 μm (Peixoto, 1981).

This radiative balance between the radiation reaching the globe and that is sent back to space, results in a surplus of energy that is responsible for temperature surface average of 15 ºC. It is estimated that in the absence of this phenomenon, greenhouse effect (GHE), the average surface temperature would be lower than 34 °C of the present day (UNEP / IUC, 1997).

2.2.2. Greenhouse effect

The GHE makes the atmosphere opaque to infrared radiation, allowing solar radiation of other wavelengths to enter the atmosphere, but any radiation of the infrared zone, issued by Earth's surface (by interaction with the solar radiation that strikes it) is retained in the atmosphere, causing a warming of the same. The greenhouse is what allows the Earth to have favourable living conditions, but in cases of excessive efficiency becomes impossible to inhabit (IPCC, 2001).

The concentration of greenhouse gases (GHG) is therefore the most important factor in regulating the climate and the occurrence of climate change, although the astronomical, geological factors (ex.: the change of the geometry of the oceans and associated ocean circulation due to the tectonic plates), biological and intrinsic variability atmospheric systems also play an important role in the genesis of these changes (IPCC, 2001).

The CO_2, methane (CH_4) and nitrous oxide (N_2O) gases are the major gases identified as responsible by the increasing of the greenhouse effect and represent 99 % of anthropogenic GHG emissions (IPCC, 2007). However, there are other GHGs also relevant, in particular the compounds halogenated (hydrofluorocarbons - HFCs, perfluorocarbons - PFCs and sulphur hexafluoride - SF_6), which they have contributed to the increase of global warming. HFCs and PFCs are produced as alternative products that deplete the ozone layer (chlorofluorocarbons - CFCs), while the SF_6 gas has the higher global warming potential (GWP), and it is widely used in the transmission and distribution of electricity systems (IPCC, 2007).

Since 1750 the concentration of CO_2 in the atmosphere has increased, and extending the observation period to the paleo-climate record of the last 420000 years, it is found that the current CO_2 concentrations are the most elevated, there are indications of the highest in the last 20 million years (IPCC, 2001). Geological and astronomical records are not deducted to any known natural causes that may justify all of this increase; however, since 1750 there has been a growing increase in fuel burning fossil and deforestation, and SIAM studies (2001) suggest that the increased CO_2 concentration is largely due to the burning of fossil fuels. Its evolutionary trend is shared by the other greenhouse gases.

The increase of GHG emissions is due, largely, to the use of fuels fossils, although deforestation, changes in land use and agriculture also provide their significant contribution, although smaller. CO_2 is the primary product of all combustion reactions and later the GHG are emitted in greater quantity to the atmosphere. The main CO_2 sinks are plants and oceans, which prevents the pollutant levels to increase even more (Teixeira, 2012).

Among other consequences of climate change include changes in patterns of precipitation, the rise of global average level of the sea because of the melting of snow and ice cases, the decline in the extent of coverage in the Arctic ice sea, increasing the risk of flooding in urban areas and ecosystems, ocean acidification and occurrence of extreme weather events, including heat waves (IPCC, 2007). Furthermore, in many cases, the flow of the rivers changed, especially in the snow fed rivers or glaciers. It is expected that the impact of climate change is felt in all regions of the world, and Europe is no exception. Unless action is taken, it is expected that climate change will lead to significant adverse impacts (Teixeira, 2012).

Due to these facts, it was necessary an action at global level to limit emissions of greenhouse gases.

A series of events began with the Toronto Conference on the Changing Atmosphere in Canada (October 1988), followed by the IPCC's First Assessment Report in Sundsvall, Sweden (August 1990) and culminating in the United Nations Framework Convention on Change climate (UNFCCC) in ECO-92 in Rio de Janeiro, Brazil (June 1992), which resulted in the Kyoto Protocol (Teixeira, 2012), the legal tool with more impact in the fight against climate change. Under this protocol, some of the industrialized countries, including Portugal, have committed to decrease their GHG emissions. The Kyoto Protocol addresses the issue of six gases that contribute to greenhouse effect, promoting their monitoring focus on gases like CO_2, CH_4, N_2O, HFCs, PFCs and SF_6 (APA, 2011).

Portugal signed the Kyoto Protocol on 31th May of 2002 and assumed the decreasing, between 2008 and 2012, of 27 % of GHG emissions related to 1990 (APA 2011). However, the emissions were higher than established, with a growth of 3 % per year by 2005 (APA 2011). In 2008 it has been found that GHG emissions were 30 % higher than 1990 (reference year). The mainly responsible for this increase sectors, totalling about 50 % of total GHG emissions were the manufacturing and production energy sectors (24.8 %) and transport (24.3 %) (REA 2009).

The latest European Union (EU) efforts have been towards finding a new agreement to continue the Kyoto Protocol and with a more ambitious and comprehensive commitment. Therefore, it was established the strategy "20-20-20 in 2020 ", which aims at a minimum 20 % reduction of CO_2 emissions (30 % if it reaches international agreement about the overall goals), the establishment of a binding target of 20 % for the use of renewable energy sources and increasing energy efficiency by 20 %, with order to limit the increase in global warming to 2 °C (Borrego et al, 2010).

2.2.3. Carbon footprint

Due to the problem of climate change, caused mainly by high harmful emissions to the environment, today many companies already account for their emissions of greenhouse gases, thus evaluating the environmental impact of their activity. To perform this evaluation is increasingly common to use the concept carbon footprint, which allows to analyse the direct and indirect emissions of greenhouse gases produced during the life cycle of an activity.

Although a clear definition of carbon footprint is not available in literature, some authors (Wiedmann, 2008) defined it by the total emission amount of carbon dioxide that are generated direct and indirectly by an activity (carbon footprint of an activity) or which is accumulated during the life cycle of a product (carbon footprint of a product) (Wiedmann, 2008). This definition focuses only on the emission of carbon dioxide does not accounting for other GHGs. There are however, other authors who rate a large number of GHGs. An example of an alternative definition is from the Carbon Trust (2007), that states that this is a methodology used to estimate the total GHG emissions expressed as carbon equivalent, of an activity or product, throughout its life cycle.

Just as there is no unanimity with regard to the concept of the carbon footprint, the same happens in the field of methodology to be followed for the calculation of their value. Thus, there are various methodologies that can be used to calculate the carbon footprint.

With regard to the most common methodologies, there hare the DEFRA methodology (Department for Environment, Food & Rural Affairs), the PAS 2050 methodology (Public Available Specification 2050) and the GHG Protocol methodology (Greenhouse Gas Protocol).

The DEFRA methodology's main function is to support UK organizations to reduce their contribution to climate change, reducing directly or indirectly the emission of greenhouse gases. The procedure adopted is based on the specific emission factors from the UK and available for public consultation, a spreadsheet where you can simulate either for a company or an individual, the corresponding carbon footprint (DEFRA, 2009).

The methodology PAS 2050 was developed by the British Standards Institution (BSI) and is co-sponsored by the Carbon Trust and DEFRA (BSI, 2008). This procedure, introduced in 2008 and revised in 2011, was developed in order to provide a consistent method for the assessment of the carbon footprint of the product, analysing the emissions of greenhouse gases (WBCSD/WRI).

Finally, the GHG methodology provides standards and guidelines for companies and organizations on emissions of greenhouse gases, in particular those covered by the Kyoto Protocol, such as CO_2, CH_4, N_2O, HFCs, PFCs and SF_6 (WRI/WBCSD). This methodology was developed based on a partnership between the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), in order to provide companies with ways to reduce their contribution to climate change (WRI/WBCSD). As the DEFRA methodology, this methodology also provides for public consultation a spreadsheet where you can calculate the carbon footprint.

However, for this paper it was used the life cycle methodology with the requirements of the ISO/TS 14067, which analyses the product since “cradle-to-gate”.

Chapter 3 - Carbon Footprint of the Insulation Cork Board

3.1. Framework

The cork oak tree (Quercus Suber L.) is a long-lived specie (250-350 years) of oak with an outer bark that is used since the classic antiquity for several applications (Perreira, 2007). It is native to the western Mediterranean region and well adapted to the region climate conditions, avoiding desertification and being the perfect habitat for many species of plants and animals (PwC, 2008), including many rare and endangered species such as the Iberian Lynx. The cork oak forest has been reported as sustainable in several studies (Gil, 2013; Barreca and Fichera, 2016), with a good potential for CO_2 capture and sequestration (Gil, 2015). Every 9-14 years, depending on the region and climatic conditions, cork is extracted from the tree, a process that does not harm the plant. This operation stimulates the rapid growth of new bark by the tree, increasing the production of cork by 3.5 to 5 times, while increasing the fixation of CO_2 (Gil, 2013). More than 80 % of cork is produced in the European Union (EU), in particular in western Mediterranean countries. Portugal is the world's largest producer with more than 50 % of the world's cork processed (Gil, 2013), being relevant from an economic point of view. The cork material has interesting properties such as impermeability, lightness, slow burning, durability, thermal and acoustic insulation, shocks and vibration control. These properties make cork a versatile material for use in many applications (Gil, 2009). Cork-based products range from the traditional cork stoppers for wine bottles to more advanced applications in a wide range of industrial and technical areas such as for insulation (Silva et al., 2005).

