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# Integrating Material Flow Cost Accounting with Life cycle assessment to Assess the Economic and Environmental Performances of Selected Wood Industries in the Landes de Gascogne Forest, France

Haji Yazdeen Haji

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PHD MANUSCRIPT PRESENTED TO OBTAIN THE DIPLOMA

**DOCTOR OF THE UNIVERSITY OF BORDEAUX**

DOCTORAL SCHOOL OF CHEMICAL SCIENCES

SPECIALTY: PROCESS ENGINEERING

By

**Haji Yazdeen Haji**

**Integrating Material Flow Cost Accounting with Life cycle assessment to Assess the Economic  
an Environmental Performances of Selected Wood Industries in the Landes de Gascogne  
Forest, France**

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Defense on 20 June 2023

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## RÉSUMÉ

Il y a une préoccupation croissante quant à l'impact de nos modes de consommation et de production sur notre planète, au point que nous atteignons les limites de croissance avec la planète incapable d'assimiler indéfiniment les effets des activités anthropiques. En conséquence, au cours des dernières années, les préoccupations croissantes concernant le changement climatique ont poussé les organisations commerciales à changer leurs priorités, non seulement pour atteindre des objectifs économiques, mais également pour considérer les objectifs écologiques. La foresterie, qui est une partie importante de la nature, a traditionnellement été un fournisseur de matières premières renouvelables pour l'utilisation industrielle (sciage, pâte et papier, panneaux de particules, etc.) et pour le bois de chauffage domestique. Bien que de nombreuses études aient été menées dans ce domaine, peu d'attention a été accordée à l'importance de l'évaluation monétaire de l'impact environnemental négatif pour déterminer le véritable prix des produits en bois et prendre une décision éclairée pour l'investissement. Cette étude vise à évaluer la performance économique et environnementale de cinq produits en bois de pin maritime, issus du processus Gate-to-Gate dans la forêt des Landes de Gascogne en France. Les données ont été collectées sur la base d'une revue de la littérature et des références mentionnées dans le chapitre quatre et le chapitre cinq de cette étude, puis ces données ont été utilisées dans l'analyse du logiciel semipro pour identifier l'impact environnemental (Gate-to-gate) pour les produits étudiés par la méthodologie d'évaluation du cycle de vie (LCA) et un modèle de coût a été établi pour chaque produit par la méthodologie de coût du cycle de vie (LCC). Ensuite, les deux méthodologies ont été liées en utilisant la comptabilité des coûts des flux de matières (MFCA), et les résultats ont correspondu à la part de marché spécifiée dans le chapitre trois par l'analyse des flux de matières (MFA).

## ABSTRACT

There is an increasing understanding that our consumption and production patterns have to change to stay within our planetary boundaries, the planet being unable to indefinitely assimilate the effects of current anthropic activities. Correspondingly, in recent years, growing concerns about climate change pollution and biodiversity loss have driven business organizations to change their priorities, not only to achieve economic objectives, but also to consider ecological goals. Forestry, an important part of natural systems, has been a traditional supplier of renewable raw materials for industrial use (e.g., sawmilling for construction wood, pulp and paper, particle boards), as well as for domestic fuelwood. Although many studies have been conducted in this field, little attention has been paid to the importance of the monetary valuation of negative environmental impacts in order to determine the true price of wood products to take informed investment decisions. This study aims to assess economic and environmental performance of five maritime pinewood products during the gate-to-gate process (harvesting to semifinal product) in the Landes de Gascogne Forest (“Landes Forest”) in the Nouvelle-Aquitaine region of France. The product groups considered are construction wood, pulp, plywood, pellets and pallets.

For this purpose, the study uses several system-analytical methods in combination: material flow analysis (MFA), life-cycle assessment (LCA), life cycle costing (LCC) and material flow cost accounting (MFCA). The relevant MFA data in Chapter 3 was collected from an industrial partner and based on databases, literature sources and other references to obtain Life Cycle Inventories for the LCA study in Chapter 4. The LCA software SimaPro was used for this analysis, applying the ReCiPe life-cycle impact assessment method to identify the environmental impact (gate-to-gate) of the studied products. A cost model based on the Environmental Prices Handbook was developed in Chapter 5 to estimate the external costs based on the environmental impact results. This has been set for each product group and integrated into environmental LCC to compare the external with the internal costs, in far as possible with the data available. The methodologies have been tied together in Chapter 6 using MFCA; results correspond to the market share specified in Chapter 3 by MFA.

We found that, among the studied products, unbleached pulp and plywood production have the highest economic and environmental costs at €32.36/€15.13 and €27.22/€7.14, respectively. That means that the best use of raw timber is as construction wood due to two reasons: first, the long lifespan of construction wood compared to other studied products; second, not only is less energy is required in the production process, but chemical materials are also absent from the process. This study proposes a suitable methodology framework for the economic and environmental assessment of forest products and other industries. Moreover, this work reviews the design and monitoring of wood from a sustainable resource and environmental impact perspective

The environmental impacts costs (external costs or externalities) and key internal costs have been estimated for studied product groups. The result identifies pulp production as having the highest environmental cost among the studied products, due to the various production elements and the large amount of energy used in the heating step; construction wood has the smallest environmental cost, due to the small number of production elements and steps compared with the other products.

This study makes it possible to determine the most important contributors to environmental impacts and the consequent economic and environmental costs. In another words, the hotspots in life-cycle assessment of the products studied during the system boundary are specified in this study. It is possible to achieve better economic and environmental performance for each product if alternative practices are considered.

This study provides valuable information that can help the forest industry to increase sustainability and reduce environmental impacts. Future work will need to consider the internal costs (CapEx and OpEx) of pulp, plywood, pellets, and pallets, and extend the system boundary to cover the entire life of each product (cradle-to-grave) to reach even more holistic results than this study.

Key words: Life cycle assessment, Material flow analysis, Wood Forest sector, Life cycle cost analysis, Assessment of economic and environmental performance, Material flow cost accounting.

## **List of Abbreviations and Acronyms**

<b>AEBIOM</b>	The European Biomass Association
<b>AR</b>	Appenzell Ausserrhoden
<b>AS</b>	Standards Australia
<b>CapEx</b>	Capital Expenditure
<b>CC</b>	Climate change
<b>CEPI</b>	Confederation of European Paper Industries
<b>CORRIM</b>	Consortium for Research on Renewable Industrial Materials
<b>CP</b>	Cleaner production
<b>DBU</b>	German Federal Environmental Foundation (Deutsche Bundesstiftung Umwelt)
<b>EC</b>	European Commission
<b>ELV</b>	End-of life vehicles
<b>EMA</b>	Environmental management accounting
<b>EMS</b>	Extensive Management Scenario
<b>EoL</b>	End of life



<b>EPD</b>	Environmental Product Declaration
<b>EU</b>	European Union
<b>FAO</b>	Food and Agriculture Organization of the United Nations
<b>FEP</b>	Freshwater eutrophication potential
<b>FETP</b>	Fresh water eco-toxicity potential
<b>FU</b>	Functional Unit
<b>GHG</b>	Greenhouse gases
<b>GtC</b>	Gigaton(s) of carbon
<b>GWP</b>	Global warming potential
<b>ha</b>	hectare
<b>HTP</b>	Human toxicity potential
<b>ILCD</b>	International Reference life cycle Data system
<b>ILO</b>	International Labor Organization
<b>IMS</b>	Intensive Management Scenario
<b>IOA</b>	Input-output analysis
<b>IPCC</b>	Intergovernmental Panel on Climate Change

<b>IRP</b>	Ionizing radiation potential
<b>ISO</b>	International Organization of the Standardization
<b>LCA</b>	Life-cycle assessment
<b>LCC</b>	Life-cycle cost
<b>LCI</b>	Life-cycle inventory
<b>LCIA</b>	Life-cycle impact assessment
<b>LCM</b>	Life-cycle management
<b>MEP</b>	Marine eutrophication potential
<b>METP</b>	Marine Eco toxicity potential
<b>MFA</b>	Material Flow Analysis
<b>MFCA</b>	Material Flow Cost Accounting
<b>MJ</b>	Mega joule
<b>NMVOC</b>	Non-Methane Volatile Organic Compound
<b>NZS</b>	Standards New Zealand
<b>ob</b>	over bark
<b>ODP</b>	Ozone Depletion Potential

<b>OpEx</b>	Operational expenditure
<b>PMFP</b>	Particulate matter formation potential
<b>PNW</b>	Pacific north-west
<b>POFP</b>	Photochemical oxidant formation potential
<b>R&amp;D</b>	Research and development
<b>SD</b>	Sustainable development
<b>SDGs</b>	Sustainable Development Goals
<b>SE</b>	South-east
<b>SETAC</b>	Society of Environmental Toxicology and Chemistry
<b>SFA</b>	Substance flow analysis
<b>SME</b>	Small and medium-sized enterprises
<b>STREAMS</b>	Method for material flow analysis based on national supply and use tables
<b>TAP</b>	Terrestrial acidification potential
<b>TBA</b>	Total biomass appropriation
<b>TETP</b>	Terrestrial ecotoxicity potential
<b>TEV</b>	Total Economic Value.

**TRACI** Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts

**ub** Under bark

**UNECE** United Nations Economic Commission for Europe

**WEEE** Waste Electrical and Electronic Equipment



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# CHAPTER 1

## 1.1. CONTEXT

Forests are considered an important component in the global ecosystem and play a key role in preserving the environment and reducing climate change. Forest resources are recognized to have a number of values, including intrinsic, economic, ecological, cultural, and aesthetic values. The continued existence of forests provides a stream of goods and services including both timber and non-timber products, recreation, climate regulation, carbon sequestration, and so forth.

The importance of forests for human livelihood is increasing due to the wide range of products (both wood and non-wood) and the amount of money generated by the forest industry sector, the essential ecosystem services that forests supply (such as preventing soil erosion and protecting biodiversity), as well as the space for recreation, relaxation and enjoyment that forests provide (European Union, 2017; FAO, 2012). The world has a total forest area of approximately 4.06 billion ha, equivalent to 31% of the total land area (FAO, 2020).

Europe holds 25% of the world's forests and the overall area is slowly increasing. It has been estimated that the world's forests stored about 662,088 million tons of carbon in 2020, which clearly demonstrates the key role that forests and forest products play in carbon storage (FAO, 2020). Such facts demonstrate why forests are at the heart of the transition to low carbon economies and it is therefore no surprise that a majority of countries included forests in their Intended Nationally Determined Contributions under the Paris Climate (United Nations, 2015).

According to the FAO Yearbook of Forest Products (FAO, 2020), global production of industrial round wood (all round wood used for any purpose other than energy) amounted to 2,024,660,000 m<sup>3</sup> in 2019, of which 639,347,000 m<sup>3</sup> (31.5%) was produced in Europe (including the Russian Federation). Similarly, for 2019, global production of fuelwood (round wood used as fuel for cooking, heating or

power production, as well as for charcoal, pellets and other agglomerates) amounted to 1,945 million m<sup>3</sup>.

Forestry is also an important source of employment, providing more than 33 million jobs worldwide, or 1% of global employment (ILO, 2022). The global forest sector had a direct contribution of more than \$539 billion and a total contribution of more than \$1,298 billion to world GDP (Li et al., 2019).

The Global Forest Resources Assessment (FAO, 2020) estimated the surface area of forests in France at 17.253 million ha, or 30% of total land area. About 33% of forest area in France was occupied by coniferous species in 2019, with the remaining 67% occupied by hardwoods.

The French forest-timber sector directly or indirectly generates about 440,000 jobs through nearly 60,000 primary processors (crushing, sawmilling), secondary processors (packaging, cooperage, carpentry, flooring, furniture, paper and cardboard), distribution and application (wood frames, carpentry, fittings), and wood energy, generating about 440,000 jobs (directly and indirectly). The industry also supports the growth and development of local areas. The total economic value (TEV) of forests is defined as the number of resources, expressed in common units of money, that society would be worse off if the forests were lost. TEV is given by the sum of a number of components. It accounts for nearly €60 billion of turnover in France.

One of the most significant current discussions in forestry is how our consumption and production in the forest sector impact our planet to the point that we are reaching the limits of growth (United Nations Environment Programme, 2010; Commission of the European Communities, 2011), with the planet being unable to indefinitely assimilate the effects of anthropic activities (Rockström et al., 2009; Steffen et al., 2015). However, natural resources are vital to industrial production, without which value creation is impossible (Gutenberg et al., 1983). Life-cycle management represents a key approach for businesses to address this challenge and offers a comprehensive range of decision-supporting instruments to analyze material flows and the associated environmental impacts of products and services over their life cycle (Hunkeler et al., 2003; Power, w 2009). It can thereby make an important contribution to relaxing economic-

environmental trade-offs and fostering sustainable innovations, resource security, and even competitive advantages (Porter & Van der Linde 1995; Hunkeler et al., 2003; Power, 2009).

Therefore, the necessity of accomplishing global sustainable development as a principle political goal in natural resource planning and management—in synergy with economic, social and environmental contexts—must be the real basis for creating accurate measures (with clear values) and methodologies to help to determine the most appropriate decisions for both the private and public sectors. Decision-makers need to take environmental impacts into account when making decisions about projects and investments. Results from impact assessments can however be both extensive and diverse, which makes comparison of alternatives difficult. To help decision-makers interpret the results, many impact assessment tools include a possibility to aggregate results to an index or a few indicators, by translating them into a common unit. In other tools, such as strategic environmental assessment (Brown & Therivel, 2000), weighting in order to aggregate the results is often made by monetary valuation.

Consequently, in the new global economy, determination of environmental impact values has become a central issue for decision-makers when choosing among various projects. Monetary valuation is the practice of converting measures of social and biophysical impacts into monetary units so that they can be compared against each other and against the costs and benefits already expressed in monetary units. This study focuses on the use of monetary valuation to determine the economic value of negative environmental impacts of each wood-industry product during its life cycle as determined in the study's system boundary in. Monetary valuation is strictly related to the concept of externalities in welfare economics. Externalities are the unaccounted costs and benefits arising from economic activities of one agent that impact on another (Pearce & Barbier, 2000). According to this definition, externalities can be divided into positive (benefits) and negative (costs, or external costs). We will present only the negative environmental impact of wood-industry products from gate-to-gate (product cutting) because the system boundary specified in this study includes only the negative environmental impact resulting from the harvesting, transportation and production processes (starting from cradle,

it would be necessary to assess the environmental impact value of trees from planting seedlings until the wood-harvest gate). This study has been carried out based on knowledge of direct and indirect forestry advantages, in addition to knowledge of the forest economy. Cutting trees for industrial purposes sacrifices the alternative opportunity derived from the environmental benefits of tree use (the opportunity cost of tree cutting). Therefore, from gate-to-gate (from the harvest gate to the wood-product manufacture gate) is more precise than cradle-to-gate. To correct market failures, and achieve what in economic terms is defined as “optimal” resource allocation, externalities must be internalized, namely, accounted for in the economic system (and hence reflected in the price of goods and services) and associated decision making. A key issue here is the quantification of the negative impacts of externalities and the total value of wood, which is where monetary valuation of environmental impacts becomes relevant.

In addition, the assessment of the economic and environmental performance of studied products has significant importance in relation to the aims of both the “Fit for 55” package of legislation, which implements the EU Climate Law, committing all 27 EU Member States to reduce emissions by at least 55% (compared to 1990 levels) by 2030 and the European Green Deal. The latter, approved in 2020, is a set of policy initiatives by the European Commission with the overarching aim of making the EU climate neutral in 2050 (Tamma et al., 2019; Simon, 2019.)

However, far too little attention has been paid to the importance of the monetary valuation of negative environmental impacts with regard to appropriate decision-making and determination of the real price of goods. Therefore, for joint environmental and economic performance evaluations, scholars typically suggest life-cycle assessment (LCA) and life-cycle costing (LCC) for products and services (e.g., Rebitzer, 2002; Klöpffer & Renner, 2008). The former is a non-monetary instrument visualizing environmental impacts that cannot easily be internalized as costs (ISO 14040: 2006), the latter a monetary instrument to evaluate internalized and also, where applicable, external costs and revenues borne by third parties (Hunkeler et al., 2008).

While they provide two separate instruments for non-monetary or monetary appraisals, another instrument, material flow cost accounting (MFCA), is put forward as a tie between LCC and LCA (Bierer et al., 2015: 1289) to improve their flow perspective. MFCA is one of the major tools for environmental management accounting and promotes increased transparency of material use practices through the development of a material flow model that traces and quantifies the flows and stocks of materials within an organization in physical and monetary units. MFCA identifies internalized cost drivers for desired product outputs and undesired non-product outputs (ISO 14051: 2011), and operates at the intersection of production technology, environmental as well as cost accounting and management (e.g., Burritt et al., 2002; Nakajima 2011; Guenther et al., 2017). In addition, MFA is another environmental management tool that deals with the analysis of material and energy input and output processes, resource use and stock calculations, and hotspot assessment (Zhang, 2013, as cited by Wang & Ma, 2018). Named material flow management (MFM), this approach has been developed to use natural resources efficiently and create sustainable production. A distinction is made between material flow management on a national or regional level, which focuses more on creating ecologically sustainable cycles, with the aim of environmental protection and efficient use of resources. Whereas in industrial or operational material flow management, the consideration of energy and material flows and the measure of the output (expressed either as units produced or as economic value) per unit of resource input should contribute to the optimization within production systems (“Material flow analysis” – in simple terms). A linkage of all four instruments is interesting for high-end integrated evaluations over the whole supply chain and life cycle. This study, however, takes the perspective of organizations that are still at the starting point and therefore might initially focus only on the economic-environmental aspects under their control (from cradle-to-gate or gate-to-gate), as mentioned before, including raw material extraction, transportation, and manufacturing.

For such cradle-to-gate evaluations, a combination of LCA and MFCA is particularly suitable, as both build on a similar understanding of material and methodology (Viere et al., 2011a; Kokubu et al., 2009; Sygulla et al., 2014) and



address the common denominator of the foci of engineers, managers, and environmental officers (Guenther et al., 2017). They are therefore valuable when appraising resource scarcity, as well as the economic and environmental scarcity of the environment's provisioning and regulating functions (Assessment, M. E. (2005).; Davide, 2021). A number of studies have already suggested the integrated use of both instruments to support interdisciplinary collaboration and informed choices (e.g., Kokubu et al., 2009; Schmidt & Nakajima, 2013). As no existing study elaborates on the methodological facets of integrated assessments using LCA and MFCA, there is a need to expand existing knowledge in this field in order to support more systematic, consistent and transparent assessments of costs alongside scarce resources and environmental impacts, in particular in the case of the wood industries mentioned. The study is focused on the system boundary of Alliance Forêts Bois: gate-to-gate, from the raw material in entering the companies to the products made in the same place. The system boundary is built to compare the impact of different companies in the maritime pine sector situated in Landes de Gascogne.

## **1.2. Research problem**

There is an increasing concern about the impact of societies' consumption and production patterns on our planet in such a way that we are reaching planetary boundaries (United Nations Environment Programme, 2010; Commission of the European Communities, 2011) and are unable to indefinitely assimilate the effects of anthropic activities (Rockström et al., 2009; Steffen et al., 2015). However, natural resources are vital to industrial production, without which value creation is impossible (Gutenberg 1983).

Therefore, the necessity of achieving global sustainable development as a primary political objective in natural resource planning and management, in harmony with economic, social, and environmental contexts, must be the true foundation for developing accurate measures and methodologies to assist in determining the best decisions for both the private and public sectors. When making decisions regarding projects and investments, decision-makers must consider environmental impacts into account. However, the results of impact assessments can be both extensive and diverse, making it difficult to compare alternatives. In order to assist decision-makers in interpreting the results, numerous impact assessment tools provide the option of aggregating

them into an index or a few indicators by converting them into a common unit for strategic environmental assessment (Brown & Therivel, 2000). Monetary valuation is frequently used to aggregate results.

Correspondingly, in recent years, growing concerns about climate change have driven business organizations to change their priorities, not only to achieve economic objectives, but also to consider ecological objectives (Knauer & Moslang, 2018; Rodríguez & Emblemsvåg, 2007). This coincides with the recent global trend towards sustainable development. Forestry, which is an important part of natural capital, has been a traditional supplier of renewable raw materials for industrial use (e.g., sawmilling, pulp and paper, particle boards), for households, and for fuelwood. From a production-context point of view, LCA is a suitable tool to assess wood-supply systems, as it was designed for product systems (ISO, 2006b). In addition, in the new global economy, determination of environmental impact values has become a central issue for decision-makers when choosing between various projects. Monetary valuation is the practice of converting measures of social and biophysical impacts into monetary units.

Fortunately, life-cycle costing (LCC) and life-cycle assessment (LCA) are promising modern cost and externalities management tools that are well known in practice, which can be used to integrate economic and environmental aspects (Bierer et al., 2015). LCC and LCA are distinctive because they focus on a long-term life cycle perspective in cost accounting practices and counteract management tendencies to focus on the short term (Knauer and Moslang, 2018). According to ISO 15686-5, 2008, LCC calculates the total costs arising through the life cycle of a product/service from raw material acquisition to disposal (Dunk, 2004; He et al., 2020). In contrast, LCA aims to assess processes and product impacts, where it focuses on environmental emissions during a product/service life-cycle (Aryan et al., 2019; Emblemsvåg, 2001). Moreover, LCC evaluates all economic outcomes, such as costs and revenues. Therefore, LCC directs costs not only during the manufacturing stage, but also in earlier and/or later stages of a system (Dunk, 2004), while LCA captures and evaluates inputs and outputs of environmental impacts (Bierer et al., 2013). Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a

system defined in space and time (Brunner and Rechberger, 2004), whereas material flow cost accounting (MFCA) identifies internalized cost drivers for desired product outputs and undesired non-product outputs (ISO 14051: 2011) and operates at the intersection of production technology, environmental, as well as cost accounting and management (e.g., Burritt et al., 2002; Nakajima, 2011; Guenther et al., 2017).

As mentioned previously, far too little attention has been paid to the importance of the monetary valuation of negative environmental impacts with regard to appropriate decision-making and determination of the real price of goods. Therefore, life-cycle assessment (LCA) and life-cycle costing (LCC) are typically recommended for joint environmental and economic performance evaluations of products and services (e.g., Rebitzer, 2002; Klopffer and Renner, 2008). The former is a non-monetary tool for visualizing environmental impacts that cannot be readily internalized as costs (ISO 14040: 2006), while the latter is a monetary tool for evaluating internalized and, where applicable, external costs and revenues borne by third parties (Hunkeler et al., 2008).

However, by using the above four instruments (LCA, LCC, ICC, and MFA) separately, we cannot reach systematic, consistent, and transparent assessments of costs alongside the scarce resources and environmental impacts of the wood industry and consequently we cannot determine the correct price of wood products, with subsequent market failure. Neither in the system boundary (cradle-to-gate) or cradle-to-grave the evaluation will not be as precise, because they didn't account the value of environmental impacts as costs of production this will lead to underestimating products' value and will affect negatively on the taken decision. Thus, important relationships between the economic and environmental aspects are ignored (Norris, 2001). Because of this research gap and since there is no existing study that elaborates on the methodological facets of integrated assessments using LCA and MFCA, a number of studies already suggest the integrated use of these instruments (LCA and LCC, as well as MFA and MFCA) to support interdisciplinary collaboration and informed choices (e.g., Viere et al., 2011a; Kokubu et al., 2009; Schmidt & Nakajima 2013), and support decision-makers to take a sound decision.

### **1.3. Research Questions**

No previous study elaborates on the methodological facets of integrated assessments using LCA and LCC together with MFA and MFCA to evaluate the economic and environmental performance of wood industries, and we can thus formulate the research problem through the following questions:

1. How can we measure the total value (internal costs, external costs and added value during a certain period and stages of its life cycle, as well as the related externalities) of wood products for each wood industry specified in the system boundaries of a specific study by integrating material flow analysis, material flow cost accounting, life-cycle assessment and life cycle costing?
2. How can we assess the economic and environmental performance performances for selected wood industries in the Landes Forest, to get an insight into their overall resource productivity?

### **1.4. Research hypothesis**

In the context of the interrelationship between the research problem, its importance and its objectives, the following hypotheses can be formulated:

1. Material flow analysis is the suitable tool to assess the amount flow and stock of material specified in specific area and time
2. Life-cycle assessment is the modern and promising tool to assess the environmental impacts resulting during the production process of studied products within the system boundary specified in this study.
3. Life cycle costing is adequate tools for calculation of internal (CapEx & OpEx) and external cost (environmental cost) during the production process of studied products within the system boundary in this study.
4. Economic and environmental performance can be assessed by integrating life-cycle assessment, life-cycle costing, material flow analysis and material flow cost accounting for the wood industries specified in the study and adequate data are available in the Landes Forest, France.

## 1.5. Research Goal

The objective of material flow management (MFM) is to produce sustainable production while utilizing natural resources sparingly. On a national or regional scale, material flow management is distinguished by its emphasis on establishing ecologically sustainable cycles for environmental protection and efficient resource utilization. Whereas in industrial or operational material flow management such in this study, the consideration of energy and material flows and the measurement of output per unit of resource input should contribute to the optimization of production systems (Material flow analysis (MFA)-definition– Ipoint- System, 2023). A connection between all four instruments is beneficial for high-end integrated evaluations across the entire supply chain and life cycle. This study, however, takes the perspective of organizations that are just getting started and, as such, may initially focus only on economic-environmental aspects within system boundary gate-to-gate, as previously mentioned, including raw material extraction, transportation, and manufacturing.

The main goal of this study is addressed through the following six sub-objectives:

1. To estimate the volume of wood products for each wood industry specified in the study, these objectives are achieved through conducting material flow analysis in chapter three.
2. To estimate the environmental impacts within the system boundary of wood product life cycles specified in this study. This objective is achieved by conducting life-cycle assessment in chapter four.
3. To estimate wood products' internal (CapEx & OpEx) and external costs (environmental impact costs) within the system boundary of wood product life cycles in this study, depending on the life-cycle assessment results, by applying life cycle costing in chapter five.
4. To improve sustainability and address the market failure in the pricing of forest products by taking into account the production costs of undesirable outputs (such as emissions to air, water, and land coming from the production process) and to expand existing knowledge in this field in order to support decision-makers to encourage the wood industry, to support more systematic,

consistent, and transparent assessments of costs alongside scarce resources and environmental impacts, and to understand how to construct a reliable flow structure model by applying material flow costs accounting (MFCA), which will be conducted in Chapter six.

5. To provide foundation information to cover the total life span of studied products
6. To create suitable methodology to assess economic and environmental performance of wood products different from soft wood, as well as that of other types of goods in other sectors.

### **1.6. An outline of the thesis**

The dissertation is divided into six chapters. Chapters 1–6, as outlined in Figure 1, discuss the four objectives that contribute to the achievement of this thesis's purpose.

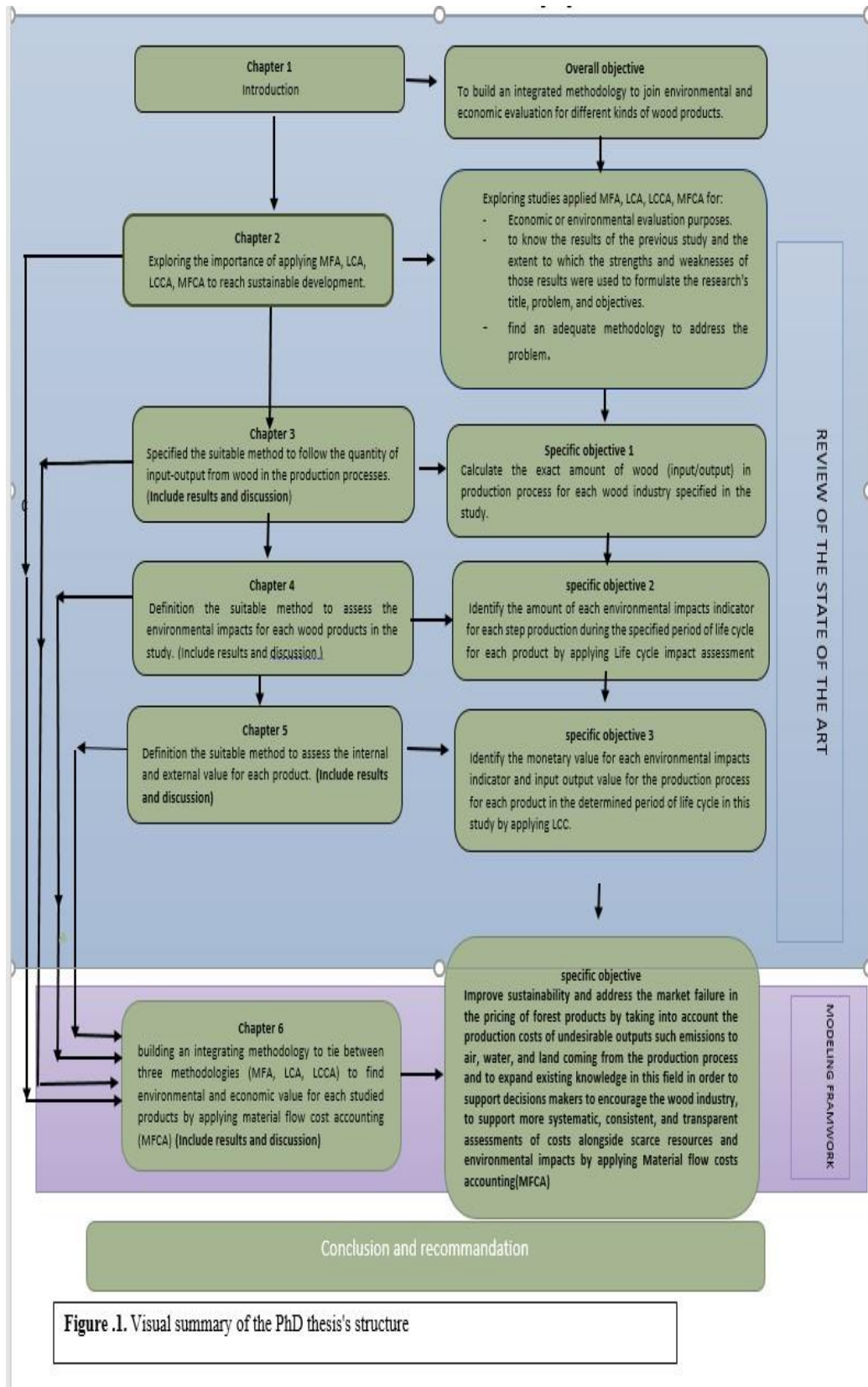


Figure 1: Visual summary of the PhD thesis's structure

## CHAPTER 2

### Literature Review

A literature review has been carried out in this chapter on the subjects listed below:

1. Previous studies
2. Aspects of agreement and disagreement between the previous studies.
3. Research gap addressed by the current study
4. Benefits from previous studies

These bullet points will be used to structure the chapter in sections

#### 2.1. Review of previous studies

In this section, a review of previous studies will be presented methodologically, looking at material flow analysis, life-cycle assessment, life-cycle costing and material flow cost accounting. Each system analytical tool will be described from the point of its history and application cases, first in general and then in the forest and wood sector. Sometimes, criticism, limitations and links to other tools are discussed at the end of the literature review of a specific tool. Later on, each individual tool will be more described in detail with regard to its methodological procedure in the methods and materials part of the chapter where it will be applied.

