CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

FACULTY OF FORESTRY AND WOOD SCIENCES

MSc. THESIS

CARBON FIXING AND CARBON FOOTPRINT ANALYSIS OF NATURAL AND ARTIFICIAL CHRISTMAS TREES

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JULY, 2017

To my parents and my sister

"Everything around me—the dark brown stretches of withered grassland where the snow had completely vanished, leaving the soil parched and powerless as yet to put forth new life, even the somber evergreen heights of the forest beyond the groves of great deciduous trees—had an air of indefinable loss, like the dead ruin of a human being, that awoke an obscure uneasiness in me as my gaze roved across the hollow"

Kenzaburō Ōe.

The Silent Cry. 1967.

Czech University of Life Sciences Prague

Faculty of Forestry and Wood Sciences

DIPLOMA THESIS TOPIC

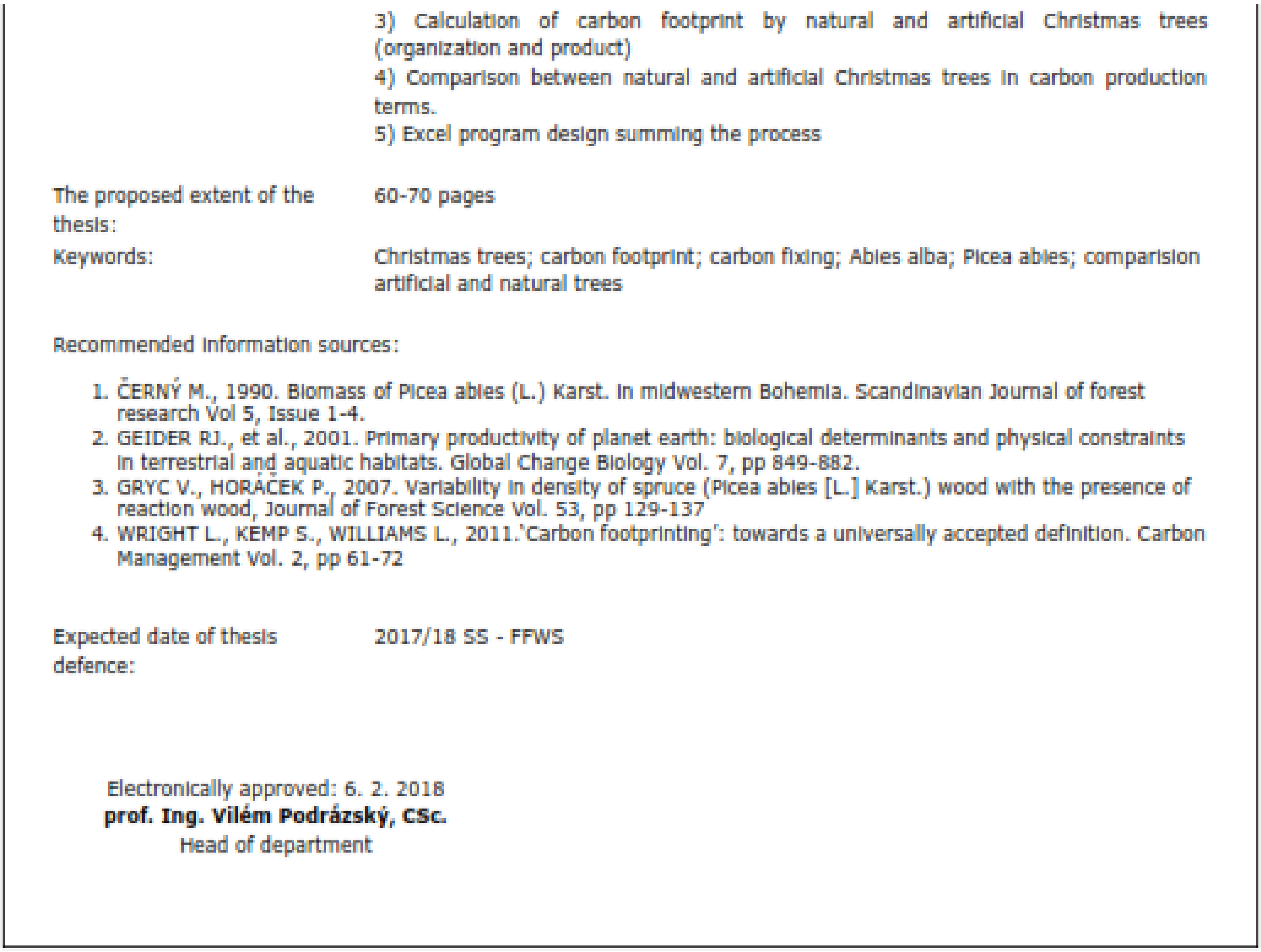
Author of thesis:	Daniel González Gaarslev
Study programme:	Forestry Engineering
Field of study:	Forestry, Water and Landscape Management
Thesis supervisor:	prof. Ing. Ivo Kupka, CSc.
Supervising department:	Department of Silviculture
Language of a thesis:	English

Thesis title: **Carbon Fixing and Carbon Footprint Analysis of Natural and Artificial Christmas Trees**

Objectives of thesis: A comparison of footprint of natural Christmas tree and plastic one is an important analyse namely in Spain where plastic trees are prevailing. This means to calculate the carbon absorption that natural Christmas trees can reach during their life-cycle based on some measurable parameters of living trees as a first step. This cannot be calculated for artificial Christmas trees as plastic does not absorb any carbon whereas wood does. Thus the carbon footprint of both processes of commercialization and distribution of both products should be estimated, in order to get an accurate and comparable value of the amount of CO2 that each type of tree emits to the atmosphere. For this analysis of all the activities involved in the processes of production and distribution should be done in order to give trustful data of the carbon emitted on each activity. The product the carbon footprint of the raw material should be quantified and also the carbon footprint generated at the end of the products life.
A simplified computer programme could be developed which allows the user to enter the particular data from their situation (for example the size of the tree, the distance from the factory, if it is planted after Christmas) for being able to estimate, with an acceptable accuracy, the CO2 emissions of their available Christmas trees options.

Methodology:

1) Establishment of the study categories
2) Calculation of carbon fixing by natural Christmas trees



	3) Calculation of carbon footprint by natural and artificial Christmas trees (organization and product) 4) Comparison between natural and artificial Christmas trees in carbon production terms. 5) Excel program design summing the process
The proposed extent of the thesis:	60-70 pages
Keywords:	Christmas trees; carbon footprint; carbon fixing; Abies alba; Picea abies; comparision artificial and natural trees

Recommended information sources:

1. ČERNÝ M., 1990. Biomass of Picea abies (L.) Karst. in midwestern Bohemia. Scandinavian Journal of forest research Vol 5, Issue 1-4.
2. GEIDER RJ., et al., 2001. Primary productivity of planet earth: biological determinants and physical constraints in terrestrial and aquatic habitats. Global Change Biology Vol. 7, pp 849-882.
3. GRYC V., HORÁČEK P., 2007. Variability in density of spruce (Picea abies [L.] Karst.) wood with the presence of reaction wood, Journal of Forest Science Vol. 53, pp 129-137
4. WRIGHT L., KEMP S., WILLIAMS L., 2011.'Carbon footprinting': towards a universally accepted definition. Carbon Management Vol. 2, pp 61-72

Expected date of thesis defence:	2017/18 SS - FFWS

Electronically approved: 6. 2. 2018
prof. Ing. Vilém Podrázský, CSc.
Head of department

“Carbon fixing and carbon footprint analysis of natural and artificial Christmas trees”

I declare that I wrote my graduation dissertation (bachelor's/graduate) independently, and that I have stated all the information sources and literature I used. Neither this thesis nor any substantial part of it has been submitted for the acquisition of another or the same academic degree.

I consent to the lending of my dissertation for study purposes. By affixing his or her signature the user confirms using this dissertation for study purposes and declares that he or she has listed it among the sources used.

In Prague, 6th of February of 2018

Author : Ing. Daniel González Gaarslev	Tutor: Prof. Ing. Ivo Kupka, CSc
Signed:	Checked and signed:

Abstract

Are natural Christmas trees more eco-friendly than plastic Christmas trees?

To answer this question under the most accurate way and always under scientific premises the author analyzed the whole process of fabrication and distribution of both kinds of trees (also having in mind some possible variations such as size, material or type of company that commercializes the trees) under a CO_2 production point of view.

This means to calculate the carbon absorption that natural Christmas trees can reach during their life-cycle based on some measurable parameters of living trees as a first step. This cannot be calculated for artificial Christmas trees as plastic does not absorb any carbon whereas wood does.

Thus the carbon footprint of both processes of commercialization and distribution of both products was estimated, in order to get an accurate and comparable value of the amount of CO_2 that each type of tree emits to the atmosphere. For this and exhaustive analysis of all the activities involved in the processes of production and distribution was done in order to be able to give trustful data of the carbon emitted on each activity. About the product the carbon footprint of the raw material was quantified and also the carbon footprint generated at the end of the products life. This provided values of the amount of carbon emitted by each kind of tree.

Once these values were reached a compartmentalization of the results was done in order to explain which variation of Christmas tree is the less pollutant and why. Also the most pollutant parts of the process were identified.

To end, a simplified computer programme was developed. This programme allows the user to enter the particular data from their situation (for example the size of the tree, the distance from the factory, if it is planted after Christmas) for being able to estimate, with an acceptable accuracy, the CO2 emissions of their available Christmas trees options.

0.1. List of charts, pictures and graphs

1. Introduction

Every year, as Christmas period gets closer, people all over the world start to decorate their homes with a wide variety of Christmas decorations and ornaments. In many cases the main character of these moments is the Christmas tree. But, in this times, where people is getting conscious of the importance of preserving nature and being eco-friendly some doubts about the topic arise. Some people opt for natural Christmas trees and some others choose plastic ones (***Picture 1***). Some others directly don't purchase a Christmas tree of any type. All three groups think that their option is the most eco-friendly one but; who is, scientifically talking, right?

Picture 1. *At the left natural Christmas tree, at the right plastic Christmas tree.*

The aim of this final master thesis is to answer to this particular question that most of the people (involved in forestry or not) have made to themselves when the Christmas period comes.

Are natural Christmas trees the least polluting and most ecological option or it is better for the environment to purchase a plastic Christmas tree?

Although this is a very usual question (asked and discussed by lots of people every year), it seems that it has not been answered by scientific literature yet. This might be, in my opinion, caused by the high amount of really specific facts that have to be taken in consideration in addition to the absence of reliable sources or scientific papers to extract some specific and necessary data. This makes it very difficult to evaluate which option is better.

Obviously it is not the same to buy a 2,5 meters spruce (which, at that height, is normally sold without roots) than to buy a 1,5 meters fir with roots, because the carbon sequestration they achieve during their growth is not the same and the carbon footprint left by both of them at the end of their lifetime is neither the same.

And it also seems to be difficult to get trustworthy information about the real carbon footprint of a plastic Christmas tree, as this information is not supposed to be provided by the manufacturer. So with this lack of information in all the aspects involved, it appears to be really necessary to find or to elaborate some specific sources of knowledge about this topic. For this reason in this work some methods for quantifying the carbon footprint and fixing of both natural and plastic Christmas trees are going to be elaborated. The aim of elaborating this methods is to be able to later on compare the results and tell, from a scientific point of view, which option is less pollutant.

This work might also serve as a marketing tool for Christmas trees companies, which will be able to add some extra value to their products as they can, in scientific terms, ensure that their product has some clear environmental advantages when talking about carbon production.

1.1. Natural Christmas trees

In order to cover the most common options, the investigation is going to be focused in two of the most important species used for this purpose, Norway spruce (*Picea abies*) and silver fir (*Abies alba*) and some parameters as the height or the wood density are going to be taken into account, to be as closer to reality as possible (***Picture 2***).

Picture 2. *Left: Abies alba. Right: Picea abies*

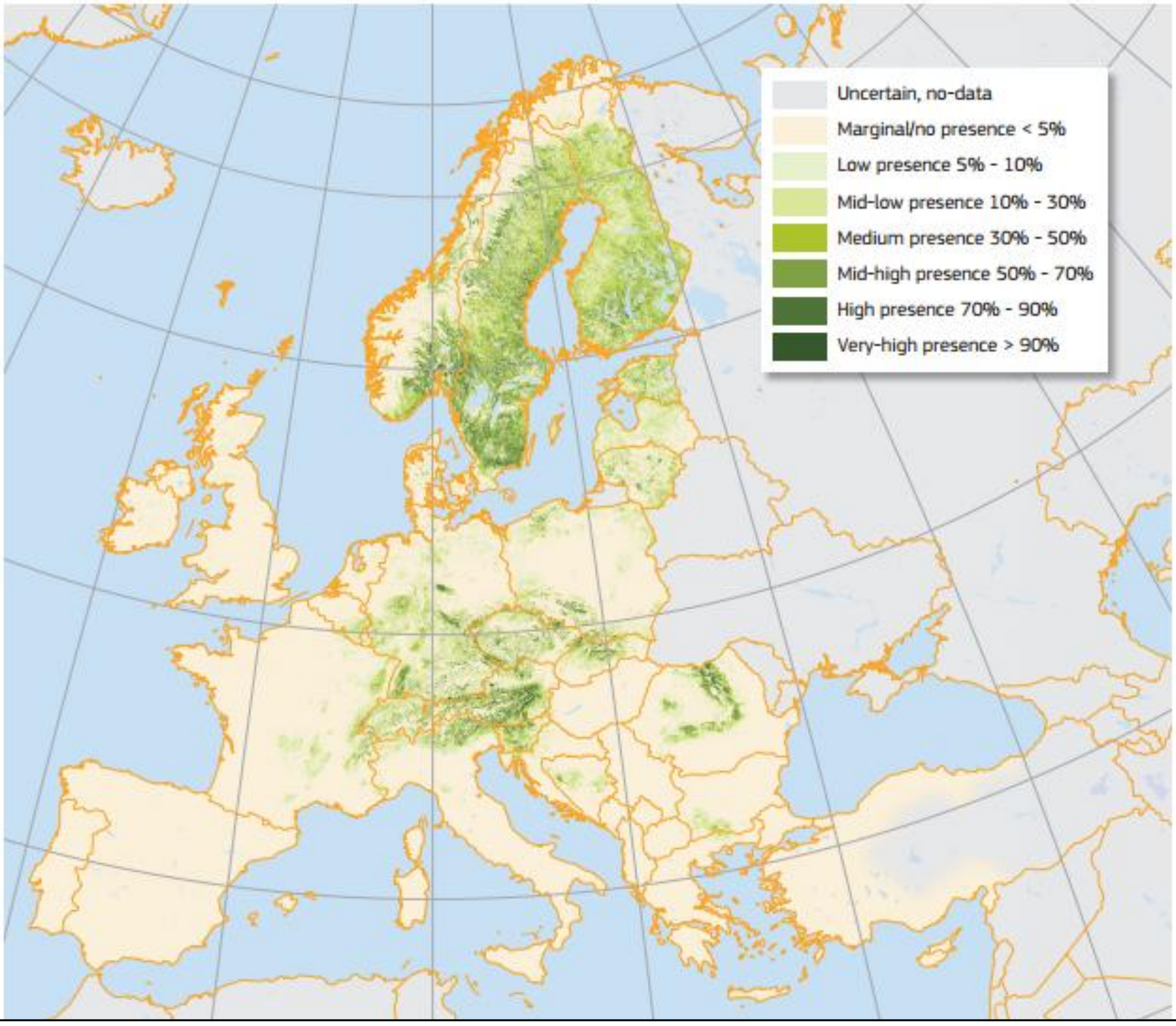
1.1.1. Norway spruce (*Picea abies*)

This evergreen coniferous is native from Northern, Central and Eastern Europe. It has a really fast growing rate, being able to reach, in perfect conditions, 25 meters height in 25 years. Its average height is between 35 and 55 meters and its diameter at breast height can reach between 1 to 1.5 meters.