In the EU the energy consumption in buildings accounts for about 40 % of total energy consumption (Directive 2010/31/EU), half of that is used in space acclimatization and lost to the environment (Gil, 2013). Thus, the importance of insulation materials for buildings and industrial facilities is increasing, aiming to improve the energy efficiency and reduce the environmental impact of building utilization. Insulation Cork Board (ICB), also known as black expanded cork board, has an important role to play since it has a thermal conductivity coefficient of 0.045 W/m.°C (Matias et al., 2007). ICB is produced from the expanded cork agglomerate, commonly known as black expanded cork, and sold as insulation boards of different thicknesses depending on their final application. It is increasingly used in the construction of buildings due to its excellent insulation characteristics, which can be even better that those of natural cork (Barreca, and Fichera, 2016). Also, it is a renewable material, made with low value cork or forestry residues, obtained from the periodic pruning of cork trees, by removing the bark from the cork tree's branches.

For the manufacture of ICB only cork granules are used as raw-material, without the need of adding any binding agent necessary to obtain other agglomerated cork boards. Thus, ICB is a totally natural product, completely recyclable, and durable. Some sampling and testing of insulation corkboard used in buildings for 30-50 years showed that its look and essential properties did not changed significantly with time (Gil, 2013). Based on the above-mentioned characteristics and the guidelines for sustainable products (Allione et al., 2012), it may be assumed that ICB is a green and sustainable solution for the thermal insulation of buildings, considering that it does not exceed the natural regeneration capacity of the cork tree.

Despite the advantages of ICB, the European market for insulation materials is still dominated by the inorganic fibrous materials for insulation (with about 60 % of the market) such as the stone wool (SW) and glass wool (GW), followed by the organic foamy materials (with about 30 % of the market), such as the expanded polystyrene (EPS), extruded polystyrene (XPS) and polyurethane (PU). The remaining market share is composed of other materials, such as the light expanded clay aggregates (LECA), agglomerate cork boards, kenaf-fibres, jute, cotton, hemp, flax, among others (Sierra-Pérez et al., 2016). Current construction habits and practices, and the lack of quantitative information concerning the environmental performance justify the low market share of more adequate options. To fulfil this gap, the European Union is promoting the utilization of common schemes for the eco labelling of construction materials, including the Environmental Production Declaration (EPD) among other possibilities (EU, 2004). Some of the companies involved in the production of the most common insulation materials have developed and published their respective Environmental Product Declarations (EPD). However, no study has performed a comparison on the environmental implications of the several alternatives present in the market. Also, very few studies have been published on the environmental aspects of the agglomerate cork boards for the building sector (Sierra-Pérez et al., 2016), in particular ICB (Silvestre et al., 2016). To the authors' knowledge, this is the first study to report the carbon footprint of an ICB and compare it with other common insulation materials. In the Portuguese context, one Environmental Product Declaration (EPD) of ICB was already published (DAP 001, 2015) and Silvestre et al. (2016) performed a life-cycle assessment (LCA) study of ICB. Gil (2013) discussed the sustainability and environmental aspects related with ICB, enumerating several of its main characteristics. Matias et al. (2007) determined experimentally the thermal conductivity coefficient of ICB (0.045 W/m. °C) for the thermal insulating of buildings. In the Spanish context, Sierra-Pérez et al. (2016) performed an environmental assessment of a competing product for ICB, the white agglomerate cork board, which is produced differently. It uses a synthetic binder of the cork granules, such as polyurethane, while the ICB is exclusively made of cork expanded into autoclaves (using steam at >300 ºC) and agglomerated together by pressure without the addition of any synthetic binders.

This paper calculates the CF of the ICB produced by a Portuguese company, following a life cycle approach and the ISO/TS 14067 requirements. Therefore, a "cradle-to-gate" life cycle analysis was developed (Mata et al., 2005), considering the following steps: growth of cork trees, pruning of cork tree's branches, cork extraction from the tree's branches, transportation of cork to the factory site, milling and cleaning of cork to produce cork granules, autoclaving of the cork granules to produce a block of expanded cork, steam production to this process, cutting of the cork block into boards with different thicknesses, ICB packaging, transportation of residues to final disposal and transportation of materials and product inside the factory. The life cycle steps of ICB usage and final distribution are not included in this study, in order to ensure an objective comparison with the other insulation materials available in the market (EPS, XPS, PU, SW and LECA), since their EPDs are also based on a "cradle-to-gate" analysis.

3.2. Methods

Several CF assessment standards/methodologies were proposed in the last years by several national or international organizations, in particular: the ISO technical specification ISO/TS 14067 (ISO, 2013), the GHG Protocol Product Standard (WRI, 2011) and the PAS 2050 (BSI, 2011). All three are similar, and in particular, are based on a Life Cycle Thinking Approach, and differ mainly on how certain types of emissions are taken into account and the requirements for reporting.

In this work the ISO/TS 14067 is used to quantify the CF of ICB. This technical specification presents specific requirements and guidelines on how to quantify and communicate the CF of products, and it is based on the existing ISO 14040 and ISO 14044 standards of Life Cycle Assessment (ISO, 2006a, b) and on the ISO 14021 and ISO 14025 standards of Environmental Labels and Declarations (ISO, 2000; ISO 2006c). Moreover, this allows a more objective comparison between the CF of ICB and other insulation materials, as the data used will be obtained from EPDs that comply with the ISO standards. No Product Category Rules applicable to this product were found in the literature (Environdec, 2016).

3.2.1. Scope

ICB is the product system for which the CF will be calculated, based on a cradle-to-gate system. The main goals of the study are threefold:

- To calculate the CF of ICB produced at a Portuguese company, allowing it to be proactive regarding the European environmental regulations,
- To inform customers on the environmental performance of the ICB, thus supporting more environmentally friendly buying decisions;
- To compare the ICB's CF with other insulation materials available in the market.

3.2.2. Functional unit

The functional unit chosen for this study is defined as 1 m^3 of ICB produced, as it is the common unit used by the insulation materials' industry for benchmarking and marketing purposes. As this work entails a comparison between different product systems with the same function, a reference flow should be defined according to ISO/TS 14067 (section 6.3.3). For this system, the reference flow is equivalent to the functional unit, as the carbon footprint is determined based on the total amount of final product, and the same basis should be used for the comparison. The average density of ICB is about 115 kg/m^3 and a common ICB, of 50 mm thick, has a thermal resistance of R = 1.25 $m^2.K/W$ (Gil, 2013).

3.2.3. Reference year for the study

The inventory analysis and data calculation presented in this work were based on a typical annual industrial production of ICB. In this case, the year of reference chosen is 2010.

3.2.4. System boundary definition and process description

In Figure 2 shows the system boundary considered for this study, including the ICB's life cycle steps from growth of cork trees, pruning of cork tree's branches, to cork extraction from the tree's branches, transportation of cork to the factory site, milling and cleaning of cork to produce cork granules, autoclaving of the cork granules to produce a block of expanded cork, steam production to this process, cutting of the cork block into boards with different thicknesses and ICB packaging, transportation of residues to final disposal and transportation of materials and product inside the factory.

The life cycle of ICB starts with the growth and caring of cork trees. During its growth, CO_2 is captured by the tree. ICB is manufactured with cork granules obtained from the pruned branches of the cork oak tree. Each year the cork tree branches are pruned and the cork strips are separated from the wood. Pruning is normally performed using a mechanical chainsaw (running with gasoline), and the cork is extracted from the tree branches using a mechanic equipment (running with diesel fuel), sometimes complemented manually. As a result of this operation it is obtained the raw material for the ICB, commonly named as "falca" that is transported to the factory site, and the leftover firewood is sold for other purposes. "Falca" is not pure cork, but contains small pieces of wood that are difficult to separate from the cork strips. Therefore, "falca" cannot be used in more noble and high value applications such as bottle stoppers (Barreca and Fichera, 2016).

At the factory site, the cork strips are conveyed to the feed hopper of a grinding equipment (working with diesel fuel) and it is processed through a series of crushers, mills and sieves (running with electricity). After grinding and partial cleaning of “falca”, it is obtained the cork granules (in the range of 5-20 mm), residual biomass (mainly cork and wood powder) that will be burned for heat and steam production in a furnace, and soil/sand that is transported by diesel vehicles to be disposed-off in the fields surrounding the factory, as it represents an inert residue and helps restoring and/or improve the soil in the vicinity.