**Material Flow Analysis:** Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner & Rechberger, 2004).

In the 20th century, material flow analysis (MFA) ideas have appeared in different fields of study at various times. Before the name had been invented, and before its complete methodology had been developed, many researchers used the law of preservation of matter to balance processes. In process and chemical engineering, it was general practice to analyze and balance inputs and outputs of chemical reactions. In the economics field, Leontief introduced input–output tables in the 1930s and thus set the base for extensive application of input–output methods to solve economic



problems. The metabolism of cities and the analysis of pollutant pathway in regions such as watershed or urban areas where the two first innovative areas of application of MFA. In recent decades, MFA became an extensive tool in many fields, including process control, waste and wastewater treatment, agricultural nutrient management, water-quality management, resource conservation and recovery, product design and others. This information stems from the Practical Handbook of Material Flow Analysis by Brunner & Rechberger (2004), Lewis Publishers. Baccine & Brunner (1991) stated that material flow analysis is a physical accounting instrument based on the mass balance principle. Brunner & Rechberger (2004) explained that material flow analysis is applied to examine outputs, inputs and stock of specific materials or substance within a certain system boundary for a defined period. According to Bouman et al. (2000), material flow analysis has the ability to deal with large economic systems. Based on the scope and boundary of an MFA study, the processes occurring—such as transformation, production and consumption—in the system under study can be modelled by static and/or dynamic modelling.

As noted by Jeppsson & Hellstrom (2002) material flow analysis also supports the combination of economic and environmental accounting. Nevertheless, the economic value of flow is not comprised. Relying on how the system boundary is specified, shifting of the problem beyond the system boundary cannot be followed or quantified. Brunner & Rechberger (2004) state that by using material flow analysis, environmental problems can be traced back to their origin.

A study of Brunner & Rechberger (2004) indicates that material flow can be studied without knowing all indirect and direct, global and local, long term and short term and this is what distinguish life cycle assessment. In an additional material flow analysis present knowledge further than single indicators with interconnections of different flows and the in proportion to the interdependencies of various flows and the in proportion to interdependencies with anthropoid actions accounted for.

According to Brunner & Rechberger (2004), the flow and stock of materials complex system and can be measured by material flow analysis. Another usage of material flow analysis stated by Chen & Cradle (2012) and Mahler et al.

(2014) is that MFA is broadly used to explore resources and recycling systems, providing useful information concerning the configuration of resource use and emission to the environment. Mass conservation law is the basic principle of the MFA, consequently the sum of inputs needs to be equal to both the sum of output and potential change in stock for every process in the model (Dubois et al., 2014).

Material flow and stocks can be measured by material flow analysis and it is also valuable for the analysis of waste management. Consequently, the MFA methodology has been broadly taken on in the quantitative appraisal to construction and demolition waste recycle and disposal (Dahlbo et al., 2015; Caoet et al., 2019). For instance, European waste management systems, which include construction and demolition waste treating, have been evaluated by material flow analysis by Bertram et al. (2002). Several MFA studies have been done on the processing and management of this type of waste, both as a single waste material (Chong & Hermreck, 2011) and as a mixture of wastes (Luciano et al., 2018), on regional (Zhanget et al., 2018; Hu, 2010), national (Luciano et al., 2018; Kapur, 2009), and global scales (Miatto, 2017). Moreover, Gu (2019) and Gonda (2019) state that, in certain cases, municipal solid waste recycling process analysis relies on the material flow analysis method. Additionally, MFA is critical in developing waste management plans and strategies (Markic et al., 2019). New environmental policies and taxation may also be proposed in developing economies based on evidence from MFA (Tangtinthai et al., 2019).

Material flow analysis has undergone several enhancements and extensions in recent years to provide dynamic, robust and multifaceted assessment results (Zange et al., 2018; De Meester, 2019). Typically, a material flow is bounded by time and space. When confronted with a dynamic and long-term period, dynamic material flow analysis (DMFA) is commonly used to quantify the stocks and flows of material (Hu et al., 2010; Müller, 2006; Bergsdal, 2007), like the European copper flows (Soulier et al., 2018), timber from 2012 to 2100 (Kalcher et al., 2017), and strategic construction and demolition waste management (Hu et al., 2010). Additionally, by integrating MFA and its spatial distribution, a broader scale of material use can be described, which benefits sustainable strategic planning (Font, 2012),

since this integration lays the foundation for developing a plan for sustainable growth (Royet et al., 2009).

MFA is now widely recognized as a scientifically-sound decision-support tool, especially in the field of environmental policy. MFA can lead to an overall ‘win-win’ approach (Gibbs et al., 2005). The wood industry gives an excellent example of this. It provides employment, some of which is not relocatable, recreation, and contributes to the rural area resource management and development.

Quite an important number of MFA studies for wood exist. However, as far as we know, only Lenglet et al. (2017), Džubur et al. (2017), and Bais et al. (2015) have extensively quantified global wood flows, indicating that there are still significant uncertainties about global wood extraction, particularly for wood fuels.

Global patterns and trends of wood harvesting and use between 1990 and 2010 was studied by Bais et al. (2015). A full assessment of woody biomass flows in 11 regions of the world from 1990 to 2010 is presented. They discovered that global total biomass appropriation (TBA) was 1.81 GtC/year in 1990 but increased to 1.94 GtC/year in 2010 (+7%). Total biomass appropriation accounted for 4% of global forest net primary production in 2010. Only 54% of TBA enters socio-economic systems, while 46% remain in forests or is discarded. Around 56% of economically viable wood biomass is used in the energy sector. The study showed that the wood biomass flows vary significantly across world regions, because of differences in population, affluence, and area. Global demand for wood is expected to rise in the coming years, which will be putting additional strain on forest ecosystems.

Multiple MFA studies have been done at the national or subnational level:

Binder et al. (2004) combine material flux analysis and agent analysis as a foundation for a transition toward improved regional forest management in Appenzell Ausserrhoden (AR), a small Swiss half-canton situated in the Swiss Pre-Alps. The researchers introduce a wood flow analysis in AR, taking into account various wood products, for forests, wood processing industries, and consumption. The study finds that the forest is presently considerably underused,

despite the fact that significant amounts of wood and fuel are imported into this small region. The underproduction of the forest participates in the skewed age distribution, jeopardizing the forest's long-term viability, as the forest's protective and production functions are likely to be compromised. Also, the researcher concludes that combining wood flow analysis and factor analysis provides a simple and effective tool for initiating a process in order to improved regional wood flows, which should contribute to sustainable forest management.

Material flow analysis has been conducted by Hekkert et al. (2000) for the analysis of paper and wood flow in the Netherlands. Current production structures consume a large number of primary materials and cannot be sustained without having a negative impact on the environment. A thorough understanding of societal metabolism is likely to result in more environmentally friendly production and consumption. The purpose of the MFA is to provide insight into material flows to support this understanding. The STREAMS material flow analysis method is applied in this article. The analysis of the paper and timber flow through the Netherlands' economic system. The study is based on data known as the supply and use tables provided by Statistics Netherlands, which outlines the supply and use of goods and services in an economy. Research has demonstrated that this method to be very effective in analyzing paper and wood-pulp flow in the Netherlands. The method provides comprehensive data on the final consumption of paper and wood, including packaging materials and product components made of paper and wood. However, researchers have found that that trends indicate that statistics offices are collecting fewer physical data on material flows. This will make it more difficult in the future to construct material flow analyses.

Material and carbon flow of harvested wood from Japan has been studied by Hashimoto & Moriguchi (2004). Japan receives harvested wood (such as roundwood, sawn wood and paper) from other countries. There is a large Japanese market for harvesting wood. The approximate value of global roundwood production, including firewood, is 1.5 billion m<sup>3</sup>, and Japanese consumption is about 100,000,000 m<sup>3</sup>, making Japan one of the world's leading consumers of harvested wood. Wood harvest should be improved in terms of productivity as well as resource efficiency.

Piskur & Krajnc (2007) based two roundwood balances on the roundwood flow model. A broad range of available data was considered; the quality of the data was evaluated, and a proposal for improving its quality was developed. The researcher found that the roundwood balance results for the reference year 2004 indicate that, when official data for annual removals are used, a deficit of 536,000 m<sup>3</sup> occurs. They concluded that a roundwood balance is positive in the case of modelled (enlarged) removals. The researcher recommended that wood flow and data analysis should play a significant role in sectoral, local, regional, and national strategic planning and decision-making. Knaggs & O'Driscoll (2007) state that the Irish forest products sector expanded significantly in 2007, when Ireland harvested a record 3 million m<sup>3</sup> of roundwood from its forests, supplying the sawmilling, wood-based panel and energy sectors. Coillte supplied 87% of this harvest, while the remainder was supplied by an expanding private forest estate. Harvest levels in private sector forests are increasing rapidly and have the potential to more than double in the next decade.

The development of a framework for evaluating resource efficiency has been studied by Cheng et al. (2010). The study presented a conceptual framework for resource flow analysis based on China's forest production and trade data, calculated the quantities and analyzed the characteristics of forest resource flows (primarily wood and wood byproducts) during China's critical early economic development period (from 1953 to 2000) by converting the forest resource flows to log equivalents (i.e., the quantity of logs required to generate a unit of each type of product). Throughout the study period, consumption of forest resources increased, while the structure and efficiency of forest resource utilization improved. The researcher recommended that to improve the economics and sustainability of its forest resource use.

Sevola et al. (2000) presented information on roundwood processing and transportation, forest resources, silviculture, forest health and biodiversity, roundwood markets, multi-use forests, forest sector labor, forest industries, wood consumption, forest industry exports and the forest sector's contribution to Finland's national economy.

Parobek et al. (2014) discussed the raw wood flow in Slovakia. The material flow analysis was employed to

elucidate and measure the relationships between wood resources and primary uses. Two distinct approaches to modelling wood flow were used: wood balance and wood resource balance. As a more detailed analysis, the wood resource balance considers both the uses of wood as a material and the by-products and waste generated during production that could be used as inputs in the wood processing or energy sectors. The latter balance was created using publicly available data and a questionnaire to estimate missing waste stream data. With a total consumption of 11,964,000 m<sup>3</sup> of roundwood equivalents, the cascade factor was 1.11. Over 84% of all resources were used for industrial purposes, while nearly 16% were used to generate energy.

Mantau (2012) studied the supply chain of every European wood product; the amount of both energy and material is shown on a single flow chart. Along with the sectors covered by the Wood Resource Balance (EUwood, 2010), the paper industry and recovered paper are included. Additionally, an analysis of the end-use sector was included. The final flow chart demonstrates the sectors' significance in terms of volume (m<sup>3</sup> solid wood equivalents) and the flows between sectors.

Džubur et al. (2017) developed an applied a probabilistic context for data balancing in the MFA to case study on wood flow in Austria. Data characterization and reconciliation step are included in the framework. A quality assessment of the collected data is provided.

Finally, Lenglet et al. (2017) analyzed the difficulties that part of the French timber transformation industry had in adapting to recent global market changes. et exports of raw wood and imports of processed products harm the balance of trade as well as local wealth creation. Simultaneously, there are currently no consistent and homogeneous accounts for wood product production and consumption. This article begins by objectively analyzing the French forest-wood supply chain for the first time. Then, they assess the potential effects of various scenarios of raw wood export reduction policies, including subsidies for consumption or transformation and imposing taxes, export, on both economic outcomes for various actors and material flows. Thus, they demonstrate how to integrate material flow analysis and economic modeling in order to progress from the diagnostic

phase to the evaluation of possible actions from a decision-making perspective.

One of material flow analysis criticism commonly noted is the scarcity of data and the unreliability of the information (Schwab et al., 2016; Patricio et al., 2015). To overcome this challenge, an option is using the MFA framework recommended by Courtonne et al. (2015).

**Life-Cycle Assessment:** According to ISO 14040 Life Cycle Assessment (LCA) is defined as the systematic analysis of the potential environmental impacts of products or services during their entire life cycle, It aims to assess these impacts based on the compilation of resource consumptions and emissions from and into the environment through the life cycle of a product system. (Aryan et al., 2019; Emblemståg, 2001).

The concept of life-cycle assessment (LCA) dates all the way back to the early 1970s. The early adult applications of LCA to substantiate consumer arguments necessitated method standardization. Udo de Haes and Van der Voet (1997) state that after around 1990, experts collaborated within the Society of Environmental Toxicology and Chemistry (SETAC) to develop a Code of Practice for Life Cycle Assessment. Later the International Organization for Standardization (ISO, 2006) played a significant part in the standardization of methodologies and the development of guidelines. Early in the implementation of LCA, the provision of sound methods has already been pointed out as playing an important role in the process of acquiring and interpreting information. It has become clear that holistic and rigorous LCAs would provide the foundation for decision-making (Richter and Sell, 1992).

LCA is a technique developed to evaluate the environmental impacts of a product, process, or operation from conception to disposal. This is accomplished by taking into account all inputs (raw materials and energy) and outputs (pollution streams and avoided products) at all stages of a system's life cycle, including manufacturing, transportation, usage, and end-of-life, and translating them to possible impacts using multiple equivalency factors (Hertwich et al., 1997; Bouman et al., 2000). Based on mass and energy balances, LCA is capable of addressing all forms of flows and/or impacts (Balkema et al., 2002). Balkema et al. (2002)

states that traditionally LCA classifies environmental impacts into resource depletion, global warming potential, ozone depletion, photochemical ozone formation, acidification, Eco toxicity, human toxicity, eutrophication, and landscape degradation.

The first actual life cycle assessments (LCAs) for the European forestry and wood products sector emerged in the 1990s intending to scientifically analyze the impacts of nonrenewable inputs into a system (Frühwald & Wegener, 1993; Karjalainen & Asikainen, 1996; Richter and Gugerli, 1996; Zimmer & Wegener, 1996; Frühwald et al., 1997; Schweinle, 1997). Frühwald & Wegener (1993) concluded that wood can be used to replace more energy-intensive materials with higher GHG-emitting footprints at their manufacturing and end-of-life periods. Besides that, when the wood is burned at the end of its life cycle, pollution from fossil fuels can be avoided (Frühwald & Wegener, 1993).

Because of the general view that wood does not produce high GHG emissions as a raw material, wood and wood products are usually referred to as “carbon-neutrals.” The view shows that all re-moved biomass from sustainable forests will be re-moved in the future (Helin et al., 2013), while the concept of carbon neutrality is still debated controversy (Miner & Gaudreault, 2013). In addition, no generally accepted methodical approach is currently used to perform a forest LCA, and critical matters such as the functional unit or system boundaries vary between the studies. Wood as a raw material has yet to be proved carbon neutral and relies, among other factors, on the system of management. Where, for example, forest products are produced from un-sustained forests with long-term reductions in local storage due to changes in land use, carbon neutrality cannot be proven (Zanchi et al., 2012). Numerous processes occur in the forestry field, from planting to the supply of raw wood material to the factory gate, necessitating the consideration of a variety of ecological burdens, depending on management systems, the characteristics of the site, or transportation assumption.

Life cycle benefits related with two wood-based household heating system (old and modern stove) has been assessed in Norway by Solli et al. (2009). The researcher investigated the differential environmental impact between old and modern stove, the modern technology causes a



significantly improved performance (28-80%) for all kinds of environmental impact studied, over 60% of the impact within all environmental impact categories is a result of the wood combustion. One of the most important strengths of this article is that it takes into consideration the two weaknesses of life-cycle assessment in the forest sector that according to Heinemann (2012) are the limited scope by having only a cradle-to-gate life-cycle assessment of wood products and the limited environmental impacts considered of the stove production processes.

There is a large volume of published studies of applying life-cycle assessment in the forest sector. Cradle-to-gate life-cycle assessment of softwood plywood production from the Southeast of the United States has been applied by Oneil et al. (2012) to specify energy and materials input and output related with softwood plywood production from the manufacturing base located in the Southeast region of North America. The data were obtained through a scientifically correct and consistent process provided by the Consortium for Research on Renewable Industrial Materials (CORRIM) following ISO 14044 standards (ISO, 2006). The study found that the energy used by manufacturing plywood is ruled by the combustion of wood fuel (biomass) and represented 77% of the mill site use of heat energy. And energy generated by renewable fuels, such as woody biomass represented about 57% of the total energy from cradle-to-gate. 99% of the renewable biomass fuels were wood fuel for plywood production and 37% of the total energy for cradle-to-gate is non-renewable fossil fuel. 99% of the consumed fossil fuel is due to forestry operations. The study also found that 59 % of the total energy from biomass (wood fuel) and 35% from non-renewable fossil fuel are consumed by the plywood production.

Bergman's study on "Life-cycle impacts of North American wood panel manufacturing" (2015), aimed to quantify environmental impacts using the life-cycle assessment method, through a sample represented by five wood based-panel products made in North America during 2012. An LCA survey tool was used to collect data from a factory on emissions to water and air, solid waste generation and energy consumption and resource use. The study was carried out by including the cradle-to-gate production of non-wood materials including additives and energy products, such as natural gas and coal used up at the production processes, as

well as including the delivery of wood to the factory (initial transport). For each 1 m<sup>3</sup> of panel produced, the primary data was entered in the life-cycle assessment software to assess the life cycle inventory flows and environmental impacts of the wood panel manufacturing. The following products were evaluated: strand board, Southeast and Pacific Northwest (PNW) softwood, plywood, cellulosic fiberboard, and hardboard. The study recommended that using woody biomass energy for panel production would reduce their impact on climate change. The main weakness was that it was not taken into consideration the environmental impact of harvesting wood.

Another cradle-to-gate life-cycle assessment for the production of softwood lumber in the United States northwest was done by Milota (2015). This study included data for seven mills in 2012, considering lumber and co-product production, raw materials and fuel use, electricity consumption and on-site emissions. There are five processes considered: log yard, sawing, drying, planning and energy generation. A survey has been conducted to collect data for the first four processes. The research depends on the nationwide wood boiler survey that included the Pacific Northwest lumber mills to obtain data for energy generation. The above-mentioned CORRIM life-cycle inventory dataset and reports are the source of the forest operation data. In terms of most energy-consuming processes, the results of this study are consistent with previous studies in this field, as the study found that 96% of energy consumed is for log transportation and wood processing, including the drying process. The study demonstrated that 1 m<sup>3</sup> of planed dry lumber store 856 kg CO<sub>2</sub> eq. Consequently, due to this storage, many researchers recommended that the amount of CO<sub>2</sub> releases from the production of lumber should not to be accounted as environmental impact.

Milota & Puettmann published a paper (2017) on life-cycle assessment for the cradle-to gate production of softwood lumber in the Pacific Northwest and South East region in the United States of America. The study was conducted in seven mills in the Pacific Northwest and 11 mills in the South East; the system boundary was determined in five processes: log yard, sawing, drying, planning and energy generation. A survey was conducted to obtain data for the first four processes, while the researcher depended on a National Wood Boiler survey to obtain data for energy

generation. As in many previous studies, 1 m<sup>3</sup> was the functional unit. 3,434 MJ was consumed during the cradle-to-gate for 1 m<sup>3</sup> of dry planed lumber, and the amount of consumed energy was higher in the south-east region which reach to 5.151MJ/m<sup>3</sup>, thus returning to a higher initial wood moisture content. Transportation and wood processing account for 96% of the total amount of energy consumed during the five processes specified in this study. The amount of CO<sub>2</sub> emitted in the SE was 81.4 kg CO<sub>2</sub> eq./m<sup>3</sup> and 58.7 kg CO<sub>2</sub>/m<sup>3</sup> in the Pacific north-west, long transport and processes account 85% of the total amount of CO<sub>2</sub> released. The researcher found that the amount of CO<sub>2</sub> stored in (1 m<sup>3</sup>) of the planes, dry lumber in the Pacific north-west and south-east was 856 kg CO<sub>2</sub>/m<sup>3</sup> and 935 kg CO<sub>2</sub>/m<sup>3</sup> respectively.

Kayo Chihire et al. (2019) quantified the environmental impacts and impact reductions related to wood consumption in Japan from 1970 to 2013, and then produced further expectations of the impacts and reductions until 2050. They expressed the results of the impact assessment and their characterization with the Japanese Yen (JPY) monetary unit by an integrated environmental and economic evaluation approach. They found that paper consumption has significant environmental impacts such as climate change and urban air pollution. Accordingly, the researchers could show that decreasing of greenhouse gas, nitrogen oxide and sulfur oxide emissions from paper production would be an effective action to decrease the total environmental impacts. The researchers recommended that an increase in wood use in building construction, civil engineering, furniture material and energy production could lead to the reduction of environmental impacts. They evaluated the material substitution and carbon storage to have a value of 357 billion JPY in 2050 which is equivalent to 168% of the 2013 level.

Following the life-cycle assessment method and eBalance software, Jia et al. (2019) published a paper to assess the environmental impact of traditionally plywood manufacturing and determined the environmental hotspots. Impact categories were calculated, including abiotic depletion, acidification potential, primary energy depletion, fresh water eutrophication, global warming potential and particular matter to analyze environmental hotspots. The source of data for this study was on-site measurements for plywood production as well as inventory data from the eco-invent data base and the ILCD database. The study suggested

an eco-design strategy with eco-alternatives, such as pyrolysis bio-oil to be used to produce green resin in state of traditional phenolic formaldehyde resin to decrease the environmental impacts. They state also that instead of combusting fossil fuels wood waste could be used for producing less climate relevant carbon emissions.

Ahmad et al. (2020) studied gate-to-gate life-cycle assessment of hardwood lumber production in selected districts (Haripur and Abbottabad) of the Hazara region in Pakistan. A questionnaire-based survey was conducted of 22 sawmills in the Haripur district and 18 sawmills in the Abbottabad district to collect primary data regarding input and output from sawmill during the year 2017-2018. Life-cycle assessment has been applied. The system boundary of the study was gate-to-gate, and for a reference unit 1.0 m<sup>3</sup> of hardwood was used. Semaphore Software, version 8.5, was used to model the production-weighted average data for ten environmental impact indicators. The research found that the three processes which had the highest contribution to all the environmental impact categories were the diesel consumed in the transportation of raw materials, the purchase of the electricity consumed at the sawmills and the urea formaldehyde resin used for filling cracks in the hardwood lumber product.

Saho and Bergman (2020) studied a cradle-to-gate life-cycle assessment of redwood timber. The aim of this study was to conduct a cradle-to-gate life-cycle assessment and estimate the environmental impacts associated with redwood lumber production in the United States. The paper demonstrated that redwood lumber production has very low carbon footprint (37.97 CO<sub>2</sub> eq./m<sup>3</sup> of lumber) and stores about 18 times (683.46 kg CO<sub>2</sub>/m<sup>3</sup>).

An environmental impact assessment of wood pellet production for different production processes, raw materials, energy use and transportation methods was conducted by Saosee et al. (2020) in Thailand. Eight varied cases of wood pellet production differ in terms of raw materials, production processes, energy uses and transportation methods were compared with life-cycle assessment as aim of the study. According to the comparison results of the study, leuceana is better as feedstock for wood pellet production than acacia because of the shorter harvested cycle and lesser use of resources. The significant contribution to the environmental

impacts also resulted from fossil fuel used in pellet manufacturing and transportation. Another significant result of this study, in terms of resource use, human health and ecosystem quality, is that for electricity production it is better to use wood pellets than lignite.

Finally, life-cycle assessment has also been applied by Jonse et al. (2021) to assess the potential environmental impact associated with different commercial outputs of maritime pine wood (round, industrial and residual) produced in Portuguese forest under national regeneration. The scope of the life cycle assessed was from the cradle-to-gate. The researchers used SimaPro software for the inventory modelling and CML-IA Method to evaluate environmental impacts. The study found that the highest value of the environmental impact categories was presented by round wood and the lowest value by industrial wood.

**Life Cycle Costing:** Life Cycle Costing (LCC) is a technique used calculates the total costs arising through the life cycle of a product/service from raw materials acquisition to disposal (Dunk, 2004; He et al., 2020).

The life cycle costing approach was developed in the 1970s as a tool for measuring the overall life cycle costs of goods (Brown 1979) and then later as a source of knowledge for strategic business and policy decision-making for environment and economy (Valdivia et al. 2013 UNEP/SETAC, 2010). According to Jolliet et al. (2015), there are also prior references to the US Department of Defense using this tool in the 1960s with regard to acquisition and use of military equipment. Differently from LCA, which has a general ISO standard (ISO, 2006) that offers instructions for its application, LCC does not have a generic one. However, ISO 15686-5 (ISO, 2017) is one of the most frequently used guidelines, since it focuses on planning the life of buildings and built properties. Moreover, SETAC has developed a code of practice on environmental life cycle costing (Valdivia et al. 2013 SETAC, 2013). Life-cycle costing summarizes all costs associated with the life cycle of a product that are directly covered by one or more the actors in the product life-cycle (e.g. supplier, producer, user/consumer, End-of-Life actor). Costs are the monetary value of goods and services that producers and consumers purchase (real-money flows).

Barringer et al. (1995) defined life cycle costs as summaries of cost figures for all equipment and programs from initiation to dispose, as calculated by an analytical study and an estimation of cumulative costs incurred over their life. Relying on Norris (2001), the object of life-cycle costing is to compare the cost-effectiveness of investment alternatives or business decisions from the viewpoint of an economic policymaker, such as a production plant or a customer. These distinctions in purpose have, predictably, resulted in distinctions in scope and methodology. Life-Cycle Cost Analysis is an economic project assessment approach where the decision is based on all costs resulting as a result of project ownership, operation, maintenance, and disposal. LCC research aims to choose, from a range of alternatives, the most economical solution to achieve the least long-term ownership cost (Barringer et al., 1995).

As specified by Hunkeler et al. (2008), LCC aims to quantify not just the costs of raw materials acquisition, but also those of production, maintenance, and final disposal. Thus, policy makers should take action to strengthen the economic metrics associated with the life cycle of the system (Fallah et al., 2013). Relying on Steen (2005), externalities may also be included in the LCC research, i.e., the costs of environmental impacts caused by the device or product, stimulated by the “polluter pays” concept. Numerous studies agreed that LCC is gaining traction in some spheres of public administration, most notably for public procurement (Hochschorner & Finnveden, 2006; Sterner, 2002; von Deimling et al., 2016).

He, S., Salem, O., & Salman, B. (2021) introduced a decision support system for identifying the major life cycle economic and environmental impacts of highway treatment activities and programs by combining life-cycle assessment (LCA) and life-cycle cost analysis, thus assisting practitioners in selecting the most suitable project alternatives. To assess life-cycle impacts from both organization and consumer viewpoints, databases and simulation models (e.g., Athena Pavement Life-cycle assessment and Motor Vehicle Emission Simulator) were used. Project alternatives studied included warm-mix asphalt overlay, cold in-place recycling, full depth reclamation, intelligent compaction, and pre-cast concrete pavement systems. Practitioners can gain a greater understanding of the consequences of project-level decisions, conduct what-if analyses to examine trade-offs between

options, and achieve agency-level sustainability priorities and objectives.

To improve the sustainability of concrete bridge infrastructure, an incorporated life-cycle assessment and life cycle cost analysis model was developed and implemented by Kendall et al. (2008). The aim of this model was to compare alternative bridge deck designs from a sustainability perspective that includes the entire life cycle costs, which are the organization, consumer, and environmental costs. The construction of a traditional concrete bridge deck was compared to that of an engineered cementitious composite link slab. The findings demonstrated the importance of life-cycle modeling as a decision-making method, as initial costs and agency costs are not indicative of the overall life cycle costs. Additionally, it was important to account for construction-related traffic delays when calculating the overall economic cost and environmental effect of project design decisions (Kendall et al., 2008).

No relevant environmental LCC studies were found with regard to applications in the engineered wood products sector. Only dedicated products were studied in its use. Concerning the use of wood in cascade, Boštjan Vimpolšek, Andrej Lisec (2022) used life-cycle thinking, also in the field of recovered wood (RW). To this end, the reverse logistics process model CATWOOD (CAscade Treatment of WOOD) with mechanistic modelling for detailed planning of the RW reverse flow with regular collection, innovative (cascade) sorting based on RW quality and environmentally sound recovery has been designed. As a decision support, the quantitative methods of life-cycle assessment (LCA) and societal life-cycle costing (SLCC) have been incorporated into the CATWOOD, which can choose among a few alternative scenarios. Gulizar Balcioglu et al. (2023) used the LCC technique to demonstrate that the electricity-only plants using wood chips have the lowest costs and generating net profits.

Balasbaneh et al. (2023) compared the environment impact, energy consumption, and life cycle cost (LCC) of different wood-based materials in identical single-story residential buildings. By the results of LCC he develops a multi-criterion decision-making (MCDM) method to know and optimize the use of mass timber in construction. Before (Balasbaneh et al. 2023) studied the LCC and LCA for the

application of the hybrid concrete/ glulam engineered products. LCC shows that a new concrete slab despite of having a higher construction cost, by considering the end of life scenario as reuse, will have a lower total cost

Amoruso, T Schuetze (2022) demonstrated the negative global warming potential, but the positive net present value, as well as the economically and ecologically profitable alternatives to use wood for new constructions. The parametric calculation system facilitates integrated economic and ecologic cost assessment and evaluation and allows for multiple scenario comparisons to develop the results.

Concerning the normalization of the methodology, a first document (European Commission, 2019) describes the LCC methodologies depending on applications.

**Material Flow Cost Accounting:** Material Flow Cost Accounting (MFCA) identifies internalized cost drivers for desired product outputs and undesired non-product outputs (ISO 14051: 2011), and operates at the intersection of production technology, environmental as well as cost accounting and management (e.g., Burritt et al., 2002; Nakajima, 2011; Guenther et al., 2017).

Contrary to what the name implies, the material flow cost accounting (MFCA) approach originates from environmental protection, not accounting. It is a management control mechanism that connects accounting and management systems. To guide and assist the reader to assess the method's current state and potential prospects, as well as to review relevant articles, in which the method has been used, we will begin with a brief history of MFCA.

The idea of material flow cost accounting, as it later appeared in the ISO 14051 (ISO, 2011) standard, evolved as a logical outcome of environmental management projects conducted in the late 1980s and early 1990s at the textile company Kunert in Southern Germany. However, the fundamental idea of MFCA was not invented in a vacuum. Certain critical elements, such as the notion of input/output mass balances and the assessment of industrial production's material flows, in physical and "value" terms, had been discussed in Germany as early as the 1920s and 1930s. In the late 1980s and 1990s, a slew of new environmental issues and terms began to appear in German and English literature, as



well as in corporate practice, for example, beginning with terms like environmental management, progressing to concepts of product or corporate eco-balances, environmental auditing, and environmental bookkeeping (Müller-Wenk, 1978), environmental reporting, eco-accounting (BUS, 1984; Ahbe et al., 1990; Callenbach et al., 1993; Müller-Wenk, 1978; EPA, 1996).

Kunert released one of the first corporate environmental studies in 1991, focused on a corporate input/output mass balance and covering the years 1989/90. Surprisingly, this study received widespread coverage in the German media, resulting in an explosion of corporate environmental studies released in subsequent years. Kunert's corporate input/output mass balance was initially developed to create metrics of resource utilization for environmental management purposes. This "balance sheet" depicted the physical quantities of input and output materials that resulted in either the product or, unprofessionally, waste, pollutants, or wastewater. EMU-Augsburg, a research and consultancy firm associated with the University of Augsburg and led by Wagner, B. (2015), performed this work as a research project. The initial studies on the Kunert case argued that measurable environmental data (such as pollution or waste) must be translated into cost and benefit values in order to become a topic of management awareness. Management reacted to waste costs rather than waste volumes. By taking into account and making clear both the environmental and financial dimensions of the same coin – material flows new words and definitions such as "flow accounting", "flow cost accounting", or "extended cost accounting" emerged. However, the word "environmental cost accounting" ("Umweltkostenrechnung") was the most frequently used at the time (Bundesumweltministerium, 1995; Schmidt, 2012).