It has needle-like leaves with blunt tips about 20 mm long and in dark green colour. The seed cones are reddish or green, about 14 cm long and they mature from 5 to 7 months after pollination.

Seeds are black with a brown wing, being the whole seed about 20 mm long.

About its natural distribution its northwest limit is Poland, and in the Northeast it reaches Poland. The northern limit is the Arctic. Southwest the limit are the Alps and Southwest the Balkans. It has some isolated populations on the Pyrenees and in central - Italy (***Picture 3***):



Picture 3. *Natural distribution of Picea abies. Taken from* ***G. Caudullo, W. Tinner, D. de Rigo, 2016****.*

About its ecology it is important to say that Norway spruce is a medium light species, so it has some potential as a colonizer. It needs tempered to cold climate, but it is very sensitive to late frost. It can grow in the shadow of other trees but reaches its optimum when it gets full sun radiation.

About soil this species needs humid and deep soils, being the lack of humidity in summer period one of its most limiting features. It does not grow properly in calcareous soils.

In the Christmas trees business this species is one of the most common ones, being sold in all heights from 1 meter to 3 or even 4 meters. It is a really emblematic tree en Europe, which in addition to its citric smell and its beautiful shape makes it one of the top seller species.

1.1.2. Silver fir (*Abies alba*)

This evergreen coniferous tree can get up to 60 meters, but its usual height is between 40 and 50 meters. The breast height diameter can be up to 3,5 meter, but its most common size when full-developed adult is around 1,5 m.

It presents needle-shaped leaves in a glossy dark green. Its dimensions are of 2-3 cm long and 2 mm wide. The cones have a longitude between 9 and 17 centimetres with around 175 scales. Each scale contains two seeds. This seeds are winged, and when they reach maturity the scales disintegrate to release them.

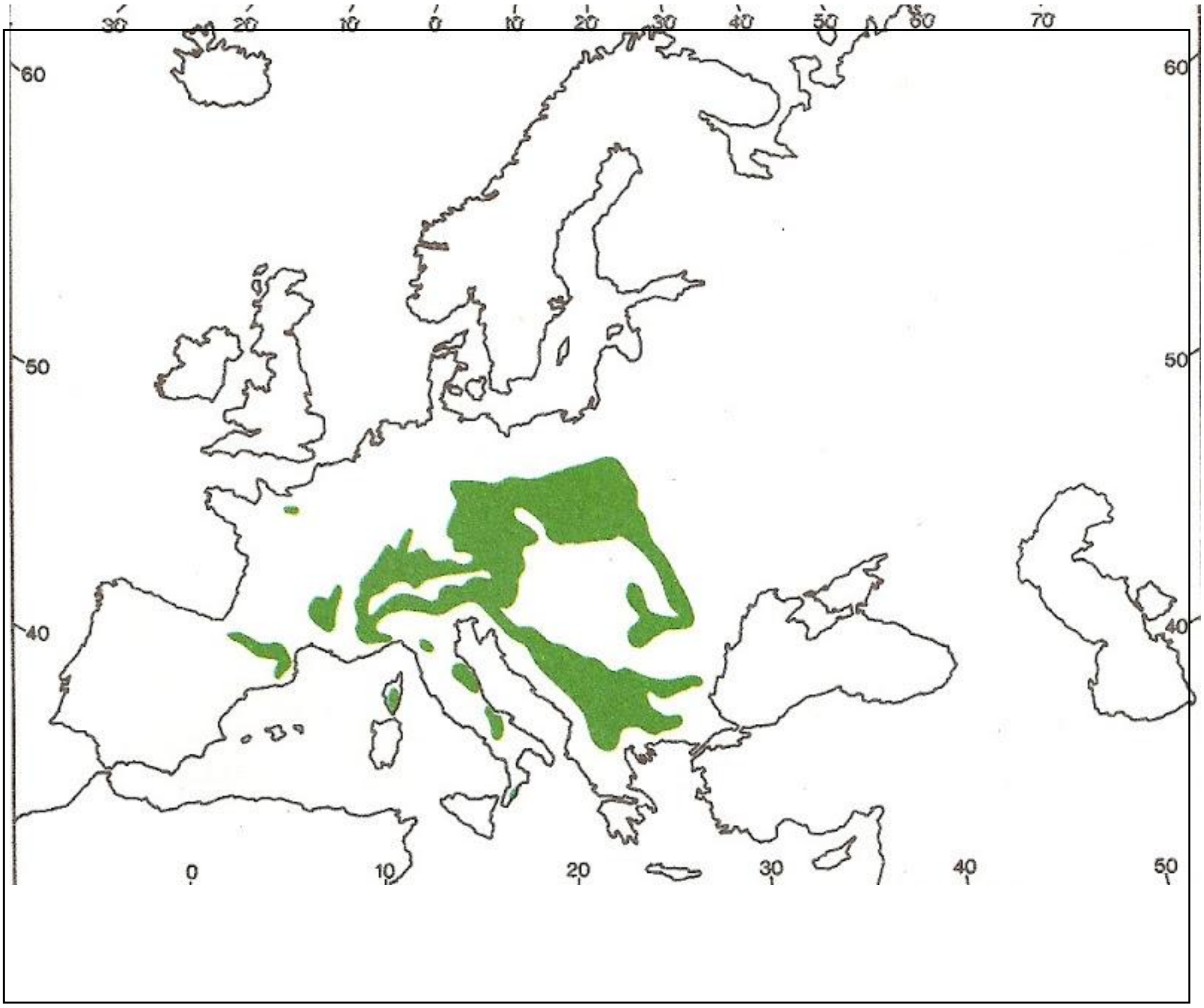
As a curiosity, the wood of this species is almost white, reason of the epithet *alba*, which means "white" in Latin.

Most commonly founded in monospecific forests or mixed with beech.

According to its distribution it is important to say that this species is native to most of the mountain systems in Europe. In west Europe it is present in the Pyrenees, and in the north it goes up to Normandy. Facing east it reaches the Alps and the Carpathians, and its presence is very common in Slovenia, Croatia or Serbia. Southern it reaches some parts of Italy, Bulgaria and northern Greece (***Picture 4***).

About its ecology it is important to point out that this species needs deep and humid soils for its proper development. It is indifferent about the type of substrate. It can easily handle low temperatures, but soaked soils and late frosts are really harmful for this fir. It needs a humid climate and does not resist summer drought. It is shadow tempered

Its behaviour on the Christmas trees business is really similar to *Picea abies*, and its popular for exactly the same reasons.



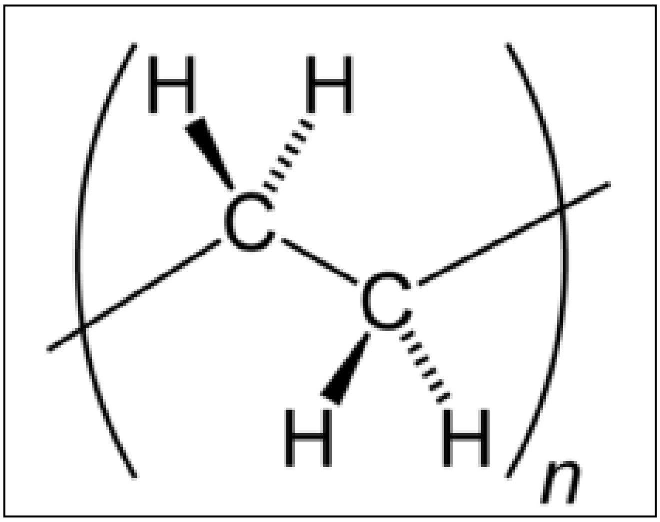
Picture 4. *Natural distribution of Abies alba. Taken from arbolesdeeuropa.blogspot*

1.2. Artificial Christmas trees

About the plastic Christmas trees two options are going to be explored, the trees made of Poly Ethylene (PE) and the trees made of Poly Vinyl Chloride (PVC) and also the height and the distance between the production (mostly Asia) and where the product is purchased (Europe).

PE is the most common and widely used type of plastic in the world. 80 million tons of this plastic are annually produced mainly for packaging, in items such as plastic bags, bottles or plastic films among others. It comes from the Polymerization upon contact with catalysts of the monomer ethylene (IUPAC ethene).

This monomer is a gaseous hydrocarbon built of two methylene groups connected to each other. The formula is $(C_2H_4)_n$ (***Picture 5***).



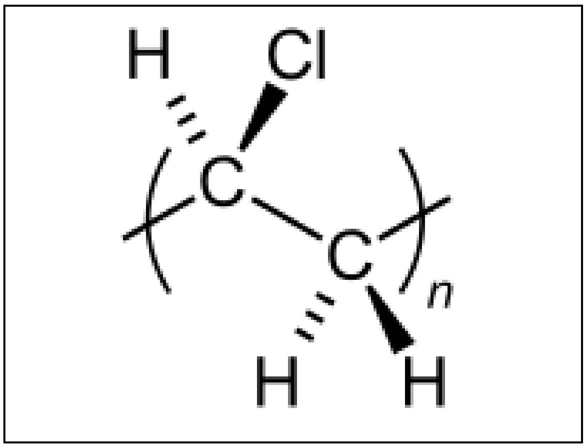
Picture 5. *Polyethilene structure.*

This material has some interesting mechanical, thermal and chemical properties. It is a common material for artificial trees because of its ductility and low rigidity, facts that make this material really easy to handle and to give shape. Also it is easy to obtain from it a texture which is similar to natural trees (***Picture 6***).

Picture 6. *Left: Detail of a PE Christmas tree. Right: Needles of a real Picea abies.*

About PVC, or Polyvinyl chloride, first it is important to remark that again is one of the most widely used and produced plastics of the world, in this case the third. For this reason it has been exhaustively studied and most of its properties and particularities are very well known, which, for the matter of this thesis are really good news.

This material is again synthesized by polymerization of a monomer, in this case the vinyl chloride monomer (VCM). The formula of PVC is $(C_2H_3Cl)_n$ (***Picture 7***).



Picture 7. *Polyvinyl chloride structure.*

PVC has two basic forms, rigid, very used in construction (pipes, windows...) and flexible, which is the form used for the construction of artificial Christmas trees.

Again, this material has quite important mechanical, thermal, electrical and chemical properties, being the most important one for our matters its malleability. It is also a really cheap and durable material.

In the Christmas trees application this material is again widely used by many companies, but the result is not as realistic as with PE, as PVC is not thermo stable (***Picture 8***). In the other hand this material is quite cheaper than PE, the texture is more pleasant when touched, and it allows to build much more leafy but less realistic imitations (***Picture 9***).

Picture 8. *Left: Detail of a PVC Christmas tree. Right: Needles of a real Picea abies.*

Picture 9. *Left: Detail of a PE Christmas tree. Right: Detail of a PVC Christmas tree.*

1.3. Carbon fixation and carbon footprint

The reader of this thesis might not be familiar with this terms. As they are really important for the understanding of the whole process some basic explanation about them is going to be given.

In this XXI century, and mainly because of the climate change threat, carbon, more concretely CO_2, is becoming a really important subject in science and society as its emissions (derived from all aspects of modern life, from industry to human day-life) are believed to be one of the leading agents of climate change. At this point is where this two concepts arise.

Starting with carbon fixation (or carbon assimilation) the first thing to say and that, in general terms summarizes the concept, is that is a conversion process on which inorganic carbon (CO_2) turns into organic compounds. This process of conversion has to be done by living organisms. This organisms are able to get energy from carbon fixation and they are called autotrophs. The rest of the organisms, heterotrophs, get their energy by using this carbon, previously fixed by autotrophs. The main process that leads to this fixation is photosynthesis.

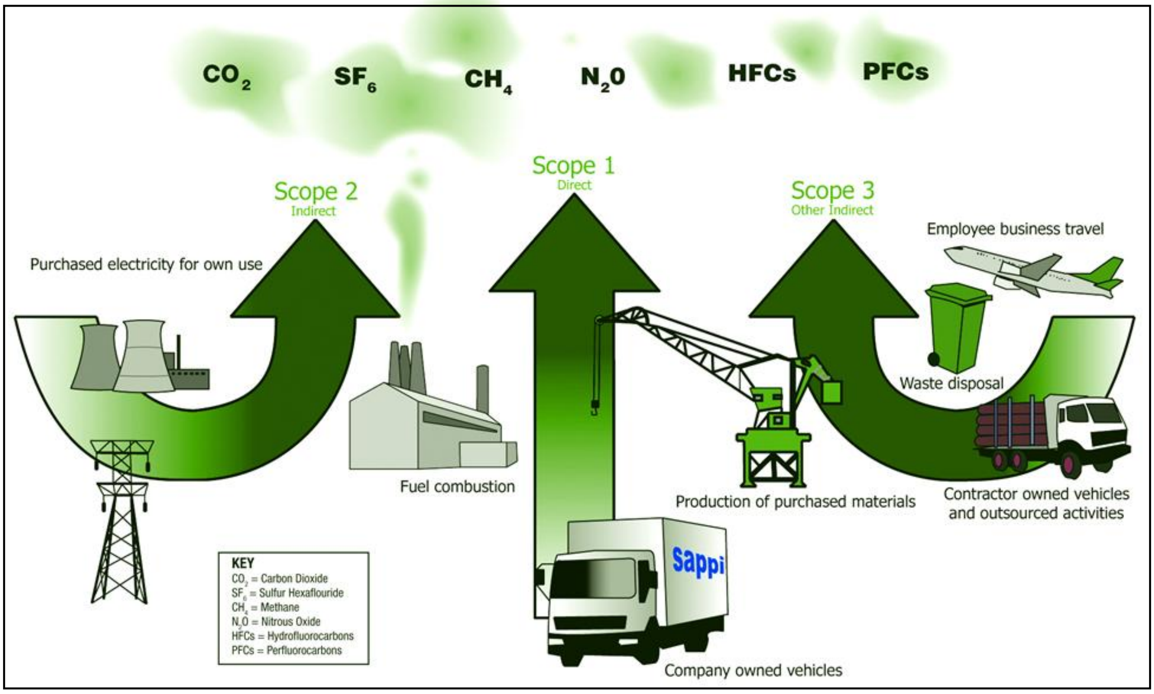
About numbers, approximately 258 billion tons of CO_2 are fixed by photosynthesis each year, but the fixed amount is presumably larger as approximately 40% more of this quantity is consumed by the plant respiration that follows photosynthesis (***Geider, R. J., et al.*****, 2001**). Only a half of this fixation is made by terrestrial organism (vascular plants mainly) and the rest by marine organisms.