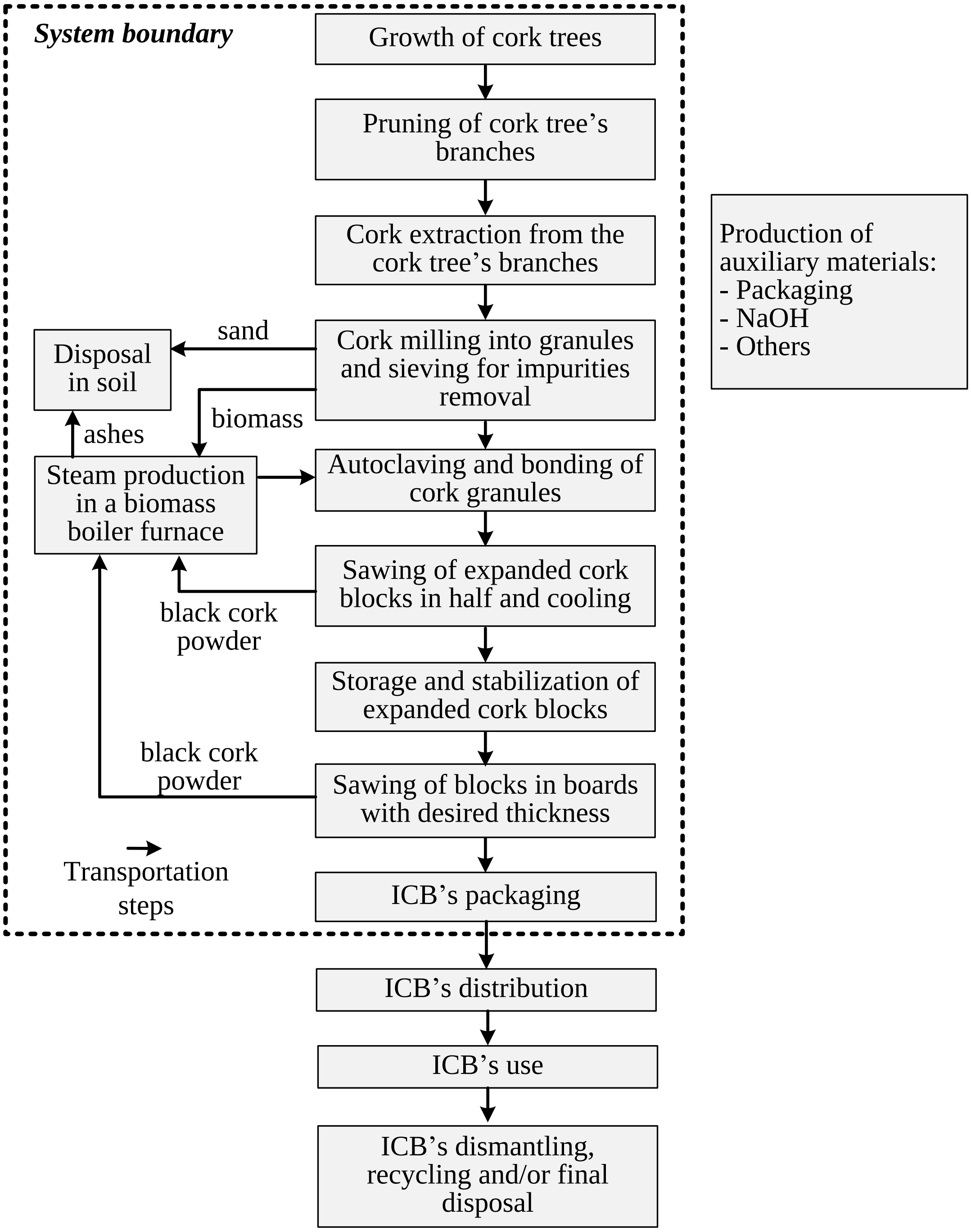


Figure 3 - System boundary definition for the ICB's life cycle study

Then, the cork granules are placed into autoclaves that are closed and the granules undergo pre-compression followed by steaming at 300-350 °C and 30-60 kPa. This way, the particles are expanded and self-bonded with their natural resins, without the need of external adhesives. When the autoclave is open the output is a block of cork agglomerate (with the parallelepiped shape of the inside of the autoclave) and gaseous emissions. These gaseous emissions are monitored every six months by an independent certified laboratory and were quantified for this study purpose.

The expanded cork block coming out from the autoclave is sawed in half and cooled in a water shower at about 100 °C (which is reused by recirculating). The blocks are then placed in a storehouse where they are left for stabilization for 15 days. The global inputs to the autoclave process are granulated cork, steam and electricity. The outputs are stabilized cork block, cooling water, black cork sawdust and gaseous emissions.

The steam for the autoclaves is produced in the biomass boiler furnace that is fed with water taken from a local well (using an electric pump). In the furnace, it is burned the residual biomass resulting from the factory internal processes of milling (cork and wood powder) and sawing (black cork powder). The gaseous emissions from the furnace are monitored twice a year by an independent certified laboratory. The ashes produced in the furnace are quantified and transported by tractor and disposed-off in the fields surrounding the factory.

After stabilization, the cork blocks are transported by diesel vehicles to the place where they will be rectified (cut) to the exact measures of 1000 x 500 x 300 mm, after which they are sawed into boards (ICB) with thicknesses depending on the customer requirements and intended final application. In this process electricity is used for the saws and the black cork sawdust generated is recovered to be burned into the biomass boiler. The rejected pieces of expanded black cork are internally recycled to produce other products.

The ICB produced is packed using a low-density polyethylene film (LDPE), consuming electricity. Depending on the customer's specific requirements part of the ICB is packed in cardboard, and then it is placed in wooden pallets for shipment.

Geographically, the study covers the northern Ribatejo region of Portugal, in the vicinity of the Tagus River, where the cork raw material is collected in a radius of 30 km from the ICB producing company.

As shown in Figure 2, the life cycle stages that are excluded from this study include: ICB distribution, ICB utilization, final disposal and the production of auxiliary materials (e.g. packaging). Following the standard ISO/TS 14067 (section 6.3.4) a critical analysis of the reasons for not including these steps should be done. First of all, one of this study main goals is to compare the CF of ICB with the CF of other insulation materials using the values presented in their respective EPDs. In most of them, and in particular those considered in this work, the CF values are reported for a cradle-to-gate system. Thus, a meaningful and fair comparison is only possible if the same life cycle steps are considered. Moreover, the information concerning the remaining stages is limited and even non-existent. Concerning distribution, ICB is used in construction or refurbishment projects worldwide. Without market information, it is not possible to have an estimate of the average travel distance and dominant mode of transportation. Furthermore, for the utilization step no significant emissions of GHG are expected, as the material is normally used between layers, inside the building walls, in a way that it is not exposed to the environmental conditions. For the end of life step three scenarios are possible: recycling, landfill deposition or incineration. The first two options imply that part of the carbon stored in the ICB will be permanently sequestered, while the third implies that the carbon will be released to the atmosphere. However, no information about the end of life step of ICB and the corresponding carbon emissions is available in the literature.

3.2.5. Inventory analysis, data sources and main assumptions

This study covers the ICB's life cycle, from cradle-to-gate, i.e. from the cork oak growth, through pruning of the tree branches, cork extraction from the branches and its transportation to the factory site, the ICB production and packaging. Excluded from the study are the life cycle steps of the ICB distribution, use and final disposal or material recovery and the production of auxiliary materials.

The production of transportation fuels (gasoline and diesel) and electricity is considered in the study. The production of auxiliary materials, such as packaging materials and others, which accounts for less than 5 % of the materials used in the process, is not considered within the system boundary. Here the 5 % cut-off rule was applied because these auxiliary processes contributes with less than 5 % of mass and energy of the total, while having a low toxicity effect (Klöpffer and Grahl, 2014).

The data used for the inventory analysis regarding the core processes, in particular those concerning the ICB production, was gathered in the Portuguese ICB producing company (primary data). In this case, no allocation procedures were necessary, as the object of study is a single product system and there is no recycling of used ICB.

Data concerning the transportation of “falca” to the factory site (e.g. the average distances travelled) and the fuel consumption inside the factory was estimated considering that for small distances, of about 10 km, the transportation of “falca” is done using a tractor with trailer, and for larger distances of about 30 km, a truck of 16-32 t capacity is used. The transportation of the pruned tree branches inside the cork tree's forest is considered to be done by agricultural tractor. Both the tractor and truck use diesel fuel. The emission factors (secondary data) considered for the fuel consumption in the transportation of the pruned tree branches and “falca” were obtained from the EcoInvent V2.1 database integrated in the SimaPro 7.3 software, and from Barber et al (2008) and EUCAR/CONCAWE/JRC (2008), concerning the “well-to-wheels” data on diesel fuel production. Care was taken to ensure that the emission factors are based on the same impact assessment methods.

The emission factors (secondary data) considered for the fuel consumption in the gasoline powered chainsaws, used for pruning of cork trees, and in the diesel fuel machines, used for removing cork from the tree branches, were obtained from the Intergovernmental Panel on Climate Change (IPCC) report concerning fuel consumption in stationary machines (IPCC, 2006a).

The emission factors (secondary data) considered for the transportation, inside the factory, of “falca” to the feed hopper of the grinding equipment were obtained from the IPCC report on non-road mobile sources for construction and industrial equipment (IPCC, 2006b).

The emission factors considered for the transportation of sand and ashes from the production plant to disposal in the fields surrounding the factory and the internal transportation of the ICB blocks were obtained from the IPCC report on non-road mobile sources for farm equipment (IPCC, 2006b).