In 1993, this idea (environmental cost accounting) and the Kunert experience came to the attention of the Deutsche Bundesstiftung, which was promoting a project at the Kunert Mindelheim production site (1994-1996) to further develop the "Flow Cost Accounting" approach, which covers concurrent cost and environmental aspects of the company. The notion of Material Flow Cost Accounting was developed with the aim of more closely evaluating the cost and physical features of material flows across the organization, not just at the end-of-pipe. Although the word MFCA had not yet been formulated, its underlying conceptual elements had been

illustrated in conjunction with the aforementioned initiatives, and the first publications in German were published in 1995 (Bundesumweltministerium/Umweltbundesamt, 1995). Simultaneously, many strongly linked methods emerged in Germany, for example, in a work by Letmathe (1998), whose title translates as “Environmentally Oriented Accounting” and later as “Resource Cost Accounting”.

These methods were similar to an inclusive material flow cost accounting concept, but concentrated material losses and waste reduction, thus framing the concept of “Waste Cost Accounting” (Schmidt, 2012). According to Schmidt (2012) this strategy provided a more detailed picture of waste costs and therefore the sum of potential savings, but it did not explain how and where waste costs could be reduced. The first detailed model of a material flow cost accounting application, developed by Strobel & Wagner (1997) and using Kunert data was in a German article that translates as “Structuring and Developing Corporate Material and Energy Flows”. Rauberger & Wagner published the first English-language paper on the Kunert project in a book on sustainable procedures by Bennett, M., & James, P. (1997

The MFCA model that was the original basis for the ISO 14051 (ISO, 2011) standard was created at the Institute of Management and Environment of the University of Augsburg in Germany. In spite of the fact that the MFCA model was developed in Western Europe, its implementations (combined with further development) have grown in popularity worldwide, particularly in Japan. In 1999, the Japanese Ministry of the Economy, International Trade and Industry (METI) authorized the Japan Environmental Management Association for Industry to explore this methodology and prepare an “Environmental Management Accounting Project” (EMAP). In order to assist the implementation of this approach, the EMAP Working Group published a handbook (METI, 2007). The guidelines explain the definition and the fundamental steps to be taken for applying the MFCA. The Japanese methodology refines the system further, in particular by distinguishing the cost of energy from the material cost, which was included in the original German model in the material cost. It is critical in terms of environmental impact; the quality of life for future generations is highly dependent on rational energy management.

Kasmset et al. (2015) studied the application of MFCA (Material Flow Cost Accounting) to waste reduction: the case study examined a small textile factory in Chiang Mai, Thailand; the aim of the research was to demonstrate the contribution of MFCA in this context. Following the MFCA method, a particular style of shirt was chosen for examination. The cost of each process (negative and positive products) was determined, including cutting, stitching, quality control, dyeing, buttonhole drilling, and packing. The MFCA study determined that the costs of positive and negative goods were respectively 84.26% and 15.74%. From a total of 15.74%, the largest portion of the negative product cost was due to manufacturing costs at 14.73%. In terms of material costs, the cutting and stitching process accounted for 80% of the negative product's material costs, in contrast to other operations. Following that, a cause-and-effect diagram was used to determine the primary source of the negative product's material cost during the cutting and sewing operations. The data collection and analysis revealed that the cutting and trimming procedures accounted for three sources of material cost of the negative product during both operations. Three enhancements were proposed: (1) reducing the distance between pattern pieces, (2) reducing the width of each pattern piece's edge, and (3) using a new cloth-cutting table. The MFCA calculation revealed that the negative product costs produced by these three solutions had been reduced to 8.51%, 4.57%, and 3.06%, respectively. Additionally, when the three solutions were combined and used concurrently, the cost of the negative product decreased to 11.27%. The study recommended that, in practice, the first approach was the only one that could be implemented immediately and without incurring any costs. When additional resources for process improvement are available, the combination of the three strategies was the most successful and should be considered in earnest.

Kasemset et al. (2013) conducted the application of MFCA to improve the process of producing plastic water bottles for a selected company in Thailand. This product is manufactured in five stages: grinding, mixing, blow molding, printing, and packaging. All processes had data collected and analyzed using the MFCA methodology. The quantity of input and output material, the material cost, the device cost, and the cost of energy were all presented during the MFCA methodology. Based on mass balancing for all operations, the cost of positive and negative goods was differentiated. The

most striking result to emerge from the MFCA calculation was that the blow molding process had the highest negative product expense. Based on the MFCA results, the flow of operations during the blow molding process was analyzed in order to remove output defects. Eventually, a solution for change was suggested, and the findings indicated that defects were decreased by 26.07 percent relative to the previous negative product costs.

The case study above is not the only one for improving financial and environmental performance through material flow cost accounting. A small and medium-sized enterprise (SME) case study was conducted by Sahu et al. (2021) in an SME manufacturing steel pipes and tubes in India. The aim of this study was to determine how MFCA can be applied appropriately in an SME in order to enhance the enterprise's financial and environmental efficiency. As part of the MFCA study, material costs, device costs, and energy costs were measured at each quantity center to recognize deficiencies in the SME's manufacturing process. The research demonstrated that using MFCA resulted in increased production, increased energy usage, and improved environmental performance. The results indicated that after implementing MFCA, the SME's return on invested capital raised by 29.37% and material use costs decreased by 26.58%.

More recently, the application of MCFA in waste reduction was studied by Huang et al. (2019). The researcher examined how finance and accounting staff can use ISO 14051-based material flow cost accounting as an empirical assessment method. A flat-panel parts supplier was studied to ascertain if efficient recycling of glass could result in cost savings for the business. The primary determination was that the film coating on recycled washed glass was often removed during the manufacturing process, increasing the cost of reprocessing and thereby making green cleaning more expensive than reworking. This study showed that the ISO 14051-based material flow cost accounting analysis is an effective management method for advancing sustainable development.

With regard to the application of MFCA to the wood sector, we have found studies concerning paper or forests. Only Chompu (2015) studied and demonstrated the interest of this research for the engineered-wood sector. Doorasamy (2016) used MFCA to identify benefits of eco-efficiency and

cleaner production in paper and pulp manufacturing. The purpose of this study was to determine the level at which cleaner production (CP) could boost an organization's environmental and economic performance using material flow cost accounting. The report used an exploratory qualitative and quantitative analysis approach to conduct a case study of a paper manufacturing business. The MFCA method was used to determine the productivity of the coal-fired boiler steam production operation. The findings showed that the procedure was inefficient, with a substantial negative effect on the environment and the economy. Management grossly overlooked environmental costs, as non-product production costs were not included in the company's environmental cost calculation. The MFCA method was used to determine the productivity of the coal-fired boiler steam production operation. At the end of this study, the benefits and obstacles to CP were also discussed. Moreover, Papaspyropoulos et al. (2016) used material flow cost accounting to support sustainable forest resource management. It enabled managers to identify material and energy deficiencies of manufacturing operations and to

data from Labours sawmills examples that MCFA could also be a valuable tool for forest managers, whether they work in the public forest service or private forestry organizations.

Bierer et al. (2015) stated that there is a well-accepted need for the integration of Life Cycle Costing and Life-Cycle Assessment—the two most widely used tools for assessing the economic and ecological impact of goods and manufacturing processes over their entire life cycle, in the sense of sustainable decision making. According to the authors, no mature theoretical framework for integrating LCA and LCC exists, which means that we need to move beyond environmental life-cycle costing to address the problems at state. In fact, the authors propose to use material flow cost accounting as a bridge between the two approaches and to expand it to meet the needs of an environmental and economic life cycle analysis. Also, Chompu et al. (2015) applied a combination of Material Flow Cost Accounting and Design of Experiments techniques in a case study of a small company in order to reduce materials consumption and minimize waste. An experimental design, with hot spots observed, is developed and directly used in the company. The results showed an increase of the total material yield from 31% to

46%. Using MFCA as a tool to increase product quality and reduce the adverse environmental of production process is demonstrated first.

Concerning the forest sector, Santos et al. (2019) provided a literature review of the assessment and the optimization of sustainable forest wood supply chains. In 2021 Santos et al. presented a first study comparing different products, including environment consideration and costs. The lack of studies using MFCA was shown in this review, as well as in the Handbook of Wood Utilisation and environmental impacts (Richter et al., 2023).

## **2.2 Aspects of agreement and disagreement between the previous studies**

Looking through the review of previous studies, the following aspects of agreement and disagreement between those studies are evident:

1. Previous studies agreed on one common goal, sustainable development.
2. Previous studies differed in the sub-goals that lead to sustainable development, according to the research tool used. Some used material flow analysis to study inputs, outputs and stock of raw materials, while others used life-cycle assessment to determine the environmental effects of the product within the time and geographic scope of its life cycle that was identified. In more than one study, the monetary value of the environmental impacts was determined, as well as the monetary value of raw materials, products and outputs, all separately or in a simple combination.
3. Previous studies differed in their samples, as the scientific tools were applied to different materials.
4. Previous studies differed in the sources of data collection; some were through questionnaires, forest production data or trade data.
5. To the researcher's knowledge, most of the studies, which were conducted to analyze the input, output and stock of the raw material, were done using the material flow analysis tool, with the exception of the study of Binder et al. (2004). It relied on the combination of material flux analysis and agent analysis.
6. To the best of the researcher's knowledge, and through a review of previous studies, it is clear that a limited

amount of studies has the application of LCC and MCFA to wood products.

7. The previous studies agreed that there is a strong relationship between the type of fuel used in the production process and the environmental impacts resulting from the production process.
8. The results of the previous studies differ with each other, although this difference does not reduce the importance or the value found in the results they reached because each study was conducted in a specific place and applied to a specific product and during a certain period of time.

### **2.3. The research gap that the current study addresses; studied products basket analysis (Pulp, pallets, pellets, plywood and construction wood)**

By reviewing the points of agreement and differences of the previous studies we are able to indicate that the current study is consistent with previous studies on its main topic and the general objective, but it also differs with them in several aspects. Those are the points that represent the following research gap that this study addresses:

1. This study includes a merging of the four research tools LCA and LCC as well as MFA and MFCA that have not been used separately in all previous studies.
2. By this merging, a systematic, consistent, and transparent assessment of costs of resource use and environmental impacts for different kind of wood products can be achieved.
3. By merging the four research tools and taking into consideration the value of the environmental impacts as production costs in this study, wood products were carefully evaluated with their externalities and this can positively affect the right decisions.
4. This study was not limited to a single product, but rather included a group of wood products to ensure that this study is covering the selected wood industries in the Landes de Gascogne Forest, France.
5. This study uses multiples sources for data from primary data provided by the selected wood industries, official statistics and recognized databases in order to collect data accurately.
6. This study focuses on the relationship between the environmental and economic concepts; this fact distinguishes this study from previous studies, and this

gives an incentive and becomes a starting point for further studies that can use the lessons learnt from this study.

From the previous paper reviewed, it becomes clear that this study addresses a multifaceted research gap on the topic described in Chapter 1 by taking into consideration the relationship between environmental and economic concepts through an integrated evaluation by combining the four research tools LCA and LCC as well as MFA and MFCA to support decision-makers to take positive decisions for the environment and for the(ir) economy.

## **2.4 Aspects of benefits from previous studies**

There is no doubt that this study benefits greatly from the experiences made and the lessons learnt and described in previous studies, as they employ a lot of efforts to reach an accurate diagnosis of the problem and to address it in a comprehensive manner. Among the aspects of the scientific benefit from previous studies are the following:

1. Determination of the scientific terms and concepts
2. Identification of the strengths and weaknesses of previous studies and benefits from them for the determination of the research gap between the previous studies and this study. the selected wood industries  
The current study has benefited from all previous studies in reaching an accurate formulation of the research problem and based on this of the objectives and the corresponding title, which is “Hybrid Material Flow Cost Accounting with Life-cycle assessment to Assess the Economic and Environmental Performances for Selected Wood Industries in the Landes de Gascogne Forest, France”.
3. Benefits for this study from previous studies include indications on deciding on the appropriate approach to solve the research problem of this study.  
The current study has employed the recommendations and proposals of previous studies in support of the study problem and its importance (e.g., Viere et al., 2011; Kokubu et al., 2009; Schmidt & Nakajima, 2013; Rieckhof & Guenther, 2018).
4. Support for this study from previous studies in enriching the theoretical framework.





## **CHAPTER 3**

# **Material Flow Analysis to Evaluate Supply Chain Evolution and Management: An Example Focused on Maritime Pine in the Landes de Gascogne Forest, France**

### **3.1 Introduction**

Forests provide different ecosystem services, attending economic, social and environmental purposes. They provide a basis for economic and social development through forestry, logging activities and wood-based industries, as well as through tourism and hunting (Cook, E. . 2019). From the environmental perspective, forestry and forest management contributes to reducing the risk of natural disasters and climate change. These attributes are often highlighted in political and strategic amendments such as the second commitment period of the Kyoto Protocol, the Paris Agreement on climate change, and the Sustainable Development Goals (SDGs) (Bellassen & Luysaert, 2014; Alberdi et al., 2020) More specifically, SDG 15 (life on land) is directed to forests and calls for their restoration, protection and sustainable use and management (Cf,O.D.D.S 2015). Wood-based products play a pivotal role in the development of the bio-economy regional level. This transition in the production system must develop sustainably without negative effects on the environment or society in a region.

The regional perspective is essential when weighing the social life-cycle assessment indices and implications of products, as these are dependent on national and regional socioeconomic conditions (Siebert et al., 2018). Further, sustainable transitions made at the regional level, which incorporate methodologies and tools based on life cycle thinking and cascade mapping are crucial. In this context, Ioannidou et al. presented a framework to evaluate the risks in the construction wood product system through a criticality assessment framework (Siebert et al., 2018). Life cycle approaches can systematically support sustainable socioeconomic development at the regional level (Massari et al., 2016). Some life-cycle assessment was made by Pommier et al. (2016) concerning the engineered wood products from maritime pine trees.

In the near future (up to 2030) the global demand for the services of wood is expected to increase due to population growth and regulations promoting renewable energy and the adoption of bioeconomy strategies (Bais et al., 2015). To date, accurate and comprehensive tools that map the global environmental and socioeconomic impacts due to biomass use are unavailable. The quantification of proposed indicators can provide sector, regional and transnational insights specific to the wood-based economy (Budzinski et al., 2017); Kayo et al., (2019).

Across the European Union, there is a wide variety of forests totaling about 182 million ha or 43% of the EU's land area. In 2015, Sweden, Spain, Finland, France, Germany and Italy accounted for two-thirds of the EU's total forested area. Wood is still the main source of financial revenue from forests, and its demand is rapidly growing (Strategy, E. A. N. E. F, European Commission, 2013). Wood serves as a raw material for a wide range of products and is also used for energy purposes (Mehr et al., 2018). Germany has the largest stock of timber within the EU (3.7 billion m<sup>3</sup> or 13.7% of the EU total), followed by Sweden and France (Cook, 2019).

In 2013, the European Forest Strategy highlighted the need to increase the understanding of the complex environmental and societal challenges that the forest sector is facing Strategy, (European Commission, 2013). Mapping and assessing the state of forest ecosystems and their services is important to understand the current state of regional forests and how they are evolving. Compiling forest inventory data is vital to the success of efforts to assess forest-based resource availability (Mubareka et al., 2018). Comprehensive forest design and management is also crucial in combating specific weather events such as drought and windthrow. The role of wind as a driver of raw material flows also depends on how frequently these weather events occur within more vulnerable regions, such as the Landes Forest. This recurrent natural disturbance offers acute and often chronic effects on forests, driving ecosystem patterns and processes (Mitchell, 2013). Another aspect strongly promoted in bioeconomy strategic policies is the need for the effective cascading of woody biomass, aiming to promote resource efficiency and circular use (European Commission, 2018). More specifically, the cascading use of wood can effectively guide an enhanced regional resource use, while also decreasing greenhouse gasses (Budzinski et al., 2020).

At a global level, Bais et al. (2015) assessed the wood biomass flows in 11 world regions from 1990 to 2010 (Bais et al., 2015). The global forest productivity is increasing about 7% per year, while extraction remains stable. The authors highlighted the uncertainties on wood flows, especially of wood fuels. Other studies have focused on regional levels, including Mantau (2015) in Germany; Mantau, U. (2015). Kayo et al. (2019) in Japan; and Lenglet et al. (2017) in France. In France, 31% of land area is covered by forest (Cook (ed.), 2019). Lenglet et al. focused on the forest-wood supply chain in metropolitan France, and the scope of assessment included the upstream part of the supply chain and the transformation of lumber, industrial wood and pulpwood. The assessment allowed for an overview of flows for hard and soft round wood, industrial wood and pulpwood, including imports and exports. The results bring interesting insights to support policy and improve the development of the national wood supply chain. However, this study only provided a snapshot of the situation for a specific reference year and did not capture trends or details on supplemental species.

In this context, our study presents complementary data for the studies developed on the national and EU level, with a regional focus in one majority species of softwood. The Landes Forest, located in southwestern France (see Figure 1), has an afforestation rate of over 70%, largely due to a concentration of monospecific stands of maritime pine (*Pinus pinaster*)

The Landes de Gascogne area was originally a sandy soil of alternating dunes, wetlands and grass. It is located on the Bay of Biscay; the oceanic climate of the region thus results in important precipitations (more than 1200 mm/year), except in summer when the sand dries the soil. The poorness of the sandy soils of the Landes plateau and the high levels of its water table leave few competitors to the maritime pine's frugality and versatility (Hautdidier et al., 2018).



Figure 2: Map of Landes de Gascogne, France (source : [https://en.wikipedia.org/wiki/Landes\\_de\\_Gascogne#/media/File:LandesDe\\_Gascogne.png](https://en.wikipedia.org/wiki/Landes_de_Gascogne#/media/File:LandesDe_Gascogne.png))

The Landes Forest is unique in Europe because it was almost entirely created and managed by man for specific industries. This forest was first planted to contain littoral dunes in the middle of the 19th century. The trees were then utilized for their resins and the forest was further developed and planted inward by Napoleon III. From the harvest of resin to maintain wooden ships, to the use of turpentine for lanterns and light, to the production of timber for mining and railway infrastructure, the economic applications of this unique forest have evolved throughout the years, fueled by market changes. Currently, the regional raw material flow of timber resources rests within market pulp and wood packaging. The harvesting technique is machinery harvesting only. The machine cut the trees in 2.5 m (100 in.) logs. Today, the production of wood, populated only with maritime pine, occupies 897,000 ha out

of the 1,166,000 ha of the Gascony forest. The rest (269,000 ha) is shared between the coastal protection zone and about 100,000 ha of oaks and various other species (Strategy, E.A.N.E.F., 2013). The majority of the forest is PEFC (Programme for the Endorsement of Forest Certification) certified. The production and allocation of timber products has never been static through its history, and moving forward into the future, this resource may pivot once again (Mehr et al., 2018).

The management of the Landes Forest is a key challenge for the sustainable development in the Nouvelle-Aquitaine Region. In this context, the goal of this work is to assess the upstream supply chain of wood-based products in the Landes de Gascogne area in 2019, with a focus on maritime pine (*Pinus pinaster*). Predictive forest design planning must be supported on the basis of the current and future market needs in the context of a circular economy. This assessment aims to support decision-making and improve forest design, aiming for the effective cascading of woody biomass to promote an efficient and circular use of resources.

### 3.2. Materials and Methods

#### **3.2.1. Material Flow Analysis (MFA)**

MFA is a systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner & Rechberger, 2016; Graedel, 2019). New developments and expansions in industrial research fields emphasize the importance of MFA methods to generate a meaningful understanding of specific system functions. It can also support decision-makers, particularly in the expanding field of environmental policy. However, one main limitation of MFA is the lack of data, or its high degree of uncertainty (Schwab et al., 2017; Patrício et al., 2015).

This chapter analyzes the upstream of the forest-wood supply chain using a cradle-to-gate approach. By primarily focusing on upstream services and allocation, we can form an appropriate visualization of the beginning of this product stream. It covers all coniferous softwood log products, with an emphasis on wooden pallets, sawn wood, plywood, pulp and paper, as well as energy wood, sawmill residues and other niche products. Products with a cumulative average stream of less than 10,000 m<sup>3</sup>/year were excluded from the figure unless stated otherwise in this study.

Consequently, the MFA model used does not focus on the second or third transformation industries, for example, the furniture industry and specific construction sectors. Furthermore, because of the nature of the Landes de Gascogne region, this chapter highlights the allocation of primarily maritime pine. However, it is known that other coniferous softwoods like white, red and Corsican pine, as well as miscellaneous and undetermined pine, are also produced in the region. These other coniferous softwoods represent less than 1% of yearly harvests, and because of limits on the database used in the study, they could not be split from the flows of maritime pine.

When flows and stocks of materials are looked at from a system point of view, the review is defined as MFA (Brunner & Rechberger, 2004). The concept of mass balance says that mass cannot be created or destroyed. Instead, it can only change into different forms. This function is used to make sure that MFA results are correct by balancing the inputs, outputs and stocks of several system processes. Therefore, there can be no accidental omission of stock or flow from the study. This makes it easy to include all flows and stocks that are connected to a process. Brunner & Rechberger (2004) say that the mass balance principle makes MFA appealing as a decision-making tool in environmental management because it can be used to check the results.

Some of the common terms used in MFA are listed by Brunner & Rechberger (2004). Flow A mass or energy shift that can be expressed as tons or megajoules per year. Process Transformation-related activity, such as getting metals out of natural ores, transport-related activity, such as moving goods from one place to another, or storage-related activity, such as putting things in a landfill. Products One or more things that are either good or bad for the economy. Cars and wood are examples of things that are good or bad for the economy, while garbage is an example of something that is bad for the economy. Energy is another kind of product. Material A term for things that are not energy, like substances and goods. Metabolism Within a system, things and energy are moved, stored, and changed. Also include material and energy exchanges with the system's surroundings, which is everything outside of the system's boundaries. Stock A system or process's storage of materials or energy, which can be measured in tons or MJ. If resources and energy are added to or taken away from the system, the total amount of the stock

goes up or down, respectively. Substance Chemical elements, such as cadmium and nitrogen, or chemical substances, such as ethylene and ammonium, that are made up of the same number of atoms. System The thing being looked into in an MFA. Defined by a group of entities, such as flows, stocks, and processes, how the entities interact with each other, and the border that separates the group of entities from other systems. System boundary defines the system by a geographical boundary, which could be an area or a country, and a temporal boundary, which could be one year or several years (Furberg, et al., 2016); see Figure 3. The main purpose of this work is to detail the physical flows of timber.

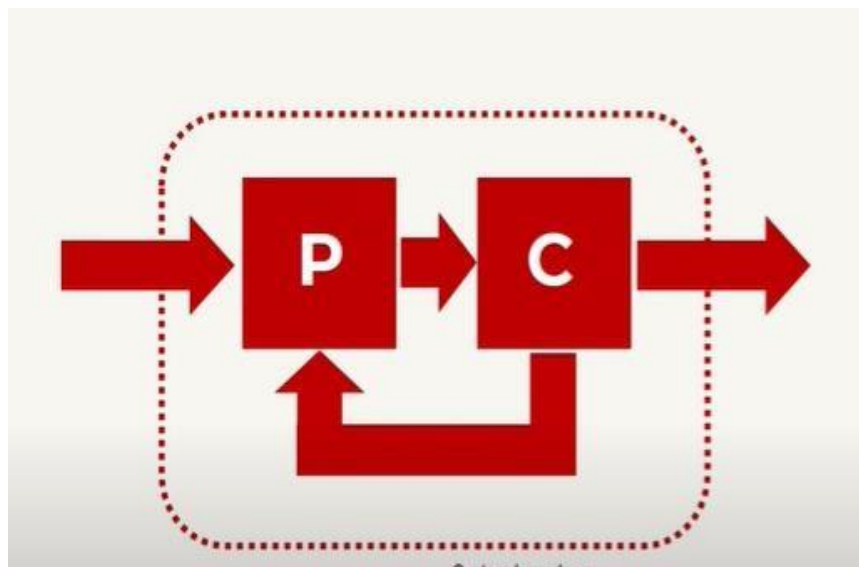


Figure 3: System boundary of material flow analysis (Brunner, P. H., & Rechberger, H. (2016).

### 3.2.2. Basic principle of materials flow

A systems approach and a process/mass balance are the two primary tenets of material flow analysis. A system definition or model definition is referred to in the system approach. A material flow system allows for control over the study's parameters and a more specialized analysis because it has defined processes and a system boundary. Exact definitions of products, substances, and materials are also part of the system approach.

Quantifying specific components of processes is the goal of mass or process balance, which goes beyond economic accounting. An industrial engineering solution must be implemented carefully in order to maintain optimal operations



and cut waste (Design system, INC. Manufacturing engineering consulting, 2023).

### **3.2.3. Steps of material flow analysis**

According to Brunner & Rechberger (2016), the process of conducting an MFA (Material Flow Analysis) involves a series of steps. Initially, the problem is defined and the goals are established. Then, relevant substances, goods, processes, and system boundaries are selected. The system definition is made up of these steps, which result in a *qualitative* model. The next step involves determining mass flows, stocks of goods, and substance concentrations using measurements, literature data, or estimations. These flows and stocks are balanced based on the principle of mass conservation for each process and the entire system, while considering any uncertainties. This step results in a *quantitative* model that is typically created using MFA software. The software assists in calculating and presenting results to visualize conclusions and aid in making goal-oriented decisions. It is important to note that these procedures are not necessarily sequential and must be optimized iteratively. The selections and provisions made during the MFA process must be continuously checked and adapted as necessary to achieve project objectives. It is advisable to begin with rough estimations and provisional data, and then refine and improve the system and data until the predefined certainty of data quality has been achieved. (Please refer to Figure 4 for further details.). The temporal boundary in many MFA studies is one year, but—if changes in stocks are considered—a longer time period is often employed.

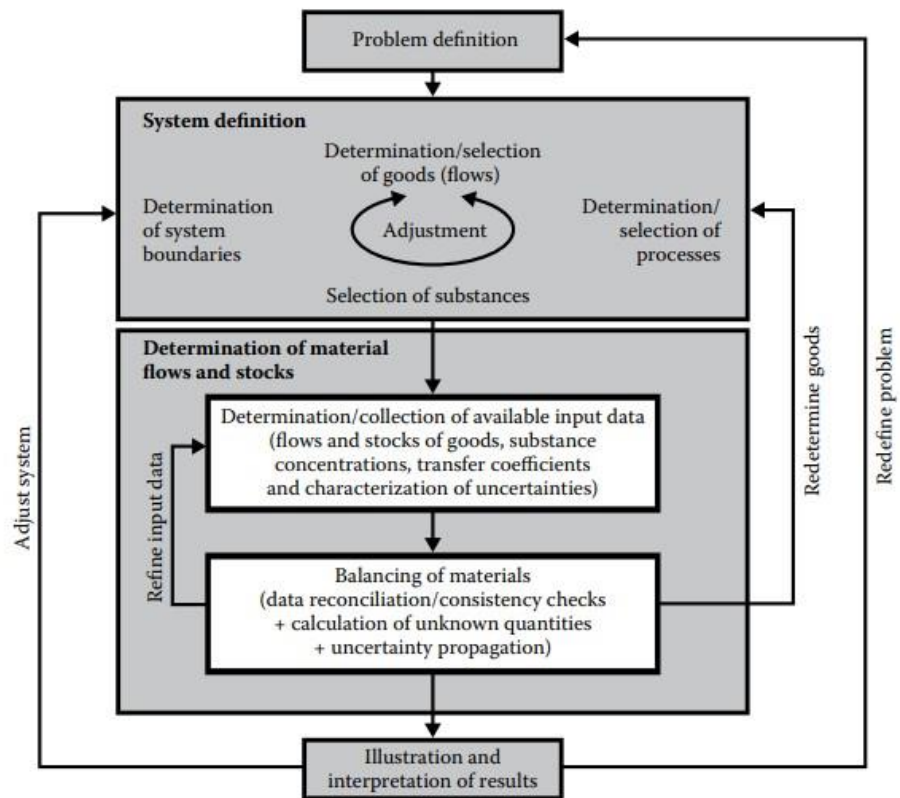


Figure 4: Material flow analysis steps (Brunner & Rechberger, 2004)

### 3.2.3.1. Objective of material flow analysis

MFA is a suitable instrument for examining the flows and stocks of any system based on materials. When integrated with other sciences like energy-flow analysis, economic analysis, and consumer-oriented analysis, it helps to govern an anthropogenic system by providing insight into the behavior of the system (Bennett, 2004). The MFA's aims are to:

1. Early detection of harmful/useful material accumulation or depletion in anthropogenic/natural sub-system (e.g., metal enrichment in landfills due to the deposition of slag).
2. Prediction of future quantities in anthropogenic/natural subsystem.
3. Identification of the need for action in the areas of environmental, resource, waste and policy management.
4. Evaluation of the effectiveness of current/planned measures
5. Design of ecologically-optimized products, processes, and system (e.g., green design, eco-design)

### **3.2.3.2. Boundaries and raw materials of the study**

Using a “cradle to gate” method, this chapter looks at the upstream of the forest-wood supply chain. By putting most of our attention on upstream services and allocation, we can get a good picture of where this product stream starts. So, the MFA model doesn’t focus on industries that go through a second or third transformation, such as the furniture industry and certain building sectors. Due to the nature of the Landes de Gascogne region, this paper focuses mostly on the allocation of Maritime Pine.

Yet, other coniferous softwoods—such as White, Red, and Corsican Pine, together with miscellaneous and undetermined pine—are included in small amounts (less than 1% of annual harvests) and are therefore grouped with Maritime Pine. More specifically, the MFA covers all coniferous softwood log products, with a focus on wooden pallets, sawn wood, plywood, pulp and paper, energy wood, sawmill residues and other niche goods.

### **3.2.3.3. Reference unit**

To construct an accurate MFA, a similar unit for the entire wood visualization chain must be defined. Wood subcomponents are reported in several distinct units, so this is necessary. Bosch et al. (2015) point out that amounts of wooden products are equated to the same unit; consequently, the cubic meter of round wood equivalent is frequently used to compare them. This unit is the amount of round wood required to produce one unit of processed product. Nevertheless, this method can contribute to double-counting of products such as wood residues and energy wood that are processed further down the value chain within MFA studies. Using cubic meters or tons increases consistency due to chemical additives in wood and paper, which are therefore considered to be wood, whereas volume changes due to drying are not taken into consideration.

Therefore, we use the wood fiber equivalent as the reference unit. The unit is used in comparable studies in other European countries (Mantau, 2012; Bösch et al., 2015; Weimar, 2009). The name “m<sup>3</sup> of fiber equivalent” was taken from Weimar (2009) and Bösch et al. (2015), while Mantau et al. (2010) and the forest department of UNECE/FAO (Fonseca, M. (2010). use the term “solid wood equivalent” to

refer to the same component. The main advantage of using  $m^3$  of fiber equivalent compared to a mass unit is that it is equivalent to  $m^3$  of round wood in the case of greenwood (e.g., wood increment, harvest).