Nowadays, up to six autotrophic carbon fixation pathways are known, being the most important ones oxygenic photosynthesis, reductive citric acid cycle, reductive acetyl CoA pathway and 3-Hydroxypropionate cycles (***Swan BK, Martinez-Garcia M, Preston CM, Sczyrba A, Woyke T, Lamy D, Reinthaler T, Poulton NJ, Masland ED, Gomez ML, Sieracki ME, DeLong EF, Herndl GJ, Stepanauskas R.*, 2011**).

This thesis will be focused on the oxygenic photosynthesis. This path is based on the Calvin cycle, and very briefly, consists on converting carbon dioxide into sugar.

The carbon footprint can be considered the other side of the coin. This concept can be explained as "A measure of the total amount of carbon dioxide (CO_2) and methane (CH_4) emissions of a defined population, system or activity, considering all relevant sources, sinks and storage within the spatial and temporal boundary of the population, system or activity of interest. Calculated as carbon dioxide equivalent using the relevant 100-year global warming potential (GWP100)" (***Wright, L.; Kemp, S.; Williams, I.*, 2011**).

Carbon footprint of an organization can come from indirect sources, which is the Carbon produced in foreign sources but are necessary for the company, or from direct sources, which would be the emissions made by sources property of the organization (***Picture 10***). In this thesis the carbon footprint of the product, which computes all the carbon produced during the elaboration and distribution of a product (in this cases natural and artificial Christmas trees) is also going to be taken in account.



Picture 10. *Carbon footprint diagram. Direct and Indirect sources. Taken from http://carbonfootprintacp.com*

In the following pages, and always in order to answer the question previously quoted, an exhaustive investigation of this two previously mentioned species and their plastic counterparts is going to be done, trying to explore the higher amount of cases to have a whole picture of the situation and to try to get a valid and reliable answer. This answer might also serve as a beginning point for further studies and even a marketing strategy for Christmas trees companies.

To end with this introduction it must be said that the author is aware of other comprisable advantages and disadvantages that both natural and artificial Christmas tree have. Some examples are the soil retention, oxygen production, or landscape improvement in the case of natural trees and durability through various years and in the side of the artificial ones. But in order to keep the project under a comprehensive perspective for a master thesis both sides are only going to be compared under CO_2 production terms, leaving for successive investigation important things such as the social benefits, air production or the economic impact derived from its production.

2. Objectives

After this introduction, the objectives of this project are going to be briefly explained in order to set a strong guideline on which the whole thesis is going to lay. Then all the processes to reach this pre-established objectives will be explained in the materials and methodology chapter, and answered in the results and discussion chapters.

2.1. Calculation of average carbon fixing made by natural Christmas trees

This first objective verses about measuring the capacity for carbon fixing depending on the species (*Picea abies* or *Abies alba*) and the size of the tree. This is going to be really important in order to answer the question asked in the introduction. In addition, natural trees seem to start with some advantage respect to artificial ones, as this flux of carbon reduces the overall emissions during the process.

More details are going to be given in the methods chapter, but in summary, to reach this objective some parameters of the trees are going to be measured in order to estimate the biomass of the trees. With this information of the biomass it is easier to know the carbon fixing, as it is proved to be directly related to biomass.

2.2. Calculation and comparison of the average carbon footprint left by natural Christmas trees and artificial Christmas trees.

This objective is focused on the importance of knowing whether natural or artificial Christmas trees produce more carbon in their lifetime . For making a final comparison of natural an artificial Christmas trees and see which one is less pollutant under a carbon production point of view it is essential to know how big is the carbon footprint each of them leaves.

For this the whole process of fabrication, in the case of the artificial ones, is going to be studied. Whit "whole process" is understood that the thesis is not only focusing on the product (product footprint, depends on the material and the size of the artificial tree) itself, but also in the issues of the companies that produce this kind of artificial trees. More details will be given in the methodology chapter, but as it is impossible and not useful to analyze all the companies that have this product, the issue will be summarized by creating two simplified "Company types", big international producer and small local producer.

In the case of natural trees the process is homologous with the difference of the product, whose carbon footprint is apparently much lower when talking about materials and production of the item (factory vs plantation). When this estimations are done the results will be compared.

2.3. Obtainment of the carbon balance made by natural Christmas trees

With the previous objectives reached this third one will be really quick to achieve. The carbon balance is nothing but the contraposition of the data obtained for the carbon fixing and the carbon footprint in tons of carbon per year. The nearest to 0 the balance is the more innocuous the product is.

2.4. Comparison between natural and artificial Christmas trees in carbon production terms. Methodological and program design.

The last objective is just to make a comparison with all the previous data and knowledge and give a final answer to the question. There will be also a trial to sum all the work into an "easy" methodology and support it with an small computer programme powered by *Microsoft Excel*, where data about the natural and artificial trees to be compared would be the input and the output would be which one of the options has the least carbon impact.

3. Materials and methodology

In this part of the thesis the materials and the methodology on which the whole study is based are shown and explained. The materials are the objects, tools and, in this case, Christmas trees plantations, that are going to be used to obtain relevant data for the thesis, so a well description of what each material is and how it has been used is completely necessary.

This chapter will also cover all the methodology followed to reach the previously quoted objectives. As this kind of studies require a lot of data analysis and a well formed idea of the whole process of distribution and production of Christmas trees, methodology has to be very clear and exhaustive in order not to leave any relevant knowledge areas out of the analysis.

3.1. Materials

Next all the materials used are going to be listed and explained.

3.1.1. Computer programmes

This project, although is quite technical and needs from deep comprehension of the topic and has to be backed by some (more or less complex) calculations does not need any specific informatic programme or tool to be done. All the text processing is going to be done with *Microsoft Word 2007*, developed by Microsoft and one of the most known and worldwide used word processors. About the calculations, the graphic outputs and the translation of the methodology into a simplified computer programme, this tasks are going to be accomplished with *Microsoft Excel 2007*, again developed by Microsoft and once again worldwide used and the most popular spreadsheet.

3.1.2. Tools and Gear

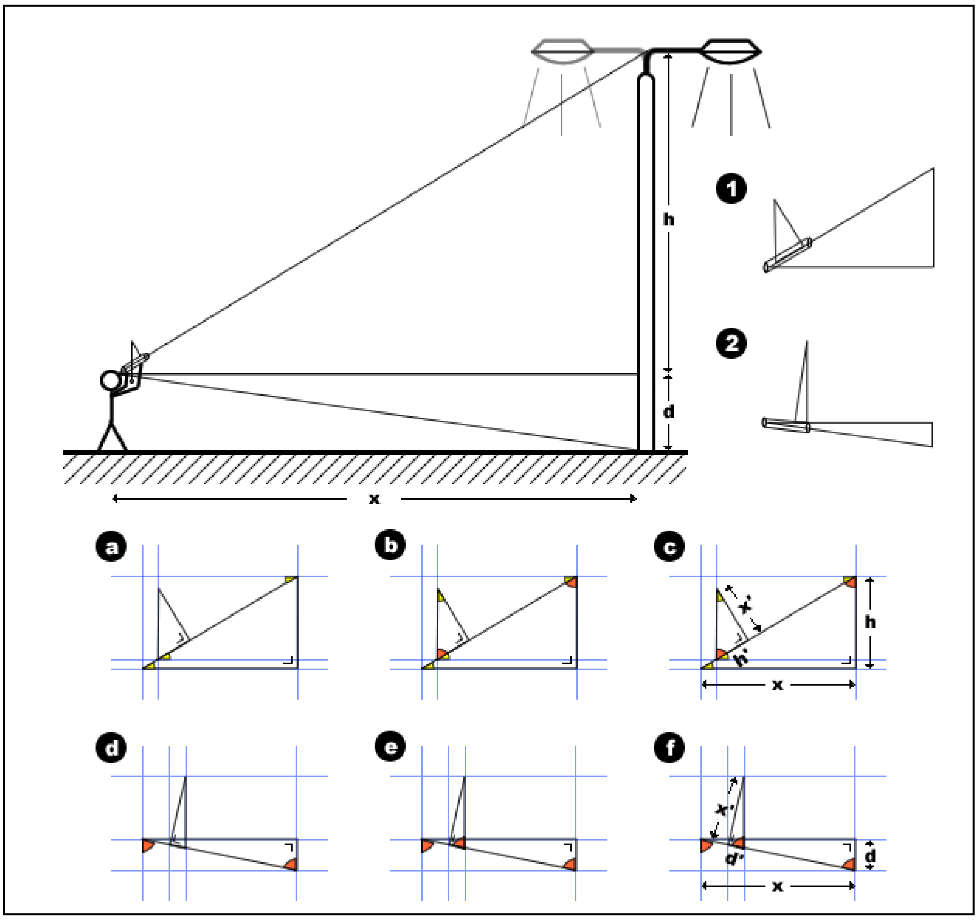
The tools and gear were used to measure basic parameters of trees in order to estimate the biomass in natural tress and mass in artificial trees and thus be able to calculate the carbon fixation and the carbon footprint. Starting with natural Christmas trees, the biomass had to be calculated.

For this the stem biomass had to be calculated, and intermediate parameters such as diameter at breast height (DBH) and stem height had to be measured. For DBH a caliper was used for measuring the diameter at breast height. Calipers (***Picture 11***) consist on a fixed part, a scale and a mobile part, where the fixed part is situated in the target part of the stem and the mobile part is closed against it, resulting on a measure in the scale (***Rivas Torres, D.*, 2010**). About height of the stem, the parameter was measured with an

Hypsometer (***Picture 11***). This tool is based on leaving a sensor at a known height of the stem and then, at a known distance point to the sensor and to the upper and lower part of the stem.

Picture 11. *Caliper is shown on the left part. Hypsometer is shown on the right.*

After that and with the similarity of triangles principle, the stem height can be easily obtained (***Picture 12***).



Picture 12. *Operating principle of a hypsometer.*

The density was obtained from bibliography without the need of any tool.

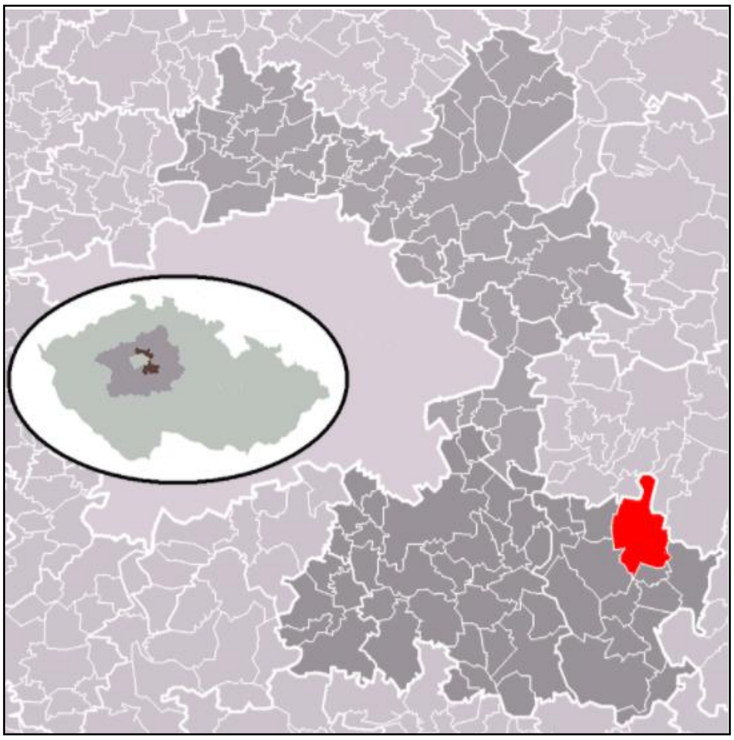
Then the canopy biomass had to be calculated, and for this purpose own methodology was used. In this case, and in order to keep the process as simple as possible, the methodology developed only involves the use of a measuring tape and a weighing machine.

3.1.3. Artificial Christmas trees

Here the materials needed are artificial Christmas trees whose masswas from its volume and the density of the material they are made of. For this purpose trees from heights between 1.5 and 2.5 meters and made of PCE and PE were selected from online catalogues and their volume was estimated based on the parameters displayed in the catalogues. This catalogues are the ones available in ***amazon.es*** and ***arbolesdenavidadartificiales.es***. With this data and knowing the density of the materials they are made of , the mass was easily calculated.

3.1.4. Natural Christmas trees

All the measurements and field issues related to natural Christmas trees were done in the forests and plantations around the village of Kostelec nad Černými lesy, in the central part of the Czech Republic, in the Central Bohemian region and in the Říčany commune (***Picture 13***).



Picture 13. *Faculty headquarters in Kostelec nad Černými lesy (in red) among the Czech Republic.*

For the species *Picea abies*, the measurements were taken in a stand of a monospecific Norway spruce forest managed under the clearcut method. This stand had been clearcut few years ago so it was in regeneration stage, reaching tree heights from 0,5 to 3 meters.

Although the density was quite high at the moment, it allowed the full development and growth of the top sized trees which, in this case, were the target ones. This trees between 1,5 and 2,5 meters could be considered as full developed for their age and in optimum conditions as commercial Christmas trees are.

About the other species, silver fir, what seemed a small non comercial plantation was founded. The trees presented in the same stand a wide variety of heights up to approximately 10 meters, but as the stand was based, most of it, on artificial regeneration the trees had great separation among them. This means that the light, nutrient and space availability allow the growth of the target trees (between 1.5 and 2.5 meters) almost the same as if they were growing on a Christmas trees plantation for commercial purposes.