The emission factor considered for the electrical energy production (0.16139 kg CO_2/kWh) was obtained from the Portuguese electricity company available in its website (EDP, 2016)

Data concerning the amount of CO_2 embodied in the ICB (expanded black cork) was obtained from Gil et al. (2011), equal to 272.186 kg CO_2 per m^3 ICB. This value is estimated based on the experimental determination of the ICB carbon content (64.55 wt%) and multiplied by 44/12 to obtain the CO_2 emissions, considering an average density of ICB of about 115 kg/m^3.

Data concerning the amount of CO_2 embodied in the raw cork during the cork tree growth was obtained from Gil et al. (2007), equal to 454.942 kg CO_2 per m^3 cork. This value is estimated based on the experimental determination of the virgin cork carbon content (55.14 wt%) and multiplied by 44/12 to obtain the CO_2 emissions, considering an average cork density of about 225 kg/m^3.

The gaseous emissions generated in the ICB production process (in the biomass boiler furnace and in the autoclave) were monitored every six months by an independent certified laboratory and were quantified for this study. The estimated net CO_2 emissions in biomass furnace were neutral (zero) because the amount of CO_2 emitted equals the amount of CO_2 absorbed in the biomass that was burned, so that the balance is zero. This estimation of zero CO_2 emissions is also according to the IPCC's rules (Amous, 2006).

The net equivalent carbon emissions for the other common insulation materials available in the market (EPS, XPS, PU, SW, and LECA) were obtained from their Environmental Product Declarations (EPDs), in which the reported results are based on a LCA study. To ensure an objective comparison only EPDs based on "cradle-to-gate" systems were considered. Thus, the life cycle steps of ICB distribution, use and end-of life (final disposal, reuse or recycled) are out of this study scope. Therefore, the net equivalent carbon emissions for EPS were obtained from the EPD-EPS-20130078-CBG1-EN (2013), for XPS were obtained from the EPD-EXI-20140155-IBE1-EN (2014), for PU from the EPD-PUE-20140017-CBE1-EN (2014), for SW from the EPD-DRW-2012111-EN (2012) and for LECA from the EPD 00120 rev1 (2013).

3.3. Results and Discussion

3.3.1. ICB's energy consumption and carbon footprint

In Table 2 shows the inventory data with all the relevant inputs and outputs, in particular the energy consumption and the GHG emissions associated to the ICB's life-cycle steps. As shown in Table 2 the energy consumption in the internal transportation (inside the factory site) of materials, residuals and product, represents about 38 % of the energy consumption in the external transportation of "falca" from the oak tree fields to the factory site. Also, the CO_2 emissions associated to the internal transportation are about 28 % lower than those associated to the external transportation. The GHG emissions occurring as a result of Direct Land Use Changes (DLUC) or Indirect Land Use Changes (ILUC) must also be accounted for, according to ISO/TS 14067 (section 6.4.9.4). In this study, they are considered to be zero, as the cork extraction does not involve cutting the tree, the soil is not plowed and no fertilizer is used.

Table 2 - Energy consumption and GHG in the ICB's life cycle

Energy consumption and GHG emissions in the ICB's life cycle steps	
Growth of cork trees	
CO_2 embodied in the ICB, kg CO_2/ m^3 ICB	-272.186
Pruning of cork tree's branches	
Gasoline consumption in chainsaws, kg gasoline/ m^3 ICB	0.949
Emissions "well-to-wheel" for pruning, kg CO_2 eq./ m^3 ICB	3.670
Cork extraction from cork tree's branches	
Diesel fuel consumption in cork extraction machines, kg diesel/ m^3 ICB	33.296
Emissions "well-to-wheel" for cork removal, kg CO_2 eq./ m^3 ICB	142.174
Transportation of "falca" to the factory site	
Diesel fuel consumption in tractor and truck, kg diesel/ m^3 ICB	1.574
Emissions "well-to-wheel" for transportation of "falca", kg CO_2 eq./ m^3 ICB	6.722
Cork milling into granules and sieving for impurities removal	
Electricity consumption for milling and cleaning, kWh/ m^3 ICB	6.434
Emissions from electricity generation in Portugal, kg CO_2 eq./ m^3 ICB	1.038
Transportation by truck of sand to disposal in soil	
Diesel fuel consumption in transportation of sand, kg diesel/ m^3 ICB	0.030
Emissions "well-to-wheel" for transportation of sand, kg CO_2 eq./ m^3 ICB	0.095

Steam production in a biomass boiler furnace	
Cork powder to be burned, kg/ m^3 ICB	157.961
Black cork powder to be burned, kg/ m^3 ICB	10.990
Emissions from burning biomass for steam production, kg CO_2/ m^3 ICB	345.404
CO_2 absorbed in the biomass burned for steam production, kg CO_2/ m^3 ICB	-345.404
Transportation by truck of ashes and particles to disposal in soil	
Diesel fuel consumption in transportation of ashes, kg diesel/ m^3 ICB	0.059
Emissions "well-to-wheel" for transportation of ashes, kg CO_2 eq./ m^3 ICB	0.191
Transportation of cork granules to autoclaving	
Diesel fuel consumption in transportation machines, kg diesel/ m^3 ICB	0.267
Emissions "well-to-wheel" for transportation of cork, kg CO_2 eq./ m^3 ICB	0.857
Autoclaving, sawing in half, and cooling of expanded cork blocks	
Electricity consumption for autoclaving, kWh/ m^3 ICB	1.109
Emissions from electricity generation in Portugal, kg CO_2 eq./ m^3 ICB	0.179
Transportation of expanded cork blocks for rectification and sawing	
Diesel fuel consumption in transportation of cork blocks, kg diesel/ m^3 ICB	0.178
Emissions "well-to-wheel" for transportation of blocks, kg CO_2 eq./ m^3 ICB	0.573
Rectification and sawing of blocks in boards with desired thickness	
Electricity consumption for rectification and sawing, kWh/ m^3 ICB	0.016
Emissions from electricity generation in Portugal, kg CO_2 eq./ m^3 ICB	0.003
De-dusting	
CO_2 emissions in de-dusting, kg CO_2 eq./ m^3 ICB	0.007
Internal transportation of ICB for packaging	
Diesel fuel consumption in transportation of ICB, kg diesel/ m^3 ICB	0.059
Emissions "well-to-wheel" for transportation of ICB, kg CO_2 eq./ m^3 ICB	0.191
ICB's packaging	
Electricity consumption in packaging, kWh/ m^3 ICB	1.597
Emissions from electricity generation in Portugal, kg CO_2 eq./ m^3 ICB	0.258

Table 3 summarizes the contribution to global warming (GW) of the various ICB's life cycle steps. Bold value represents sum of non-bold values directly above. Table 3 shows that the ICB's life cycle has negative net CO_2 emissions of -116.229 kg CO_2 eq/ m^3 ICB. The total life cycle CO_2 emissions are 155.957 kg CO_2 eq./ m^3 ICB and the CO_2 embodied in the ICB is -272.186 kg CO_2/ m^3 ICB. Table 3 also shows that pruning and cork extraction are the life cycle steps with the largest relative contribution to global warming, corresponding to about 93.5 % of the total. This is because the separation of cork from the tree's branches is an energy intensive step. Also, it shows that the transportation steps (to and inside the factory) have a relative contribution to GW of about 5.5 % and that the ICB production has the lowest relative contribution of about 1 %. This low value for the ICB production is explained because although steam is produced in the process, the boiler furnace uses residual biomass, generated in the ICB production process, hence with zero net carbon emissions according to the IPCC's rules (Amous, 2006).

Table 3 - ICB's Carbon footprint

ICB's life cycle steps	**Contribution to Global Warming or Carbon Footprint (kg CO_2 eq./ m^3 ICB)**
CO_2 embodied in the ICB, kg CO_2/ m^3 ICB	-272.186
Pruning and cork extraction from tree's branches	145.843
Transportation of cork to the factory site	6.722
Transportation inside the factory	1.906
ICB production	1.485
Net CO_2 equivalent emissions	**-116.229**

ISO/TS 14067 also requires that the sources and sinks of biogenic carbon are identified and quantified separately (section 6.4.9.2). Thus, for the product system under study the main source of emissions is the burning of cork powder in the furnace, corresponding to an emission of 345.404 kg CO_2 eq./ m^3 ICB. There are two carbon sinks. One sink is the carbon sequestered in the ICB, corresponding to the value of 272.186 kg CO_2 eq./ m^3 ICB. The other sink is the carbon embodied in the cork powder used in the furnace, corresponding to the value of 345.404 kg CO_2 eq./ m^3 ICB.

A sensitivity analysis of the external transportation was performed to have an idea on how the distance between the factory and the cork producers influence the relative contribution of the transportation steps to the net CO_2 emissions. Thus, considering that "falca" comes from a distance of 300 km to the factory site, the relative contribution of transportation to GW is about 55.4 % (corresponding to about 86.4 kg CO_2 eq./m^3 ICB). This result shows that the environmental performance of ICB is directly related with the localization of the production factory. Thus, being raw material transportation a key factor, the ICB production unit should be as close as possible to the cork tree fields to reduce the carbon footprint of the ICB, otherwise the sustainability advantage of ICB is lost by increasing the distance in the external transportation. This is relevant in the Portuguese context, as most of the processing companies are far away from the cork production regions.