The wood fiber equivalent (referred to as  $m^3 [f]$  in the text) is the volume of wood fibers that are contained in the product at the fiber saturation point to take into account the swelling and shrinking of wood fibers (Weimar, 2009). For each wood-based product (e.g., fiber board, plywood, pulp, etc.), a specific conversion factor was calculated depending on its primary measurement units.

#### **3.2.3.4. Data sources**

Alliance Forêts Bois provided access to their database, including information on the physical flows of wood products from different types of species (e.g., maritime pine, corsican, poplar and douglas-fir, as well as red and white pine) and their customers. Alliance Forêts Bois is a French cooperative group, originally from the Landes Forest, whose portfolio occupies the western half of France and has positioned itself in the last decade as a national leader in the production and mobilization of forest resources. The data represent more than 30% of the harvested maritime pine in the considered region (Agreste Database—Wood harvesting in France). This database is representative of the regional harvesting, as the use of maritime pine is dependent on its overall quality. Since this variety is a monoculture, the collected data can be representative of a wider harvest area. Overall, 80% of maritime pines' material viability is due to the internal tree variation of quality (Pommier et al., 2014). The remaining part (20%) is directed by the quality of the soil. The database utilized is geographically constant and independent to different harvests in one territorial zone.

Considering the scope of this study, only data regarding maritime pine and centering in the Landes de Gascogne region were considered. Thus, before analyzing the data, it was necessary to extract the data applicable to the scope of the study. For example, in relation to geographical scope (Landes de Gascogne region), only data from customers with French zip codes beginning with 33, 40 and 47 were considered. This flow does not represent the exact processing flow on the wood or fibers, but is a highlight of the upstream product delivery and divisions of the raw material.

### 3.2.3.5. Visualization and Software

Complementary to the data spreadsheets, the software utilized for this analysis was e!Sankey5. Sankey diagrams allow users to depict any kind of flow energy, material, or cost flows, for example, in the form of an arrow. The thickness of the arrow directly reflects the relative flow volume, i.e., a flow with twice the volume as another is indicated by an arrow twice as wide. The goal of visualizing flows with Sankey diagrams is to identify inefficiencies and potentials for savings or establishing added value. Sankey diagrams are gaining increasing importance, especially in the context of the growing demand for more efficient technologies. They can also be a helpful instrument in the business sector, since production systems, including their technical and economical inter-relationships, are becoming increasingly complex and therefore must be represented in an intelligible way (Schmidt, 2008).

## 3.3. Results and discussions

### 3.3.1. Wood Flow Analysis

The results of the maritime pine supply chain in France, considering a cradle-to-gate approach, are presented in this section. A summary of the upstream part of the supply chain (forest stock, energy wood, industrial, processed) in 2019. Every flow specifies the quantity of wood in m<sup>3</sup>(f) fiber equivalent, simplified as m<sup>3</sup>, as well as main product percentages above 5%.

Table 1 summarizes the amount of wood harvested in Landes Forest in 2019. As can be seen, there is a difference between the amount of wood destined for different products. From total amount of wood (1,424,413 m<sup>3</sup>) harvested in 2019, (640,985.85 m<sup>3</sup>) was used for pulp production and (612,497.59 m<sup>3</sup>) was allocated for timber; only 199,417.82 m<sup>3</sup> of total harvest wood was dedicated for high quality application for construction sector in the form of high quality. is due to the high number of knots and the general slope of the grain, and This species, when relatively young, are highly vulnerable to weather events.

Figure 5 presents the total amount of maritime pine harvested in 2019 and the flows consumed by different sectors: lumber, industrial and fuel. The last assessment level

of the Sankey graph presents the application to the different products associated with the three industries.

Table 1: Amount of Wood Harvested for Different Application (2019)

Wood application	Pulpwood	Lumber						Fuel wood
		Wood packaging	Canter logs	Plywood no knots	Log high quality	Log intermediate quality	Plywood standard	
Amount of wood (m <sup>3</sup> )	640,985.85	213,661.95	142,441.30	113,953.04	85,464.78	56,976.52	14,244.13	156,685.43

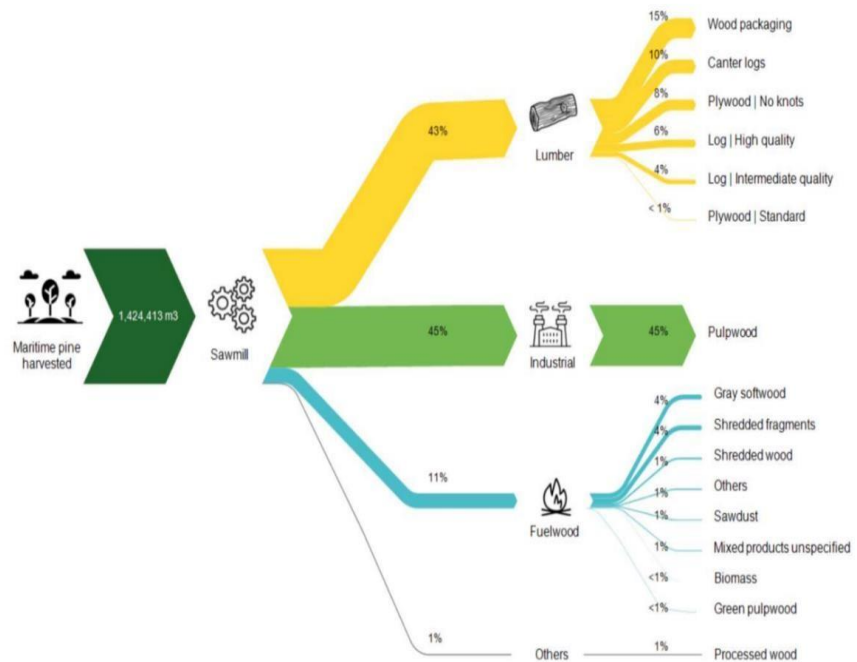


Figure 5: Sankey MFA diagram of Cradle-to-gate maritime pine flows in 2019: upstream section of forest wood.

In 2019, the difference between lumber and industrial wood allocation was almost balanced and equal, with 43% of timber allocated to lumber and 45% allocated to industrial wood. Among the flows destined for lumber production, 10% was for canter logs and 15% was allocated to wood packaging. Only 14% of the total harvest was dedicated to the construction sector in the form of high-quality logs (6%) and plywood (8%). High-quality logs are further processed into flooring, siding and joinery. The limited use for higher quality applications is due to the high number of knots and the general slope of the grain; therefore, it is not considered as standard wood for timber. Fuelwood represented a total of 11% of the flow, with a majority of this being shredded fragments and grey softwood.

From 2018—and accelerated by the pandemic crisis—the use of cardboard packaging has increased. According to the Confederation of European Paper Industries (CEPI), exports of market pulp rose close to 40% in 2019. To respond to this higher demand, CEPI currently invests €5.5 billion annually to increase the production of market pulp and further implement bio refinery concepts, which create highly innovative bio-based products Confederation of European Paper Industries (2019).

Softwoods, like maritime pine, are better for paper pulp because the increased fiber length usually translates into more inter-fiber bonding. This increase in bonding generates stronger paper. Furthermore, softwood pulps impart greater strength to the products into which they are made, compared to hardwood pulps manufactured in the same process. The major environmental impacts of producing wood pulp come from its impact on forest sources and from the waste generated González-García et al. (2009). The practice of clear cutting, or removing all trees in a specified sector, is a particularly sensitive issue due to the process being highly visible. Reforestation, or the planting of tree seedlings on logged areas, is also criticized for decreasing biodiversity because reforested areas are monocultures. Furthermore, the logging of old growth forest accounts for 10% of wood pulp; however, this is one of the more controversial issues in forest harvesting. Current product diversification also shows that the use of maritime pine has changed and expanded compared to past uses. Different parts of the tree now have different industries they are allocated too, i.e., the tops of trees to market pulp and the trunks for building or structural materials. Focusing exclusively on one type of valorization could be dangerous for the potential value and services of the forest in the future.

### **3.3.2. An Improved Regional Assessment**

When analyzing all individual flows based on the Alliance Forêts Bois database, there were, on average, significant differences between the amount of raw wood dedicated for studied products. There were some abnormalities regarding fuelwood, most likely a result of variations in supply and demand. There was clearly a dedication to specific industries, namely wood packaging and pulp wood. This is due in part to the overall design of the current territory, species of tree and its dedication, driven by

market values in the pulp and paper industry. This design and focus are difficult to transition into a focus on providing more old growth forest and more construction-based products. However, the history of raw timber allocation shows no static norm, and industries must be prepared to evolve in order to expand economic viability to new sectors. This design and focus are difficult to transition into a focus on providing more old growth forest and more construction-based products. However, the history of raw timber allocation shows no static norm, and industries must be prepared to evolve in order to expand economic viability to new sectors.

Currently, the French forestry industry employs around 450,000 individuals; Germany, with a slightly smaller forest area, employs 1.3 million. Proactive policies are required to shape this industry and focus on its future growth in the region. These policies will have to balance the design of the forests in line with future economic added value gain, as well as continue to support social aspects of everyday life. It is important to arrive at a consensus of what type of forest will be generated. A forest that primarily supports industrial and economic viability or a forest that promotes biodiversity. There are ways to build a bridge connecting these types. This balance can be achieved by infrastructure investments towards improving harvesting techniques, and specifically, sawmill advancements.

It is clear that the Landes Forest is being primarily utilized for the wood and pulp industry. This means that the harvesting of new growth is primarily fueling economic turnover and profits. However, with the yearly harvest decreasing from 2013, in connection to catastrophic losses from wind throw in 2009, the long-term economic viability must be addressed. Young trees, which are more susceptible to wind, are mainly used within the wood pulp and packaging industries. Therefore, raw material valorization and quality are dependent on design and management. This viability could be dependent on the creation of added value products focused in various sectors. Prices for these products are forecast to remain level in the short-term; therefore, with no added value implemented through the growth of lumber harvest, there is potential for a diminishing market return for market pulp and cardboard.

Buildings in a sustainable world require strong, highly flexible and light materials that have also been harvested in a



more sustainable way. This has provided good opportunities for the steel sector, although currently, it is also a threat, as more cost-effective substitutes (such as composites and cross laminated timber) are being developed. Rapid changes are occurring in technology and also in the economy. This means that only organizations that are flexible will be able to adapt to these changes and succeed. This understanding gives flexible organizations a massive advantage over more rigid ones. Strong demand for timber resources in a sustainable world makes these materials critical to supporting the energy, social and urban needs of a larger, wealthier global population.

### **3.3.3. Conclusions**

In this paper, we described the evolution of a cultivated forest, subjected to climate change, market fluctuations, human design and management. We described the upstream raw material stocks and flows, from harvested lumber through its valorization in various industries. The results showed that, in a representative period, the valorization of raw materials decreased when the overall quality and amount of high-value timber deteriorated. In light of increasing catastrophic wind storms, it should be noted that, the younger the trees, the more susceptible they are to breakage and a lower potential raw material valorization. Generally, the younger the tree, the lower the environmental potential to store carbon. Larger and older trees actively fix higher amounts of carbon compared to smaller trees due to increases in the trees' total leaf area

We can see from the results that this region has a specific upstream input dedicated primarily to pulpwood. With contributing factors, including human design and management, disease, weather events and market fluctuations, a concise supply of raw material designated to deliver short- and long-term economic benefits can be challenging to reach. We saw from the data that certain designs or disturbances lead to a limited industrial use of raw materials, which are designated to highly specific industries and solely deliver short-term added value at the cost of long-term economic gain. The benefit of harvesting young trees generates revenue within the market pulp global structure, while simultaneously enhancing vulnerabilities from wind throw and other weather events. As timber becomes a more powerful market driver in the construction sector, and as

technologies such as cross-laminated timber continue to deliver the ability to build bigger and higher, the growth and development of this region to meet a new product demand will be crucial in the private and public sector. Predictive forest design planning, paired with tools such as material flow analysis, must be supported and implemented considering the current and future market needs in the context of a circular economy study.



## **CHAPTER 4**

### **Life-cycle assessment of selected maritime pinewood industries in the Landes de Gascogne area of France.**

#### **4.1. Introduction**

Since the nineteenth century, the global consumption of raw materials for the production of food, energy, and buildings has expanded enormously (Bringezu, 2017) and Krausmann, 2017). Population growth and economic expansion indicate that the demand for food, fuel, and building materials will increase in the future (Bringezu, 2017). Furthermore, climate change and resource loss represent a grave threat to human civilization and the Earth as a whole. More than 35% of global final energy consumption and approximately 40% of energy-related CO<sub>2</sub> emissions are attributable to buildings and construction (Abergel et al., 2017). Forest resources supply sustainable building materials (particularly for buildings), pulp and paper, energy, bio products, and more (Canadell & Raupach, 2008). Trees that sequester carbon and wood products that store carbon have the greatest potential to ameliorate climate changes. Combining carbon storage and carbon displaced from using forest-based construction materials, particularly in building construction, is one of the most effective strategies for mitigating climate change (Oliver et al., 2014; Bowyer et al., 2012). It may be difficult to meet the global demand for forest resources to produce needed construction wood, pulp and paper, energy and fuel, pallets, and plywood without continuing to practice sustainable forest management (Johnston et al., 2019; Solomon et al., 2015). Forests are currently viewed as a source of renewable and sustainable natural resources for construction material, fibers, biofuel and other renewable materials to mitigate climate change and meet society's rising expectations for economic prosperity (Jakes et al., 2016;). The efficient and prudent use of scarce resources is essential; thus, the real environmental and economic performance of various goods and services derived from forest resources must be evaluated. Wood products bring economic, environmental, and societal benefits, and all these benefits must be measured using tools that can analyze and compare the benefits of various wood products (Chang et al., 2014; ISO, 2006a).

Due to the wide variety of products—both wood and others—and the amount of revenue created by the forest industry sector, as well as the important ecosystem services they offer (such as avoiding erosion of soil and maintaining biodiversity) and the space they provide for rest, relaxation and exercise forests are essential for human survival (European Union, 2017; FAO, 2012). It is anticipated that the overall area of the world's forests in 2020 was 4,06 billion ha or 31 percent of the entire land surface of the planet (FAO, 2020). The European Union contains roughly 5 percent of the world's woods and the total forest area is progressively expanding. In 2020, the world's forests were predicted to have stored around 662 gigatons (i.e., 163 tons per hectare) of carbon, including 300 gigatons in soil organic matter, 295 gigatons in living biomass, and 68 gigatons in dead wood and litter (FAO, 2020). According to FAO forest product statistics (FAO, 2019), the global industrial roundwood production (all roundwood used for purposes other than energy) was 2,024,660 billion m<sup>3</sup> in 2019, of which 639,347 billion m<sup>3</sup> (31.5%) was generated in Europe (including the Russian Federation). In 2019, worldwide fuelwood output (roundwood that will be used as fuel for cooking, heating or power production, as well as wood that will be used for charcoal, pellets and other agglomerates) totaled 1,944,715 million m<sup>3</sup>, a decline of less than one percent from 2018. Fuelwood production in Europe declined by 1% over the same period.

According to the (FAO stat, 2019) the total area of French forests in 2019 was 17,253 million ha, or 30% of the total land area. The area occupied by coniferous species in 2019 corresponded to 33% of these forests, with the remaining 67% occupied by hardwoods. Maritime pine (*Pinus pinaster*), with a land occupation of 1,030 million ha, represented 7% of the total forest area and 23% of the total coniferous area.

Recent years have seen a focus on quantifying the environmental characteristics of forest activities in order to make them more competitive on a worldwide scale (González-García et al., 2014a). Life-cycle assessment (LCA) is a systematic approach that permits evaluating environmental consequences related with materials, goods, and services over their production systems, as well as supporting sustainability-oriented decision-making strategies (Baumann & Tillman, 2004; ISO, 2006a).

Many environmental studies utilizing LCA methods to identify the environmental characteristics of specialized industrial forest systems are found in scientific literature. Examples include Norway spruce and Scots pine production in Finland and Sweden (Berg & Karjalainen, 2003), maritime pine production in Portugal and France (Dias & Arroja, 2012; González-García et al., 2009b; González-García et al., 2014a; González-García et al., 2014b), and European beech in Germany in (Berg et al., 2012).

This chapter seeks to identify and evaluate environmental impacts resulting from industrial production of maritime pine round wood in forest stands located in the Landes de Gascogne area of France. In order to accomplish this, current procedures in Landes de Gascogne were examined and evaluated in depth. The maritime pine was selected as the target species due to its enormous economic significance to the region.

This study is different from the papers previously mentioned because it goes beyond using the life-cycle assessment method to determine the environmental impacts of the production gate-to-gate systems boundaries for the following five wood-based products: construction wood, plywood, pulp, pallets, and pellets. Instead, it uses the results of the life-cycle assessment method to find the economic value of the negative effects of externalities, which is one reason why the market is not good at either estimating true costs or comparing them with the market costs. This will be done in later chapters of this study.

The current chapter will present the results and compare the environmental impact of the mentioned five wood-based products identified from the Landes de Gascogne Forest by the life-cycle assessment of those wood-based products to help guide decision-making at the value-chain level based on material flow analysis (MFA) as the main applications of the maritime pinewood transformation in the Nouvelle-Aquitaine region.

## **4.2. Materials and method**

### **4.2.1. Study Area**

As stated in the previous chapter, the study area is the Landes de Gascogne Forest—which covers 10,000 km<sup>2</sup> in the

Nouvelle-Aquitaine region in France—where maritime pine is the predominant species, as stated in the previous chapter.

#### 4.2.2. Life-cycle assessment

LCA is a globally recognized and defined method for assessing the environmental effects of products. LCA is a scientific technique for quantifying the potential environmental impacts of a product. This is done through a compilation of the resources utilized and emissions emitted, as well as an evaluation of the related effects on the environment. An LCA can assess the life cycle of a product from the extraction of raw materials through the point of product creation (gate-to-grave) or through distribution, usage, and disposal (cradle-to-grave) (ISO 2006a and 2006b; Wolf et al., 2012). The LCA research was conducted using ISO suggested methodologies (ISO 14040 [ISO, 2006a] and ISO 14044 [ISO, 2006b]), but is currently without critical review. It is organized into four stages: goal and scope definition (defining the purpose and scope of this study, as well as the functional units), inventory analysis (enumerating the emissions of pollutants into air, water and soil, solid wastes, and consumption of resources per functional unit), impact assessment (evaluating the environmental impact of the pollution generated throughout their life cycle), and interpretation of the results (interpreting the findings of the inventory analysis and/or the impact assessment). An overview of the four stages is presented in Figure 6.

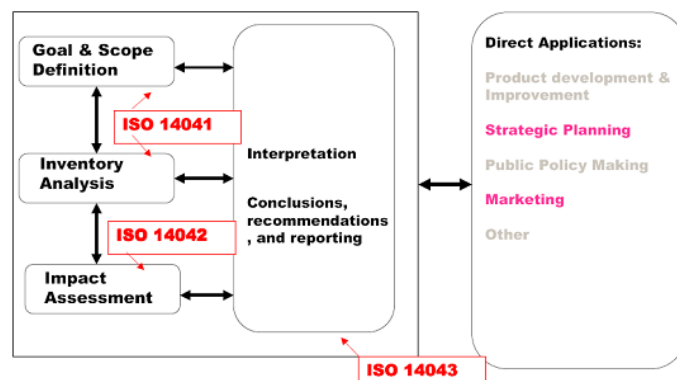


Figure 6: Life-cycle assessment framework (ISO, 2006a, 2006b)

### **4.2.3. Goal and scope of the study**

#### **4.2.3.1 Objective of the study**

The primary objective of this chapter is to evaluate the potential life cycle environmental impact affiliated with the harvesting operations (felling, cutting, extraction, and loading) and transportation operations and production of various types of maritime pine (*Pinus pinaster*) wood (for pallets, plywood, construction wood, paper pulp, and pellets) in the Landes Forest, by applying LCA as the principal implementation tool for the maritime pinewood products in the Nouvelle-Aquitaine region. Another purpose of the study is to determine which wood product has the greatest environmental impact among the product systems examined. This chapter gives inventories for the mentioned five major wood products based on literature or specialized data collection.

#### **4.2.3.2 System boundary**

According to the ISO 14040 and 14044 standards, a four-step structure is specified for this sort of evaluation. This must explicitly describe the system boundaries, to prevent double-counting and omissions. Figure 7 is a simplified representation of the system boundaries for the examined product system. The modules included in the gate-to-gate boundaries range from thinning and final cutting to the production of the five products: construction wood, pulp, plywood, pallets, and pellets in 2019.

Although we acknowledge the interdependence of the forest products value chain, the data utilized to model the LCA and assign environmental impacts is based on Chapter 3. It focuses on the initial transformation of maritime pinewood based on the functional unit established in 4.2.3.3.



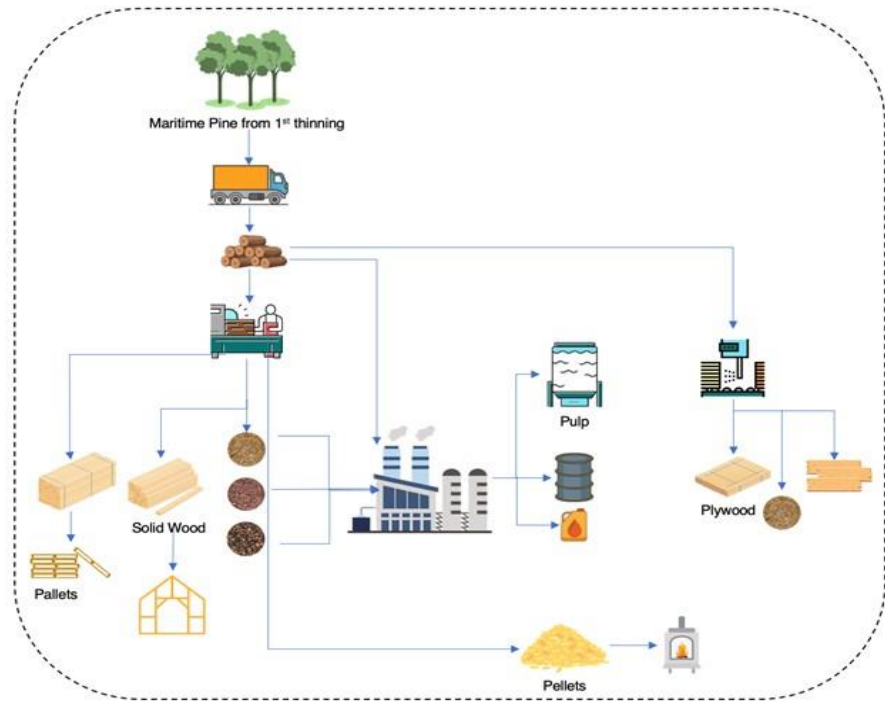


Figure 7 - Studied system boundaries (Wood destination shares are based on chapter 3)

#### 4.2.3.3 Function of the system and functional unit

The system under study is designed to harvest and manufacture maritime pinewood for a variety of uses, including the production of lumber, plywood, and pallets in the sawmill sector, pulp paper in the paper industry, and pellets from residual wood (branches and tiny trees from thinning). The functional unit in this study is given as 1 m<sup>3</sup> under bark (“ub”) of greenwood (recently harvested wood) with a moisture content of 45%, since the volume remains more or less constant with changing water content. This functional unit’s selection is consistent with other wood systems examined using LCA (González-García et al., 2009; Klein et al., 2015; May et al., 2012; Werner et al., 2007) and is encouraged by PCR 2012:01 v2.2 (EPD International, 2017). The fundamental benefit of adopting m<sup>3</sup> of fiber equivalent in place of a mass unit is that, in the case of greenwood, it is equivalent to m<sup>3</sup> of round wood.

A quantitative description of the service performance (the needs met) of the under-investigation product system is provided by the functional unit (s). Typically, the functional unit is not merely a material quantity. Practitioners may, for instance, analyze various packaging options based on 1 m<sup>3</sup> of

delivered and packed goods—the service that the product offers. Depending on the packaging option chosen, the reference flow, or needed amount of packing material, can change (paper, plastic, metal, composite, etc.).

We examine a “reversed” functional unit based on the amount of wood consumed in the manufacture of the various products rather than their application depending on the intended application of the study and the data used to simulate the system “Producing each wood product based on the transformation of 1 m<sup>3</sup> over bark (“ob”) of maritime pinewood from the Landes de Gascogne Forest.

In accordance with the 2019 market share percentage identified in the previous chapter, adjustments are made by multiplying the Environmental Prices method values by the MFA percentages. The reference flows according to this FU are shown in Table 2.

Table 2: Reference flows of studied products

Product	Reference flow	Unit	Reference
Solid wood	0.549	m <sup>3</sup>	S. K. Diederichs, “2010 status quo for life cycle inventory and environmental impact assessment of wood-based panel products in Germany,” <i>Wood Fiber Sci.</i> , vol. 46, no. 3, pp. 340–355, 2014.
Plywood	0.48	m <sup>3</sup>	Ecoinvent 3.8 Plywood, for indoor use {RER}  production, APOS, U
Pallets	354	kg	Gascogne
Unbleached pulp	166.7	Kg	M. Suhr et al., <i>Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board</i> . 2015.
Pellets	375	kg	D. Reed et al., “Cradle-to-gate life-cycle inventory and impact assessment of wood fuel pellet manufacturing from hardwood flooring residues in the southeastern United States,” <i>For. Prod. J.</i> , vol. 62, no. 4, pp. 280–288, 2012, doi: 10.13073/FPJ-D-

#### 4.2.3.4. Allocation procedure

The distribution of effects is a crucial methodological concern for those who practice life-cycle assessment (LCA). A product system under investigation and one or more additional product systems are divided up according to how their input or output flows are allocated in a process or product system (ISO 2006a, 4). In guideline 14044 (ISO, 2006b), the International Organization for Standardization (ISO) outlines a specific allocation process:

1. Allocation should be avoided whenever possible by either:

- a. Splitting the unit process to be assigned into two or more subprocesses, or
  - b. Adding new features to the product system that are connected to the coproducts.
2. In cases when allocation is unavoidable, the system's inputs and outputs should be divided among its various products or functions in a way that accurately depicts the underlying physical connections between them.
  3. When a physical connection cannot be made or used as the basis for allocation, the inputs should be distributed among the products and functions in a way that takes into account other connections between them. Input and output information, for instance, might be divided between coproducts in proportion to the economic value of the goods (ISO 2006b, 14).

Changing the ratio between the various co-products in order to observe how the data set changes with this change in product output is one method used to identify such a physical characteristic.

$$MP_i = \frac{Mass P_i}{\sum_{i=1}^n Mass P_i}$$

(Equation 2)

Where:

- $MP_i$ - Is the mass partitioning factor of the  $i$ th coproduct /co-service
- $Mass P_i$ - is the quantity of the  $i$ th product/service,  $\sum_{i=1}^n Mass P_i$  Is the total amount of products / service

This method fails because, in some cases, the range of possible variations for the mass ratio between a product and its coproducts is too narrow, necessitating a substantial adjustment to the process's other parameters, such as energy usage. Physical factors could be taken into account, but none of them—according to the ISO assessment “can be substantiated as being preferred to the other ones” (ISO,2000, 24) Hence it is possible to use economic allocation (Ardente & Cellura; 2012).

Ardente & Cellura (2012) state that the economic partitioning factors are determined as the portion of one product's or service's proceeds in the sum of all products and services proceeds in a shared process that provides co-products or co-services, as follows:

$$P_i = (N_i \cdot X_i) / (\sum_i (N_i \cdot X_i)) \text{ -----(Equation 3)}$$

Where:

$N_i$ - is the quantity of the  $i$ th product/service,

$X_i$ -is the price of the  $i$ th product/service

It has been long argued how to handle allocation in the descriptive LCA of wood-based products, and several solutions have been put forth. It is well acknowledged that differing allocation techniques can have a considerable impact on the LCA outcomes for products made of wood. Wood is a renewable resource that may be utilized to make energy and wood products. In order to properly address the dual character of wood as a material and as a fuel, the multi-functional wood processing that generates huge numbers of by-products, and reuse or recycling of paper and wood, consistent methodological processes are required. The following ten processes are listed in LCAs of wood-based goods where allocation concerns may arise: forestry, sawmills, the wood industry, pulp and paper manufacturing, particle board manufacturing, paper recycling, waste wood recycling, combined heat and power generation, and landfills.

In forestry, allocation refers to distributing the environmental impacts of forest management among the many forestry by products. Forest management encompasses a variety of tasks, from planting trees to caring for, thinning down, and harvesting wood. As mentioned above, forestry co-products can include roundwood, fiber wood, firewood, or recreation, and the environmental effects can be attributed to any of them. Identifying the primary function(s) of the forest under consideration serves as the foundation for allocation in forestry. There are three primary categories of forests that can be recognized:

1. Type 1: Fuel wood and forest wastes from tops and branches are considered waste; the goal of the forest is the production of roundwood with a high market price. Consequently, the amount ( $m^3$ ) of roundwood and fiber wood is where all environmental effects associated with forest management are attributed. The forest's other uses, such recreation, are not taken into account.
2. Type 2: The purpose of the forest is to provide fuel and the raw materials for wood products, as all of these by products have a positive economic worth. The environmental costs are divided among the total amount

(*t* dry) of all co-products. The other uses of the forest are not taken into account, including enjoyment.

3. Type 3: In addition to producing wood, managing forests has as its primary objectives all the other forestry functions. These purposes may include leisure, welfare, defense and hunting, among others. The environmental costs associated with managing forests are spread over all of the forest's uses, not only the extraction of wood (e.g., on an economic basis) (Jungmeier et al., 2002).

The following forest models for data inventories can be found, in addition to the description of the forest type:

1. Model I: An examination of a forest over a one-hectare area from planting to ultimate felling (after 70-100 years).
2. Model II: yearly investigation of a forestry system with a linear distribution of age classes, which entails a unit of area of one hectare for each age class, with the number of hectares being defined by the year of final felling (e.g., 100 ha in a system where final felling takes place after 100 years).
3. Model III: analysis of an actual, functioning forestry system that includes varied age classes and an annual data inventory.

Referring to Jungmeire et al. (2002), it is necessary to describe the primary purpose of the forest where the raw material is extracted in order to allocate the forestry processes. In some circumstances, it is also necessary to take into account and describe various forest types or functions. According to the example experiences described, the following allocations were found to be the most useful for some particular processes: forestry (volume or mass), sawmill (volume or mass and earnings), wood industry (volume and earnings).

The ILCD Handbook states that economic allocation is based on the co-products' economic worth at the point (i.e., at the plant or service provider), in the quantity (i.e., bulk), condition (i.e., not purified/technical quality) and amount (e.g., bulk) that the multifunctional process provides. The market price must be determined using information on production costs and the market price of the co-product that has been further processed, packaged, transported, etc. if the co-products are not exchanged at that point of allocation and

with their unique characteristics. To ensure that the economic value used for allocation accurately captures the value of each co-product at the point and in the condition where it is delivered, any additional transit, conditioning, packaging, etc. must be taken into account (EC, 2010). The manual claims that “applying the allocation at the incorrect position is a frequent error for this type of allocation. The use of the market price as a criterion is most frequently included in this. Pricing should actually refer to the value as soon as a thing is produced, rather than the price consumers pay, which instead takes into account various external considerations” (EC, 2010).