Note that the surrounding areas of the Kostelec nad Černými lesy village are completely covered by forest and, although this two locations where selected, many others around the area were perfectly suitable for the measurements needed, as the only requirements were a stand whit full space, sun and nutrients availability and with trees of the target species with heights between 1.5 and 2.5 meters. This requirements were set in order to measure trees as similar as possible to commercial Christmas trees.

3.2. Categories of the study

As mentioned at some point before, Christmas trees have a wide variety of typologies, so a slight compartmentalization in categories was needed for being able to interpret the results. This division was also important in terms of organising the work, allowing to make a further and more accurate analysis. Also, and always in order to evaluate the carbon footprint, another division was done in terms of companies producing Christmas trees, as a distribution distance of a few hundred kilometres and a distribution distance of various thousands of kilometres mean different carbon footprints . It is also remarkable that a division based on the size of the company was also needed as big companies are usually much more optimised in all aspects, including carbon generation.

3.2.1. Categories of Christmas trees

The Christmas trees were divided according to its origin, to its species or material, and to its size.

3.2.1.1. Natural Christmas trees

Into the natural origin Christmas trees the study distinguished between two species; *Abies alba* and *Picea abies*. This two species are the most common ones for Christmas trees, but they present some significant differences into their volumes and biomass, as well as into their carbon fixation rates and the carbon they have absorbed during their lifetime. There was also an issue with the size, as not everybody can have in their house a 2 meter tree. Therefore the categories were the following (***Chart 1***):

Table 1. *The 4 study divisions into Natural Christmas trees.*

Species	Size (m)
Picea abies	1.5 - 2
Picea abies	2 - 2.5
Abies alba	1.5 - 2
Abies alba	2 - 2.5

3.2.1.2. Artificial Christmas trees

Into the artificial origin Christmas trees the study distinguished between two composition materials; Polyvynilchlorid (PVC) and Polyethylen (PE). This two materials are the most common ones for artificial Christmas trees, but they present some significant differences into their density, as well as into their carbon footprint rates and the carbon they have inside. There was also an issue with the size, as not everybody can have in their house a 2 meter tree. Therefore the categories into this kind of tree will be the following (***Table 2***):

Table 2. *The 4 study divisions into Artificial Christmas trees.*

Composition	Size (m)
PVC	1.5 - 2
PVC	2 - 2.5
PE	1.5 - 2
PE	2 - 2.5

3.2.2. Categories Christmas trees producers and distributors

As mentioned at the beginning of this page, many important parameters for the present study vary depending on the typology of the company and the distance of the production area to the final purchase place. For this reason it was considered necessary to carry out the study in different company scenarios. This scenarios are

shown next (***Table 3***):

Table 3. *The 4 company scenarios which wer taken in account.*

Type of tree	Type of company	Location of the production
Natural	Small	Local (< 500 Km)
Natural	Big	Denmark
Artificial	Small	Local (< 500 Km)
Artificial	Big	China

This charts obviously needs further explanation. The thesis is intended to answer the question which has lees carbon implications, artificial or natural Christmas trees in a generalist way, but also a methodology for an easy calculus and comparison of the carbon footprint and the carbon fixation among both types of tree was proposed. For that reason this four scenarios were raised.

The number of categories was simplified into the most typical ones, as an exhaustive analysis of the global Christmas trees market was not among the objectives of this thesis. Into the natural trees two divisions had been made, small and big companies. When talking about small companies is common sense that they do not usually have a great distribution capacity, reason why, and always talking in average terms, natural Christmas trees grown in small plantations run by small companies are most commonly commercialised near its growing sites.

In the other hand, big companies have great distribution capacity, so they can easily sell their trees into a much larger scale. In Europe, although the greatest producer is Germany with around 20 million trees, the greatest exporter is Denmark (***Chastanger, G. and Benson, M.*****, 2007**), reason why this country was taken as a reference for distribution of natural Christmas trees at a large scale.

For the artificial trees a similar division was made. When talking about small companies some of them are located through Europe, especially in central-eastern Europe, but when talking about big producers, all of them are in China and, in less proportion, in Thailand.

3.3. Calculation of carbon fixing

After this introductory part of the methodology where the materials and the categories of trees and companies have been described, the process of how the carbon fixing of natural Christmas trees (as artificial trees do not fix any carbon) was obtained is going to be explained.

3.3.1. Volume and density of the stem calculation

In this paragraphs the reasoning made for obtaining this parameters and the mathematical expressions from which they are obtained will be explained. As there are two species, this parameters are not the same, thus a division between them and particular explanation for each species became necessary. Each parameter needed was measured in at least 10 trees. At this point it is important to mention that, although there are volume equations for all domestic species in Czech Republics, specifically designed equations for smaller trees were preferred, as this volume equations are mainly for bigger trees, with larger than 5cm DBH.

3.3.1.1. *Picea abies*

Starting with the volume, some options were explored. A really common way to estimate the stem volume is the analytic way, more specifically using some of the traditional volume equations based on the similarity (in volumetric terms) between the stem of a tree and some solid figures such as paraboloids, cones and neophytes. This traditional equations are summed in ***Table 4***.

Table 4. *Traditional stem volume expressions and the solid they are related to. Being Ab area of the base, Am area of the middle part, As area of the upper part and L the length of the stem. Own elaboration..*

Solid	Expression	Name
Paraboloid	$v = \left[\frac{A_b + A_s}{2}\right]L$	*Smalian*
	$v = A_m L$	*Huber*
Neloid	$v = \left[A_s + \frac{A_s - A_b}{\left(A_s/A_b\right)^{1/3} - 1}\right]\frac{L}{4}$	*Northway*
Paraboloid, cone, neloid	$v = \left[\frac{A_b + 4A_m + A_s}{6}\right]L$	*Newton*

But this expressions seemed to generalist as the purpose was to measure the volume of trees of an specific species, of an specific height and in a specific location (plantations). After some research about specific expressions for the purpose in the Czech Republic, the following expression {1} was founded (***Cerný M.*, 1990**):

$$v = a\cdot(H\cdot D^2)^b \qquad \{1\}$$

Where:

v = Volume in m^3

D= Diameter at breast height in cm

H = Height in m

a = 0.00011261

b = 0.87852

This expression is valid for trees with any range of height and breast height diameter (DBH). It was chosen because it is the most accurate expression for this parameter in the Czech Republic.

About stem density, as said before, no field measures were going to be taken. Instead some research was made and specific data about density of *Picea abies* was founded (***Gryc V.*, *Horáček P.*, 2007**) and served as reliable data. According to the investigation mentioned the authors give 4 density values depending on the part of the section that is analysed, as it can be compression wood (CW), opposite side of the compression wood (OW) or side wood (SWL and SWR) . This values, and always for trees with DBH close to 6 cm are the following (***Table 5***):

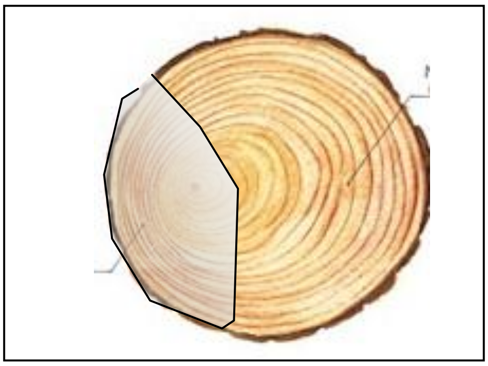
Table 5. *Density values depending on the area of the cross-section according to* ***Gryc V., Horáček P., 2007.***

	CW	OW	SWL	SWR
kg/m3	498,57	458,4	468,57	454,21

As only one value for density was needed, a weighted average of this 4 values was calculated based on the average distribution of compression wood in a stem cross-section (***Picture 14***).

The shaded area (CW) of the previous picture fills 30% of the section, whereas the OW fills the other 30% and SWL and SWR cover a 20% each.

With this data a weighted mean was done with the next expression {2}:



Picture 14. *Proportion of compression wood (grey shaded) in an average stem cross-section*

$$\bar{X} = \frac{CW*30+OW*30+SWL*20+SWR*20}{30+30+20+20} \qquad \{2\}$$

The result of {2} expression led to the definite average density for *Picea abies* with DBH of 6 cm, which appeared to be:

$$d = 471{,}75\frac{kg}{m^3}$$

3.3.1.2. *Abies alba*

As in the previous case, for this species the traditional equations were considered too broad, so more specific expresions were searched in the bibliography. There were not stem volume equations for this species in the Czech Republic, but the next one {3} was founded for Norway (**Øen, S., Bauger, E. & Øyen, B.-H., 2001**):

$$v = a \cdot H^b \cdot D^c \cdot (H-1.3)^d \cdot (D+100)^e \qquad \{3\}$$

Where:

v = Volume in dm^3

D= Diameter at breast height in cm

H = Height in m

a = 1.6662

b = 3.2394

c = 1.9334

d = –1.8997

e = –0.9739

This equation was considered valid for the purpose as is the most specific one founded for the species *Abies alba*. Although Norway and Czech Republic have obviously great differences in many aspects, both are European countries and they are relatively close, so this equation is considered the most accurate one available. Note that this equation was developed under plantation conditions, which is also the case of this thesis. About the cons it is important to point that the authors only guarantee the accuracy for trees over 5 cm of DBH.

About stem density, and following the pattern of *Picea abies*, no field measures were taken. Instead some research was made and specific data about density of *Abies alba* was founded (***Rodrigo B. G., Esteban L. G., de Palacios P., García-Fernández F., Guindeo A.*, 2012**) and served as reliable data. The parameter given in this paper for the stem density of *Abies alba* is:

$$d = 480 \frac{kg}{m^3}$$

3.3.2. Biomass calculation

With the procurement of this data the biomass was then calculated. With the addition of the stem biomass to the crown biomass the average biomass for each category tree of each species was obtained {4}:

$$B_T = B_s + B_c \qquad \{4\}$$

Where:

B_T = Total average biomass of one tree in kg

B_s = Average biomass of the stem of one tree in kg {5}

B_c = Average biomass of the crown of one tree in kg {6}

3.3.2.1. Stem biomass

The stem biomass was calculated having in mind the previously mentioned parameters of stem volume and stem density. The stem biomass was calculated by using the following expression {5}:

$$B_s = v_s \cdot d_s \qquad \{5\}$$

Where:

B_s = Stem biomass in kg

v_s = Stem volume in m^3

d_s = Stem density in kg/m^3

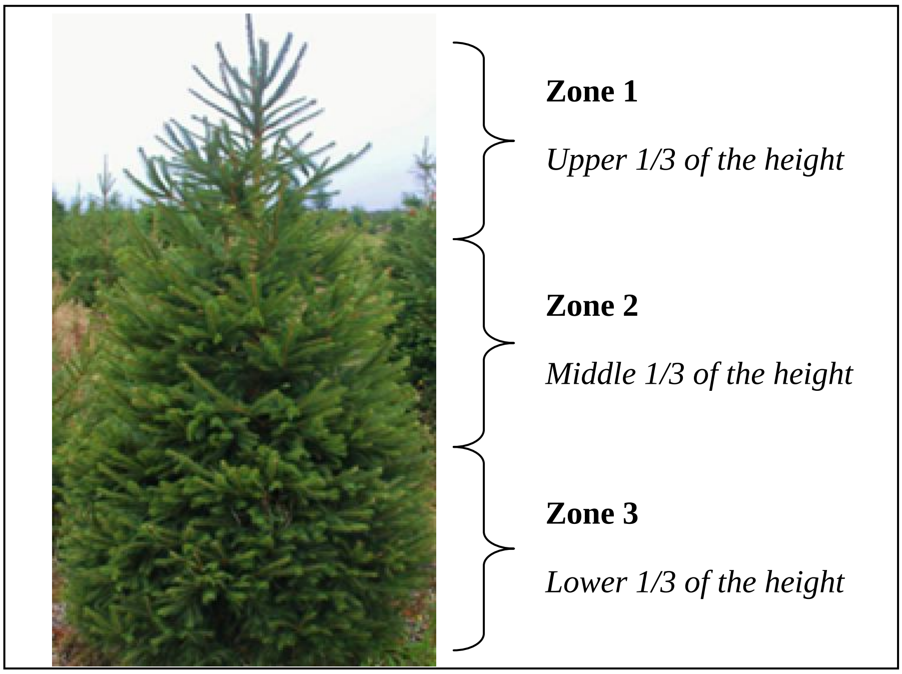
The stem biomass was calculated for each of the categories described in the previous paragraphs and for both species, *Picea abies* and *Abies alba*, in order to be able to calculate de carbon fixing based on the relationship between this two parameters.

3.3.2.2. Crown biomass

This parameter was calculated with an approximated method designed by the author. The bibliography about crown biomass calculation for the desired species and for the desired size is almost inexistent so, due to the impossibility of finding reliable equations for the matter of this thesis, the following method was to be applied.

The thing to do was to establish a division among the different parts of the crown according to the picture (***Picture 15***).

Once the divisions were made the next step was to count the number of branches on each division for at least 5 trees of each of the species and each of the height intervals that are needed for the realization of this thesis. Once this data was collected an average calculation of the number of branches on each division was made for each species (*Picea abies* and *Abies alba*) and for each height interval (1.5-2m and 2-2.5m).



Picture 15. *Divisions of the crown in order toestimate the crown biomass, The full height is divided inti three parts, and each third is a zone.*

The next step was to extract at least 5 average looking branches from each division (and again for each species and each height interval) and weight them. With this the average weight of the branches of each of the divisions was obtained.

The final issue to do for this crown biomass calculation was to multiply the average single branch weight of each division by the average number of branches in that division previously calculated. The sum of the results for each of the three division resulted on the total crown biomass. As mentioned before the whole process was done for each species and for each height interval.

The following expression {6} describes the whole process:

$$B_c = (n_{b1} \cdot w_{b1}) + (n_{b2} \cdot w_{b2}) + (n_{b3} \cdot w_{b3}) \qquad \{6\}$$

Where:

B_c = Total crown biomass in kg

n_{b1}, n_{b2} and n_{b3} = Average number of branches on each of the crown divisions

w_{b1}, w_{b2} and w_{b3} = Average weight of individual branches for each crown division in kg

3.3.3. Measurements

As said before, it was necessary to obtain some data about specific tree parameters in order to obtain the average volume and the average density the stem for a single trees in the species *Picea abies* and *Abies alba.* This data served for the calculation of the biomass. For the procurement of this data some specific field measurements, which are described in the following lines, were needed.

The measurements for both mentioned species, in order to estimate the biomass of the stem, were the following:

- Diameter at breast height
- Height of the stem

To estimate the density of the stem no measures were needed as this parameter could be found on the bibliography.