3.3.2. ICB comparison to other insulating materials

According to the ISO/TS 14067, the comparison between different product systems having the same function should take into account how the CF is assessed, in particular the calculation methods, functional units, system boundaries, data quality and sources (Annex D). To ensure a fair comparison only EPDs considering a cradle-to-gate system were used.

Table 4 shows the comparison of the ICB's carbon footprint to other common insulation construction materials available in the market, in particular: EPS, XPS, PU, SW, and LECA.

Table 4 - ICB's carbon footprint versus other common insulation materials.

Common insulation materials	**Contribution to Global Warming or Carbon Footprint (kg CO_2 eq./ m^3 ICB)**
Expanded Polystyrene (EPS)	59.00
Extruded Polystyrene (XPS)	94.44
Polyurethane (PU)	127.70
Stone Wool (SW)	34.35
Light Expanded Clay Aggregates (LECA)	53.77
Insulation Cork Board (ICB)	-116.23

Table 4 shows that ICB is the only insulation material with a negative net carbon footprint. Indeed, this result is a consequence of the renewable nature of the cork raw material and of an almost chemical free production process. This last property is true because the cork granules become agglomerated due to their natural resin that is released at the bonding process, using high temperatures promoted by the presence of moisture in which the autoclaving process occurs.

PU is the insulation material with the highest value of CF. PU is a closed-cell polyurethane foam made from MDI (50 %), polyols (31 %), hydrofluorocarbons (HFC) (5 %) and additives (14 %). Production of the polyurethane insulation spray foam is very energy intensive, with the corresponding impact on the GHG emissions, and thus, on GW (EPD-PUE-20140017-CBE1-EN, 2014)

XPS is the second insulation material, after EPS, with the highest contribution to global warming. XPS foams are mostly made of polystyrene (90-95 %), blown with carbon dioxide and halogen-free co-blowing agents, altogether up to 8 % by weight. Despite the potential to generate electricity from the incineration of the waste generated in the production process, the energy requirements during manufacturing are very high. Moreover, the process itself uses carbon dioxide, thus increasing the GHG emissions (EPD-EXI-20140155-IBE1-EN, 2014).

EPS is the third insulation material, after EPS and LECA, with the highest contribution to global warming. EPS is made by polystyrene (95 %), mainly produced with oil, a non-renewable resource, blown with pentane (6 %), which is released partly during or shortly after production. Thus, the production of polystyrene granules mix id the main contributor to the GW impact (EPD-EPS-20130078-CBG1-EN, 2013).

LECA has an in-between contribution to global warming in comparison to the other insulation materials. LECA is made by clay (98 %) and dolomite (2%). During its production, the clay is mixed with organic material, dried and expanded at temperatures of about 1150 °C. The heating needed for this process requires the utilization of large quantities of energy, most of it non-renewable, which generates significant carbon dioxide emissions (EPD 00120 rev1, 2013).

SW has, after ICB, the lowest contribution to global warming. It is a closed-cell polyurethane foam made from modified methyl diphenyl di-isocyanate (MDI) (60.5 %), polyols (29 %), pentane (5 %) and additives (5.5 %). CO2 is primarily generated during the melting process while converting coke in the cupola furnace. The life cycle steps associated with the production of electricity as well as the direct emissions in the plant owing to thermal conversion of natural gas are the main contributors to the GW (EPD-DRW-2012111-EN, 2012).

All the insulation materials considered in the comparison are obtained essentially using non-renewable resources and energy obtained from fossil fuels. To properly assess the sustainability and the efficiency of the ICB production one should discount the biogenic carbon embodied in the cork that is stored in the ICB. This lead to a value of CF of 501.361 kg CO_2 eq./m^3 ICB, showing that without the embodied carbon ICB is the worst performing material. This is due, in particular, to the cork extraction process, a very energy and work intensive process, that is not easy to automate as care is needed to remove the cork tree bark from the pruned branches.

Moreover, the transportation of cork to the factory site is also relevant. As shown in Figure 2, the CF depends strongly on the transportation distance. Thus, to ensure that ICB is a more adequate option from a sustainability point of view, its production should be done as close as possible where cork is extracted.

Concerning the life cycle stages not considered in this study (distribution, use and end of life), eventually only the final disposal step may have an impact on the overall product sustainability, depending on the scenario considered. In particular, if the ICB is disposed in a landfill or even recycled. The distribution and use steps should have a similar impact in all the insulation materials present in the market.

The ICB is clearly better from a sustainability point of view as it is produced from a renewable raw material, and in its production processes biomass is used as fuel. This contributes to a more circular economy, an essential part of a more sustainable world, and at regional level contributes to fix populations in rural areas and maintain a natural ecosystem, key to protect endangered species and protect forest from fires. Notwithstanding, the CF of ICB can be further reduced, making it even a better option from a sustainability point of view. This can be achieved for example by improving the cork extraction process and cork transportation to the factory site, for example by replacing fossil diesel by biofuels, or by using electric machinery with batteries powered using photovoltaic systems.

Chapter 4 - Cork powder: adsorption of aroma compounds

4.1. Framework

The cork, over the years, has been shown as a product applicable in various fields such as an insulating material for construction, also applicable in floating floors, insulation material for space shuttles, airplanes and trains, other fields like clothes, shoes and fashion accessories, among others, and even then, its visibility is the natural cork stopper.

Cork is a natural product which has several advantages on an ecological and commercial point of view.

Cork is the bark of the oak tree, and it is removed from the tree in general every 9 years, which means, it isn’t necessary to cut down the tree to remove this material, and in this case, the oak is preserved and the growth of the bark is respected. The other advantage is the fact that the oak tree is a conserved specie, and there are laws that must be followed regarding its preservation. During its life span, the oak tree can capture and sequestrate CO_2, which is very important regarding the fact of the current global problem, the climate change, which results in the increase of the greenhouse gas emissions, namely, carbon dioxide.

Cork has many properties that gives him an economic advantage, such impermeability, low thermal conductivity, low density, high energy absorption, excellent insulation properties and resistance to fire, among others. For this reason, cork has been used as a raw material in various fields, and consequently, its derivatives and its wastes, such as cork powder, have been increasingly used for commercial value. For this reasons, the use of waste cork, more properly the cork powder, is used in this study, so is important to explain where it comes from.

Throughout the process of transforming cork, and depending on its application, there is always waste generated in the process. The surplus powder comes from a process of rectification of natural cork stoppers.

Depending on the applications of this waste, it’s important to choose the powder based on its origin, if its derivative of stoppers that are 100% natural cork or not, because the powder does not contain the same priorities, depending of the process of which it came from.

The cork powder, in the current market, has the main purpose of “colmatagem” (is a process of filling some critical defects of the cork stopper, more specifically slots and holes, that utilizes cork powder and glue). The fact of focusing on the current market is because there are variable and oscillating findings to behold the most profitable product solutions. It’s important to note this because a few years before, cork powder was considered a waste, without application and commercial value, in which as been pointed out above, this fact has been change.

The basis of this article sustains on adsorption of aromas through the cork powder, proving thus more a function and application area that can henceforth be considered for the various problems that may arise within the same business scope or the posed problem.

4.1.1. Use of cork powder as adsorbent

There are different types of cork powder according to origin: the grinding powder, from granulation or pre-grinding; the cleaning powder, without impurities; the finishing powder, from cut and sanding operations; the active cork panels finishing powder; the active cork stoppers and disks finishing powder; and the insulation board cork powder (Gil et al., 2015). The mixture of these powders is considered the "powder burning," and it is used to feed boilers due to its high heating value (Fernandes et al, 2010; Gil, 2015). Other applications include the use of the agent filling, mixed with glues, for enhancement of the quality of cork stoppers, production of linoleum, application in agglomerates, briquettes, agricultural substrate, source of chemicals (extractives), and more recently, agglomeration with polymers (Fernandes et al., 2010).

Due to its properties, it has been demonstrated that cork powder can be used as a biosorbent of different kinds of pollutants, such as volatile phenols (Karbowiak et al., 2010), polycyclic aromatic hydrocarbons (PAHs) (Olivella et al., 2011a) and heavy metals (Chubar et al., 2003).

It can also be used as an active carbon for many applications, from medicine to industrial plants and treatments of wastewaters or gaseous effluents (Cardoso et al, 2008; Carvalho et al., 2006).

4.1.2. The objectives of this chapter

During the life cycle analysis of ICB, a potential problem related to its utilization was the release of a characteristic aroma that, if ICB are used in close rooms without ventilation would become an issue. To deal with this problem a two-step strategy was designed using only cork materials: (i) analyse the aroma constitution to assess its origin; (ii) investigate the adsorption capabilities of cork powder to be used as aroma removals coupled to ICB.

4.2. Methods and Materials

This chapter describes the materials and methods used for the preparation of all the procedures and tests carried out following this work. Experimental tests were carried out at the Faculty of Sciences of University of Porto.

4.2.1. Materials

The black corkboards were provided by SOFALCA. The cork powder used in the sorption assays was supplied by a cork factory and was obtained from raw cork material, from the rectification process, a process where the properties of the cork are not altered. The chemicals used were obtained from Sigma-Aldrich Co.