It is well acknowledged that the outcomes of the life-cycle evaluation of wood-based goods can be significantly influenced by various allocation techniques. In addition, wood is a renewable material that can be used for wood products and energy production. In order to properly address the dual character of wood as a material and fuel, the multi-functional wood processing that generates huge numbers of byproducts, and recycling or reuse of paper and wood, consistent methodological processes are required.

Assigning environmental and economic performances to each by-product resulting from multifunctional processes producing many good is a crucial topic for this study. Various allocation techniques, including substitution, expansion or partitioning, can be used. According to a method proposed by Schrijvers et al. (2020), the allocation method should be chosen based on the criteria specified during the goal and scope. Partitioning is advised in our situation since we are comparing the environmental effects of various wood products from an attributional standpoint.

The most popular dividing techniques are mass and economic allocations. When the price difference between the by-products is significant (>25%) and the International Organization for Standardization (2006) suggests using priority mass allocation, AFNOR-CEN (2012) and the EPD International System (2017) tend to use economic allocation.

According to Schrijvers et al. (2021), allocation should be chosen based on target specification and supported by practitioner’s vision. Also, there is a distinct allocation for each forest process. In the forest, we should employ proceeds- or mass-based allocation; in the sawmill, proceeds- and mass-

based allocation; and in the wood industry, proceeds- or mass-based allocation. In our study, allocation is applied at various levels, in this study, the mass allocation based on market share shown in table two applied.

Table 3: Mass allocation based on market share (%) identify in chapter three

Level	Item	Amount (see chapter 3)	Volume allocation ratio
	Roundwood (lumber)	612,497.6 m <sup>3</sup>	0,43
	Construction wood	122,499.5 m <sup>3</sup>	0.20
	Pellets	156,685.4 m <sup>3</sup>	0,11
	Pallets	91,874.6 m <sup>3</sup>	0.15
	Plywood	55,124.8 m <sup>3</sup>	0.09
	Industrial wood (pulpwood)	640,985.85 m <sup>3</sup>	0,45

Forest	Roundwood (=Lumber)	6,12E+05 m3 (chapter 3)	0,43
	Industrial wood (=Pulpwood)	6,41E+05 m3 (chapter 3)	0,45
	Fuelwood	9,97E+04 m3 (chapter 3)	0,11
Sawmill (green sawnwood)	Wood for boards and beams	5,49E-01 m3 (Diederichs, 2014)	0,55
	Wood for palettes		
	Bark	9,45E-02 m3 (Diederichs, 2014)	0,09
	Dust and cuttings	3,60E-01 m3 (Diederichs, 2014)	0,36
Kraft process	Paper	1,67E+02 kg	0,92
	Turpentine	1,25E+01 kg	0,07
	Tall Oil	2,50E+00 kg	0,01
	Pallets	3.539 E+02 Kg (Gascogne Bois)	0.78 353.9 Kg
	Pellets	3.75E-01 Kg Reed, D. et al.;2012)	0.83 (375 Kg)
	Plywood	48E-01 Wilson, J. B., & Sakimoto, E. T. (2005)	0.48

#### 4.2.4. Life-cycle inventory (LCI)

The life cycle inventory analysis enumerates emissions in to air, water and soil, solid waste and consumption of resources per functional unit. In this study most of inventory come from either business communications or literature. This applies for the forest, sawmill for boards and beams, Kraft process for paper, plywood, pallets and Pellets). The harvesting (from initial thinning), shipping, and

processing procedures for pallets, construction wood, pulp paper, plywood manufacture, and pellets are summarized in the part that follows, along with our study assumptions.

All incoming (inputs) and outgoing (outputs) flows for each stage of the life cycle inside the system boundaries are listed during the inventory phase. Foreground data and background data are the two categories of inventory data. Foreground data are activities of main interest in the systems under study, such as the quantity of sawn wood entering the sawmill. The majority of the information for this inventory was gathered from published works (González-García et al., 2014; Diederichs, 2014; Wilson & Sakimoto, 2005); Gasol et al., 2008). Together with the underlying information, secondary activities are mentioned (as electricity production). In this situation, we used Eco invent database (Hauschild, 2018). Background data is generic and existent data are found in databases. All of the inputs and outputs discussed in the purpose and scope section are included in inventories for the Forest operation, which are based on literature (González-García et al., 2014). The sawmill scenario is based on research (Diederichs, 2014), data from Labours sawmills, and the construction wood inventory (Diederichs, 2014) that was covered in the previous chapter. Wilson and Sakimoto (2005) provided data on the inventory of plywood, and Reed et al., 2012) provided data on the inventory of pellets

#### **4.2.4.1. Resources**

The largest forest massif in Europe is the Landes de Gascogne Forest. This forest is divided among many landowners due to historical reasons. A federation of actors manages the country's forests, though direct forest work is done on a local level and forest practices differ greatly, depending on the exact location. In their LCA study, González-García et al. (2014) outlined these techniques in Table 4.



Table 4: Extensive and Intensive management scenario of forest (Gonzalez-Garcia et al., 2014)

	Extensive Management Scenario	Intensive Management Scenario
Time period	47 years	36 years
Inputs	Machinery, fuel, lubricating oil	Machinery, fuel, lubricating oil, triple superphosphate, glyphosate
Steps	Site preparation (cut-over, ploughing), stand establishment (planting, tillage) and tending (pruning: 2, thinning: 3), logging	Site preparation (cut-over, herbicide, ploughing, fertilization), stand establishment (sowing, mechanical weed control) and tending (thinning: 1), logging

According to the evaluation findings of each management situation, extensive management scenario (EMS) has more effects than intensive management scenario (IMS). EMS will be utilized as a cautious assumption in order to simulate the entire supply chain. Gonzalez-Garcia et al. inventories do not account for carbon capture and sequestration.

In accordance with the objectives and scope of this investigation, we took into account the input/output of one cubic meter of maritime pinewood within a scenario of extensive forest management, beginning with the initial thinning and building on the findings of González-García et al. (2014) in the study explained in Table 5.

Table 5: Fuel requirement for produce 1 m<sup>3</sup> of maritime pinewood from first thinning to the log yard

Products					
Outputs to techno sphere: Products and co-products	Amount	Unit	Quantity	Allocation %	Category
Maritime pine, from first thinning (EMS)	1	m <sup>3</sup>	Volume	100%	00-Wood products\Biomass\Maritime Pine

Inputs						
Inputs from techno sphere: materials/fuels		Amount	Unit	Distribution		
Diesel combustion		2.31	kg	Undefined		
Lubricating oil {RER}  production   APOS, U		0.11	kg	Undefined		
Tractor, 4-wheel, agricultural {CH}  production   APOS, U		0.18	kg	Undefined		

#### 4.2.4.2. Transportation

The wood must be transported from the harvesting area (the log yard) to the production site, and occasionally from the first manufacture to the second. We estimate a typical distance from the first thinning of the forest to the manufacturing site of 100 kilometers because we are using the Landes de Gascogne massif as our geographic scope.

#### 4.2.4.3. Products manufacturing

##### Construction wood

At a sawmill, beams and boards are made. We decided to restrict the study to their initial transformation because they can be used in a variety of applications (sawing and planning). Debarking, sawing, drying, and planning are the main processes in sawmill processing, as shown in Figure 8. The secondary processes include the burning of fuels to produce heat, the use of compressors to provide compressed air, the removal of dust, and other infrastructure-related operations. Items are stacked or plastic-wrapped before leaving the location. Construction wood is one of the last products following sawmill operations. Debarking, which is often one of the first on-site activities, is the first sawmill phase mentioned. Forklifts are used to move logs from the log yard to the debarking station. Logs are debarked, cut to the desired length, and sorted after being checked for screws. Chips, bark, and sawdust are examples of secondary products from cutting. Electricity, compressed air, diesel engine oil for the machinery, lubricants, and other resources are used in debarking. Sawlogs that have been debarked are the intermediate product. They have moved on to the sawing phase. The coniferous (in this case, maritime pine) saw logs

are cut with chipper canters or circular saws. The sawing technique utilized affects the rate of feeding, the quality of the byproducts, and the yield. Chips, sawdust, and edgings are the most typical by-products; however, there are more. Sawing uses lubricants and cutting instruments in addition to power and compressed air. Conveyor belts are primarily used to remove particles; therefore, vacuum removal is not required. After being sawed, coniferous sawn wood must be dried. In this study, the natural drying of coniferous sawn wood has been taken into consideration and an input-output table has been created based on data and findings from González-García et al. (2014) and Diederichs (2014).

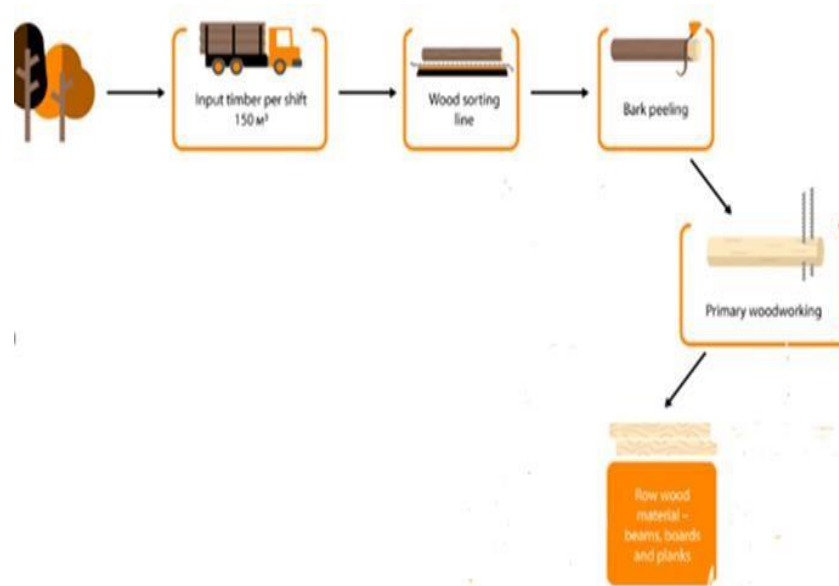


Figure 8: Construction wood production process (source: Wood manufacturing transformation processes)

Diederichs (2014) provides inventories for different types of sawmill processes allowing the modelling of various wood products. After contacting a sawmill based in the Landes de Gascogne region, we considered that boards, beams, and waste of wood for pellets production correspond to “coniferous sawn wood, green”. The data analyzed by SimaPro software 9.3 is the top of live cycle assessment and sustainability software in the world used by business and academia in more than 80 countries. Software and tools have been developed at PRé to assist us in making educated decisions, enabling better choices, and reducing the environmental impact of goods and services. SimaPro’s

creation thirty years ago was the catalyst for everything (LCA software for informed change-makers).

However, we charged all the costs on the solid wood without conducting the allocation process in SimaPro 9.3 analysis because we will correspond the results of SimaPro 9.3 analysis to the market share of each product (mass allocation) that has been done in the material flow analysis in Chapter 3, which is the base ground of this study in order to avoid double allocation. This will be done with all studied products in the study (Solid wood, plywood, pallets, pellets, and pulp). The input output data of construction wood are represented in Table 6.

Table 6: Life cycle inventory (Input out-put table) of construction woods process.

Products					
Outputs to technosphere: products and co-products	Amount	Unit	Volume	Allocation%	Distribution
Solid wood from 1st thinning	0.549	m3	Volume	100.00	
Inputs					
<b>Inputs from technosphere: materials/fuels</b>					
Maritime pine, from first thinning (EMS)	1	m3	Undefined		
Diesel, burned in agricultural machinery {GLO} market for diesel, burned in agricultural machinery   APOS, U	19.1	MJ	Undefined		
Light fuel oil {RER} market group for   APOS, U	8.571	g	Undefined		
Lubricating oil {RER} market for lubricating oil   APOS, U	49.89	g	Undefined		
Steel, low-alloyed {RER} steel production, converter, low-alloyed   APOS, U	51.5	g	Undefined		
Tap water {RER} market group for   APOS, U	1.319	kg	Undefined		
Water, completely softened {RER} market for water, completely softened   APOS, U	3.681	kg	Undefined		
Wood chips, dry, measured as dry mass {RER} market for   APOS, U	808.242	g	Undefined		
Corrugated board box {RER} market for corrugated board box   APOS, U	13.187	g	Undefined		
<b>Inputs from technosphere: electricity/heat</b>					
Electricity, medium voltage {FR} market for   APOS, U	12	kWh			
Output					
<b>Emissions to air</b>					
Carbon monoxide	7.198	g	Undefined		
Carbon dioxide, fossil	1.429	kg	Undefined		
NMVOC, non-methane volatile organic compounds, unspecified origin	2.396	g	Undefined		
Sulfur dioxide, FR	1.808	g	Undefined		
Nitrogen oxides, FR	23.077	g	Undefined		
<b>Emissions to water</b>					
Water, unspecified natural origin/kg	4.988	kg			
<b>Final waste flows</b>					
Waste, solid	0.053	kg			
Products					
Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation %	Category
Maritime pine, from first thinning (EMS)	1	m3	Volume	100%	products\Bio
Inputs					
<b>Inputs from technosphere: materials/fuels</b>					
Diesel combustion	2.31	kg	Undefined		
Lubricating oil {RER} production   APOS, U	0.11	kg	Undefined		
Tractor, 4-wheel, agricultural {CH} production   APOS, U	0.18	kg	Undefined		

## Pallets

The pinewood used to make wood pallets in the line with system boundaries shown in Figure 9, is combined with additional components, including steel nails, paint, and other materials. The dimensions of a standard pallet were determined by international logistics standards to be 1.2 by 0.8 meters (length by width). Hence, the wooden pallet has a particular weight of 25 kg. Each wooden pallet manufacturing process has unique requirements.

Despite the differences in size of pallets, the fundamental flow processes for all of them are the same, so in this study, we will concentrate on the environmental impact of turning 1 m<sup>3</sup> of raw wood material into pallets. Two components make up the primary processes of pallet fabrication that are analyzed. Pallet assembly comes next after the processing of the wood (Gasol et al., 2008). Products identified as EPAL 1 pallets are referred to as “flat pallets and pallet collars of wood” in German production data. Pallets are the primary completed wooden product in this category as well. Another important product with even higher production rates is lumber, or goods made from planed wood. Nevertheless, these goods can be categorized as completed or semi-finished wood goods depending on the circumstances (Schweinle et al., 2020).

The process of making wood pallets may be broken down into a few easy phases (Figure 9). The first step is performing board shape and wood preparation. This entails categorizing, repurposing, and naturally drying the wood. The next step is to assemble the product, which involves using nails (among other materials), to create the finished wood pallet. The sawing of the logs that arrived from the sawmill into particular dimensions is part of the first phase of preparing the wood and shaping the boards (desired pallet size, depends on the manufacturer). Wooden boards, blocks, and disks are produced as the main components in this process, along with wood remnants such as slabs and edgings. The final stage, product assembly, will involve those major wooden components. To strengthen the wooden pallet construction, producers may choose to utilize supplementary materials such as glues and wires in addition to steel nails for assembly (with hammers) (Adre). The input-output table of

pallets prepared rely on Gascogne Bois: Technology, Ecologie, Tendence.

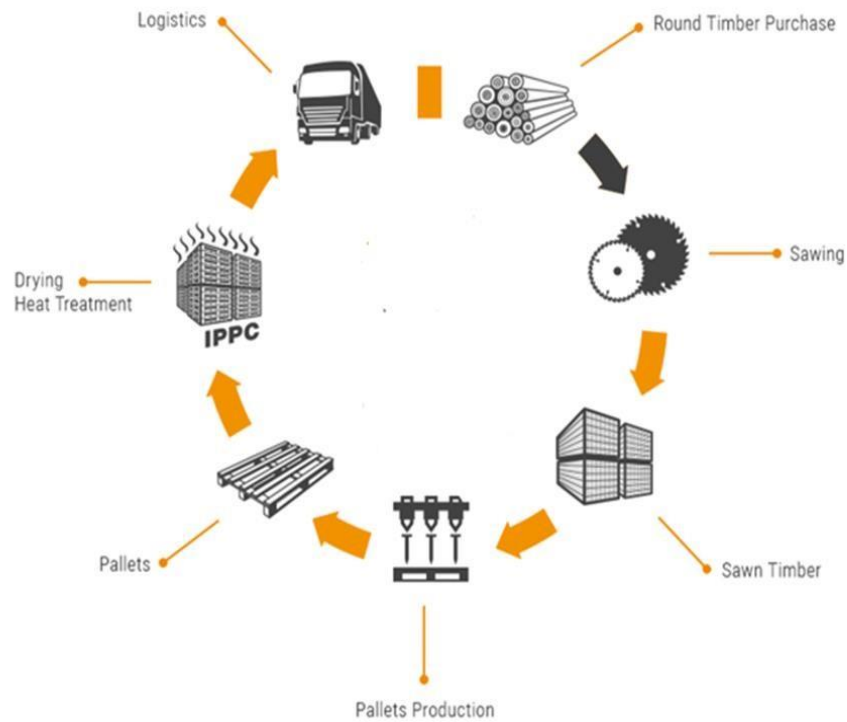


Figure 9: Gate-to wooden pallets gate system boundaries with the process chain steps included in wood pallets manufacturing (source: <https://www.klaustimber.cz/en/from-a-forest-to-you-how-is-a-pallet-born>)

Pallets are manufactured thanks to treated green sawn wood and steel nails. Input output materials are explained in Table 7.

Table 7: Life cycle inventory (Input out-put table) of pallet production process

Products					
<b>Outputs to technosphere: products and co-products</b>					
Pallets	354	kg	96.38	00-Wood products\Tests Veronica	
Wood dust	2.58	kg	0.70		
Wood boards	10.72	kg	2.92		
Inputs					
<b>Inputs from technosphere: materials/fuels</b>					
Maritime pine, from first thinning (EMS)	1	m3	Undefined		
<b>Inputs from technosphere: electricity/heat</b>					
Electricity, medium voltage (FR) market for   APOS, U	29.38	kWh	Undefined		
Natural gas, burned in gas motor, for storage (GLO) market for   APOS, U	15.82	kWh	Undefined		
Alkyd paint, white, without solvent, in 60% solution state (RER) market for alkyd paint, white, without solvent, in 60% solution state   APOS, U	0.41	kg	Undefined		
Steel, low-alloyed (RER) steel production, converter, low-alloyed   APOS, U	6.37	kg	Undefined		
Output					
<b>Outputs to technosphere: waste to treatment</b>					
Waste wood, untreated (FR) market for waste wood, untreated   APOS, U	13.31	kg	Undefined		
Products					
<b>Outputs to technosphere: Products and co-products</b>					
Maritime pine, from first thinning (EMS)	1	m3	Volume	100%	00-Wood products\Biomass\Maritime Pine
<b>Inputs from technosphere: materials/fuels</b>					
Diesel combustion	2.31	kg	Undefined		
Lubricating oil (RER) production   APOS, U	0.11	kg	Undefined		
Tractor, 4-wheel, agricultural (CH) production   APOS, U	0.18	kg	Undefined		



## Plywood

Softwood plywood (see Figure 10) is a structural building material with a long history that can be used for a variety of construction projects. For both commercial and residential building, plywood is frequently employed. It serves as a sheathing material for floors, walls, and roofs in private settings. Plywood is made from various types of wood. In addition to other species such as spruce and western larch, North America uses douglas-fir and western hemlock. Other species of wood are employed in other places, primarily pine, as in this study, which depends on maritime pine for the production of plywood. The plywood is made using a few traditional procedures. Debarking, peeling, drying, sorting, gluing, laying up, and hot pressing are all steps in the production of plywood. After the veneer sheets have cured, resin (mostly phenol-formaldehyde) is used as a glue to stack the sheets. Stacks of sheets are heated and heated in a hot press to produce panels. The panel is then further treated by cutting to the required size (Wilson & Sakimoto, 2005; Jia et al., 2019).

As illustrated in Figure 10, the manufacturing process for plywood may be broken down into six interconnected processes. The input-output table for plywood production process in Table 8 was created using information from Wilson & Sakimoto (2005).

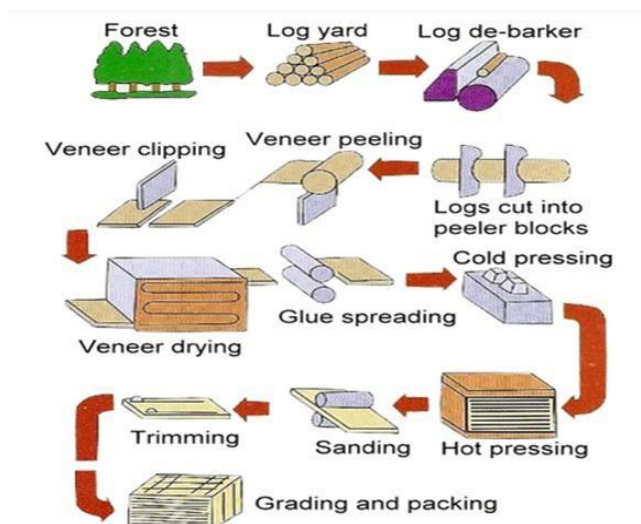


Figure 10: Plywood manufacturing process flows with the related inputs and outputs (Plywood manufacturing process) (Wilson & Sakimoto, 2005)

Table 8: Life cycle inventory (Input out-put table) of plywood production process.

Products						
Outputs to technosphere: products and co-products	Amount	Unit	Allocation%	Distribution	Category	
Plywood from Maritime pine  1st thinning	0.48	m3	100		00-Wood products\Tests Veronica	
Inputs						
<b>Inputs from nature</b>						
Water, cooling, unspecified natural origin, FR	0.68	m3		Undefined		
<b>Inputs from technosphere: materials/fuels</b>						
Maritime pine, from first thinning (EMS)	1	m3		Undefined		
Diesel, burned in agricultural machinery (GLO) market for diesel, burned in agricultural machinery   APOS, U	1.19	MJ		Undefined		
Melamine formaldehyde resin (RER) production   APOS, U	30.8	kg		Undefined		
Wooden board factory, organic bonded boards (RER) construction   APOS, U	0.000000012	p		Undefined		
<b>Inputs from technosphere: electricity/heat</b>						
Electricity, medium voltage (FR) market for   APOS, U	113	kWh		Undefined		
Heat, central or small-scale, other than natural gas (RoW) heat production, hardwood chips from forest, at furnace 50kW   APOS, U	2400	MJ		Undefined		
Outputs						
<b>Emissions to air</b>						
Formaldehyde	0.031	kg		Undefined		
<b>Emissions to water</b>						
Cooling water, FR	0.264	m3		Undefined		
<b>Outputs to technosphere: waste to treatment</b>						
Wastewater from plywood production (GLO) market for   APOS, U	0.681	m3		Undefined		
Products						
Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation %	Category	
Maritime pine, from first thinning (EMS)		1 m3	Volume	100%	00-Wood products\Biomass\Maritime Pine	
<b>Inputs from technosphere: materials/fuels</b>	<b>Amount</b>	<b>Unit</b>	<b>Distribution</b>			
Diesel combustion	2.31	kg	Undefined			
Lubricating oil (RER) production   APOS, U	0.11	kg	Undefined			
Tractor, 4-wheel, agricultural (CH) production   APOS, U	0.18	kg	Undefined			
Products						
Outputs to technosphere: products and co-products	Amount	Unit	Allocation%	Distribution	Category	
Plywood from Maritime pine  1st thinning	0.48	m3	100		00-Wood products\Tests Veronica	
Inputs						
<b>Inputs from nature</b>						
Water, cooling, unspecified natural origin, FR	0.68	m3		Undefined		
<b>Inputs from technosphere: materials/fuels</b>						
Maritime pine, from first thinning (EMS)	1	m3		Undefined		
Diesel, burned in agricultural machinery (GLO) market for diesel, burned in agricultural machinery   APOS, U	1.19	MJ		Undefined		
Melamine formaldehyde resin (RER) production   APOS, U	30.8	kg		Undefined		
Wooden board factory, organic bonded boards (RER) construction   APOS, U	0.000000012	p		Undefined		
<b>Inputs from technosphere: electricity/heat</b>						
Electricity, medium voltage (FR) market for   APOS, U	113	kWh		Undefined		
Heat, central or small-scale, other than natural gas (RoW) heat production, hardwood chips from forest, at furnace 50kW   APOS, U	2400	MJ		Undefined		
Outputs						
<b>Emissions to air</b>						
Formaldehyde	0.031	kg		Undefined		
<b>Emissions to water</b>						
Cooling water, FR	0.264	m3		Undefined		
<b>Outputs to technosphere: waste to treatment</b>						
Wastewater from plywood production (GLO) market for   APOS, U	0.681	m3		Undefined		
Products						
Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation %	Category	
Maritime pine, from first thinning (EMS)		1 m3	Volume	100%	00-Wood products\Biomass\Maritime Pine	
<b>Inputs from technosphere: materials/fuels</b>	<b>Amount</b>	<b>Unit</b>	<b>Distribution</b>			
Diesel combustion	2.31	kg	Undefined			
Lubricating oil (RER) production   APOS, U	0.11	kg	Undefined			
Tractor, 4-wheel, agricultural (CH) production   APOS, U	0.18	kg	Undefined			

## Pellets

The potential to lessen reliance on fossil fuels and greenhouse gas (GHG) emissions has led to an increase in the use of woody biomass for energy in recent decades (Branck, 2017; Bioenergy IEA, 2002), underscoring the significance of woody resources in sustainable economies. The use of woody biomass is encouraged by Directive 2009/28/EC (Renewable Energy Directive), which seeks to achieve a 20% share of renewable energy sources in the final energy mix of the European Union (EU) by 2020. In order to achieve 32% renewable energy in the EU's energy mix by 2030 and define a "bioenergy sustainability policy," a new Renewable Energy Regulation for the years beyond 2020 just received approval (European Commission, 2018). Woody biomass accounted for 46% of all renewable energy generated in the EU in 2015. In addition, over half of the thermal energy generated from woody biomass (82,921 ktoe) was used for domestic heating (AEBIOM, 2017).

According to information recently released by Bioenergy Europe, the 28 then member states of the European Union generated close to 17 million metric tons of wood pellets in 2018 and used close to 27 million metric tons. The pellet publication indicates that 27 million metric tons of pellets were consumed in Europe, of which 26.1 million metric tons were consumed by the EU28, an increase of 8% from 2017. The EU 28 generated approximately 17 million metric tons of wood pellets in 2018, an increase of about 10% from 2017. Germany produced the most pellets in Europe, at 2.4 million metric tons, an increase of 7.3%. Additionally, the output of pellets climbed in Sweden by 9.3 percent, reaching 1.8 million metric tons, Russia by 12.2 percent, 1.6 million metric tons, Latvia by 7.6 percent, and in France by 11.1 percent, reaching 1.5 million metric tons. (European pellet consumption, production up in 2019)

Pellets made from maritime pine are produced during the production step. The following five processes are taken into account (see Figure 11): (1) log chipping, (2) milling, (3) drying using the heat generated by the combustion of maritime pine logging residues, chipped at the forest roadside, (4) pelletizing, and (5) packaging (Quinteiro et al., 2019). Based on research (Reed et al., 2012), the input-output of pellets production presented in Table 9. We relied on the inputs and outputs of pellet production from hardwood due to the lack of data on softwood. In addition, according to Parajuli (2021), the wood pellets industry has led to increases in pine pulpwood, but no statistically significant impact has been found on hardwood pulpwood prices, so alongside the global direction, we prefer the results remain for hardwood data.



Figure 11: Production steps of wood pellets from maritime pine wood (small pellets line production process)

Table 9: Life cycle inventory (input-output) of pellets production process.

Products					
Outputs to technosphere: products and co-products	Amount	Unit	Allocation%	Distribution	Category
Pellets  1st thinning	375	kg	100		00-Wood products\Tests Veronica
Inputs					
Inputs from technosphere: materials/fuels					
Maritime pine, from first thinning (EMS)	1	m3		Undefined	
Diesel, burned in agricultural machinery (GLO)  market for diesel, burned in agricultural machinery   APOS, U	12.47	MJ		Undefined	
Packaging film, low density polyethylene {RER}  production   APOS, U	0.00013	kg		Undefined	
Inputs from technosphere: electricity/heat					
Electricity, medium voltage (FR)  market for   APOS, U	59.25	kWh		Undefined	
Output					
Emissions to air					
Carbon monoxide	0.00091125	kg		Undefined	
Carbon dioxide, fossil	1.02375	kg		Undefined	
Nitrogen oxides, FR	0.115875	kg		Undefined	
Sulfur dioxide, FR	0.015	kg		Undefined	
Methane, biogenic	0.00135	kg		Undefined	
Methane, fossil	2.0738E-05	kg		Undefined	
NMVOC, non-methane volatile organic compounds, unspecified origin	0.0102	kg		Undefined	
Outputs to technosphere: waste to treatment					
Wood ash mixture, pure {Europe without Switzerland}  market for wood ash mixture, pure   APOS, S	0.8025	kg		Undefined	
Products					
Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation %	Category
Maritime pine, from first thinning (EMS)	1	m3	Volume	100%	00-Wood products\Biomass\Maritime Pine
Inputs					
Inputs from technosphere: materials/fuels	Amout	Unit	Distribution		
Diesel combustion	2.31	kg	Undefined		
Lubricating oil {RER}  production   APOS, U	0.11	kg	Undefined		
Tractor, 4-wheel, agricultural {CH}  production   APOS, U	0.18	kg	Undefined		

## Wood pulp

Pulp is a fibrous substance produced by intricate industrial procedures that entail the mechanical and chemical processing of various plant materials. Around 90% of the world's pulp output now is based on wood, with 10% coming from annual plants. Pulp is one of the most widely used raw materials in the world, used primarily to make paper and paperboard but also increasingly in the textile, food, and pharmaceutical industries as a wide range of cellulose products (Gordeeva, E., Weber, N., & Wolfslehner, B. (2022). Chemically treated pulp is utilized extensively in a variety of industries, including the textile, paper, and packaging sectors, as well as the pharmaceutical, novel materials, and fuel production sectors (Food and Agricultural Organization, Year book of forest products2020). It is one of the final consumers of wood from forestry and aids in the growth of the bioenergy and biomaterials industries.

In 2019, there were 404.288 million tons of pulp, paper, and paperboard produced worldwide, and there were 190.35 million metric tons of wood pulp produced. (Food and Agriculture Organization of the United Nation-Forest products Statistics). France produced 1536000 units in 2019 while importing 1043901 units. Figure 12 represents the relative contribution of continents of the world in pulp production.