In order to estimate the biomass of the crown, and according to the own designed method, the following parameters were field measured:

- Number of branches per division of the crown
- Weight of single branches of each division

The materials needed for this operations were previously described in the materials paragraph. Also the plantation where all this field operations were going to be executed had been previously described.

3.3.4. Relationship between biomass and carbon fixing

Always according to the ***Guide for the estimation of Carbon Dioxide absorptions (2015)***, this relationship is part of what is commonly called "*Ex post calculus*", which means to estimate the carbon absorption (fixing) in the moment it is happening.

The calculus is then based on models that estimate the dry biomass (as the ones proposed in the previous paragraphs) of the trees form data collected directly from the plantation.

Once the dry biomass weight was known, the weight of fixed carbon was calculated in function of the fraction of carbon contained in dry matter (FC) which, generically speaking, is believed to be around 0,5 kg C/kg dry matter (***IPCC, 2003***).

Then, as a last step, the conversion from fixed carbon to carbon dioxide was done from the relationship between their molecular weights, that is to say, multiplying the C fixed value by 44/12.

The equation that sums all the process will be then the following {7}:

$$F_{CO_2} = B_t \cdot Fc \cdot \frac{44}{12} \qquad \{7\}$$

Where:

F_{CO_2}= Carbon dioxide fixing in tons of CO_2 per tree

B_t = Total biomass in tons {4}

F_c = Fraction of carbon contained in dry matter in kg C/kg of dry matter. Corresponds to 0,5 kg C/kg dry matter.

This equation was repeated for each species and each height category in order to calculate the carbon fixing during its life of each kind of natural Christmas tree.

3.4. Calculation of carbon footprint

In the following paragraphs the methodology for estimating the carbon footprint left in the whole process of producing and commercialising natural and artificial Christmas trees is going to be explained in detail. For those who may need a slight memory refresh, the carbon footprint can be described as the totality of greenhouse effect gases (GHG) emitted, directly or indirectly, by any individual, organization, event or product.

3.4.1. Carbon footprint of the organization

As a first approach to this concept, it can be said that the carbon footprint of an organization measures the quantity of the GHG emissions coming from whether direct or not-direct sources derived from the company's activity.

This means that all the sources of CO_2 emission of an organization were measured, from energy consumption derived emissions to emissions of the distribution vehicles, in order to give a realistic idea about which process is less pollutant, an artificial Christmas tree going from the factory to the buyers house or an natural Christmas tree going from the plantation to a Christmas decorated living room.

To be more accurate, this could be better expressed as "carbon footprint of the commercializing process"

3.4.1.1. Direct and indirect emissions. Emission scopes.

The first division to be made among the carbon emissions of an organization is between direct and indirect emissions.

Direct emissions are the ones that come from sources that are property or are controlled by the organization. In a simplified way this emissions are the ones produced in the place where the activity takes place in. For example in a natural Christmas trees plantation this emissions will be the ones derived from the use of machines in silvicultural activities, if they are based on fossil fuels.

In the other hand, indirect emissions are the ones consequence of the organization's activities, but occur on places that are not property or controlled by other organizations. An example of this kind of emissions for an artificial Christmas trees company might be the emissions derived from the electric consumption of the factory. This emissions are generated in another place (a energy plant) but the result of them is used by the company.

From this previous division, and in order to keep the identification of the different emissions simple, the following emission scopes were established:

- **First scope**: This are GHG direct emissions. Some generic examples might be: Combustion in boilers, factories, nurseries, vehicles that are property of the organization. It also includes non-expected emissions such as the ones derived from failures or accidents.

- **Second scope**: All the indirect GHG emissions derived from generation of the electric energy acquired and consumed by an organization.

- **Third scope**: Other indirect emissions. Some examples of activities that fit into this scope are extraction and production of materials that the organization acquires, business trips with external vehicles, etc.

In order to be accurate and not to exceed the supposed complexity and length for a master thesis, only first and second scope emissions were taken into account

With this previous concepts explained, particular assumptions were done for this thesis's purposes. In this case the organization footprint was not exactly that, as the carbon footprint calculation was needed for the whole process of Christmas trees production and commercialization, independently on the organizations involved. So in this case the so called process emissions was divided into the two sub-processes involved in the whole Christmas trees business:

- **Productions sub-process**: The carbon footprint left by the sub-process of producing the product, whether it is a plastic Christmas tree produced in a factory or a natural Christmas tree obtained from a plantation.

- **Distribution sub-process:** Is the carbon footprint left by the sub-process of distributing the product from the place of its production to the place where it is purchased by consumers.

As might be understood from the previously said, on each of these sub-processes all first and second scope emissions were identified and estimated.

3.4.1.2. Methodological basis

As a first approach, carbon footprint consist on the application of the following formula {8}:

$$C_f = AD \cdot EF \qquad \{8\}$$

Where:

C_f = The carbon footprint of a process or organization in mass units of equivalent carbon (m.u. eq CO_2)

AD = Activity data. Is the parameter that defines the degree or level of a GHG emissions generating activity. For example the litres of fuel used by a truck per every shipping distance (distribution sub-process) in litres

EF = Emission factor. Are the amount of GHG produced by the activities of the previous factor. This factor varies depending on the activity the carbon footprint is being calculated for. For example for the previously described activity (fuel consumption transporting the product) the emission fact might be measured in mass units of equivalent CO_2 per fuel litre (m.u. eq CO_2 /lf).

The units on which each emission factor is expressed were chosen depending on the available information. The GHG producing activities for both sub-processes previously described are going to be, in the following paragraphs, identified and described, and the data for their EF was extracted from bibliography.

As a last comment it is important to point that, as the CO_2 is the leading agent to global warning (over the other defined GHG CH_4, *N(OH)₂*, FCs, PFCs and NF_3) the unit to measure the GHG emissions are the equivalent tons of Carbon, or eq. t CO_2.

3.4.1.3. Sources of emission identification

The sources of the carbon emissions were divided according to their sub-process and their emission scope (which can be, as said before, 1 or 2).

Into the first scope emissions all the activities derived from transportation of goods, fossil fuels consumption and emissions from failures or accidents were identified. About the second scope emissions all the emission producing activities derived from the energy consumption were identified as well.

3.4.1.3.1. Natural Christmas trees sources of emission identification

Starting with the ***production sub-process*** the following ***first scope sources*** were identified:

- **Preparation of the soil.** This activity involves the use of agricultural or forest machinery that has a consumption of fossil fuels. In this cases big and small companies do both the same, but the difference is the surface. Big Christmas trees farms can have plantations around 50 ha, whereas small companies have usually under 5 ha of plantation. This preparation happens once in the lifetime of the tree. The data for this particular activity, at a depth of 30 cm (***Saving, Energy Efficiency and Agricultural Tillage Systems, 2006***) is between 20 and 35 litres of gasoil per hectare. As big companies have, in general terms, more optimised processes and equipments, their activity data is always going to be considered the lowest one. For small companies exactly the opposite.

- **Plantation of seedlings.** This activity consists on the plantation of seedlings with a sowing machine and also involves the use of gasoil. In this case, the gasoil consumption per hectare also happens once on the trees lifetime and is lower than in the previous activity (***Saving, Energy Efficiency and Agricultural Tillage Systems, 2006***) as it is estimated to be around 4-7 litres of gasoil per hectare.

- **Cultural works and weed control activities.** In this case, the activities are the ones related to the maintenance of the health state of the plantation and the ones related to ensure the commercial quality of the Christmas trees. Some of the most relevant operations in this group are pruning, clearing operations and mowing operations. This activities are necessary at least every two years in all kinds of plantations and involve the use of tractors, chainsaws and brush cutters (***Sheridan, J., et al, 1997***) which are based again on gasoil. In big plantations, where this activities are mechanised, the weed and shrub control activities consume 40 litres of gasoil per hectare and the cultural works about 25 litres of gasoil per hectare (***Forestry Price Rates, 2014***). Talking about small plantations, where activities are most often performed manually, the weed and shrub control have a consumption of around 42 litres per hectare, two litres more than for big companies (as the works are not mechanised) and the same fuel consumption for the pruning. Note that for trees in between 1.5 and 2 meters this activities are repeated 4 times in the life-cycle (8 years) and that for trees between 2 and 2.5 meters it will be repeated 6 times, as their commercial maturity is at around 12 years (***Table 6***):

Table 6. *Summary chart of the fuel consumption in cultural and weed control activities*

Company	Height (m)	Activity	Time (h/ha)	Fuel consumption (l/h)	l/ha per actuation	Acts. per life clicle	Total (l/ha)
Big	1.5-2	Brushing, mowing	5	8	40	4	160
		Pruning	18	1,4	25,2	6	151,2
	2-2.5	Brushing, mowing	5	8	40	4	160
		Pruning	18	1,4	25,2	6	151,2
Small	1.5-2	Brushing, mowing	30	1,4	42	4	168
		Pruning	18	1,4	25,2	6	151,2
	2-2.5	Brushing, mowing	30	1,4	42	4	168
		Pruning	18	1,4	25,2	6	151,2

- **Harvesting.** For this activity, a chainsaw is used. In this kind of plantations, mechanization is not usual even in big companies. Also both categories of trees have diameters below 10, so in terms of chainsaw harvesting the consumption will be always around 12.5 litres per hectare (***Forestry Price Rates, 2014***) independently of the company typology.

After the identification of this GHG emitting activities from the ***first scope***, the process was repeated for the activities of the ***second scope*** in order to identify all the activities and get all the activity data and the emission factors necessary to complete the analysis of the ***production sub-process***. The following activities that have an energy consumption were identified:

- **Lighting.** The companies facilities need from illumination. For this purpose, electric energy produced in power plants is most commonly used. This means that a specific amount of kWh is used every year for the duties related to

Christmas trees production. It is important to observe that the use of electricity will not be the same in a big plantation as in a small plantation. Depending on the size of the lightened areas (***Hernández Sánchez, J. M., 2012***) the electric consumption per year will be 82 kWh/m^2. Offices and supporting installations are suppose to be between 150 and 400 m^2 depending on the size of the plantation. It is also important to have in mind how much time is the Christmas tree going to spend in the plantation (related to the commercializing size) as it is not the same in terms of electricity use to remain 8 or 12 years in the plantation. Also note that the dedicated area on each plantation to each size is 50% distributed. Further explanation is given next (***Table 7***):

Table 7. *Summary chart of the electricity consumption in lightning activities*

Activity	Company	Consumption (kWh/m2 year)	Surface (m2)	Consumption (kWh/year)	Height (m)	Age (years)	Total life consumption (kWh)	Cultivated area (ha)	Life consumption (kWh/ha)
Lightning	Big	82	400	32800	1.5-2	8	262400	25	10496
					2-2.5	12	393600	25	15744
	Small		150	12300	1.5-2	8	98400	2.5	39360
					2-2.5	12	147600	2.5	59040

Having finished with the ***production sub-process*** the next step was to identify and evaluate the ***first scope sources*** of the ***distribution sub-process*** in the same way as for the other sub-process. Note that in this sub-process there were not second scope sources as there is not electric consumption derived from transportation. In this case the calculus was also more simple as in this sub-process only road transport is involved, and that only meant one activity which is explained next:

- **Truck road transportation.** This action takes into the account the emissions produced by the combustion of gasoil in the trucks that carry the Christmas trees from the plantations to the sales areas where they will be purchased by costumers. This activity is relatively easy to measure because, as explained before, the average distance from big plantations to its destiny will be 350 km for small plantations and 800 km for big plantations, as this big plantations are mainly in Denmark and this study is focused on Czech Republic and surrounding areas. A full charged truck has a consumption of 0,3 litres of gasoil per kilometre (***Deslauriers, M., 2015***), that is to say that big companies use around 240 litres per distribution trip and small companies around 105 litres. The problem arises when estimating the amount of trees carried on each trip. A standard truck has around 40 m^2 of carrying surface, and each Christmas tree, manually packed with a net, covers a surface of around 0,04 m^2, so about 1000 trees can be carried on each trip in optimum conditions. This means that, in order to maintain the line of the previous activities an knowing that the plantation density is always 450 trees per hectare, on each trip the trees corresponding to 2.2 hectares are transported, what is the same to say that the data activity of this particular action will be of 109.1 litres per hectare in big companies and 47.7 litres per hectare in small companies

All of this sources identified were summarized in the following chart with their data activity values and their emission factors in their respective units (***Table 8***):

***Table 8**. Summary chart of all the emission activities on each sub-process of the natural Christmas trees commercialization and their data of activity and their emission factors.*

Sub-process	Scope	Activity	Activity Data				Emission factor
			Company tipology	Tree size	Data/ha	Data/tree	
Production	Scope 1	Soil preparation	Big company (50 ha)	(1.5-2m) trees	20 (gasoil litres)	0,044 (gasoil litres)	2,828 (Kg CO2/gasoil litre)
				(2-2.5m) trees			
			Small company (5 ha)	(1.5-2m) trees	35 (gasoil litres)	0,077 (gasoil litres)	
				(2-2.5m) trees			
		Plantation of the seedlings	Big company (50 ha)	(1.5-2m) trees	4 (gasoil litres)	0,009 (gasoil litres)	
				(2-2.5m) trees			
			Small company (5 ha)	(1.5-2m) trees	7 (gasoil litres)	0,016 (gasoil litres)	
				(2-2.5m) trees			
		Silvicultural and weed control activities	Big company (50 ha)	(1.5-2m) trees	260.8 (gasoil litres)	0,58 (gasoil litres)	
				(2-2.5m) trees	391.2 (gasoil litres)	0,869 (gasoil litres)	
			Small company (5 ha)	(1.5-2m) trees	268.8 (gasoil litres)	0,597 (gasoil litres)	
				(2-2.5m) trees	403.2 (gasoil litres)	0,896 (gasoil litres)	
		Harvesting	Big company (50 ha)	(1.5-2m) trees	12.6 (gasoil litres)	0,028 (gasoil litres)	
				(2-2.5m) trees			
			Small company (5 ha)	(1.5-2m) trees			
				(2-2.5m) trees			
	Scope 2	Lightning	Big company (400 m2 office)	(1.5-2m) trees	10496 (kWh)	23,324 (kWh)	0.35 (Kg CO2/kWh)
				(2-2.5m) trees	15744 (kWh)	34,987 (kWh)	
			Small company (150 m2 office)	(1.5-2m) trees	39360 (kWh)	87,467 (kWh)	
				(2-2.5m) trees	59040 (kWh)	131,2 (kWh)	
Distribution	Scope 1	Truck road transportation	Big company (800 km)	(1.5-2m) trees	109.1 (gasoil litres)	0,242 (gasoil litres)	2.828 (KgCO2/gasoil litre)
				(2-2.5m) trees			
			Small company (350 km)	(1.5-2m) trees	47.7 (gasoil litres)	0,106 (gasoil litres)	
				(2-2.5m) trees			

3.4.1.3.2. Artificial Christmas trees sources of emission identification

Starting with the ***production sub-process*** of the artificial Christmas trees commercialization, this ***first scope sources*** were identified:

- **Storage of the product.** In this activity the fuel consumption of the storage machines, mainly forklifts (***Picture 16***), that are used in warehouses.