4.2.2. Detection of aromatic compounds in the ICB

To investigate the nature of the aromatic compounds, present in the characteristic ICB smell, several experiments were performed which consist in closing in a glass desiccator of four ICB samples. Also, inside the desiccators, beakers containing water and methanol were placed to absorb the aromatic compounds (aromas). After 7 days, when the vapour phase inside the desiccator come into balance (so that the aromas are supposed to be absorbed by water and/or methanol), samples of 0.5 mL were collected from each beaker. These samples were analysed by gas chromatography using a 1300^{TM} Trace Gas Chromatograph.

4.2.3. Calibration curves

In order to obtain a relation between the chromatographic peak area and the vapour concentration of the aroma, increased known amounts of the phenol compounds were placed inside the vials and, after evaporation, samples were taken and analysed. Figure 4 shows a typical calibration line for 2-methoxy-4-methylphenol. It was calculated the moles of the aroma to facilitate the calculation of the Langmuir isotherm model (referred in the chapter 4.2.5)

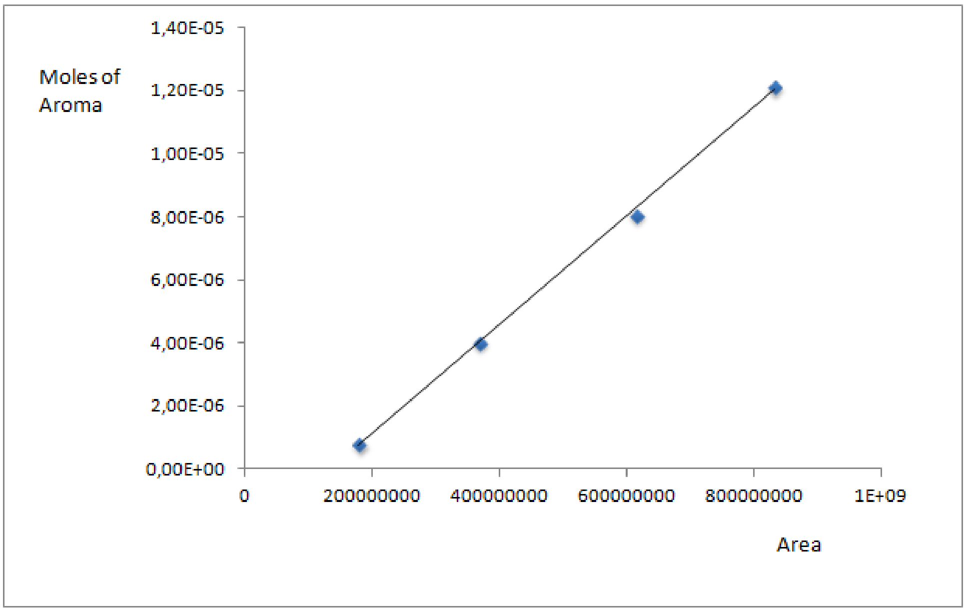


Figure 4 - Calibration curve for the phenol 2-methoxy-4-methylphenol

Several attempts were made to obtain a calibration plot for 4-ethylguaiacol but it was not possible to define a linear region because the aroma concentration in the vapour phase was almost constant (Figure 5).

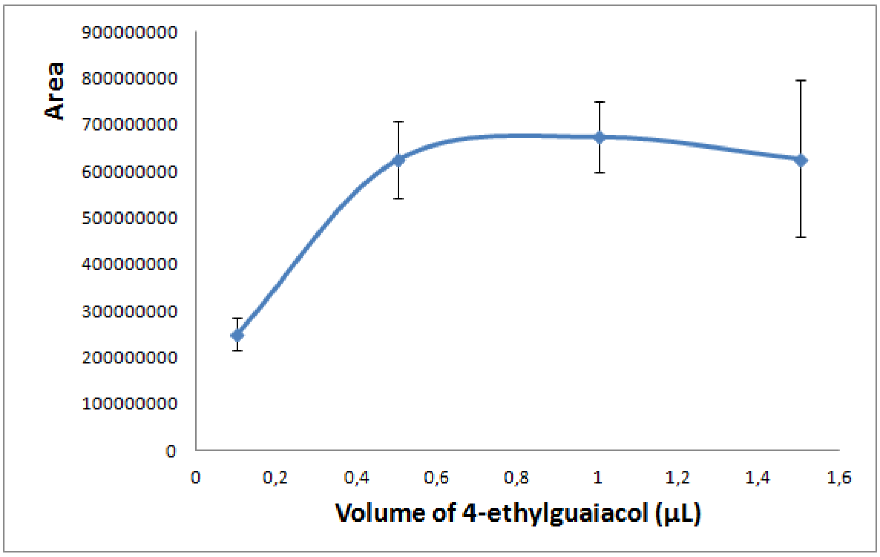


Figure 5 - Area as function of the volume of 4-ethylguaiacol placed inside the vial.

4.2.4. Adsorption of aromatic compounds with cork powder

The experimental test of the adsorption of the aroma compound by the cork powder, was only used in the phenols in a liquid state, since the powder cannot adsorb solid compounds. It was chosen not to do a phenol solution in methanol since it would encounter the problem of two compounds compete for the cork surface. This test was based on an experimental test from Karbowiat et al. (2010).

Adsorption kinetics was determined for all liquid phenols by introducing different masses of cork powder samples. Each sample was tested in triplicate, along with triplicate control samples containing the aromatic compounds and no cork samples to check the stability of the experimental system. For each experimental sample, it was weighted different samples of cork powder, between 0.01 g to 0.2 g (represented in Table 5) and 1 µL of each phenol was placed inside a 0.5 mL Eppendorf and it was inserted open into a glass vial of 40 mL (this is to avoid the direct contact of the liquid compound with the cork powder). The vials were tightly closed with Teflon-lined screw caps and parafilm to prevent the loss of the aromatic compounds and moisture penetration, and were stored in a water bath at 25 °C for 5 days (the phenol could evaporate and reach equilibrium) (Figure 6).

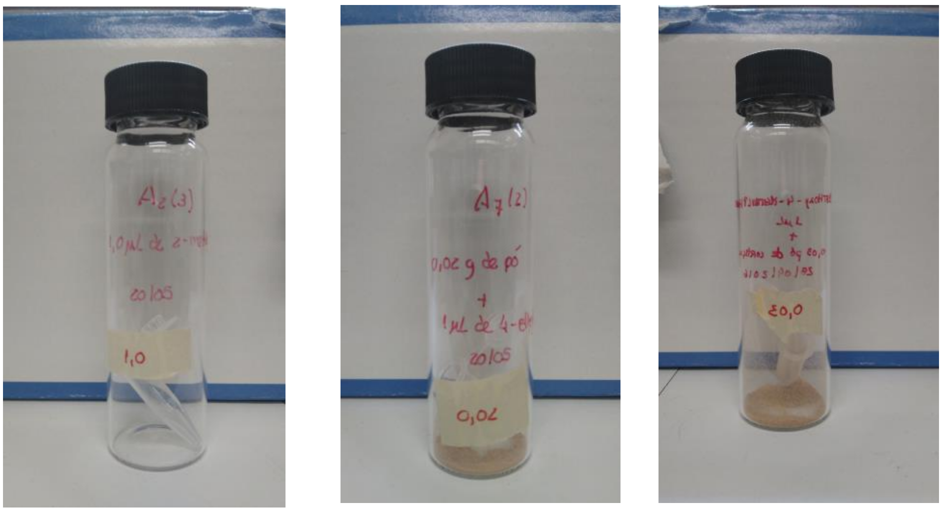


Figure 6 – an example of a vial with only the phenol, a vial with cork powder and 4-ethylguaiacol and a vial with cork powder and 2-methoxy-4-methylphenol, respectively

Samples were analysed by gas chromatography (GC), using again the Trace 1300^{TM} (Figure 7).