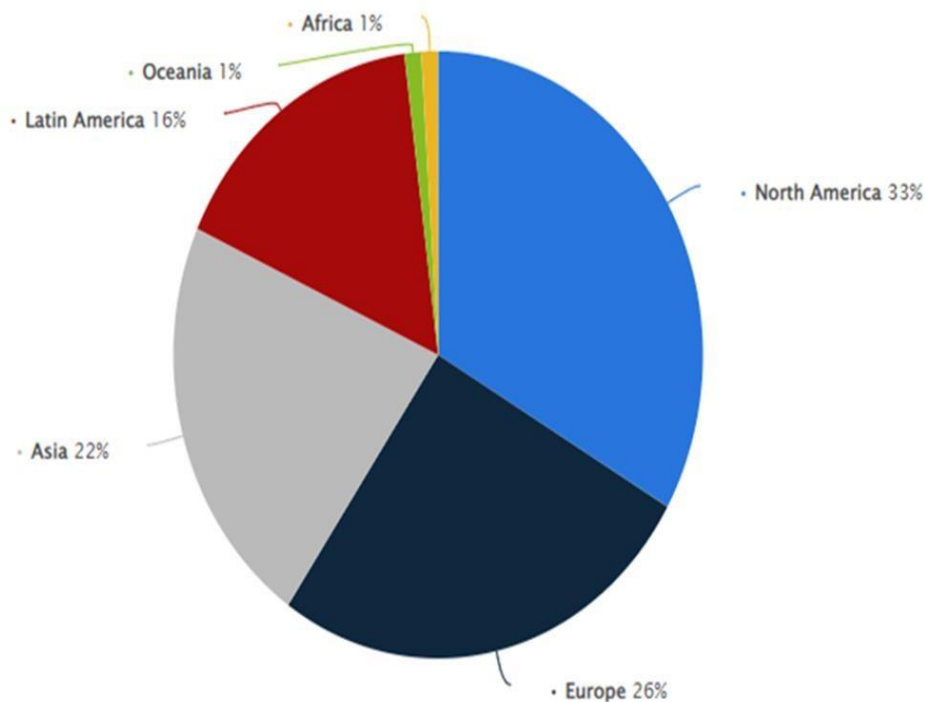


Figure 12: Distribution of pulp production worldwide in 2019, given by world region (Global pulp Production by Region)



pulping (black) liquor is processed through concentrators and evaporators to lower the moisture content to about 40%. The black fluid, which contains dissolved lignin and pulping chemicals, is subsequently burned in the chemical and energy recovery boiler. A high-pressure steam is the recovered form of energy. Sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) and sodium sulfide ( $\text{Na}_2\text{S}$ ) are extracted from the boiler's bottom to perform chemical recovery. The smelt is dissolved in water and then added back to the white liquor after reacting with calcium oxide from the lime kiln to create sodium hydroxide ( $\text{NaOH}$ ). The flowsheet for Kraft pulping in Figure. 13 provides a summary of this procedure Denes, & Young, (1999).



Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board by Suhir, M., Klein, G., Kourti, I., Gonzalo, M. R., Santonja, G. G., Roudier, S., & Sancho, L. D. (2015) has been used as a reference for pulp life cycle inventory as represented in Table 10.

Table 10. Input-output table of wood pulp chemical sulphate unbleached

	Products		Allocation %	Distribution	Category
	Amount	Unit			
<b>Outputs to technosphere: products and co-products</b>	166.7	kg	100.00		00:Wood products\Tras Varonica
Unbleached pulp   1st thinning					
<b>Inputs from nature</b>	13.33	m <sup>3</sup>		Undefined	
Water, cooling unspecified natural origin, FR					
<b>Inputs from technosphere: materials/fuels</b>	1	m <sup>3</sup>		Undefined	
Maritime pine, from first thinning (EMS)					
Sodium hydroxide, without water, in 50% solution state (GLQJ) market for   APOS, U	3.33	kg		Undefined	
Quicklime, in pieces loose (RoVj) market for quicklime, in pieces, loose   APOS, U	1.67	kg		Undefined	
<b>Inputs from technosphere: electricity/heat</b>	3.7	GJ		Undefined	
Heat, from steam, in chemical industry (RErj) market for heat, from steam, in chemical industry   APOS, U					
Electricity, high voltage, label-certified (CHj) market for   APOS, U	270	kWh		Undefined	
<b>Emissions to air</b>					
Nitrogen oxides, FR	0.37	kg		Undefined	
Sulfur	0.27	kg		Undefined	
VOC, volatile organic compounds, unspecified origin	0.37	kg		Undefined	
<b>Emissions to water</b>					
COD (Chemical Oxygen Demand), FR	3.83	g		Undefined	
Nitrogen	0.17	g		Undefined	
Phosphorus	8.33	g		Undefined	
Suspended solids, unspecified	0.54	g		Undefined	
Cadmium	0.01	g		Undefined	
Lead	0.06	g		Undefined	
Copper	0.08	g		Undefined	
Chromium	0.07	g		Undefined	
Nickel	0.07	g		Undefined	
Zinc	0.83	g		Undefined	
Sulphur	0.33	g		Undefined	
<b>Outputs to technosphere: Waste treatment</b>					
Wastewater from hand fibreboard production (SLQJ) market for   APOS, U	1.67	m <sup>3</sup>		Undefined	
Wood ash mixture, pure (RoVj) market for wood ash mixture, pure   APOS, U	1.5	kg		Undefined	
Ash from paper production sludge (RoVj) market for ash from paper production sludge   APOS, U	2.33	kg		Undefined	
Waste fibreboard (RoVj) market for waste fibreboard   APOS, U	0.83	kg		Undefined	
Green liquor dregs (SLQJ) market for   APOS, U	3.33	kg		Undefined	
Hazardous waste, for underground deposit (RoVj) treatment of hazardous waste, underground deposit   APOS, U	0.03	kg		Undefined	
<b>Outputs to technosphere: Products and co-products</b>					
Maritime pine, from first thinning (EMS)	Amount	Unit	Quantity	Allocation %	Category
	1	m <sup>3</sup>	Volume	100%	00:Wood products\Biomass\Maritime Pine
<b>Inputs from technosphere: materials/fuels</b>					
Diesel combustion	Amount	Unit	Distribution		
Lubricating oil (RErj) production   APOS, U	2.31	kg	Undefined		
Tractor, 4-wheel, agricultural (CHj) production   APOS, U	0.11	kg	Undefined		
	0.18	kg	Undefined		

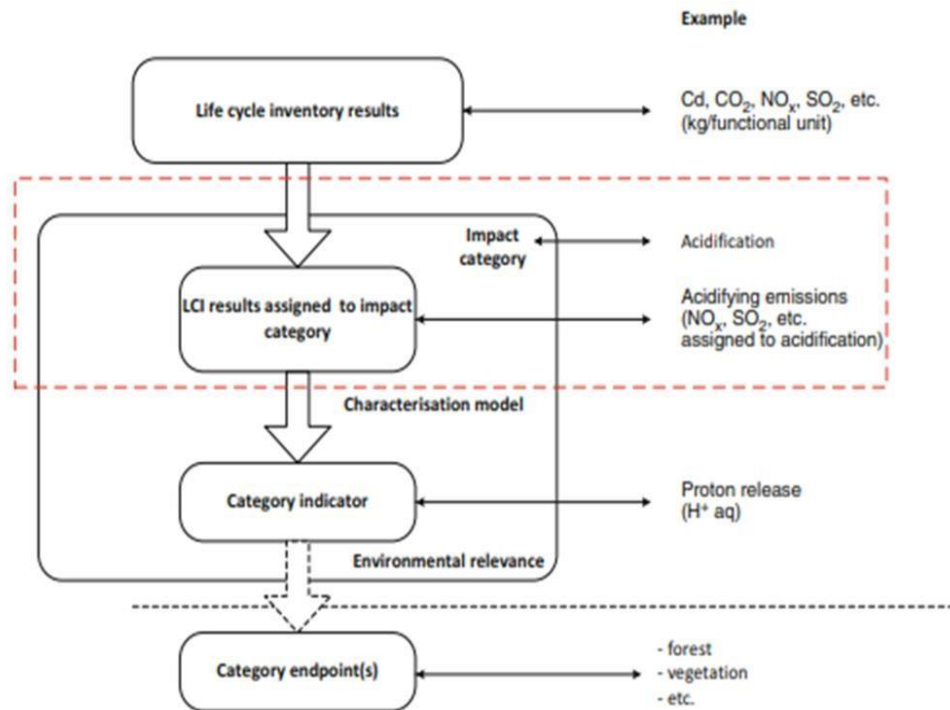


Figure 15: The conceptual framework for defining category indicators (slightly adapted from ISO14042 2000)

While the first three steps of the LCIA are mandatory for an LCA to be in compliance with the requirements of the ISO 14044 standard, the following two steps are optional:

Calculating the magnitude of category indicator results relative to reference information (normalization)

The metrics used to report the indicator scores as a consequence of the characterization stage vary depending on the effect categories. They can be stated in comparison to an all-encompassing set of available reference data to acquire a general idea of their relative magnitudes. For each of the impact categories, the annual impact from a typical person is a popular option of reference data. Hence, normalization puts the scores for the various effect categories on a comparable scale, in this instance by expressing them in person equivalents or person years, which may help identify conflicting results and facilitate the dissemination of the findings. Normalization can also be used to set up a weighting of the indicator results;

Converting indicator results of different impact categories by using numerical factors based on value-choices (weighting)

Using weighting variables that are based on value judgments and reflect the relative priority given to each of the effect categories, it is possible to facilitate a final comparison of indicator findings across impact categories. Weighting may be required to draw conclusions from studies where there are trade-offs between the findings for the various impact categories, such as the comparison between fossil fuels with a major contribution to global warming and biofuels with a major contribution to impacts on land use and water use (Herrmann et al., 2013). To make interpretation easier, the data can be combined across the effect categories after weighting to get a single score.

#### **4.2.6. Analysis method chosen: ReCiPe**

The ReCiPe method, developed by Mark Goedkoop and his team in 2009, merges endpoint (damage) and intermediate impact (midpoint) approaches. The CML technique for midpoint impacts and the Eco indicator 99 method for endpoint impacts are two analysis approaches that are used as examples for the ReCiPe. Acidification and acidification are two examples of environmental changes that are quantified by the Midpoint indicator. The Endpoint indicator, on the other hand, measures final damage to the planet, such as damage to ecosystems or human health. For instance, a product may result in the production of an oxidant at midpoint and affect ecosystems and human health at endpoint. The framework for life cycle impact analysis is shown in Figure 16.

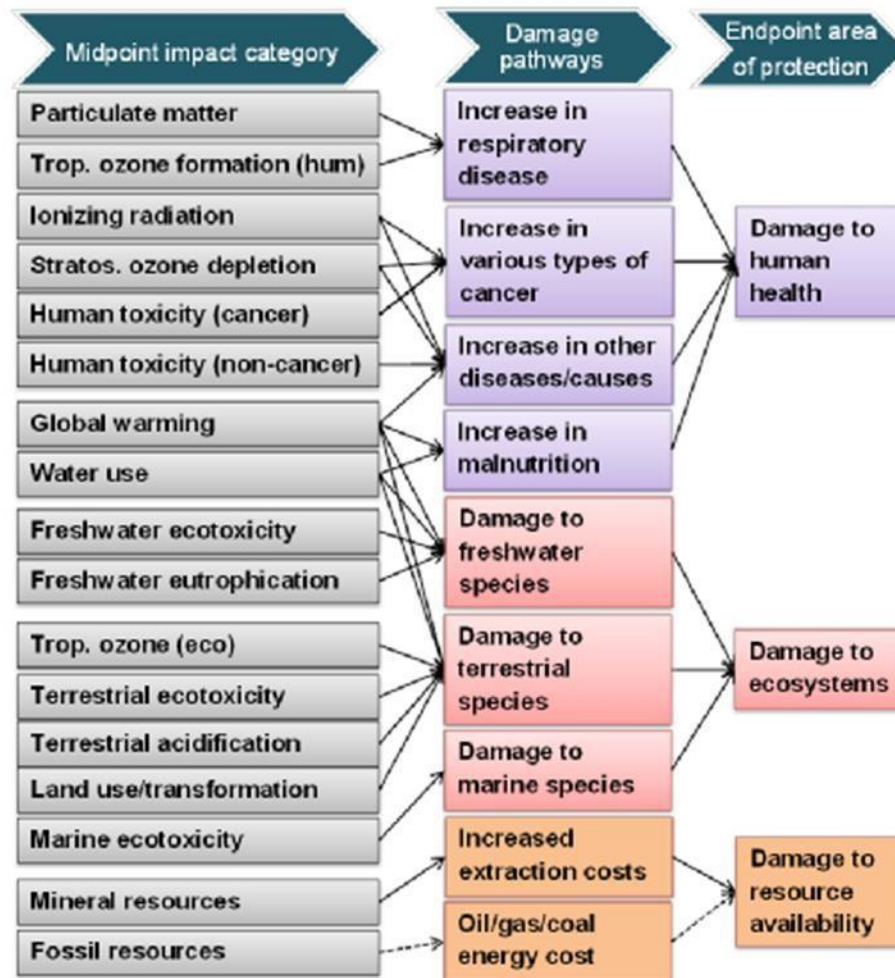


Figure 16: Overview of the impact categories that are covered in the ReCiPe2016 methodology and their relation to the areas of protection (ReCiPe methodology and their relation to the areas of protection).

#### 4.2.6.1. Midpoint impact categories

Effects can be categorized based on the amount of space they occupy in space. Global, local, and regional are all possible. Regardless of the location of emissions, a global impact occurs on a planetary scale and does not have a specific geographic location. The characterization criteria taken into account in this study are used to model global impacts into midpoint indicators (Goedkoop et al., 2009) represented in Table 11:

Table 11: overview of the midpoint categories and characterization factors in line with Geodkoop et al. (2009).

Impact category		Characterisation factor	
Abbreviation	Unit*	Name	Abbreviation
CC	kg (CO <sub>2</sub> to air)	global warming potential	GWP
OD	kg (CFC-11 <sup>5</sup> to air)	ozone depletion potential	ODP
TA	kg (SO <sub>2</sub> to air)	terrestrial acidification potential	TAP
FE	kg (P to freshwater)	freshwater eutrophication potential	FEP
ME	kg (N to freshwater)	marine eutrophication potential	MEP
HT	kg (14DCB to urban air)	human toxicity potential	HTP
POF	kg (NMVOC <sup>6</sup> to air)	photochemical oxidant formation potential	POFP
PMF	kg (PM <sub>10</sub> to air)	particulate matter formation potential	PMFP
TET	kg (14DCB to industrial soil)	terrestrial ecotoxicity potential	TETP
FET	kg (14DCB to freshwater)	freshwater ecotoxicity potential	FETP
MET	kg (14-DCB <sup>7</sup> to marine water)	marine ecotoxicity potential	METP
IR	kg (U <sup>235</sup> to air)	ionising radiation potential	IRP

Depletion of natural resources (biotic and abiotic), including water depletion (WD), is characterized by a factor called water depletion potential (WDP; unit is m<sup>3</sup> of water). Depletion of fossil resources (FD) and mineral resources (MRD) (characterization factor: MDP; unit: kg of Fe) (FDP - unit is kg of oil). Since the goal of this study is to evaluate the impact categories on the environment rather than the scars of resources, some impact categories have been left out. The term “global warming” (abbreviated “GW”; unit: kg of CO<sub>2</sub> equivalents) refers to a phenomenon associated with the concentration of greenhouse gases.

Thinness of the ozone layer (abbreviation for factor ODP - unit is kg of CFC13).

Impacts on the local and regional levels are felt near to the problem area. We will specifically focus on:

photochemical pollution, which is a collection of intricate processes that result in the generation of ozone (abbreviated “POFP” and measured in kg of non-metallic volatile organic compounds (NMVOC) in the air).

Particle formation (abbreviation for factor “PMFP” - kg of suspended particles with a diameter below 10 µm),

Ionizing radiation (also known as the “IRP” factor, or kilograms of uranium 235).

Human toxicity, or factor “HTP,” refers to any compounds that have an immediate negative influence on human health. The measurement is kilograms of 1,4-dichlorobenzene in urban air.

Eco toxicity, often known as factor “ETP” (terrestrial, freshwater, and marine), refers to the toxicity of natural ecosystems and is measured in kilograms of 1,4-dichlorobenzene (heavy metals, organic compounds, pesticides, etc.).

Eutrophication is a phenomenon causing the disruption of an aquatic ecosystem as a result of an excess of nutrients rich in nitrogen and phosphorus (abbreviated as “EP” for freshwater and marine environments, respectively; unit is kg of nitrogen or kg of phosphorus).

Acidification refers to the increase in acidity in soils and aquatic habitats (terrestrial, acronym for factor “AP”; unit is kg of SO<sub>2</sub> in the air).

### **4.3. Results and discussion**

The data has been collected and has been arranged in an input-output table during the second phase of life-cycle assessment (life cycle inventory). The SimaPro software 9.3.0 was used to analyze the data in order to determine the environmental impacts in kilos of each studied product for all impact categories by ReCiPe 2017.

Among the steps defined within the life cycle impact assessment stage of the standardized LCA methodology, classification, characterization and weighting stages were undertaken here (ISO 14040, 2006). The characterization factors reported by the Centre of Environmental Science of Leiden University (CML, 2001 method) were used (Guinée et al., 2002). The following impact potentials were evaluated according to the CML method v2.04: Climate change, Ozone depletion, Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Human toxicity, Photochemical oxidant formation, Particulate matter formation, Terrestrial Eco toxicity, Freshwater Eco toxicity, Marine Eco toxicity, Ionizing radiation. These impact categories were selected taking into account previous LCA studies of forest system (Arroja et al., 2006; González-García et al., 2009a; González-García et al., 2009b; Klein et al., 2015). Software SimaPro 9.3.0 has been used for the computational implementation of all the inventories (Santos et al., 2017).

Land use and soil quality changes caused by the forest activities been excluded considering changing nature have a very little environmental impact. and also, the resource depletion (water, fossil, and metal) has been excluded because the aim of the study is environmental impacts of products not the resources scarce.

#### **4.3.1. Construction wood**

The life cycle impact assessment (LCIA) step establishes links between the life cycle inventory results and potential environmental impacts (Puettmann et al., 2013). Table 12 present the results obtained from SimaPro soft wear analysis to estimate environmental impacts (twelve impacts categories) of construction wood production with market share 20% specified in chapter three, starting from first thinning to final products from maritime pine in Landes Gascogn , France 2019. The table shows the comparative environmental profile for each element of solid wood production. According to the Table 10, forest harvesting processes from first thinning is the most responsible of environmental burdens in eleven categories under assessment with contribution amount 2.31Kg. environmental impacts, which is great contribute to CC (1.89 CO<sub>2</sub> eq) due to the large amount of consumption fuel in this production step compare with other steps. Thus, this stage can be considered as environmental hotspot. The second largest contributor to the environmental impacts is Electricity medium voltage with amount 1.63kg from total environmental impact which is great contribute to (IR 1.27 kgBq). Tap water it is the production elements which has the smallest environmental impacts comparing with others elements.

Concerning forest harvesting stage, trees harvesting and roundwood extraction from the cutting area to the roadside landing are carried out by means of huge machines such as the harvester and the forwarder, respectively, being thus environmental hotspots (Fig.24). These machines report a significant consumption of diesel (2.60kg /m<sup>3</sup>). In fact, 83% of the total fuel requirement all over the life cycle of pine roundwood production is associated with these two specific processes.

Finally, regarding to Tap water, its contribution to the global environmental profile derived from the pine roundwood production and solid wood production processes is negligible.



Table 12: Amounts of Environmental impact categories results from construction wood production

Percentage indicated in MFA		20%											
Impact category	Unit	Maritime pir	Diesel. burni	Light fuel oil	Lubricating c	Steel. low-alloy	Tap water {R	Water. com	Wood chips.	Corrugated I	Electricity, medium	Total	
	Total	2.308885	0.6370422	0.0013682	0.0204177	0.035484431	0.0001899	0.0005861	0.0327571	0.003832	1.6306455	0	4.6712079
Climate change	kg CO2 eq	1.8941264	0.4773389	0.0008086	0.0121594	0.02197682	8.926E-05	0.0002785	0.0134207	0.0025736	0.2418822		2.6646543
Ozone depletion	kg CFC-11 eq	3.333E-07	6.426E-08	1.099E-09	6.099E-09	9.50996E-10	6.256E-12	1.433E-10	1.462E-09	2.631E-10	2.998E-08		4.375E-07
Terrestrial acidification	kg SO2 eq	0.0121073	0.0030208	7.743E-06	6.704E-05	7.11659E-05	3.809E-07	1.117E-06	7.611E-05	9.951E-06	0.0009187		0.0162804
Freshwater eutrophication	kg P eq	0.000124	7.171E-05	6.932E-08	3.877E-06	9.91406E-06	6.605E-08	2.331E-07	9.368E-06	1.26E-06	6.967E-05		0.0002902
Marine eutrophication	kg N eq	0.0006945	0.0001805	1.536E-07	2.319E-06	4.42556E-06	3.04E-08	8.572E-08	6.715E-06	4.491E-06	0.0001196		0.0010128
Human toxicity	kg 1.4-DB eq	0.1752077	0.1014715	0.0001406	0.0038282	0.009632572	6.321E-05	0.0001663	0.0150344	0.000744	0.0977375		0.4040258
Photochemical oxidant formation	kg NMVOC	0.0214149	0.0046189	5.775E-06	0.0002649	8.94464E-05	2.908E-07	7.01E-07	9.961E-05	8.882E-06	0.0006708		0.0271743
Particulate matter formation	kg PM10 eq	0.0046126	0.0016912	2.329E-06	2.396E-05	6.1131E-05	1.836E-07	4.891E-07	4.534E-05	4.005E-06	0.0003696		0.0068109
Terrestrial ecotoxicity	kg 1.4-DB eq	0.0001068	7.53E-05	1.524E-07	1.513E-06	1.60955E-06	1.07E-08	1.923E-08	1.35E-05	2.343E-05	1.762E-05		0.0002399
Freshwater ecotoxicity	kg 1.4-DB eq	0.0265894	0.0099696	6.808E-06	0.0003724	0.001353851	2.504E-06	1.025E-05	0.0009591	7.343E-05	0.0108268		0.0501642
Marine ecotoxicity	kg 1.4-DB eq	0.0235743	0.008907	5.962E-06	0.0003306	0.001301306	2.318E-06	9.295E-06	0.0008631	6.573E-05	0.0096664		0.044726
Ionising radiation	kBq U235 eq	0.1503268	0.0296967	0.0003901	0.0033634	0.000982188	3.161E-05	0.0001191	0.0022291	0.0003233	1.2683665		1.4558287



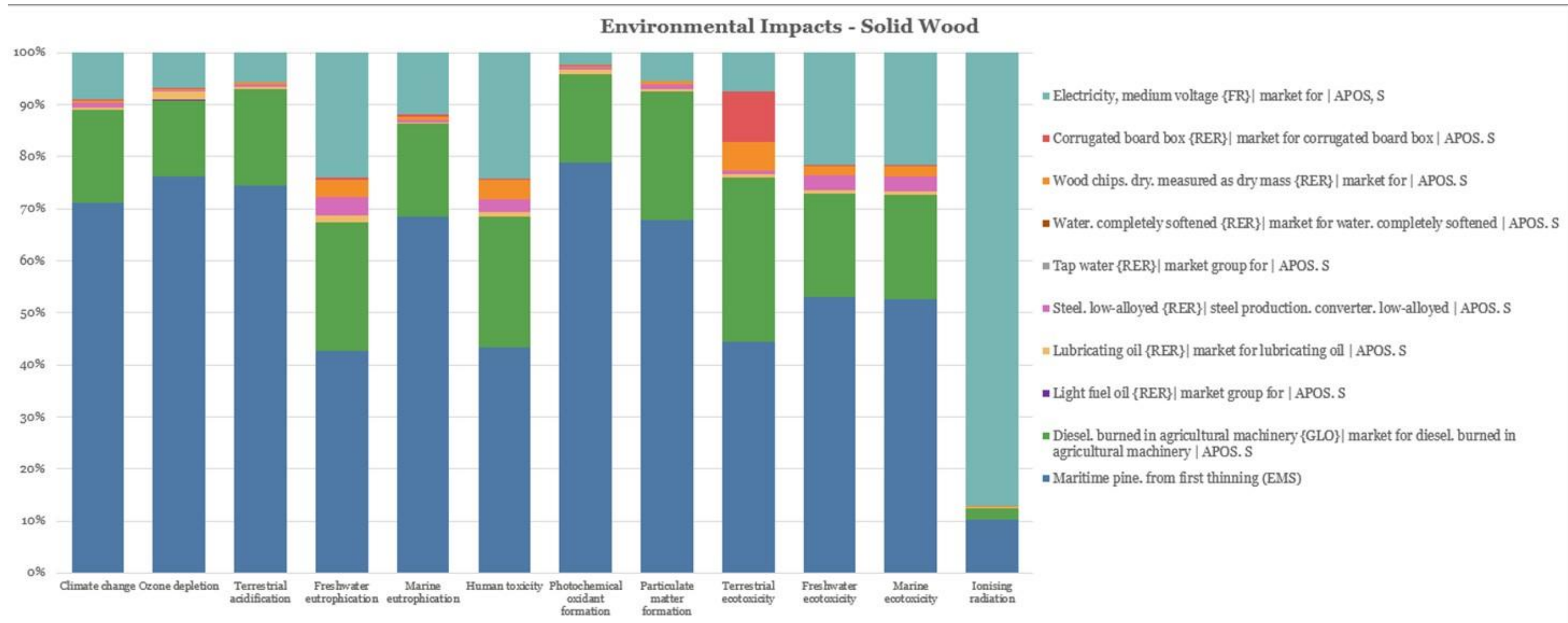


Figure 17: Relative contribution of each production process elements to the environmental results of maritime pine construction wood

Depend on Figure 17 and as explained in Table 12, maritime pine from the first thinning was the most responsible of environmental impacts with ratio 49%, which contributes significantly to climate change about 71% of total climate change impact results from different production elements of construction wood. Electricity at medium voltage, with a ratio of 34% from the total environmental impact, is the second largest contribution to the environmental impacts (IR 87%). Compared to other industrial ingredients, tap water has the least negative environmental effects.

## Discussion

Forest-based products, especially building (construction) products are recognized as a renewable resource, having low environmental impact (i.e., low fossil fuel energy consumption, few pollutants released and stores biogenic carbon), material resource-efficient and aesthetically pleasing compared with competing materials such as steel, concrete, and plastic. Moreover, products made from forest resources can replace fuels, chemicals, and bio products that come from fossil resources. Looking at the diverse use of wood and its increasing market demand, it is essential and critical to know the life cycle impacts of products coming from wood to make decisions on the most environmentally sound and sustainable use of our forest resource. Providing accurate baseline LCA data for each forest-based product is part of sustainable practices to improve energy consumption and develop sound carbon sequestration policies.

In this present study, LCA has been considered as environmental tool to quantify and identify environmental burdens related five wood products (construction wood, plywood, pallets, pellets, and pulpwood) production from maritime pine forest of Landes de Gascogne in France. The interest in this forest species is due to its relevance in the forest economy of the country and Landes de Gascogne Forest extends over 1 million ha in southwest France and constitutes 90% of maritime pine (*Pinus Pinaster*) and it is the European biggest coniferous forest cultivated. Regarding the forest management in the area under study, forest stands are mainly managed under extensive conditions.

Remarkable differences were identified between the subsystems considered in the production system analyzed Gate- to - Gate (from first thinning to final product). They are mainly related to the high consumption of diesel by forest machinery in some production steps like harvesting and roundwood extraction from the cutting area to the roadside landing and electricity consumption. This stage was identified as the most responsible in eleven impact categories analyzed and it is related to requirement of diesel by forest machinery, which involves combustion emissions derived from diesel use. This stage is responsible for 82% of climate change impact category caused in construction wood production processes from first thinning to final products.

As previously discussed, LCA was considered in numerous studies to determine environmental impacts derived from the operations carried out in different forest systems and steps of production in many European countries such as France, Germany, González-García, S., Bonnesoeur, V., Pizzi, A., Feijoo, G., & Moreira, M. T. (2014), Diederichs, S. K. (2014).

Other study concerned roundwood and focused on the same environmental impact categories in forest operations in Scandinavia (Michelsen et al., 2008), which reported that the largest impacts were associated with the logging (felling) and forwarding operations. Diederichs, S. K. (2014). 2010 state that emission of green sawn wood originates mainly from the forest and transport systems and this is in concert with the results of This study study.

The results presented in this study are limited to the different types of maritime pinewood products from the Landes Gascogn, France forest, based on afforestation under extended management scenario, and the data are representative for the year 2015.

## Conclusions

Maritime pine is a widespread forest species in the Landes Gascogn, France, having several industrial applications. This chapter's objective was to assess the environmental effects of maritpinewood production beginning with the first thinning in France's Landes Gascogne Forest following the LCA. There were five products produced: construction wood; plywood; pallets; wood pulp; and pellets. The identification of harvesting processes as environmental hotspots is the result of comparing the environmental profile with other previous studies, including those conducted on other forest species. These findings show that the consumption of fossil fuels in harvesting operations should be optimized to reduce environmental consequences. In addition, special attention must be given to the system boundaries, because uncertainty might originate from them. This study's findings may be valuable for decision-making strategies, particularly in forest-based industries where pine is the primary raw material.

### 4.3.2. Pallets

The life cycle impact assessment (LCIA) results (characterization) for pallets products from maritime pine under artificial regeneration, using Simapro soft wear are presented in Table 13 and Figure 18. They demonstrate the varying amount of environmental impact between

contributory elements of the pallet manufacturing process throughout the production process.

According to Table 13, Steel, low-alloyed {RER}| steel production, converter, low-alloyed | APOS, U was the main contribution to the total environmental impact with the amount (3.29kg) and have the highest contribution in the category's climate change, freshwater eutrophication, Human toxicity, particular mater formation, fresh water Eco toxicity, and marine Eco toxicity ranged between 2.04 kg CO<sub>2</sub> eq to 0.000297kgp eq. So, Steel. low-alloyed {RER}| steel production. converter. low-alloyed | APOS. S is the hotspot of pallet production processes. The production elements: steel, electricity and 1 m<sup>3</sup> maritime pine over bark were among the main causes of environmental impact in the pallet production process and share the main contribution to the amounts of EIA categories. Waste wood. untreated {FR}| market for waste wood. untreated | APOS. S has the lower contribution to the environmental impact (0.20kg).

The step of maritime pine production stayed has high environmental effects (third most contributor) but less than in the case of construction wood because pallet production requires more manufacturing stages, which have more environmental impacts, like steel, low-alloyed {RER}| steel production, converters, low-alloyed | APOS, U and electricity, medium- voltage {FR}| market for | APOS. S., which are the main contributors of the environmental impacts.

The pallet production process gives us a variance rate for the eleven environmental impact categories specified in this study. These statistics emphasize an important point which is the amount of environmental impact caused by pallet production. This requires thinking about real solutions to decrease the consumption of short-life goods like pallets and studying the ability to re-use pallets for the same purpose (commercial goods transmission).