Picture 16. *Detail of a forklift like the ones used for storage of items in warehouses.*

This machines can carry up to 1.8 tons, have a gasoil consumption of 3 litres per hour, have a work speed of 5 kilometres per hour and can carry a volume of 2,65 m^3 of boxes (***TOYOTA-EU, 2017 online catalogue***). This last fact led to the conclusion that this machines can carry up to fifty 0.053 m^3 (the volume of a Christmas tree box, explained next) boxes.
Having in mind that in a regular factory, the distance from the packaging area to the warehouse is around 100 meters, it can be assumed that per each storage trip the forklift consumes 0.12 litres of gasoil. As said before, in each ride the forklift carries 50 boxes, so the consumption is of 0.0025 litres of gasoil per box, or what is the same to say per artificial Christmas tree.

After the identification of this GHG emitter activities from the ***first scope***, the process was repeated for the activities of the ***second scope*** in order to identify all the activities and get all the activity data and the emission factors necessary to complete the analysis of the ***production sub-process***. The following activities that have an energy consumption were identified:

- **Packaging of the product.** This activity is really relevant and energy consuming in industrial processes. A standard packaging machine, for example the model WRAP AROUND WAR100 (***EFPACK, 2017 online catalogue***) has a capacity of ten packages of 50 x 35 x 30 cm (0.053 m^3) per minute or, what is to say, to pack one artificial Christmas tree every 0.017 hours. According to the previously quoted catalogue this machines have a installed potency of 8 kW. So, the data activity for each tree was in this case of 0.136 kWh per tree taken from electricity.

- **Fusion of the plastic material.** In the process of production of artificial Christmas trees, the plastic material, which in this case could be PVC or PE as related in previous paragraphs, needs to change its state from solid (the way that it is purchased by companies) to liquid. This needs from the use of energy and depends on properties of the plastic material such as the melting temperature and the heat capacity. The objective of this point is to obtain a value of the energy (in kWh) needed to melt the mass of the respective plastic material needed to fabricate one artificial Christmas tree. It is also necessary to have in mind that in this thesis two sizes of artificial Christmas trees are going to be taken in account. Starting with PVC, as its properties are widely known, it can be asserted that its fusion heat is of 0.047 kWh/Kg (***Vlachopoulos, J. & Strutt, D., 2002***). The average mass of 1.5-2 m PVC trees is 10.5 Kg and the average mass of 2-2.5 m PVC trees is 19.5 Kg (***ITEM International S.A., 2017 online catalogue).***

About PE trees the reasoning is exactly the same with the difference that the fusion heat is 0.07 kWh/Kg (***Vlachopoulos, J. & Strutt, D., 2002***) and the The average mass of 1.5-2 m PE trees is 6.65 Kg and the average mass of 2-2.5 m PVC trees is 12.35 Kg (***ITEM International S.A., 2017 online catalogue).***

This leads to a result between 0.47 kWh/tree and 0.87 kWh/tree depending again on the size. This values are summarized next (***Table 9***):

Table 9. *Summary chart of the fusion of the plastic materials activities.*

Activity	Material	Tree size	Heat Fusion (kWh/Kg)	Density (Kg/m3)	Tree Volume (m3)	Activity Data (kWh/tree)
Fusion	PVC	1.5-2 m	0.047	1500	0.007	0.5
		2-2.5 m			0.013	0.92
	PE	1.5-2 m	0.07	950	0.007	0.47
		2-2.5 m			0.013	0.87

- **Lighting.** The factories need from illumination. For this purpose, electric energy produced in power plants is most commonly used. This means that a specific amount of kWh is used for the duties related to artificial Christmas trees production. It is important to observe that the use of electricity will not be the same in a big factory as in a small factory. The electric consumption for lightning purposes is 131 kWh per m^2 and per year (***Hernández Sánchez, J. M., 2011***), which means that it directly depends on the size of the factory. Big companies have factories of around 4000 m^2, which is the surface to be lightened, and small factories due to its lower production volume settle with factories of half of the surface, which is around 1500 m^2. The electric consumption also depends on the number of trees produced per year which, in order to be comparable with the data for natural Christmas trees, will be of 22500 trees for big factories and 2250 for small companies. The data is further explained next (***Table 10***):

Table 10. *Summary chart of the fusion of the lightning activities.*

Activity	Company	Tree size	Consumption (kWh/m2 year)	Surface (m2)	Consumption (kWh/year)	Consumption (kWh/tree)
Lightning	Big	All	131	4000	524000	23,289
	Small			1500	196500	87,333

Having finished with the ***production sub-process*** the next step was to identify and evaluate the ***first scope sources*** of the ***distribution sub-process*** in the same way as for the other sub-process. In this case the calculus seems to be again quite simple simple as in this first scope only road transport is involved, meaning in this case one activity which is explained next:

- **Truck road transportation.** This action takes into the account the emissions produced by the combustion of gasoil in trucks that carry the Christmas trees from factories to sales areas where they will be purchased by costumers. It is important to have in mind that truck transportation happens only in small companies, like the ones located in eastern Europe. This activity is relatively easy to measure because, as explained before, the average distance is around 350 km to the Czech Republic. A full charged truck has a consumption of 0,3 litres of gasoil per kilometre (***Deslauriers, M., 2015***), that is to say that the mentioned type of companies use around 105 litres per trip. The problem arises when estimating the amount of trees carried on each trip. A standard truck has around 80 m^3 of carrying volume, and each Christmas tree, mechanically packed in a box, covers a surface of around 0,053 m^3, so about 1500 trees can be carried on each trip in optimum conditions. This means that, in order to maintain the line of the previous activities the activity data for truck road transportation in small companies is 0,07 gasoil litres per tree.

Note that in this sub-process there are ***second scope sources*** as there is electric consumption derived from the train transportation.

- **Train transportation.** For big factories that produce in China, the transportation of the goods to Europe is most commonly transported by train. This means that, for big companies, 8000 km have to be travelled by train to the European destiny. This trains have to carry a surface of 3937,5 m2 of artificial Christmas trees boxes (full stock, 22500 boxes) and have a consumption (when travelling at 1500 km/h) of 0.024 kWh/km m^2 (***Breimeir, R. 2002***), meaning this that the data of activity will be of 35 kWh/tree.

All of this sources identified were summarized in the following chart with their data activity values and their emission factors in their respective units which, in this case, and always in order to give the data in the clearest way possible are given directly in units per tree (***Table 11***).

3.4.1.4. Organization footprint calculus

Once all the sources of emission had been properly identified and evaluated, the calculus was done according to the previously quoted and explained expression {8}:

$$C_f = AD \cdot EF \qquad \{8\}$$

But, as many sources of emission had been evaluated the definite expression would be the following {10}:

$$C_f = \sum_i^j AD_{ij} \cdot EF_{ij} \qquad \{10\}$$

***Table 11**. Summary chart of all the emission activities on each sub-process of the artificial Christmas trees commercialization and their data of activity and their emission factors.*

Sub-process	Scope	Activity	Activity Data				Emission factor
			Company tipology	Tree size	Tree material	Data/tree	
Production	Scope 1	Storage of the product	Indifferent	(1.5-2m) trees	PVC	0.0025 (gasoil litres)	2,828 (Kg CO2/gasoil litre)
				(2-2.5m) trees			
				(1.5-2m) trees	PE		
				(2-2.5m) trees			
	Scope 2	Packaging of the product		(1.5-2m) trees	PVC	0.136 (kWh)	0.35 (Kg CO2/kWh)
				(2-2.5m) trees			
				(1.5-2m) trees	PE		
				(2-2.5m) trees			
		Fusion of the plastic material		(1.5-2m) trees	PVC	0.5 (kWh)	
				(2-2.5m) trees		0.92 (kWh)	
				(1.5-2m) trees	PE	0.47 (kWh)	
				(2-2.5m) trees		0.87 (kWh)	
		Lightning	Big company (4000 m2)	(1.5-2m) trees	Indifferent	23.289 (kWh)	
				(2-2.5m) trees			
			Small company (1500 m2)	(1.5-2m) trees		87.333 (kWh)	
				(2-2.5m) trees			
Distribution	Scope 1	Truck road transportation	Small company (<350 km)	(1.5-2m) trees	PVC	0,07 (gasoil litres)	2.828 (KgCO2/gasoil litre)
				(2-2.5m) trees			
				(1.5-2m) trees	PE		
				(2-2.5m) trees			
	Scope 2	Train transportation	Big company (<8000 km)	(1.5-2m) trees	PVC	35 (kWh)	0.35 (Kg CO2/kWh)
				(2-2.5m) trees			
				(1.5-2m) trees	PE		
				(2-2.5m) trees			

Where all the parameters are the same but the sum of all the activity data and emission factors of all polluting sources are needed to know the global footprint for the natural Christmas trees commercializing process and the artificial Christmas trees commercializing process.

This had as a result the amount of CO_2 emitted to the atmosphere by each kind of tree (depending on the company size, size of the tree and species or material of the trees) for both natural and artificial Christmas trees. All the emission factors, which is the relationship between the amount of CO_2 emitted to the atmosphere and the activity data, had been identified and are going to be displayed next relating them to the activities that they belong to(***Table 12***).

For a better understanding also the following data is displayed for natural Christmas trees (***Table 13***) and for artificial Christmas trees (***Table 14***).

Table 12. *Summary chart of the values of the emission factors (EF) related to each of the activities of the commercialization of natural and artificial Christmas trees.*

Type	Activity	EF	
		Value	Units
Natural Christmas trees	Soil preparation	2,828	Kg CO2/gasoil litre
	Plantation of seedlings		
	Silvicultural and weed control activities		
	Harvesting		
	Truck road transportation		
	Lightning	0,35	Kg CO2/kWh
Artificial Christmas trees	Storage of the product	2,828	Kg CO2/gasoil litre
	Truck road transportation		
	Packaging of the product	0,35	Kg CO2/kWh
	Fusion of the plastic material		
	Lightning		
	Train transportation		

***Table 13**. Summary chart of all the possible types of natural Christmas trees related to their emission activities and the data activity for each act.*

** all units are gasoil litres/tree except for the activity "Lightning" that the units are kWh/tree*

Type of tree	Type of company	Species	Size (m)	Activity	Data activity (units/tree)*
Natural Christmas trees	Big company	Picea abies	1.5-2	Soil preparation	0,044
				Plantation of seedlings	0,009
				Silvicultural and weed control activities	0,58
				Harvesting	0,028
				Lightning	23,324
				Truck and road transportation	0,242
			2-2.5	Soil preparation	0,044
				Plantation of seedlings	0,009
				Silvicultural and weed control activities	0,869
				Harvesting	0,028
				Lightning	34,987
				Truck and road transportation	0,242
		Abies alba	1.5-2	Soil preparation	0,044
				Plantation of seedlings	0,009
				Silvicultural and weed control activities	0,58
				Harvesting	0,028
				Lightning	23,324
				Truck and road transportation	0,242
			2-2.5	Soil preparation	0,044
				Plantation of seedlings	0,009
				Silvicultural and weed control activities	0,869
				Harvesting	0,028
				Lightning	34,987
				Truck and road transportation	0,242
	Small company	Picea abies	1.5-2	Soil preparation	0,077
				Plantation of seedlings	0,016
				Silvicultural and weed control activities	0,597
				Harvesting	0,028
				Lightning	87,467
				Truck and road transportation	0,106
			2-2.5	Soil preparation	0,077
				Plantation of seedlings	0,016
				Silvicultural and weed control activities	0,896
				Harvesting	0,028
				Lightning	131,2
				Truck and road transportation	0,106
		Abies alba	1.5-2	Soil preparation	0,077
				Plantation of seedlings	0,016
				Silvicultural and weed control activities	0,597
				Harvesting	0,028
				Lightning	87,467
				Truck and road transportation	0,106
			2-2.5	Soil preparation	0,077
				Plantation of seedlings	0,016
				Silvicultural and weed control activities	0,896
				Harvesting	0,028
				Lightning	131,2
				Truck and road transportation	0,106

***Table 14**. Summary chart of all the possible types of artificial Christmas trees related to their emission activities and the data activity for each act.*

** all units are kWh/tree except for the activities "Storage of the product" and "Truck road transportation" that the units are gasoil litres/tree*

Type of tree	Type of company	Material	Size (m)	Activity	Data activity (units/tree)*
Artificial Christmas trees	Big company	PVC	1.5-2	Storage of the product	0,0025
				Packaging of the product	0,136
				Fusion of the plastic material	0,5
				Lightning	23,289
				Train transportation	35
			2-2.5	Storage of the product	0,0025
				Packaging of the product	0,136
				Fusion of the plastic material	0,92
				Lightning	23,289
				Train transportation	35
		PE	1.5-2	Storage of the product	0,0025
				Packaging of the product	0,136
				Fusion of the plastic material	0,47
				Lightning	23,289
				Train transportation	35
			2-2.5	Storage of the product	0,0025
				Packaging of the product	0,136
				Fusion of the plastic material	0,87
				Lightning	23,289
				Train transportation	35
	Small company	PVC	1.5-2	Storage of the product	0,0025
				Packaging of the product	0,136
				Fusion of the plastic material	0,5
				Lightning	87,333
				Truck road transportation	0,07
			2-2.5	Storage of the product	0,0025
				Packaging of the product	0,136
				Fusion of the plastic material	0,92
				Lightning	87,333
				Truck road transportation	0,07
		PE	1.5-2	Storage of the product	0,0025
				Packaging of the product	0,136
				Fusion of the plastic material	0,47
				Lightning	87,333
				Truck road transportation	0,07
			2-2.5	Storage of the product	0,0025
				Packaging of the product	0,136
				Fusion of the plastic material	0,87
				Lightning	87,333
				Truck road transportation	0,07

Once all the data was obtained and ordered the final methodological step was to sum all the carbon footprint values obtained for each kind of tree. This resulted on one single value of kg of CO_2 emitted for the production and distribution for all the kinds of natural and artificial Christmas trees previously mentioned (type of company, size, material, species...) which were the base for the comparison in CO_2 production terms.

3.4.2. Carbon footprint of the product

Once the methodology for calculating the carbon footprint of the process was estimated, the carbon footprint needed to be calculated for the product. This means the amount of carbon generated by the materials of which the product is made of, the carbon that it may generate during its life cycle and finally the carbon generated by the product at the end of its life when discarded by the consumer.