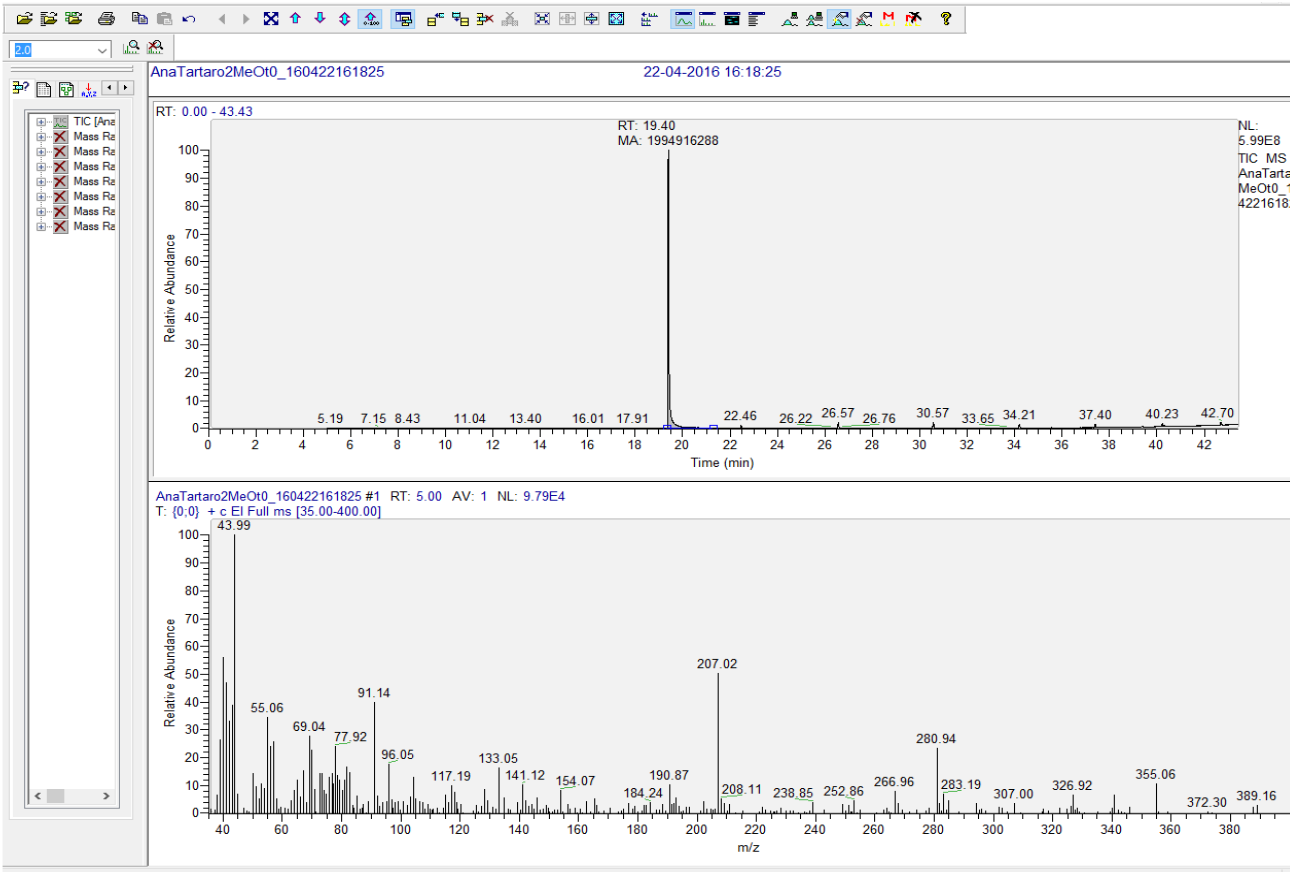


Figure 7 – example of the software used by the Trace 1300^{TM} for detecting the area of the phenol

Table 5 - Samples for each phenol with different cork powder masses.

	2-methoxy-4-methylphenol	**4-ethylguaiacol**
Samples	Cork powder (g)	Cork powder (g)
A0	0	0
A1	0,01	0.005
A2	0.03	0.01
A3	0.05	0.02
A4	0.07	0.03
A5	0.1	0.05
A6	0.2	0.07
A7		0.1
A8		0.2

It was necessary to create two more samples for the phenol 4-ethylguaiacol because between 0.01 g and 0.05 g of cork powder, the concentration was very similar.

The amount of aroma compound taken up per unit weight of cork powder was calculated by the Langmuir model linearization.

4.2.5. Adsorption Isotherms model

Adsorption is a separation process in which some materials, (adsorbate) is concentrated from a bulk vapour or liquid phase on to the surface of a porous solid (adsorbent) (Adamson, 1990). Adsorption isotherms occurs when the adsorbent and adsorbate are contacted long enough, an equilibrium will be established between the amount of adsorbate adsorbed and the amount of adsorbate in solution (Mittal et al., 2006). The adsorption isotherm is also an equation relating the amount of solute adsorbed onto the solid.

The most commonly used isotherms are the Freundlich and Langmuir models. For this paper it was used the Langmuir isotherm model because it is an empirical model assuming that adsorption can only occur at a finite number of definite localized sites, and the adsorbed layer is one molecule in thickness or monolayer adsorption (Chen, 2015). The Langmuir isotherm model can be illustrated by the fallowing equation 1:

$$q_e = \frac{\frac{(C_0 - C_e)}{V}}{m}$$

Where q_e is the amount of the phenol compound adsorbed at equilibrium, C_0 and C_e (g/mol) are the initial and equilibrium phenol concentrations, respectively, V (L) is the volume of the solution and m (g) is the mass of the adsorbent.

4.3. Results and Discussion

4.3.1. Detection of aromatic compounds in the ICB

The analysis of the water samples showed no compounds, which means that water did not adsorbed the aromas. However, the analysis of the methanol sample detected three different phenol compounds. The compounds were: 2-methoxy-4-methylphenol (liquid compound at room temperature), 4-ethylguaiacol (liquid compound at room temperature) and 4-methoxyphenol (solid compound at room temperature). These aromas are represented in the Table 6:

Table 6 - Physicochemical characteristics of aromatic phenols compounds detected above ICB.

Aroma compound (formula)	CAS number	Molar weight (g/mol)	Density (g/ml)
2-methoxy-4-methylphenol ($C_8H_{10}O_2$)	93-51-6	138.16	1.0920
4-ethylguaiacol ($C_9H_{12}O_2$)	2785-89-9	152.19	1.0630
4-methoxyphenol ($C_7H_8O_2$)	150-76-5	124.14	1.55

The liquid compounds (2-methoxy-4-methylphenol and 4-ethylguaiacol) were selected to continue the work, i.e. to investigate its adsorption by raw cork powder.

4.3.2. The capacity of adsorption on the aroma compound 2-methoxy-4-methylphenol

The results (averages of at least three independent replicas) obtained on the adsorption of the 2-methoxy-4-methylphenol are shown in Table 6. These results show that the percentage of adsorption of the compound increases with the quantity of cork powder that it was present in the assay, with a maximum capacity of adsorption of about 95 %. Figure 8 represents the data of Table 7 and shows the decreasing of the aroma concentration as function of the cork powder. These results show that more than 50 % aroma reduction is observed using 30 mg of raw cork powder.

Table 7 - Results of the analyses of the aroma compound 2-methoxy-4-methylphenol.

Sample	Aroma volume (µl)	Cork powder (g)	Peak area (UA)	Adsorption percentage (%)
A0	1	0.000	1302390420	-
A1	1	0.011	677396165	48.0
A2	1	0.0307	413336873	68.3
A3	1	0.0507	194579707	85.1
A4	1	0.0702	121016492	90.7
A5	1	0.1066	119404388	90.8
A6	1	0.2019	63882098	95.1

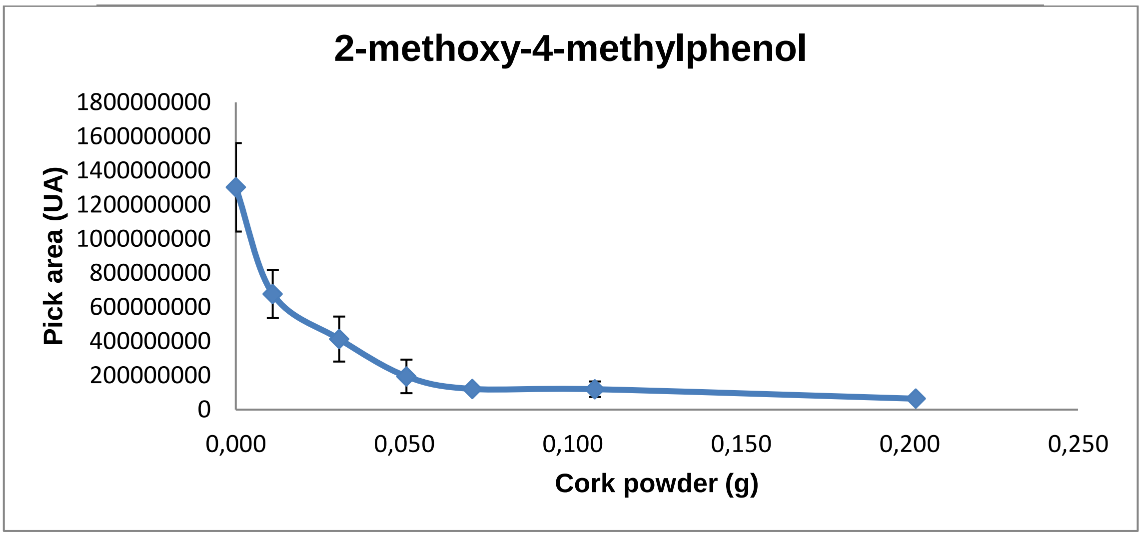


Figure 8 - Representation of the variation of the peak area with cork powder

Using the experimental data points up to 90 % adsorption, a Langmuir isothermal plot was obtained as shown in Figure 9. It was only used two points, since the other points were to closed to zero, which means those samples reach the saturation point. The isothermal plot allows data to be linearized, however it has its limitations. So it can be made a linearization of the data, the aroma must be diluted so it can be possible to obtain more data.