Table 13: The results of the characterization stage as well as the total materials used in converting one cubic meter of Maritime pine over bark to pallets

Impact category	Unit	Maritime pin										untreated Total	
		1.73	2.99	0.59	0.49	3.29	0.21	0.21	0.09563214	4.9	4.66E-07		
Climate change	kg CO2 eq	1.42	0.44	0.56	0.35	2.04	0.09563214	0.09563214	0.09563214	0.09563214	0.09563214	0.09563214	4.9
Ozone depletion	kg CFC-11 eq	2.50E-07	5.51E-08	4.22E-08	2.42E-08	8.82E-08	6.64E-09	6.64E-09	6.64E-09	6.64E-09	6.64E-09	6.64E-09	4.66E-07
Terrestrial acidification	kg SO2 eq	0.00908051	0.00168704	0.00049657	0.00294985	0.00659685	0.000297185	0.000297185	0.000297185	0.000297185	0.000297185	0.000297185	0.021
Freshwater eutrophication	kg P eq	9.2995E-05	0.00012794	4.34E-06	0.00010321	0.000919	1.22E-05	1.22E-05	1.22E-05	1.22E-05	1.22E-05	1.22E-05	0.0013
Marine eutrophication	kg N eq	0.00052089	0.00021953	1.6105E-05	0.00034813	0.00041023	0.00076372	0.00076372	0.00076372	0.00076372	0.00076372	0.00076372	0.0023
Human toxicity	kg 1.4-DB eq	0.13140576	0.18	0.02234429	0.08852832	0.89	0.102237275	0.102237275	0.102237275	0.102237275	0.102237275	0.102237275	1.42
Photochemical oxidant formation	kg NMVOC	0.01606115	0.00123184	0.00066203	0.0011523	0.0082914	0.000517477	0.000517477	0.000517477	0.000517477	0.000517477	0.000517477	0.028
Particulate matter formation	kg PM10 eq	0.00345944	0.00067875	0.00016593	0.00091183	0.00566664	0.000145217	0.000145217	0.000145217	0.000145217	0.000145217	0.000145217	0.0110
Terrestrial ecotoxicity	kg 1.4-DB eq	8.0081E-05	3.2352E-05	3.6325E-05	0.00112508	0.0001492	1.63468E-05	1.63468E-05	1.63468E-05	1.63468E-05	1.63468E-05	1.63468E-05	0.0014
Freshwater ecotoxicity	kg 1.4-DB eq	0.01994206	0.0198807	0.00255573	0.00837774	0.12549763	0.0019747	0.0019747	0.0019747	0.0019747	0.0019747	0.0019747	0.18
Marine ecotoxicity	kg 1.4-DB eq	0.01768073	0.01774991	0.00082077	0.00748548	0.12062691	0.001816515	0.001816515	0.001816515	0.001816515	0.001816515	0.001816515	0.17
Ionising radiation	kBq U235 eq	0.11274509	2.33	0.0013972	0.02526903	0.09104571	0.002864972	0.002864972	0.002864972	0.002864972	0.002864972	0.002864972	2.6

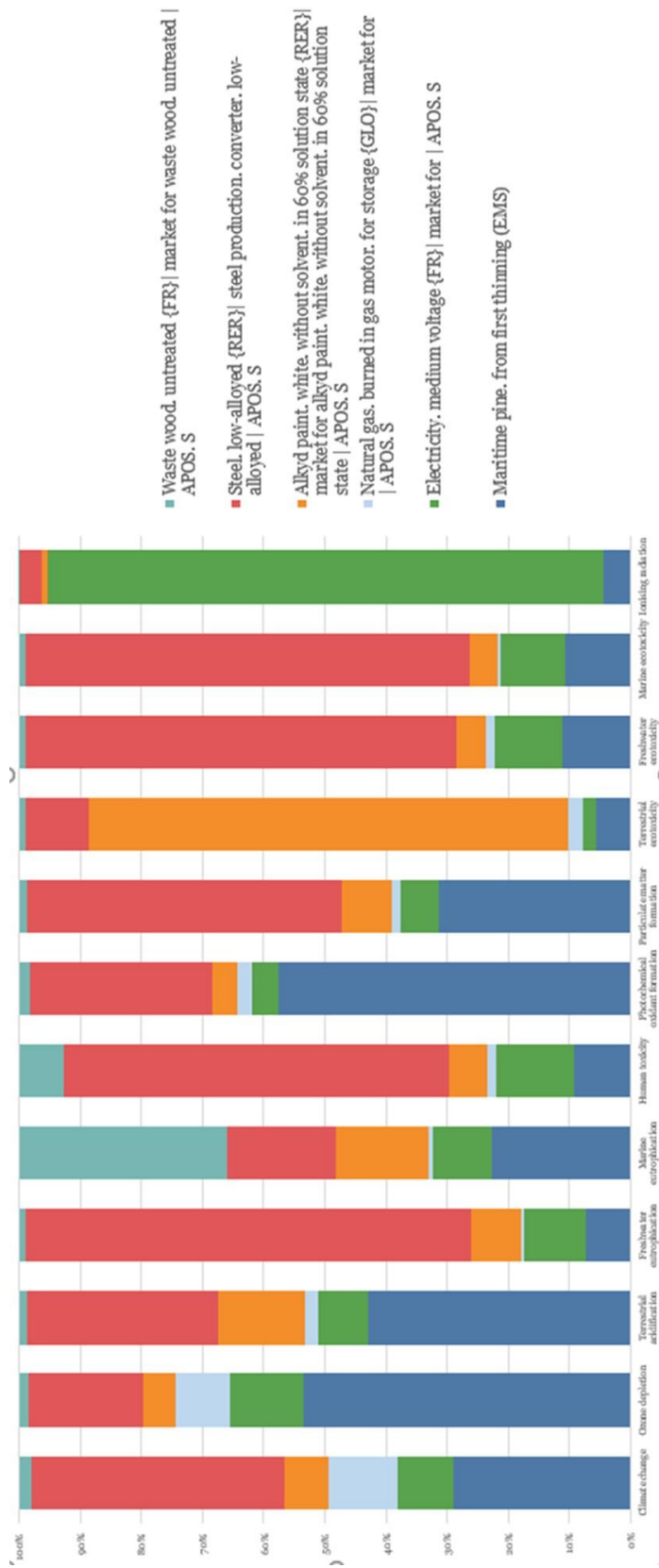


Figure 18: Relative contribution of each process to the environmental results of change of 1 m<sup>3</sup> Raw material wood of maritime pine to pallets.

Figure 18 represented the relative contribution for each pallet production element to the environmental impacts corresponding to the pallet market share determined in MFA of 1 m<sup>3</sup> of maritime pine stating from first thinning. Figure 18 shows that steel, low-alloyed RER steel production, converters, low-alloyed APOS, U had the greatest environmental impact, accounting 35% of total environmental impacts. It also had the most impact on climate change, freshwater eutrophication, human toxicity, particular matter formation, freshwater water Ecotoxicity, and marine Eco-toxicity, with contributions ranging from 41% for climate change to 73% of fresh water eutrophication. Waste wood, untreated {FR} | market for waste wood, untreated | APOS, S has the lowest environmental impact accounting (2%).

## **Discussion:**

LCA enables one to identify areas in the forest-wood chain that require improvement and to demonstrate environmentally sound wood uses for industry and consumer markets (Karjalainen et al., 2001; Werner and Nebel 2007). Using the LCA methodology, this chapter seeks to identify and quantify environmental impacts resulting from pallets production of maritime pine roundwood in forest stands located in the Lands Gascogn region of France. SimaPro Software analysis results provide characterization for all production elements of pallets production start from first thinning to final product from one cubic meter of maritime pinewood. the result showed large differences in all the categories considered regardless to the production element. The results of This study study on the environmental impacts of pallet production are in agreement with the results of Garca-Duraona, L., et al. (2016) in terms of impactful production elements steel nails and electricity. But different in the impacts categories affected by the same production elements. In This study study the big consumption electricity during the production process (Sawing) contributes about 91% in Ionizing radiation impact categories while in Garca-Duraona et al. (2016) It was the most contributor in Ozone depletion impact categories (91%).

## **Conclusion:**

This chapter aimed to find environmental impacts results from converting one cubic meter of maritime pinewood to pallets. Based on the results of SimaPro software analysis and focusing on the pallet production stage it was found that steel nails make an important contribution to most categories (Fig. 11) (from 41% of contribution in CC to 73% in FE). To enhance the efficiency of pallet production There are various possibilities, including reducing the number of nails, utilizing lighter nails, or substituting nails with wood or plastic joining systems, or reducing the number of connectors by applying pressure to sawn wood during assembly. However, the European EUR-pallet regulation specifies the required number of nails and the overall weight of steel in order to ensure the product's structural integrity and safety. This circumstance hindered the implementation of the identified choices that could improve the pallet's environmental performance. Therefore, it appears reasonable to consider making the EuroPallet standard performance-based (such as structural resistance) rather than prescriptive-based (so many Kg of nails per pallet). This would constitute a significant advancement in eco-design.

On the other hand, the electricity consumption in the manufacture of pallets in sawmill process have been identified as responsible for a substantial proportion (32%) of the total pallet environmental impact. Utilizing forest management plans is an opportunity to raise the wood's quality, that would increase the process's efficiency, decrease the sawmill's electricity consumption, and increase the profitability of forest farms. Lastly, this study gives up-to-date information for future LCAs that look at either sawn wood products or pallets made of wood, as well as the value of the environmental impact if LCA and LCC are combined.

### 4.3.3. Plywood

#### Results

A gate-to-gate Life-cycle assessment study has been conducted for converting 1  $m^3$  of maritime pine to plywood. A detailed model was prepared using SimaPro software version 9.3.0 to assess the various impact categories for the production of plywood, showing each input's relative contribution. Twelve impacts categories were analyzed in this study. As in Table 14 among all materials contribute in plywood production Melamine formaldehyde resin {RER}| production | APOS. S was account 21.37kg eq. of total environmental impact categories specified in this study and 15.40 kg CO<sub>2</sub>eq of climate change and 4.49 kg1.4-DB eq of human toxicity among all of elements of plywood production processes. Wood goods production has many environmental impacts that vary by product; for plywood, climate change and human toxicity are two main contributions 78% and 60%, respectively. While the smallest amounts of environmental impacts belong to Diesel. burned in building machine {GLO}| market for | APOS. S.



Table 14: Impact assessment results (characterization step) of plywood manufacturing form 1 m3 of maritime pine correspond to MFA market share.

Impact category	Unit	Percentage indicated in MFA 9%									Total
		Maritime	Diesel.	Melamine	Wooden	Electricity.	Heat.	Wastewater			
		1.04	0.01	21.37	0.12	6.91	5.21	0.12			34.77
Climate change	kg CO2 eq	0.85	0.00968192	15.40	0.07573762	1.02	2.27	0.08778866			19.71
Ozone depletion	kg CFC-11 eq	1.50E-07	1.67E-09	1.12E-06	5.03E-09	1.27E-07	1.67E-07	2.17E-09			1.57E-06
Terrestrial acidification	kg SO2 eq	0.00545	0.000077	0.0723	0.00047129	0.0039	0.0	0.0002356			0.115
Freshwater eutrophication	kg P eq	0.00006	2.94E-07	0.00405	2.5183E-05	0.00030	0.00	4.5685E-05			0.0058
Marine eutrophication	kg N eq	0.00031	4.63E-06	0.00362422	3.936E-05	0.00050661	0.00212384	1.6538E-05			0.0066
Human toxicity	kg 1.4-DB eq	0.078843	0.00037	4.49	0.03043215	0.41	2.45	0.01909999			7.48
Photochemical oxidant formation	kg NMVOC	0.00963669	0.00014	0.04632202	0.00032689	0.00284271	0.06566563	0.00024606			0.13
Particulate matter formation	kg PM10 eq	0.00207566	0.000040	0.02780693	0.00022236	0.00156634	0.04303539	0.00013716			0.075
Terrestrial ecotoxicity	kg 1.4-DB eq	4.8049E-05	4.20E-07	0.00152099	1.4053E-05	7.4658E-05	0.00142527	0.0000145			0.003
Freshwater ecotoxicity	kg 1.4-DB eq	0.01196524	0.000025	0.43	0.00274639	0.04587854	0.07356631	0.0016140			0.56
Marine ecotoxicity	kg 1.4-DB eq	0.01060844	0.000024	0.37	0.00241627	0.04096132	0.0704449	0.0014522			0.49
Ionising radiation	kBq U235 eq	0.06764706	0.00061	0.54	0.00466697	5.37	0.21	0.0044029			6.20

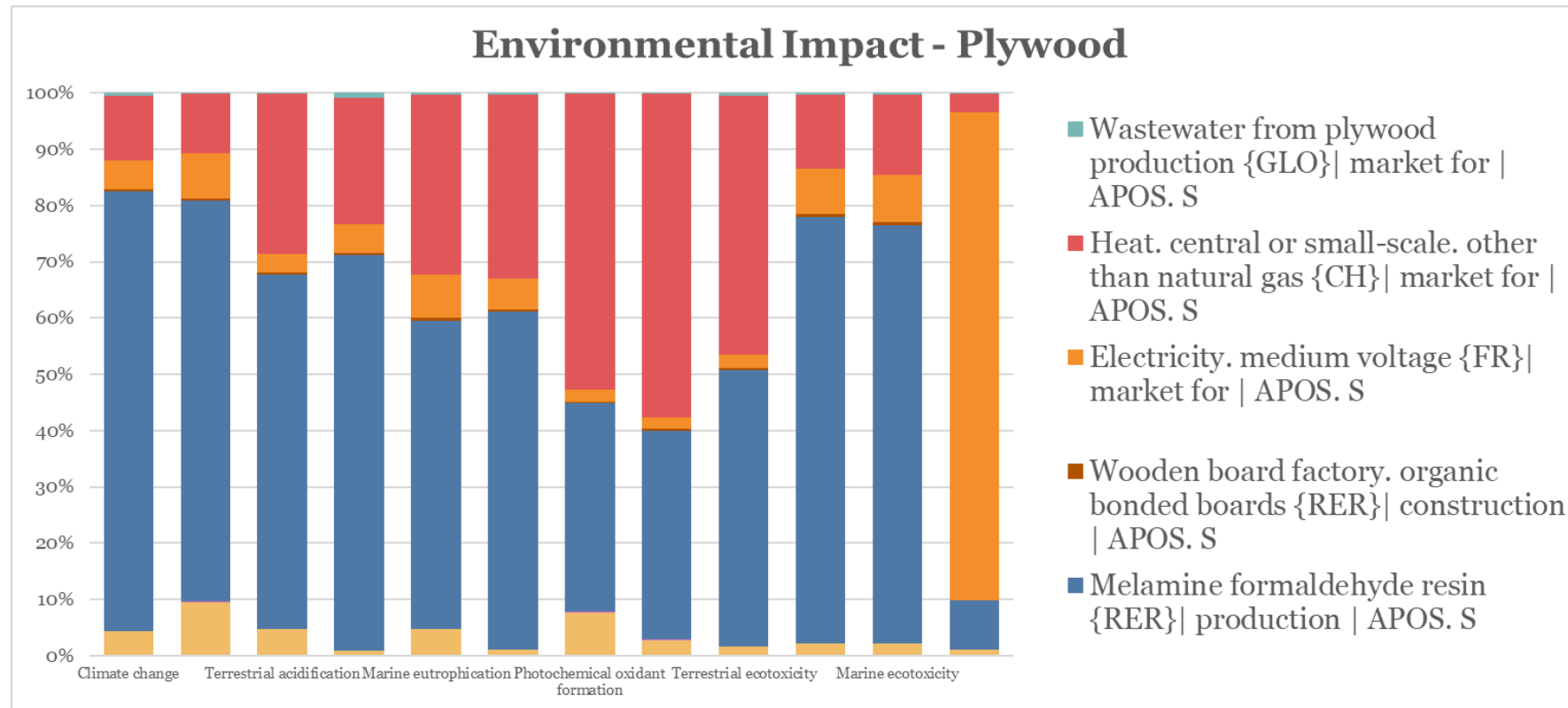


Figure 19: Relative contribution of each process to the environmental results of change of 1 m<sup>3</sup> Raw material wood of maritime pine to Plywood.

Figure 19 indicated that the Melamine formaldehyde resin represent 62% of the total environmental impact result from plywood production processes followed by electricity. medium voltage {FR}| market for | APOS. S, 20%, and Heat. central or small-scale with 15%. While, the Diesel. burned in building machine {GLO}| market for | APOS. S. represent the smallest amount of total environmental impact 1%.

## Discussion

The study set out with the aim of assessing environmental impacts including twelve impact categories of plywood production processes by life-cycle assessment using Simapro software analysis version 9.3.0. The Simapro software provide the amounts of environmental impact of twelve impacts categories, the results showed that Melamine formaldehyde resin {RER}| production | APOS. S, Electricity. medium voltage {FR}| market for | APOS. S, and Heat. central or small-scale. other than natural gas {CH}| market for | APOS. S was the greatest contributors to the environmental impact among plywood production elements, 62%, 20%, 14% respectively. Diesel. burned in building machine {GLO}| market for | APOS. S. has the least amount of environmental effects. Melamine formaldehyde is responsible of the most percent of climate change and human toxicity 78%, 60% respectively. While electricity is the greater contributor of ionizing radiation with 86% of total ionizing radiation results from the all plywood production processes. The present findings seem to be consistent with other research Jia, L., Chu, J., Ma, L., Qi, X., & Kumar, A. (2019), which found that that veneer production and the subsystems of drying and composting appeared to be the greatest contributors to environmental impact, this is very evident through the significant environmental impacts composting (Melamine formaldehyde resin), electricity (veneer manufacturing) and heat (for drying the veneers). In terms of the most significant impact categories, This study studies contrast with the Kaestner, D. (2015) study. These results have important implication to plywood development and improvement environmental performance. However, more research on this topic needs to be undertake to investigate the total environmental impact of converting 1 cubic meter of maritime pine to plywood with system boundary Cradle –to – grave.

## Conclusion

This chapter focuses on the environmental impact of plywood production in Landes Gascogn, France. Several impact categories (CC,OD,TA,FE, ME,HT,POF,PMF,TET,FET,MET,IR) were assessed to acquire results and serve as decision-making indicators in order to aid the wood-based panel industry in developing and specifying hotspots in plywood processing in order to improve production's environmental performance, and based on the results of this chapter, I was find the economic value of each environmental impact category that seems to partially solve the market failure problem to determine the precise price of goods and services as a first temptation to join LCA with forest economics. This study found that during the process of making plywood, out of all the raw materials used, the melamine formaldehyde resin used in the composition stage had the biggest effect on all categories except ionizing radiation potential, followed by electricity, which had the biggest effect on

ionizing radiation. This study examines the plywood manufacturing process from start to finish and analyzes each raw material used in the process. Advanced technology and green materials can be employed instead of traditional techniques to improve environmental performance. Moreover, the location of the factory near a rich supply of quality wood resources can control environmental impact substantially.

#### **4.3.4. Pellets**

##### **Results**

Various environmental impact categories resulting from pellet production from gate-to-gate were assessed by LCA methodology using SimaPro software version 9.3.0. This study looks at twelve environmental impact categories (CC, OD, TA, FE, ME, HT, POF, PMF, TET, MET, IR) and shows each input's contribution in environmental impacts in Table 15. It has been found that the most impactful contributor of pellets production is electricity (4.43), the main contribution of electricity in environmental impact resulting from a large amount of ionizing radiation impact categories result from electricity consumption during production process (3.4 kBqU235eq) which represent 78% environmental impacts of electricity consumption. Maritime pine (harvesting from first thinning) has most great impact on most categories except ionizing radiation, 1.8329E-06 kgCFC-11eq ozone depletion, 0.011778174 POF kg NMVOC and 0.00665938 kg CO<sub>2</sub>eq of terrestrial acidification. In contrast the smallest contributor among all input was packaging film low density.

Table 15: Environmental impact categories as a result of converting 1 m<sup>3</sup> of maritime pine to pellets (pellets account for 11% of total products produced from 1 m of wood).

<b>Percentage indicated in MFA</b>		<b>11%</b>					
<b>Impact category</b>	<b>Unit</b>	<b>Maritime pine</b>	<b>Diesel, burn</b>	<b>Packaging fil</b>	<b>Electricity, n</b>	<b>Wood ash mixture,</b>	<b>Total</b>
		<b>1.2699</b>	<b>0.2282</b>	<b>0.0001</b>	<b>4.4282</b>	<b>0.8474</b>	<b>6.77</b>
Climate change	kg CO <sub>2</sub> eq	1.04	0.17	0.000042	1	0.00140733	1.9
Ozone depletion	kg CFC-11 eq	1.83E-06	2.30E-08	1.08E-12	8.14E-08	5.72E-10	1.94E-06
Terrestrial acidification	kg SO <sub>2</sub> eq	0.0067	0.00108209	1.39E-07	0.00249496	8.87E-06	0.01
Freshwater eutrophication	kg P eq	0.00007	2.5688E-05	1.26E-08	0.00018921	0.00034409	0.0006
Marine eutrophication	kg N eq	0.00038199	6.4671E-05	8.37E-09	0.00032466	3.58E-07	0.0008
Human toxicity	kg 1.4-DB eq	0.09636422	0.03634808	9.74E-06	0.3	0.83	1.23
Photochemical oxidant formation	kg NMVOC	0.01177817	0.002	1.73E-07	0.00182177	9.16E-06	0.015
Particulate matter formation	kg PM <sub>10</sub> eq	0.0025	0.00060581	6.20E-08	0.0010038	3.76E-06	0.0042
Terrestrial ecotoxicity	kg 1.4-DB eq	0.000059	2.6975E-05	2.22E-09	4.7845E-05	0.00013	0.00026
Freshwater ecotoxicity	kg 1.4-DB eq	0.015	0.00357122	6.68E-07	0.02940151	0.007	0.054
Marine ecotoxicity	kg 1.4-DB eq	0.013	0.00319056	5.98E-07	0.02625029	0.0061	0.049
Ionising radiation	kBq U235 eq	0.083	0.01063763	4.61E-06	3.4	0.00014	3.54

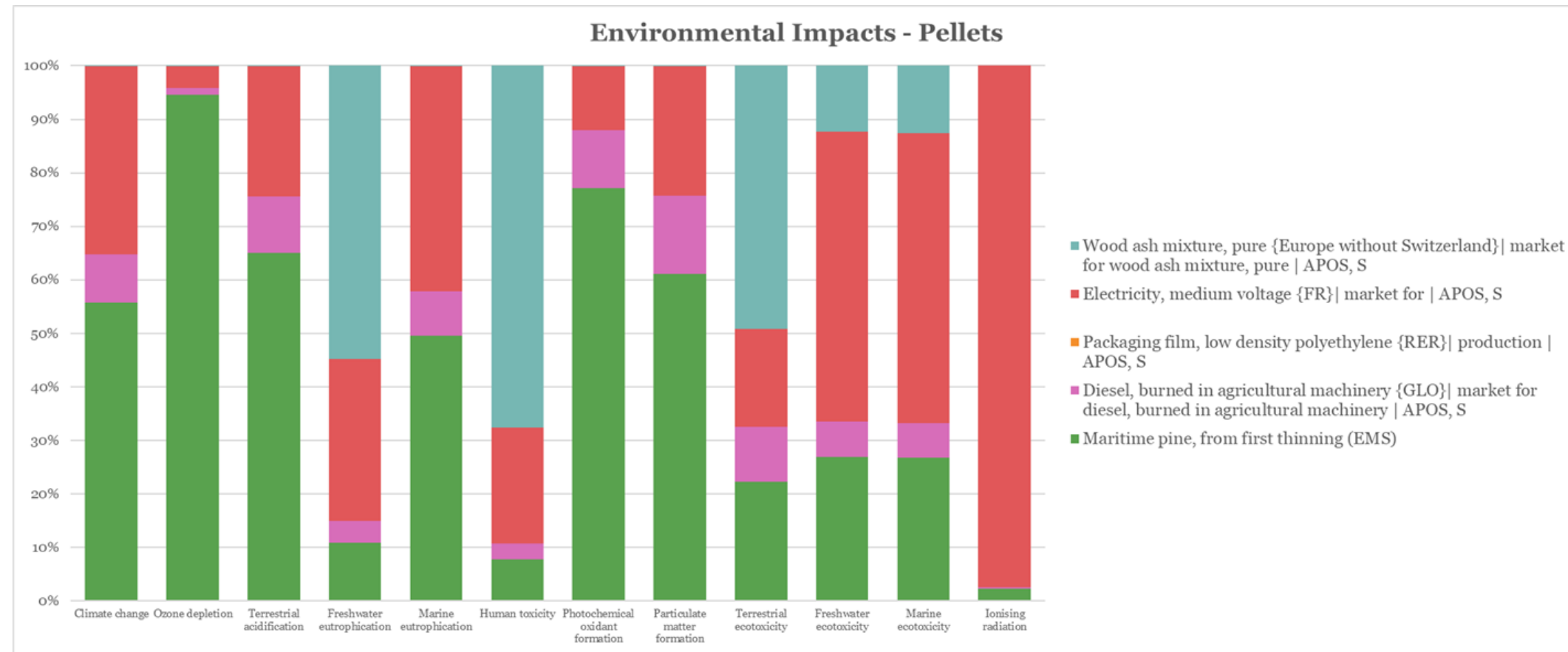


Figure 20: Contribute of maritime pine pellets life-cycle assessment to the mid-point impact categories

From Figure 20 we found that the most impactful contributor of pellets production is electricity with representative 60% of total environmental impact Figure 20. The second great contributor in environmental impact is forest harvesting from first thinning with contribute about 19% of the total environmental impact during pellet production process Figure 20. Maritime pine (harvesting from first thinning) has most great impact on most categories except ionizing radiation, ozone depletion, terrestrial acidification with relative contribution 94%, 77% and 64% respectively Table 15 and Figure (120).

## Discussions:

Environmental impact of pellet production from 1 m<sup>3</sup> of maritime pine considering mass allocation depended on MFA (11%) was assessed by LCIA methodology using Simapro software analysis tool version 9.3.0. The results indicated that there are various impact assessment environmental impact categories results from pellet production process (CC, OD, TA, FE, ME, HT, POF, PMF, TET, FET, MET, IR). Recent year grown concerns about climate change have driven business organization to change their priorities, not only to achieve economic objective but also to consider ecological objectives (Knauer and Moslang, 2018). Consequently, we will partially solve market failure to determine the precise wood products price which resulting from neglecting negative external costs (Negative environmental impacts).

In addition, the results of this study indicated that electricity used in wood processing and pellet production was the most grate contributors in total environmental impacts among all pellets production element's and also has the most grate impact on ionizing radiation, followed by maritime pine from first thinning which has the greatest amount of impacts on all impacts categories except ionizing radiation. While the diesel burned in agriculture machinery was the smallest contributor on environmental impact. From the results we find that electricity is the hotspots elements among all of pellets production process elements which is used in different stage of production process. These results are very important to think about the best industrial forest management (high yield and short harvest cycle plants). And also improve factory management by providing equipment and technology for mitigating or removing pollutant before emission to the environmental in order to increase economic and environmental performance of pellet production.

The results contradict the claims of Reed, D., Bergman, R., Kim, J. W., Taylor, A., Harper, D., Jones, D., ... & Puettmann, M. E. (2012), Saosee, P., Sajjakulnukit, B., & Gheewala, S. H. (2020) and Chen, S. (2010) as a result of different kind of raw materials, system boundary and the environmental impacts categories take in consideration during analysis process. The reliability of these results is impacted by the data source, which is for hardwoods in LCI while This study study depends on softwood (maritime pine). The system boundary choices were constrained by limited time.

## Conclusion

This chapter aimed to assess the environmental impact of pellet production from maritime pine in lands Gascoigne, France. Based on SimaPro software analysis of environmental impact categories resulting from pellet production, it can be concluded that significant environmental impacts released from pellet production should be considered in environmental impact assessments of products and production process performance. This result indicated that electricity was the largest contributor among pellet production elements in the environmental impact assessment. This study clearly illustrates how to assess the environmental impact of pellet production for specific periods of the pellet life cycle, but it also raises the question of how to find the monetary value of these impacts. A time and funds are the constraints that limit various aspects of the study. Based on these conclusion practitioners should take in them consideration the hotspots of environmental impacts pf pellets production process, and for better understanding the implication of these results, future study could address the remain part of pellets life cycle (Cradle- to-Grave) to assess all environmental impacts of pellet to take sound decision for forest and factory management.

### 4.3.5. Unbleached pulpwood

#### Results

In Table 16. SimaPro software analysis results indicated that heat from steam was the greatest contributor of environmental impact among wood pulp production input-output elements with 172.15 Kg CO<sub>2</sub> eq of climate change, and 196.75 kg eq of different kind of impacts categories, followed by wood ash mixture. Pure 6.5 kg eq (table 15). As well as in all other studied products, maritime pine from first thinning has an important impact on climate change impact categories among all input-output elements of unbleached pulp production. The heat of steam was the greatest contributor to ionizing radiation. Hazardous waste. for underground deposit {RoW} treatment of hazardous was the smallest contributor of input- output elements of unbleached pulp production Table 16



Table 16: Environmental load associated with inputs output elements of unbleached pulp production

Percentage indicated in MFA		45%											
Impact category	Unit	Maritime pi	Sodium hydr	Quicklime. ir	Heat. from s	Electricity, h	Wastewater	Wood ash m	Ash from pa	Waste fibrel	Green liquor	Hazardous w	Total
		5.19	3.18	0.92	196.75	1.80	0.64	6.49	0.27	0.10	0.69	0.00	216.04
Climate change	kg CO2 eq	4.26	1.94	0.87	172.15	1.04	0.46	0.02	0.01	0.06	0.50	0.00	181.31
Ozone depletion	kg CFC-11 eq	7.50E-07	1.19E-06	4.22E-08	2.06E-05	1.25E-07	6.05E-08	2.56E-09	3.54E-09	8.31E-10	2.43E-08	1.25E-10	2.28E-05
Terrestrial acidification	kg SO2 eq	0.0272415	0.0082446	0.0008226	0.4343313	0.0065316	0.0013907	7.714E-05	7.366E-05	0.0001775	0.0012451	8.58E-06	0.4801444
Freshwater eutrophication	kg P eq	0.000279	0.0009694	1.706E-05	0.0169776	0.000627	0.000528	0.0026251	0.0347186	6.082E-06	0.0001386	1.095E-06	0.0568874
Marine eutrophication	kg N eq	0.0015627	0.0005619	2.566E-05	0.0120722	0.0005292	0.0036088	8.015E-06	0.0066489	0.0015725	6.753E-05	6.094E-07	0.0266581
Human toxicity	kg 1.4-DB eq	0.3942173	0.8304971	0.0282273	15.147866	0.5379906	0.1152921	6.3747158	0.2009935	0.0361601	0.1520019	0.0009101	23.818872
Photochemical oxidant formatior	kg NMVOC	0.0481834	0.0060998	0.0008656	0.2810922	0.007321	0.0015762	7.742E-05	0.0001008	0.000452	0.0014023	1.198E-05	0.3471827
Particulate matter formation	kg PM10 eq	0.0103783	0.0050023	0.0003868	0.1351468	0.003852	0.0008608	3.463E-05	3.402E-05	0.0008444	0.000574	7.153E-06	0.1571214
Terrestrial ecotoxicity	kg 1.4-DB eq	0.0002402	0.0001969	2.593E-05	0.0087491	0.000399	0.0003548	0.0010022	2.412E-06	8.224E-05	2.833E-05	4.652E-07	0.0110818
Freshwater ecotoxicity	kg 1.4-DB eq	0.0598262	0.0640614	0.0007391	0.49355	0.0552053	0.0131523	0.0514696	0.0055527	0.001701	0.0088949	8.273E-05	0.7542352
Marine ecotoxicity	kg 1.4-DB eq	0.0530422	0.0568768	0.0011241	0.5403149	0.049595	0.0119648	0.047058	0.0050873	0.0014979	0.0082637	7.923E-05	0.7749039
Ionising radiation	kBq U235 eq	0.3382353	0.2651275	0.018445	7.5314048	0.0962017	0.0317054	0.0016313	0.001403	0.0003426	0.0153979	9.63E-05	8.2999907

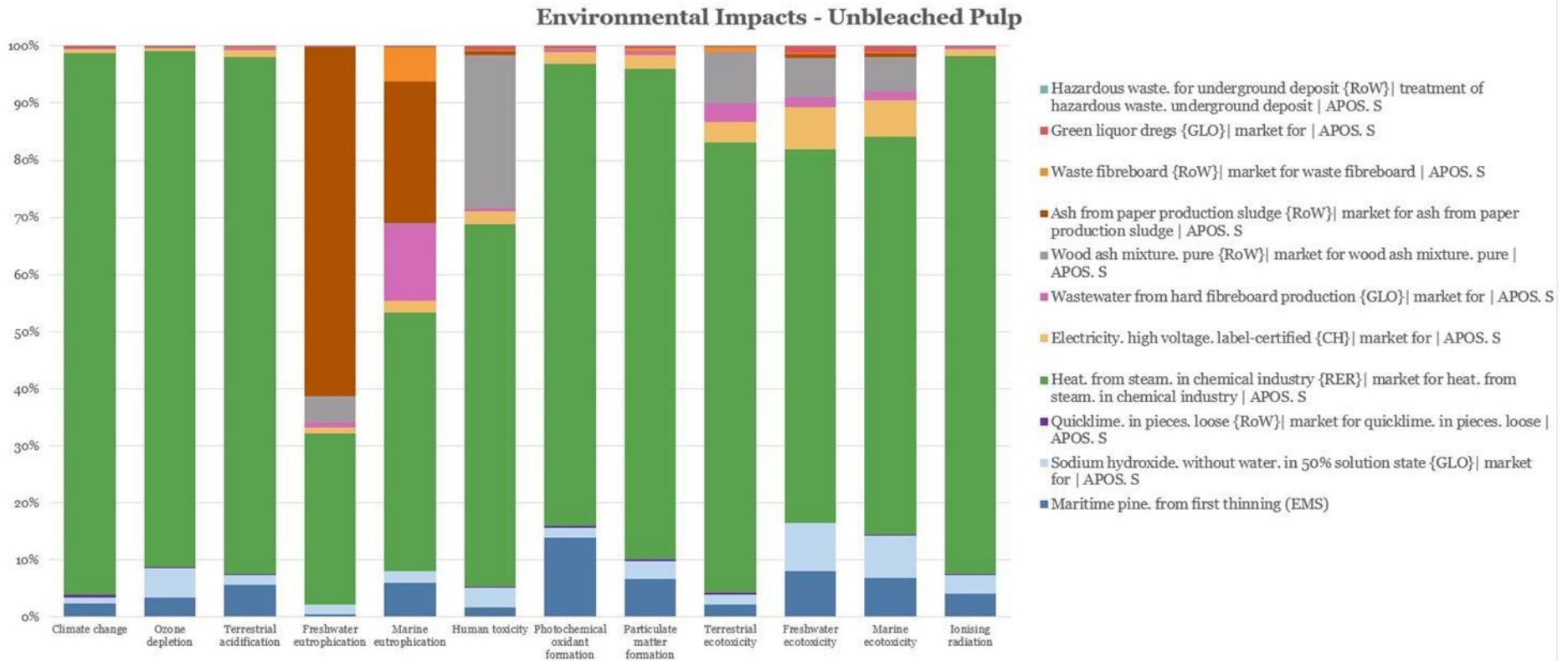


Figure 21: Contribution per subsystem (in %) to each impact category of unbleached pulp impact categories.