3.4.2.1. Natural Christmas trees

When talking about this kind of trees it is important to remark that the material, which in this case is obviously wood, does not generate any carbon in its production, as the wood is not a raw material used to manufacture the product but is the product itself that. This means that in its growing process, wood absorbs carbon (as described an explained on previous chapters) instead of emitting it to the atmosphere.

But, as everything, this natural Christmas trees have a limited lifecycle after purchased, as when the Christmas period ends they are thrown away and considered trash that will be burned in the waste treatment plants.

As in everything, there are exceptions. Some consumers opt for natural Christmas trees that can be bought with part of its root system in order to plant them in their gardens or in some field afterwards, but as this option has not been taken in account previously, and as it is an uncommon option (only local and small semi-professional producers commercialize trees with roots) this option is not going to be analysed, but it is going to be pointed that in this case the carbon absorption will continue during the whole life of the tree.

About the calculus of the CO_2 produced when the removed trees are burned, the process is the same as the one described in previous paragraphs. In this case, the activity data will be obtained by multiplying the wood Calorific Power by the mass of wood burned. This amount of wood depends again on the size of the tree. Al possible options are summed in the following chart (***Emission factors for the different types of fossil and alternative fuels consumed in Mexico. 2014***) (***Table 15***):

***Table 15**. Summary chart of all options for the CO_2 emissions in wood combustion. The Biomass has to be calculated according to the expression {4}.*

Size (m)	Biomass (Kg)	Calorific Power (TJ/Kg)	Emission Factor (KgCO2/TJ)
1.5 - 2	{4}	2.241 ×10-5	103.237
2 - 2.5			

With this data the amount of CO_2 emitted to the atmosphere at the end of a natural Christmas tree at the end of its life as a result of its combustion can be easily known.

3.4.2.2. Artificial Christmas trees

Now talking about this other kind of product the carbon generation happens again when the product is removed, but for the obtainment of the raw materials as well. This involves the process energy, the transportation energy and the process non-energy (***Plastics. US EPA Archive Document. 2015***). This leads to an emission factor depending on the amount of raw plastic material obtained. Applied to our specific problem this has to be related to the material used (PVC or PE) and the size of the tree, as summed in the following chart (***Table 16***):

***Table 16**. Summary chart of all options for the CO_2 emissions in PE and PVC raw materials productions. The Density and the Volume data took from **Table 9**.*

Size (m)	Material	Density (Kg/m3)	Volume (m3)	Emission Factor (KgCO2/Kg)
1.5 - 2	PE	950	0.007	1.73
2 - 2.5			0.013	
1.5 - 2	PVC	1500	0.007	1.96
2 - 2.5			0.013	

This data easily leads to the obtaining of the CO_2 emitted to the atmosphere in the generation of the raw material needed for one artificial Christmas tree, for each of the study categories.

This kind of decorative trees have also a finite life-cycle and are removed by the owners each couple of years. PE and PVC are two materials that can be easily recycled, but in the case of decorative trees made of them, this particular product is not so easy to recycle. The most common end to this kind of products is the waste treatment centre where they are burned among other diverse, and difficult to recycle, materials.

Burned means again that CO_2 derived from this combustion process is emitted to the atmosphere. Applied to our specific problem this CO_2 amount is related to the material used (PVC or PE) and the size of the tree, as summed in the following chart (***Table 17***):

Table 17*. Summary chart of all options for the CO_2 emissions in PE and PVC when burned. The Density and the Volume data took from* ***Table 9****.*

Size (m)	Material	Density (Kg/m3)	Volume (m3)	Emission Factor (KgCO2/Kg)
1.5 - 2	PE	950	0.007	3.08
2 - 2.5			0.013	
1.5 - 2	PVC	1500	0.007	1.38
2 - 2.5			0.013	

This data leads to the obtaining of the CO_2 emitted to the atmosphere at the end of the life-cycle of artificial Christmas trees, for each of the study categories.

3.5. Program design

All this methodology can seem a bit complex and some readers might find it messy. That is why, in order to make the process a bit more clear a spreadsheet whit sums all of this methodology was elaborated. The mentioned spreadsheet is composed of all the previously quoted and explained expressions that make up this methodology and are related ones to the others. The objective is that the user enters in the spreadsheet or "program" the data for its particular case, allowing to obtain an answer to the question (are natural Christmas trees more eco-friendly than artificial Christmas trees?) under various scenarios.

The programs interface (***Picture 17***) might look simple but is in fact really powerful and takes in account a great number the facts and possibilities.

The program is based on a series of mathematical formulas that relate all the activity data and all the emission factors for each of the pre-defined categories (big-small company, the different tree sizes, the different trees species, the different materials from which the artificial trees are made) in order to, after entering a really simple input for a particular case, obtain the comparison, in terms of CO_2 emitted, between natural Christmas trees and its plastic alternative.

The inputs are really easy to obtain data and only consists on the species, the DBH, the height and the kind of company, in the case of natural Christmas trees and the material (PVC, PE), the height and the kind of company. With all this input and a programation based on IF/AND concatenated excel function nested in other IF/AND functions, and having in mind that the organization CO_2 footprint and the product CO_2 footprint add CO_2 kilograms and the CO_2 fixing subtracts CO_2 kilograms for natural Christmas trees and that there will only be organization CO_2 footprint and product CO_2 footprint adding CO_2 kilograms in the case of artificial Christmas trees; a result depending on the origin of the tree and its category will be obtained in form of kilograms of CO_2 emitted by that particular kind of tree.

INPUT

Picea abies	
DBH(cm)	0
H(m)	0
Abies alba	
DBH(cm)	0
H(m)	0

H(m) for *Abies alba* must be >1.3

STEM BIOMASS

Picea abies	
Volume (m3)	0
Density (kg/m3)	471,75
Stem Biomass (kg)	0
Abies alba	
Volume (m3)	0
Density (kg/m3)	480
Stem Biomass (kg)	0

CROWN BIOMASS

Picea abies	
0	Kg
Abies alba	
0	Kg

TOTAL BIOMASS

Picea abies	
0	Kg
Abies alba	
0	Kg

TOTAL CO2 FIXING

Picea abies	
0	tCO2/tree
Abies alba	
0	tCO2/tree

INPUT

Company tipology (B/S)	0

OTAL CO2 Organization Footprint Natural Christmas tree

0	KgCO2/tree

Sub-process	Scope	Activity	Company tipology	Tree size	Activity data	AD units	Emission Factor	EF units
Production	Scope 1	Preparation of the soil	Big	(1.5-2m) trees	0,044	gasoil litres/tree	2,828	KgCO2/gasoil litre
				(2-2.5m) trees				
			Small	(1.5-2m) trees	0,077			
				(2-2.5m) trees				
		Plantation of seedlings	Big	(1.5-2m) trees	0,009			
				(2-2.5m) trees				
			Small	(1.5-2m) trees	0,016			
				(2-2.5m) trees				
		Cultural and weed control work	Big	(1.5-2m) trees	0,58			
				(2-2.5m) trees	0,869			
			Small	(1.5-2m) trees	0,597			
				(2-2.5m) trees	0,896			
		Harvesting	Big	(1.5-2m) trees	0,028			
				(2-2.5m) trees				
			Small	(1.5-2m) trees				
				(2-2.5m) trees				
	Scope 2	Lightning	Big	(1.5-2m) trees	23,324	kWh/tree	0,35	KgCO2/kWh
				(2-2.5m) trees	34,987			
			Small	(1.5-2m) trees	87,467			
				(2-2.5m) trees	131,2			
Distributio	Scope 1	Truck road transportation	Big	(1.5-2m) trees	0,242	gasoil litres/tree	2,828	KgCO2/gasoil litre
				(2-2.5m) trees				
			Small	(1.5-2m) trees	0,106			
				(2-2.5m) trees				

INPUT

Company tipology (B/S)	0
Tree size (in m)	0
Material (PVC/PE)	0

TAL CO2 Organization Footprint Artificial Christmas tre

0	KgCO2/tree

Sub-process	Scope	Activity	Company tipology	Tree size	Tree material	Activity data	AD units	ission Fact	EF units
Production	Scope 1	Storage of the product	Indifferent	(1.5-2m) trees	PVC	0,0025	gasoil litres/tree	2,828	KgCO2/gasoil litre
				(2-2.5m) trees					
				(1.5-2m) trees	PE				
				(2-2.5m) trees					
	Scope 2	Packaging of the product		(1.5-2m) trees	PVC	0,136	kWh/tree	0,35	KgCO2/kWh
				(2-2.5m) trees					
				(1.5-2m) trees	PE				
				(2-2.5m) trees					
		Fusion of plastic materials		(1.5-2m) trees	PVC	0,5			
				(2-2.5m) trees		0,92			
				(1.5-2m) trees	PE	0,47			
				(2-2.5m) trees		0,87			
		Lightning	Big	(1.5-2m) trees	Indifferent	23,289			
				(2-2.5m) trees					
			Small	(1.5-2m) trees		87,333			
				(2-2.5m) trees					
Distribution	Scope 1	Truck road transportation	Small	(1.5-2m) trees	PVC	0,07	gasoil litres/tree	2,828	KgCO2/gasoil litre
				(2-2.5m) trees					
				(1.5-2m) trees	PE				
				(2-2.5m) trees					
	Scope 2	Train transportation	Big	(1.5-2m) trees	PVC	35	kWh/tree	0,35	KgCO2/kWh
				(2-2.5m) trees					
				(1.5-2m) trees	PE				
				(2-2.5m) trees					

Species	Biomass (Kg)	Calorific Power (TJ/Kg)	Emission Factor (KgCO2/TJ)
Abies alba	0	0,00002241	103,237
Picea abies	0		

TOTAL CO2 Product Footprint Natural Christmas trees

Abies alba	0	KgCO2/tree
Picea abies	0	

TOTAL CO2 Product Footprint Artificial Christmas trees

0	KgCO2/tree

Size	Material	Mass	Emission Factor (KgCO2/Kg)
1.5-2	PVC	10,5	1,73
2-2.5		19,5	
1.5-2	PE	6,65	1,96
2-2.5		12,35	

Natural	Artificial
0 KgCO2/tree	0 KgCO2/tree

Picture 17*. Detail of the different parts of the program. Each square is for the different categories, Natural Christmas trees carbon fixing, natural Christmas trees organization footprint, artificial Christmas trees organization footprint, natural Christmas trees product footprint, artificial Christmas trees product footprint and results. In yellow cells the input data and in red cells the partial results. In light grey the final results*

4. Results

In this chapter all the results from the measurements and calculations showed and developed in the previous chapters are quoted and explained in order to settle a strong and accurate data background that is analysed in the discussion chapter.

4.1. Carbon fixing by natural trees

As mentioned in its corresponding chapter, trees, and in this case Christmas trees such as *Abies alba* and *Picea abies* have the capacity of fixing, or absorbing, carbon (CO_2) during their life-cycle as they incorporate it into their tissues as they grow. The way this carbon amount is calculated is explained in detail in the methodology chapter, and can be summed in estimating the total biomass of each kind of the study trees, which where *Picea abies* and *Abies alba* trees with the sizes of 1.5-2 meters and 2-2.5 meters, and multiply it by the conversion factor of wood mass to CO_2 mass in trees. Before showing the results a few notes are needed.

There are 4 possible categories depending on the species and the size, but the amount of carbon depends on a specific value for height and diameter. So, in this case, for both the height and the diameter the taken value was the average value for each category from the field measured values. The results are displayed in the following table (***Table 18***):

Table 18*. Results (in yellow) of the total amount of fixed CO2 for natural Christmas trees depending on size and species, and other relevant data for its obtention.*

Species	Category	Average Height (m)	Average Diameter (cm)	Biomass (Kg)	Fixed CO2 (Kg)
Abies alba	1.5-2	1.76	4	13.01	23.84
	2-2.5	2.32	4.9	14.42	26.42
Picea abies	1.5-2	1.68	3.2	10.62	19.46
	2-2.5	2.26	5.1	16.12	29.55

4.2. Carbon footprint by natural trees

On the other hand, the process of growth of a natural Christmas tree under an industrial point of view, that is to say plantations, has its environmental costs. There are many activities to do in plantations such as soil preparation, silvicultural works and some other (explained in detail in the corresponding chapter) that involve a consumption of whether electricity or fuel, resulting this on a CO_2 emission to the atmosphere. This amount of carbon has been estimated from a careful understanding and evaluation of the fuel or electricity consumption of all the; previously classified by scopes and sub-processes, activities involved in this industrial process.

In addition, this carbon footprint was divided in two sub-categories, the one left by the organization that carries the industrial process and the one left by the product itself when it is disposed. Into each of this categories there are again some divisions. In the case of the organization footprint it depends on the size of the organization (company) and some characteristics of the final product, in this case the height. For the product footprint another 4 variations were necessary. As this product footprint depends again on the biomass the variations are, as for the carbon fixing, depending on the species and the size (depending as well on the height and the diameter) of the final product. Again for the height and diameter values the average value of the field measured values was taken.

In the following tables the results of the organization carbon footprint (***Table 19***) and the product carbon footprint (***Table 20***) left by natural Christmas trees are displayed as previous results.

Table 19*. Results (in yellow) of the total CO2organization footprint for natural Christmas trees depending on size and organization typology.*

Company size	Category	CO2 Footprint (Kg)
Big	1.5-2	10.72
	2-2.5	15.62
Small	1.5-2	32.94
	2-2.5	49.11

Table 20*. Results (in yellow) of the total CO2product footprint for natural Christmas trees depending on size and species.*

Species	Category	Biomass (Kg)	CO2 Footprint (Kg)
Abies alba	1.5-2	13.01	0.03
	2-2.5	14.42	0.033
Picea abies	1.5-2	10.62	0.025
	2-2.5	16.12	0.037

Knowing this results for both organization and product footprint it appears to be 8 possible categories for the total footprint of natural Christmas trees depending on company typology, size and species (***Table 21***):

Table 21. *Results (in yellow) of the total CO_2 footprint for natural Christmas trees depending on size, company typology and species.*

Company size	Species	Category	Org CO2 Footprint (Kg	Prod CO2 Footprint (Kg)	Total CO2 Footprint (Kg)
Big	*Abies alba*	1.5-2	10.72	0.03	10.75
		2-2.5	15.62	0.033	15.65
	Picea abies	1.5-2	10.72	0.025	10.75
		2-2.5	15.62	0.037	15.66
Small	*Abies alba*	1.5-2	32.94	0.03	32.97
		2-2.5	49.11	0.033	49.14
	Picea abies	1.5-2	32.94	0.025	32.97
		2-2.5	49.11	0.037	49.15

4.3. Carbon balance of natural trees

At this point, with all the previous results, it became possible to get a estimation of the final value of the total CO_2 emissions for natural Christmas trees. This concept is the carbon balance and consists on the CO_2 fixation minus the CO_2 footprint. Again 8 results were obtained depending on the company typology, the size and the species (***Table 22***). Note that if the result is positive means that specific kind of tree emits that amount of CO_2 and if the result is negative it means that it absorbs it..