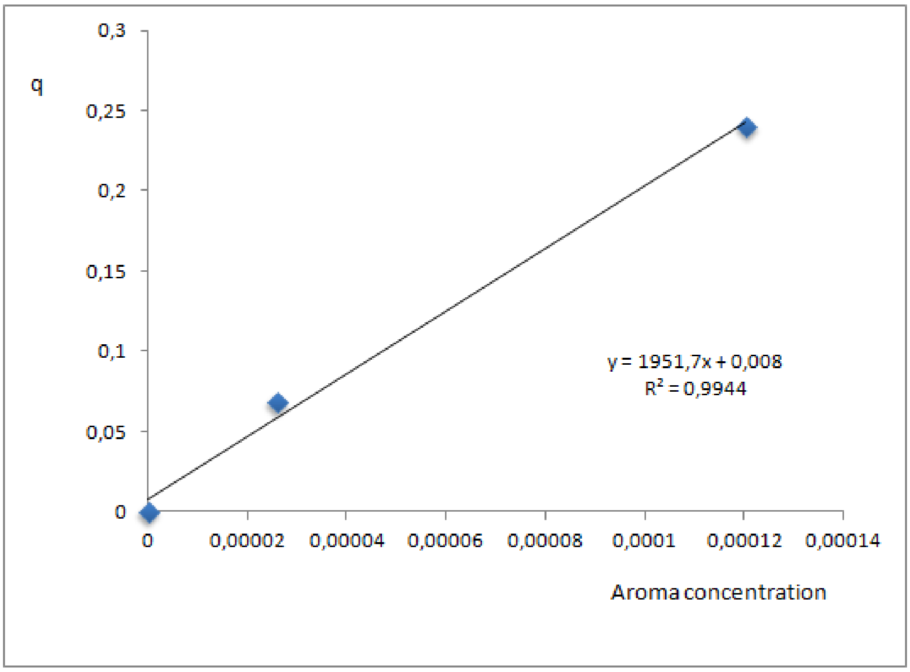


Figure 9 - Langmuir plot for the 2-methoxy-4-methylphenol.

4.3.3. The capacity of adsorption on the aroma compound 4-ethylguaiacol

The results obtained of the adsorption of this aroma compound are shown in Table 8 and Figure 10. The adsorption trend is similar to that observed for 2-methoxy-4-methylphenol, although apparently, the adsorption is now more efficient. However, because it was not achieved the saturation point of this compound, a calibration curve couldn't be obtained and no further analysis was made.

Table 8 - Results of the analyses of the aroma compound 4-ethylguaiacol.

Sample	Aroma volume (µl)	Cork powder (g)	Peak area (UA)	Adsorption percentage (%)
A0	1	0.0000	854582099	-
A1	1	0.0050	397930156	53.4
A2	1	0.0108	386112893	54.8
A3	1	0.0205	234814778	72.5
A4	1	0.0307	127803311	85.0
A5	1	0.0502	107966547	87.4
A6	1	0.0705	145071962	83.0
A7	1	0.1037	137546529	83.9
A8	1	0.2038	34174697	96.0

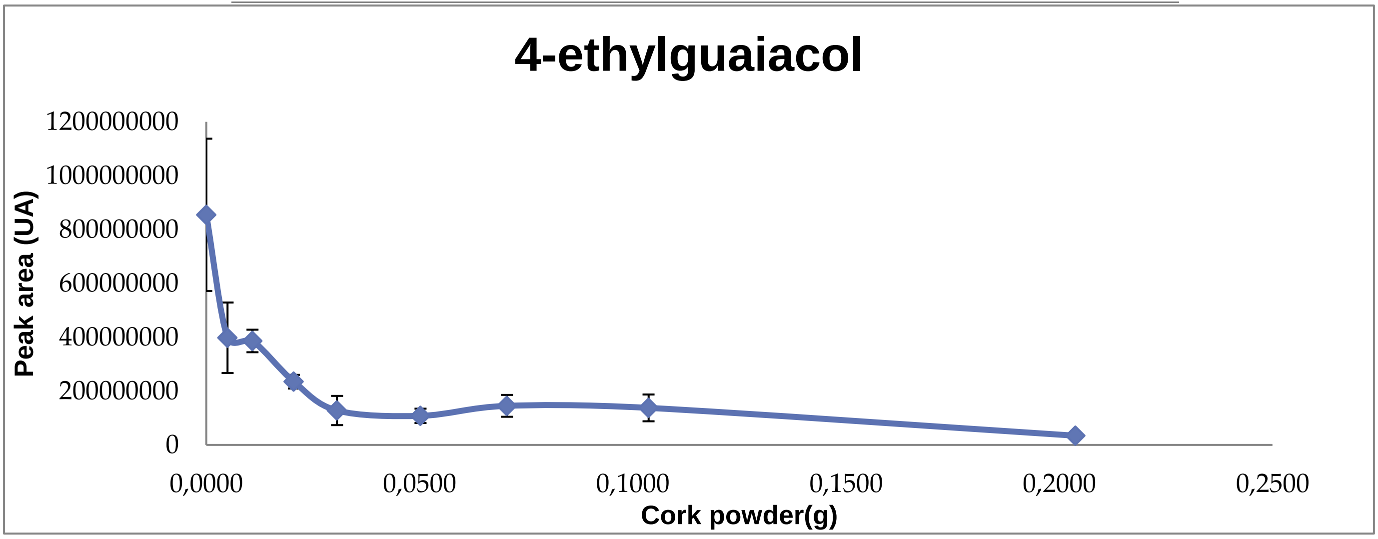


Figure 10 - Representation of the variation of the peak area with cork powder

Chapter 5 – Conclusions and future work prospects

5.1. Conclusions

During the process of the calculation of the carbon footprint of the ICB, in comparison to the other insulation materials present in the market, ICB has the lowest and negative carbon footprint of -116.229 kg CO_2 equivalent per m^3 of ICB. It has significant embodied carbon since cork absorbs carbon during its growth and the net energy consumption and GHG emissions through the ICB's life cycle are very low in comparison to its embodied carbon. When the biogenic emissions are excluded, in particular the carbon embodied in the cork, ICB has the largest CF, showing that the utilization of cork, a renewable resource, is key to its sustainability. The ICB's life cycle step with the greatest contribution to GW is the cork extraction from cork tree's branches followed by the transportation of "falca" to the factory site. Thus, an environmental strategy or recommendation from this study could be the replacement of the fuel engines, for example, by electrical vehicles and equipment, using stored energy produced from renewable sources, in order to decrease the carbon dioxide emissions.

For the process of the adsorption of aroma compounds by the cork powder, it was possible to obtain conclusive results. After the analyses of the aromatic compounds present in the ICB, which was detected two aromatic compounds: 2-methoxy-4-methylphenol and 4-ethylguaiacol, it was proceed the capacity of adsorption by the cork powder for these two aromas, which was concluded that with the increase of the quantity of cork powder, the higher the percentage of adsorption capacity.

To the aromatic compound 4-ethylguaiacol the results were not conclusive since in some analysis it was not achieved the saturation point, hence the absence of necessary data to perform the calibration line and likewise to obtain conclusive and viable results. However, the cork powder was able to achieve 96 % adsorption capacity to this compound.

Comparatively, the aromatic compound 2-methoxy-4-methylphenol showed better results, since it was possible to obtained a calibration curve to this phenol and a Langmuir isothermal plot, though it was only used to points since the rest reached a saturation point. For this compound, the maximum capacity of adsorption was of 95 %.

Throughout this process it is important to note that the resolution of the ICB problem, a derivative of cork product, the resolution of the same is in its origin.

5.2. Future work prospects

The following points developed in this work could be studied in more detail in future work:

- Further analyses of the aroma compound 4-ethylguaiacol so it can be possible to find the saturation point;
- Try to analyse the solid aroma compound 4-methoxyphenol, so it can be determinate the adsorption capacity of the cork powder in this compound;
- Find an application method too applicate the cork powder in the ICB to solve the problem of the burning smell;
- Try to apply this methodology in the chemical compound trichloroanisole (TCA), since it is a major problem in the cork industry, because of the musty smell it gives to the cork stoppers.

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Appendix

I. Abstract of the work presented in the IJUP's conference of 2016

Carbon Footprint of the Insulation Cork Board

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Cork is a natural, versatile and sustainable raw material extracted from the oak bark with interesting thermal and sonorous insulation properties, aside from impermeability, slow burning and durability. The Insulation Cork Board (ICB), commonly known as black cork agglomerate, is produced from the expanded cork in the form of insulation plates with different thicknesses. This work aims to calculate the carbon footprint of ICB produced by the Portuguese company SOFALCA, following the life cycle assessment (LCA) methodology. Therefore, all process steps from "cradle-to-gate" were taken into account, from cork extraction to transportation and ICB production. The data needed for the analysis and quantification of the net greenhouse gas emissions was gathered from the company's environmental product declaration (EPD) (http://sofalca.pt/en/pdf/EPD_Solfalca_EN.pdf) and complemented with data available in the LCA SimaPro 7.3 software, concerning the transportation of cork, and in the Intergovernmental Panel on Climate Change (IPCC) database, concerning the company internal transportation. Results of the ICB carbon footprint can be used for comparison or benchmarking purposes with other insulation materials available in the market (e.g. Expanded Polystyrene (EPS), Extruded Polystyrene (XPS), Polyurethane (PUR), Stone Wool (SW), or Light Expanded Clay Aggregates (LECA)) and for the identification of possible improvements in the ICB life cycle steps.