Table 22. *Results (in yellow) of the total CO2 balance for natural Christmas trees depending on size, company typology and species.*

Company size	Species	Category	CO2 balance (Kg)
Big	*Abies alba*	1.5-2	-13,09
		2-2.5	-10,77
	Picea abies	1.5-2	-8,71
		2-2.5	-13,89
Small	*Abies alba*	1.5-2	9,13
		2-2.5	22,72
	Picea abies	1.5-2	13,51
		2-2.5	19,6

4.4. Carbon footprint by artificial trees

The process of fabrication of artificial Christmas trees has its costs under an environmental point of view. There are many activities to do in factories such as fusion of plastic materials, packaging and some others (explained in detail in the corresponding chapter) that involve a consumption of whether electricity or fuel, resulting this on a

CO_2 emission to the atmosphere. This amount of carbon has been estimated from a careful understanding and evaluation of the fuel or electricity consumption of all the; previously classified by scopes and sub-processes, activities involved in this industrial process.

In addition, this carbon footprint can be divided in two sub-categories, the one left by the organization that carries the industrial process and the one left by the product itself when it is disposed. Into each of this categories there are again some divisions. In the case of the organization footprint it depends on the size of the organization (company) and some characteristics of the final product, in this case the size (height). For the product footprint another 4 variations were necessary. As this product footprint depends on the mass and the material, the variations depend on the plastic material and the size of the final product.

In the following tables the results of the organization carbon footprint (***Table 23***) and the product carbon footprint (***Table 24***) left by artificial Christmas trees are displayed as previous results.

Table 23*. Results (in yellow) of the total CO2organization footprint for artificial Christmas trees depending on size, material and organization typology.*

Company size	Material	Category	Organization CO2 Footprint (Kg)
Big	*PVC*	1.5-2	20.63
		2-2.5	20.78
	PE	1.5-2	20.62
		2-2.5	20.76
Small	*PVC*	1.5-2	30.99
		2-2.5	31.14
	PE	1.5-2	30.98
		2-2.5	31.12

Table 24*. Results (in yellow) of the total CO2product footprint for artificial Christmas trees depending on size and material.*

Material	Category	Product CO2 Footprint (Kg)
PVC	1.5-2	18.17
	2-2.5	33.74
PE	1.5-2	13.03
	2-2.5	24.21

Knowing this results for both organization and product footprint it appears to be 8 possible categories for the total footprint of artificial Christmas trees depending on company typology, size and material (***Table 25***):

Table 25. *Results (in yellow) of the total CO2 footprint for artificial Christmas trees depending on size, company typology and material.*

Company size	Material	Category	Org CO2 Footprint (Kg)	Prod CO2 Footprint (Kg)	Total CO2 Footprint (Kg)
Big	*PVC*	1.5-2	20.63	18.17	38,8
		2-2.5	20.78	33.74	54,52
	PE	1.5-2	20.62	13.03	33,65
		2-2.5	20.76	24.21	44,97
Small	*PVC*	1.5-2	30.99	18.17	49,16
		2-2.5	31.14	33.74	64,88
	PE	1.5-2	30.98	13.03	44,01
		2-2.5	31.12	24.21	55,33

In this case of artificial Christmas trees there is no need for a balance as there is no CO_2 absorption at any point of its fabrication process, being thus the total CO_2 footprint the equivalent of the CO_2 balance calculated for natural Christmas trees.

5. Discussion

As seen during the realization of this thesis, the calculation of the carbon emissions is a hard and long process that needs from lots of information and great knowledge of the processes involved. All the data, expressions and processes are strongly backed by bibliography, which is the only proper way to face this kind of work.

A few conclusions were achieved and they are going to be explained and discussed next.

The first important conclusion is that, in general terms, the total CO_2 footprint, for all combinations of sizes, type of company an species is lower, in general terms on natural Christmas trees. The values range from negative values, such as -13.89 Kg of CO_2 for *Picea abies* trees from big companies with a 2 to 2.5 meter size (meaning this negative value that the process of production and distribution absorbs CO_2) to values up to 22.72 Kg of CO_2 for *Abies alba* trees from small companies with a 2 to 2.5 meters size. In the case of artificial Christmas trees the values are always positive (meaning that this kind of tree, obviously, is not capable of absorbing any CO_2) ranging from 33.65 Kg of CO_2 for PE trees produced by Big companies and with a 1.5 to 2 meters size to a maximum of 64.88 Kg of CO_2 for PVC trees produced by Small companies with a 2 to 2.5 meters size.

This leads to some predictable secondary conclusions like the CO_2 footprint is always greater in Small companies compared to big companies independently whether talking about the species, the material or the size of the trees. This is, in my opinion because the processes of fabrication and transportation, although small companies produce less tress and are closer to the purchase points, are more optimized in big companies, being this optimization more important in terms of CO_2 production than the lower production and distance travelled for the small company trees.

Other conclusion that can be obtained is that the most common situation is that trees from the 2 to 2.5 meters have a higher CO_2 footprint. This can be easily explained for artificial Christmas trees as the more plastic used the more CO_2 emitted during its production and combustion. But the case of natural Christmas trees is not as clear, in fact, for the case of the species *Picea abies* (produced by big companies) the CO_2 balance, which by the way resulted as an absorption, was lower in 2 to 2.5 meters trees than in the smaller ones. This can be explained by the fact that the balance depends on three variables, the fixation, the footprint by the organization and the footprint by the product, and the relation between this facts is not lineal. This means that separately the relation between the two mentioned sizes of *Picea abies* from big companies always results on a lower value for the smallest size in terms of footprint but results on greater values of fixation for the bigger size. in this case the carbon fixation is 10 kg greater for the bigger size and the footprint is only 5 Kg lower on the shorter size, resulting in this case on a lower value in the balance for the 2 to 2.5 meters size.

About the species there is no significant difference in the carbon balance. In equality of the other conditions (company typology and size) the values are really similar, with differences not greater than 3 CO_2 Kg, in low sizes this difference favours *Abies alba* and in the upper size it favours *Picea abies*.

Talking about artificial trees, the material is more significant than the species in the previous case, being always, in equality of the other facts, higher the values for PVC, around a 16%. This is because, although the emission factor is lower than PE, the density is much higher and, in proportion, results on higher footprint values both in the organization and product sides for PVC.

Other conclusion is that CO_2 production is strongly based on the organization footprint in the case of natural Christmas trees, but in the case of artificial Christmas trees this CO_2 production splits between the organization and the product footprint. This leads to the idea of the importance of recycling the plastic materials from which artificial trees are made of after is use, whereas the product footprint for natural Christmas trees hasn't almost relevance due to the fact that the combustion of wooden untreated materials generates a low CO_2 amount. The following table shows a comparison between the product footprint of both kinds of trees (***Table 26***):

Table 26*. Comparison between the product CO_2 footprint left by artificial and natural Christmas trees.*

Company size	Species	Category	Nat Footprint (Kg)	Art Footprint (Kg)	Category	Material	Company size
Big	*Abies alba*	1.5-2	0.03	18.17	1.5-2	*PVC*	Big
		2-2.5	0.033	33.74	2-2.5		
	Picea abies	1.5-2	0.025	13.03	1.5-2	*PE*	
		2-2.5	0.037	24.21	2-2.5		
Small	*Abies alba*	1.5-2	0.03	18.17	1.5-2	*PVC*	*Small*
		2-2.5	0.033	33.74	2-2.5		
	Picea abies	1.5-2	0.025	13.03	1.5-2	*PE*	
		2-2.5	0.037	24.21	2-2.5		

Continuing with the analysis, in this case with the organization footprint of again both kind of trees it can be easily pointed that, in general terms and as can be in part deduced from the previous table, is much more relevant in the case of natural Christmas trees. The values of the organization footprint for natural and artificial Christmas trees are compared next (***Table 27***):

Table 27*. Comparison between the organization CO2 footprint left by artificial and natural Christmas trees.*

Company size	Species	Category	Nat Footprint (Kg)	Art Footprint (Kg)	Category	Material	Company size
Big	*Abies alba*	1.5-2	10.75	20.63	1.5-2	PVC	Big
		2-2.5	15.65	20.78	2-2.5		
	Picea abies	1.5-2	10.75	20.62	1.5-2	PE	
		2-2.5	15.66	20.76	2-2.5		
Small	*Abies alba*	1.5-2	32.97	30.99	1.5-2	PVC	*Small*
		2-2.5	49.14	31.14	2-2.5		
	Picea abies	1.5-2	32.97	30.98	1.5-2	PE	
		2-2.5	49.15	31.12	2-2.5		

When looking at both sets of data it can be deduced that the production in big companies is much more efficient for natural Christmas trees than for artificial, but in the case of small companies artificial Christmas trees are produced more effectively. In fact the organization footprint is in case of small companies lower for artificial Christmas trees than for natural Christmas trees, being this the only particular case against the first conclusion. This can be answered by the fact that forestry, agriculture and other activities related with the environment and the management of vegetal species is really undeveloped in its local facet, whereas the industrial activity, which is responsible for the production of artificial Christmas trees, is mucho more optimised and thus lees CO_2 producing due to a greater development of this sector at low inversions and business rates. When the production and the inversion grows Christmas trees companies are less related to rural environment and more optimised, which explains why in this last table big natural Christmas trees companies can compete with big artificial Christmas trees companies under this CO_2 production angle, which is in last term nothing but an indicator of the optimization of the processes and energy efficiency of the activities of the companies.

To end with this conclusions and discussion part the values of total CO_2 emission for all the kinds of trees studied are listed (from lowest to highest emission) in the following table (***Table 28***):

Table 28 *Ranking of the CO_2 emission for all the kinds of studied trees.*

Company size	Species/Material	Category	CO2 emission (Kg)
Big	*Picea abies*	2-2.5	-13,89
Big	*Abies alba*	1.5-2	-13,09
Big	*Abies alba*	2-2.5	-10,77
Big	*Picea abies*	1.5-2	-8,71
Small	*Abies alba*	1.5-2	9,13
Small	*Picea abies*	1.5-2	13,51
Small	*Picea abies*	2-2.5	19,6
Small	*Abies alba*	2-2.5	22,72
Big	PE	1.5-2	33.65
Big	PVC	1.5-2	38.8
Small	PE	1.5-2	44.01
Big	PE	2-2.5	44.97
Small	PVC	1.5-2	49.16
Big	PVC	2-2.5	54.52
Small	PE	2-2.5	55.33
Small	PVC	2-2.5	64.88

So this means that the best purchase in terms of being eco-friendly is a *Picea abies* between 2 and 2.5 meters from a big company. In the other hand the worst purchase is a 2 to 2.5 meters PVC tree from a small company.

As said before all natural trees are more eco-friendly than artificial Christmas trees. Among the natural Christmas trees the most CO_2 emitting one in an *Abies alba* between 2 and 2.5 meter from a small company. For artificial Christmas trees, the best purchase in terms of CO_2 saving would be, as expected, a PE tree between 1.5 and 2 meters from a big company.

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7. Annexes

7.1. Fieldsheets

Date:
Name:
Location:

DBH and stem height											
		Sample tree									
		1	2	3	4	5	6	7	8	9	10
Picea abies (1.5-2m)											
	DBH (cm)										
	Height (m)										
Picea abies (2-2.5m)											
	DBH (cm)										
	Height (m)										
Abies alba (1.5-2m)											
	DBH (cm)										
	Height (m)										
Abies alba (2-2.5m)											
	DBH (cm)										
	Height (m)										

Date:
Name:
Location:

All weights are in kg

		Number of branches and weight per crown division				
		Sample tree				
		1	2	3	4	5
Picea abies (1.5-2m)						
	Number of branches Division 1					
	Number of branches Division 2					
	Number of branches Division 3					
	Weight of branch Division 1					
	Weight of branch Division 2					
	Weight of branch Division 3					
Picea abies (2-2.5m)						
	Number of branches Division 1					
	Number of branches Division 2					
	Number of branches Division 3					
	Weight of branch Division 1					
	Weight of branch Division 2					
	Weight of branch Division 3					
Abies alba (1.5-2m)						
	Number of branches Division 1					
	Number of branches Division 2					
	Number of branches Division 3					
	Weight of branch Division 1					
	Weight of branch Division 2					
	Weight of branch Division 3					
Abies alba (2-2.5m)						
	Number of branches Division 1					
	Number of branches Division 2					
	Number of branches Division 3					
	Weight of branch Division 1					
	Weight of branch Division 2					
	Weight of branch Division 3					

7.2. Abbreviations dictionary

Ab: Basal area

Am: Middle part area

As: Upper part area

AD: Activity data

Art: Artificial

B_c: Crown Biomass

B_s: Stem Biomass

B_t: Total Biomass

C: Carbon

C_f: Carbon footprint

CH_4: Methane

C_2H_4: Methylene

cm: Centimetres

CO_2: Carbon dioxide

CW: Compression wood

d: Density

d_s: Stem density

DBH: Diameter at breast height

EF: Emission factor

eq. t CO_2: Carbon dioxide equivalent tons

et al.: Et alii (and others).

etc: et cetera

Fc: Fraction of carbon contained in dry matter

F_{CO_2}: Carbon dioxide fixing

FCs: Fluorinated chemicals

GHG: Greenhouse effect Gases

GWP100: 100-year Global Warming Potential

H: Height

h: Hour

ha: Hectares

IPCC: Intergovernmental Panel on Climate Change

IUPAC: International Union of Pure and Applied Chemistry

Km: Kilometres

kWh: Kilowatts per hour

L: Stem length

l: Litres

m: Metres

m^2: Square meters

m^3: Cubic metres

mm: Milimetres

n_{b1}, n_{b2} *and* n_{b3} : Average number of branches on each of the crown divisions

Nat: Natural

NF_3: Nitrogen triflouride

$N(OH)_2$: Nitrogen hidroxide

Org: Organization

OW: Opposite side of the compression wood

PE: Poly Ethilene

PFCs: Perfluorinated chemicals

Prod: Product

PVC: Poly Vinyl Chloride

SWL: Left side wood

SWR: Right side wood

TJ: Terajoule

v: Volume

v_s: Stem volume

VCM: Vinyl Chloride Monomer

w_{b1}, w_{b2} *and* w_{b3} : Average weight of individual branches for each crown division