Figure 21 show that the heat from steam was the greatest contributor of environmental impact among wood pulp production input-output elements which represent 95% of total climate change, and of different kind of impacts categories which represent 91% of the total environmental impacts categories. followed by wood ash mixture. Pure which represent 3% of total environmental impacts

## Discussion

Various amount of negative environmental impact categories result from pulp production. Those negative environmental impact categories were being assessed by life cycle impact assessment methodology using simaPro software analyzing version 9.3.0. The results of this study show the amounts of various negative environmental impact categories of pulp production process (CC, OD, TA, FE, ME, HT, POF, PMF, TET, FET, MET, IR). The increasing environmental awareness of consumers, evident in global certification schemes, requires increased knowledge concerning the environmental impacts of forest practices. The European industry consists of more than 1,000 paper mills and 220 pulp mills. France is the fourth paper producer after German, Finland and Sweden, in addition that pulp industry is the most polluted wood industries among all wood products industries. So, it is crucial to understand the life cycle effects of wood-derived goods in order to ensure the most sustainable and environmentally friendly use of our forest resource.

In the line with the hypothesis, the results show the various negative environmental impact categories from pulp production, Heat from steam was the most significant contributor of negative environmental impact and we find from the results that are mainly the impacts linked to climate change and ionizing radiation due to a large amount of electricity consumed in heating process during pulp production. The second most significant contributor of negative environmental impact was wood ash mixture, and the most significant impact of wood ash is linked to human toxicity caused by chemically treating wood waste with sulfuric acid solution to eliminate hemicelluloses. The present findings seem to be consistent with other research (M'hamdi, A. I., Kandri, N. I., Zerouale, A., Blumberga, D., & Gusca, J. (2017). Which found that are the mainly impacts linked to climate change and human toxicity. These results should be taken into account when considering how to extend the system boundary to find negative environmental impacts for the total life-cycle assessment from cradle-to-grave of pulp production and also to find the monetary value of environmental impacts. time and money constraint to cover the environmental impacts of the entire life cycle of pulp. All environmental impacts of the life cycle of wood pulp from maritime pine in Landes Gascogne, France, should be considered in future research.

## Conclusion

In this study the production of chemical unbleached pulp from maritime pine in Landes Gascogne, France was Assessed from an environmental point of view following the life-cycle assessment method. Comparison of the environmental profile with other study available in literature even of the different system boundary and form of raw material leads to the identification of heat and wood as mixture as hotspots. These results suggest that both electricity required for heating and wood ash should be optimized to reduce environmental impacts. Furthermore, because ambiguity can raise, extra extension must be made to system boundary, assumption and methodological concerns. The Results of this study could be relevant in making decision strategies particularly in forest-based companies using maritime pine as the primary raw material.

As This study study aim to an economic and environmental performance assessment of five wood-based products, LCA provides the mechanism for measuring the criteria or indicators that will demonstrate the environmental performance or acceptability of a product to the marketplace but it cannot find out the costs of the same in terms of economic terms. This study study seeks to applied suitable strategic cost management instrument to evaluate economic and environmental performance; to provide appropriate information about product/service life cycle which raise the performance efficiency and accuracy in decision making and provide more efficient systems where life cycle cost and life-cycle assessment integration can be used to overcome deficiencies and improve waste management. Consequently, we will apply Life Cycle Cost and combine it with Life-cycle assessment to achieve comprehensive, transparent and precise economic and environmental assessment. This will be done in the chapter Five.

As i mentioned before, in recent years, growing concerns about climate change have driven business organizations to change their priorities not only to achieve economic objectives but also to consider ecological objectives (Knauer and Moslang, 2018; Rodríguez and Emblemståg, 2007). This coincides with the recent global trend towards sustainable development (SD) and customers looking to utilize environmental products and services (Turner et al., 2016).

Life-cycle assessment (LCA) was developed to meet the specific needs raised by organizations trying to embrace the protection of the environment in the Product development and improvement. LCA provides the mechanism for measuring the criteria or indicators that will demonstrate the environmental performance or acceptability of a product to the marketplace. But it cannot find out the costs of the same in terms of economic terms. Basically, this model intends to incorporate the environmental costs into the LCA of any product. These costs can be avoided or reduced through pollution prevention (P2) activities such as product design, materials substitution, process re-design etc.

This model attempts to prescribe a life cycle cost model to estimate as well correlate the effects of these costs in all the life cycle stages of the product.

In addition, private sector decision making contexts addressed by LCA must also eventually take the economic consequences of alternative products or product designs into account. However, neither the internal nor external economic aspects of the decisions are within the scope of developed LCA methodology, nor are they properly addressed by traditional LCA tools. Neither has the ISO 14040 series of standards for LCA methodology addressed the integration of economic analysis with LCA tools.

Combining Life Cycle Cost analysis with Life-cycle assessment are a promising modern methodology for cost management tools that are well known in practice which can be used to integrate economic and environmental aspects (Bierer et al., 2015). To explain previous ambiguous results on the effect of trade-off between economic and environmental aspects, specifically our study seek to applied suitable strategic cost management instrument to evaluate economic and environmental performance; to provide appropriate information about product/service life cycle which raise the performance efficiency and accuracy in decision making and provide more efficient systems where life cycle cost and life-cycle assessment integration can be used to overcome deficiencies and improve waste management. Consequently, we will apply Life Cycle Cost and combine it with Life-cycle assessment to achieve the above-mentioned point and comprehensive, transparent and precise economic and environmental assessment. This will be done in the Next chapter.

### **Conclusion (General conclusion)**

This section summarizes the key research findings in relation to the research questions, as well as the value and contribution thereof with regard to the present chapter. This section will also review the limitations of the study and propose opportunities for future research.

This chapter aimed to investigate the environmental impact of twelve impact categories result from converting 1 m<sup>3</sup> of raw wood material to each five studied products (Unbleached pulp, plywood, pallet, pellets and construction wood with the system boundary specified in this study. Further, findings show that the construction wood has lowest environmental impacts. The unbleached pulp was the greatest contribution of environmental impact among five studied products. The system boundary chosen and the data availability were the most relevant limitation of this study. Whereas the study was limited by the system boundary of Alliance Forêts Bois as mentioned in chapter 3 (materials follow analysis) and focused on the first wood transformation and doesn't go to the second and third stage. While in data availability limitation side, there is lack of capital and operation cost of data

for Unbleached pulp, plywood, pellets and pallet. Furthermore, because ambiguity can raise, extra extension must be made to system boundary, assumption and methodological concerns. The results of this study could be relevant in making decision strategies particularly in forest-based company using maritime pine as the primary raw material.



## **CHAPTER 5**

### **Gate –to- Gate Environmental Life Cycle Costing of Selected Wood Industries Based on Maritime Pine in Landes de Gascogne, France.**

#### **5.1. Introduction**

The choice of the best approach to evaluate a system from a large variety of available options continues to be a difficult undertaking that entails many technological, financial, and organizational complications. Developing analytical tools and procedures that can evaluate plans in terms of their related costs and tangible benefits in order to meet this problem is a huge transdisciplinary challenge. Life Cycle Costing (LCC) is one of these tools. The LCC of a system must be well studied for a complex decision-making process (Animah et al., 2018; Heralova, 2014). LCC is found by Patil et al. (2017) to be crucial to the system's dependability and maintainability. LCC enables businesses to get design-phase improvement measures (Mannub et al., 2012). Additionally, this methodology's advantages not only save life cycle costs but also increase service accessibility and capacity by reducing failures (Ghosh et al., 2018). On the other side, it can also be associated with the increased demand for more environmentally friendly replacements. These patterns resulted in a considerable rise in LCC-related research publications (Goh and Sun, 2016)

Business organizations have recently changed their priorities to take ecological goals into account in addition to economic ones as a result of growing worries about climate change (Knauer and Moslang, 2018; Rodriguez and Emblem SVG, 2007). The well-known modern cost and environmental management methods Life Cycle Costing (LCC) and Life-cycle assessment (LCA) can be used together to incorporate economic and environmental elements (Bierer et al., 2015). Despite both using a life cycle approach for evaluation, LCC and LCA are frequently used separately. As a result, crucial connections between economic and environmental issues are disregarded (Norris, 2001).

According to Hamner, B., & Stinson, C. H. (1995); Bennett, M., & James, P. (1997). conventional costing methods can result in accurate investment choices when it comes to environmental issues. For instance, that is expenditures associated with recycling and disposal appear beyond the purview of the conventional accounting system. The use of life cycle costing (LCC), which covers these expenses, has been recommended as a popular approach to solving this issue (Abraham DM, Dickinson RJ. (1998).



In order to minimize costs, improve environmental performance, and increase economic and environmental efficiency in order to make strategic decisions toward sustainable development in the forest industry, this chapter aims to integrate environmental life cycle costing and life-cycle assessment throughout the value chain. On a more pragmatic note, this study provides total internal costs in the form of Operational Expenditures (OpEx) and Capital Expenditures (CapEx) and external (environmental externality) costs for construction wood and input output cost (OpEx) and environmental cost for construction wood, plywood, pallet, pellets, and unbleached pulp as the five most significant wood products. The data used are based either on a life cycle inventory of the literature or on specialist data collection, using the data as far as possible available but for CapEx only for construction products.

## **5.2. Life Cycle Costs**

### **5.2.1. History and development of conventional LCC**

In the early 1970s, the US Department of Defense issued various guidelines for the computation of life cycle costs and design to costs, both of which examine the cost of a product or system over its full life cycle during the R&D process (US Department of Defense (DoD). 1973.). Similarly, in the United States, numerous rules concerning the computation of life cycle costs for the acquisition of public buildings have been issued (Zehbold 1996). Nevertheless, LCC uses have typically been sector- or product-specific. Sherif and Kolarik (1981) present a complete analysis of the previously stated applications, costing methods, and related literature. They note that “LCC has progressed more as a result of specific applications than theoretical models.” This finding is still mostly applicable today. A generally applicable methodological framework or model has not, however, been formed, despite trends in this direction (Rebitzer 2005).

Blanchard (1978) and Blanchard and Fabrycky (1998) developed the concept that most closely resembles a general LCC method; other examples are given in the standards ISO 15663 (International Organization for Standardization (ISO). (2000-2001)), IEC 60300-3-3 (International Electrotechnical Commission 2004), and AS/NZS 4536 (Standards Australia and Standards New Zealand 1999).

These strategies, which have their roots in systems engineering, concentrate on evaluating and contrasting technical alternatives. They divide the phases of the life cycle of a system or product into four categories: manufacturing and construction, operation and support, and retirement and disposal. In addition to the cost categories taken into account and the systems perspective, this structure is extremely similar to

the life cycle method used in life cycle management (LCM) and is thus an excellent foundation for the creation of an LCC technique for LCM. Nevertheless, Blanchard and Fabrycky (1998) and the standards do not specify a technique that provides instructions on how to compute and compare costs; instead, they present LCC in the sense of “life cycle thinking” and emphasize the significance of the systems approach. As a brief summary of the historical origins and advancements of LCC, it can be said that traditional LCC has never been officially created into a comprehensive and widely usable approach. Rather, it was created from the standpoint of industry-specific application-specific methods, based on the primary life cycle view. In light of this, one may wonder why, unlike quality management strategies for example, this attractive and straightforward idea was never widely adopted by business and government. Certain industrial sectors, including the railroad sector, have just begun to realize the significance of LCC for purchasing and maintenance choices. One justification for not using a typical LCC method in popular commercial applications is that it often wouldn’t fit the cost system of the business or government entity that initiates the LCC analysis, such as a buyer of railroads, for example. The LCC technique must agree with the costs reported by a corporation. Any wider scope would be less effective, and any attempt to give a more generally applicable LCC technique requires, to some extent, the need to translate company-specific cost data to more universal ones.

### **5.2.2. Type of life cycle cost**

The Working Group on Life Cycle Costing at SETAC-Europe (Swarr, et al.,2011) has recognized three categories. These kinds are summarized in Figure 22 and independently defined in the sections that follow.

#### **Conventional LCC:**

The evaluation of all costs incurred during a product’s life cycle that are clearly funded by the primary producer or consumer. The appraisal is primarily concerned with actual internal costs, sometimes even excluding EoL or use expenses if these are covered by third parties. Typically, distinct LCA results are not provided along with a standard LCC. The viewpoint is primarily that of one market actor, such as a manufacturer, user, or customer.

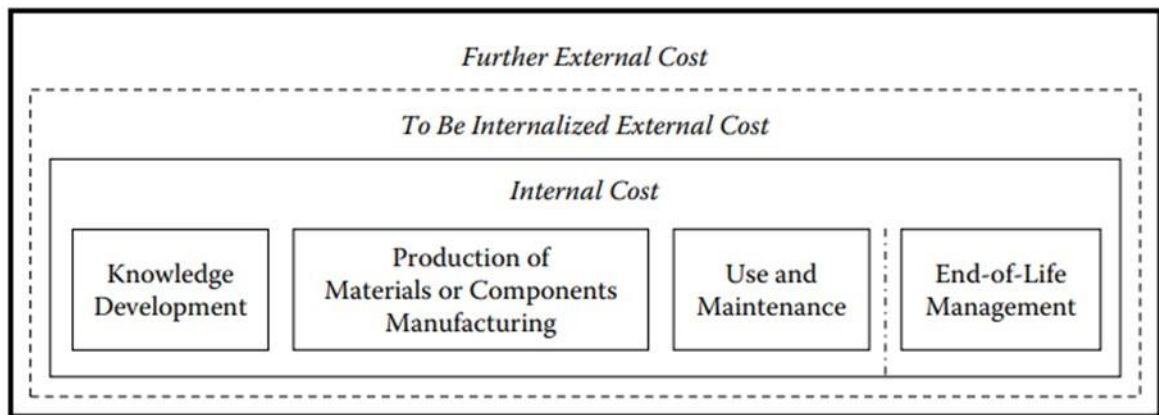
#### **Environmental LCC:**

The evaluation of all costs associated with the life cycle of a product that are directly borne by one or more actors in the product’s life

cycle (supplier, manufacturer, user or consumer, and/or EoL actor), with the inclusion of externalities\* that are anticipated to be internalized in the decision-relevant future (definition as suggested by Rebitzer and Hunkeler 2003). Environmental LCC improves traditional LCC by mandating, on the one hand, the including of all life cycle stages and to-be-internalized costs in the decision-relevant future (thus, projected costs) and, on the other side, the separation of non-monetized LCA data. A product system in accordance with ISO 14040/44 (2006) should serve as the foundation for both. The viewpoint is that of one or more specified market participants, predominantly manufacturers. Subsidies and taxes, if applicable, are included in environmental LCC.

Societal LCC:

Societal LCC: The evaluation of all costs related with the life cycle of a product that are borne by anybody in the society, either today or in the distant future. Societal LCC encompasses the entirety of environmental LCC in addition to the evaluation of additional external costs, typically in monetary terms (for example, based on willingness-to-pay methods). The viewpoint is from the entirety of society, both nationally and internationally, including governments. Unlike environmental LCC, subsidies and taxes have no net cost effect and are therefore excluded from social LCC.



- Conventional LCC: Assessment of internal costs, mostly without EoL costs; no LCA
- Environmental LCC: Additional assessment of external costs anticipated to be internalized in the decision relevant future; plus LCA in societal = natural boundaries
- Societal LCC: Additional assessment of further external costs

Figure 22: The three types of Life cycle cost (Hunkeler, D., Lichtenvort, K., & Rebitzer, G. (2008)

### 5.3. The Life Cycle Costing Concept

As previously established, there is no accepted definition of life cycle costing, nor is there a consistent methodological framework that is typically employed in business. The following discussions of life cycle costing are based on Blanchard and Fabrycky's definition, which states that "lifecycle cost refers to all costs connected with the system across its defined life cycle" (Blanchard and Fabrycky, 1998, p. 560). In this sense, the phrase life cycle refers to the activities related with the manufacture, use, and end-of-life (reuse, recycling, waste disposal) of a good or service (Rebitzer, 2000). This economic cycle is depicted in Figure 23. Under this Lee approach, the expenses normally accounted for by a product's maker are augmented by the user's expenditures, which include use and end-of-life costs.

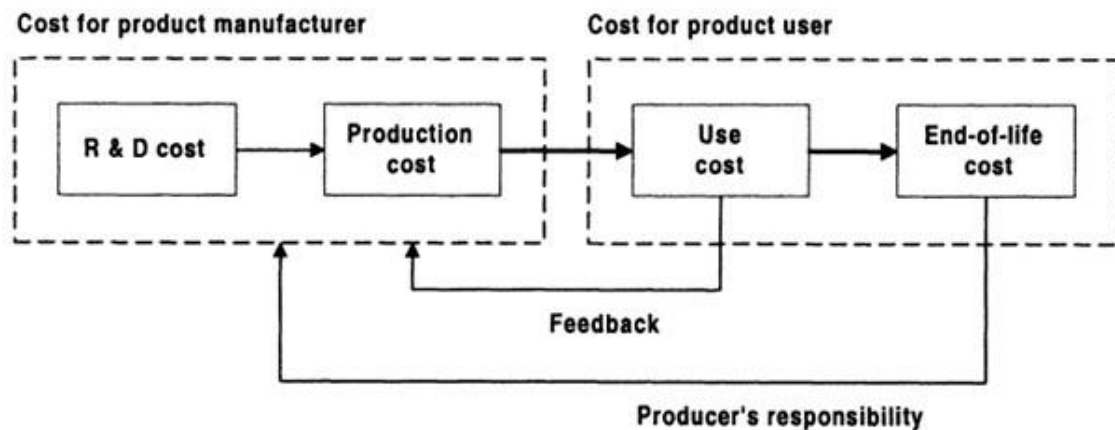


Figure 23: The Economic Life Cycle (the bold lines represent the LCI flows) (Rebitzer, 2000))

Developing and marketing products with minimum life cycle costs is possible when these expenses are considered. Reduced expense for the user results in advantages on the market, possibly leading to a higher selling price. Reduced end-of-life costs are important for the same reason, but also because of existing and increasing rules regarding the take-back of items from the automotive and electronics industries (WEEE (2001) and ELV (2000)).

Other costs, such as labor expenses or costs for using knowledge (such as patents), as well as transaction costs (such as information flows), must be taken into account in addition to the expenditures brought on by physical processes and the related material and energy flows (LCI). For instance, all expenditures associated with R&D that are unrelated to material flows must be included (Rebitzer 2000).

A product's development, production, use, and end-of-life costs can all be calculated using the LCC concept, which also provides the methodological framework for identifying cost-drivers in the life cycle and supply chain and for identifying trade-offs in order to achieve the lowest possible total cost. It must be mentioned that this life cycle costing model is intended for use in making preliminary cost estimates for product development, marketing analysis, etc. It is not a technique to take the place of conventional commission cost accounting procedures.

#### 5.4. life cycle costing based on life-cycle assessment

The details presented in the preceding chapter demonstrate how the data collected in a life cycle inventory study can be effectively applied to life cycle cost evaluations. This section examines the similarities between LCA and LCC and explains an LCC technique that is based on LCA but is specifically designed for use in product development, see Figure 24 for an illustration of this idea.

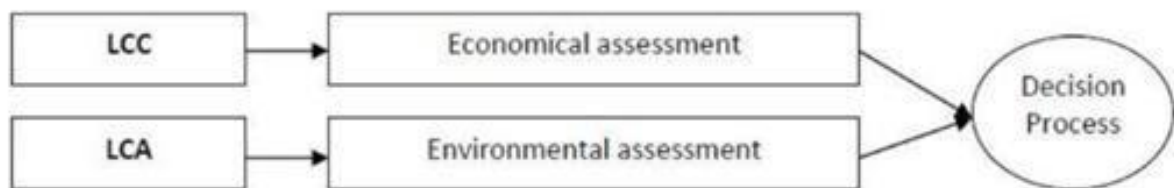


Figure 24: Life-cycle assessment and life cycle cost goals in parallel (Rebitzer,2002)

The most important aspects of life cycle costing are presented in Table 17, together with a connection between them and data from life cycle assessment. **bold italic text** indicates costs features that can be obtained straight from an LCA. The amounts of these flows are provided by the inventory of an LCA, and the cost is calculated by multiplying these flows by the relevant corporate costs or market prices (e.g., materials purchasing). The information in an LCI can be used directly or indirectly to generate the costing aspects that are stated in regular italics. Further data, such as the labor required to operate a particular process, must be acquired for these aspects. As all processes are thoroughly researched and examined for the LCI, there is little more work needed if this is done concurrently with the creation of the LCI model. The only costs that cannot be calculated from the LCA model are those related to the product's research and development (R&D). They need to be chosen independently. The same principles apply for services; there is no methodological distinction between them and tangible goods. Overall, the life cycle inventory analysis

of an LCA can be used directly or indirectly to collect all required base data for a life cycle costing evaluation with the exception of the R&D period

Table 17: Common elements of life cycle cost and life-cycle assessment (Rebitzer, G. (2002))

	<b>Cost for Product Manufacturer</b>	<b>Cost for Product User</b>
<b>R&amp;D</b>	<ul style="list-style-type: none"> <li>• Market Research</li> <li>• Development costs</li> </ul>	
<b>Production</b>	<ul style="list-style-type: none"> <li>• <i>Materials</i></li> <li>• <i>Energy</i></li> <li>• <i>Machines, plants</i></li> <li>• <i>Labor</i></li> <li>• <i>Waste Management</i></li> <li>• <i>Emission Controls</i></li> <li>• <i>Transports</i></li> </ul>	
<b>Use</b>	<ul style="list-style-type: none"> <li>• <i>Maintenance/Repair (Warranty)</i></li> <li>• <i>Liability</i></li> <li>• <i>Infrastructure</i></li> </ul>	<ul style="list-style-type: none"> <li>• <i>Transport</i></li> <li>• <i>Storage</i></li> <li>• <i>Materials</i></li> <li>• <i>Energy</i></li> <li>• <i>Maintenance/Repair</i></li> <li>• <i>Infrastructure</i></li> </ul>
<b>End-of-Life</b>		<ul style="list-style-type: none"> <li>• <i>Waste Collection</i></li> <li>• <i>Disassembly/Recycling/Disposal</i></li> </ul>

### 5.5. Environmental Life Cycle Costing

The fact that evaluation techniques like LCA are frequently seen as barriers to corporate development, particularly in the short term, is one justification for environmental LCC, albeit a subtle one (Rebitzer, G., & Hunkeler, D. (2003)). Finding win-win scenarios, maximizing trade-offs between the environmental view and the economic and business view, and guiding technological development and managerial decisions in a more rational direction can all be aided by a new methodology that offers a sound combination of both the environmental and economic performance of a product.

Figure 25 illustrates a conceptual framework that defines the basic scope of environmental LCC and explains the relationship of LCC to LCA

and societal assessments (e.g., employment circumstances, unemployment rates, and general social impacts on communities) in LCM.

Research and development, manufacture of materials or components, manufacturing, usage and maintenance, and EoL management are the five stages of the physical product life cycle that make up the conceptual framework for environmental LCC. These stages can be further developed as needed.

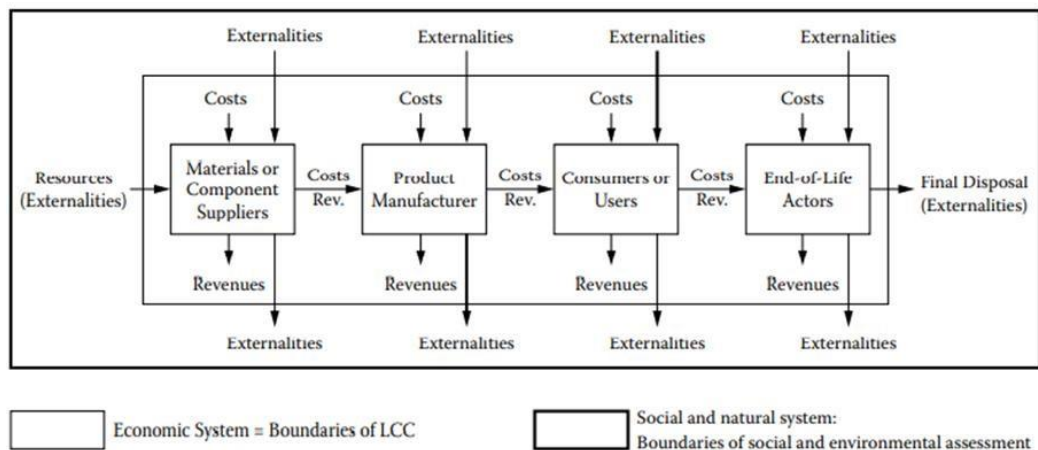


Figure 25: Conceptual framework of environmental LCC. (Rebitzer and Hunkeler (2003)).

The actors involved in each of the five stages of the life cycle are shown in the Figure above. These actors include those involved in product makers’ research and development (R&D) and manufacturing, consumers’ use and maintenance of products, and EoL actors’ involvement in EoL management.

There are 2 different types of expenses that can be distinguished (Rebitzer and Hunkeler 2003):

Internal costs across the course of a product’s life cycle, where “internal” implies that someone is paying for the production, usage, or EoL costs (such as a producer, transporter, consumer, or other directly involved stakeholder), and the costs can therefore be linked to a business cost. This notion of cost includes all expenditures and income within the economic system. Depending on the viewpoint, internal costs can be split into costs incurred inside or outside of a business.

External costs (externalities), which are environmental impacts evaluated with LCA whose damages have already been priced in monetary units because they will be internally standardized in the decision-relevant

future, and they stay that way; there is no conversion from environmental measures to monetary measures, or the other way around. Externalities in the complimentary LCA and LCC should not be duplicated and counted for twice.

## **5.6. Methodology**

### **5.6.1. The requirement and general framework for environmental life cycle costing**

As mentioned at the outset of this chapter, environmental LCC is not envisioned as a standalone technique, but is seen as a complementary analysis to environmental LCA. Therefore, environmental LCC should be developed in analogy to LCA conducted in the previous chapter. This means that for environmental life cycle costing, we will use LCI from LCA as the source data for the input and output of the system boundary determined in the study (Gate- To- Gate (from harvesting to production) to investigate the internal and external costs for the five studied products: pulp, plywood, pallet, pellets and construction wood conducted identified via the MFA described in chapter 3 as the main applications of the maritime pinewood transformation in the Nouvelle-Aquitaine region) on their environmental performances and identify the different market shares for each product to minimize environmental impacts in order to guide decision making for the supply chain.

Environmental LCC steps analysis include:

Goal and scope definition

Information gathering

Interpretation and identification of hotspots

Sensitivity analysis and discussion

### **5.6.2. Goal and scope definition**

This chapter's objective was to provide environmental life cycle costing for selected wood products evaluated in this study, based on the general criteria of ISO 15686-5 standards (ISO 2017) on requirements and guidelines for performing life-cycle cost analyses of buildings and constructed assets and their parts:



Determine the various eco-costs associated with each stage of the product's life cycle.

Determine the overall price of each product (Internal costs and external costs),

Integrate cost into the items' eco-design.

Construct a life cycle cost model to evaluate and compare the investigated products with one another.

### Scope of environmental LCC

As costs rather than environmental consequences are the focus, it is obvious that the scope of environmental LCC must differ from that of LCA. However, there are also links and overlaps in this instance. A few of those cost factors can be obtained directly from an LCA. Others may be indirectly or partially derived from the information in an LCI. The amounts of these flows are provided by the life cycle inventory of an LCA, and the costs can be calculated by multiplying these flows by the relevant corporate costs or market prices (e.g., materials purchasing). Table 18 explains how LCA components relate to costs associated with life cycle costing for product manufacturers in this study. In the Table 18, costing factors that can be partially or indirectly deduced from the data in an LCI are written only in italics, whereas those that can be directly deduced from an LCA are put in bold. If, as is typically the case, the R&D phase is eliminated from the LCA, only the expenses related to the product's research and development (R&D) can be determined from the model (see above). As we were relying solely on LCI from the life cycle assessment, we removed R&D costs from This study study. They would therefore need to be determined independently.

Table 18: Connection of LCA elements with costs in life cycle costing

	Cost of product manufacturer
Production	Material Energy Machine, plan Labor Waste management Emission control Transport Marketing activity
Use	Maintenance and repair Liability Infrastructure

The scope of environmental life cycle costing in this chapter includes costs of raw materials (wood) production, manufacturing processes of studied products, which means internal costs (OpEx & CapEx) and external costs (externalities of environmental impacts) of five wood products from first thinning to final products (solid wood, plywood, pallets, pellets, and wood- pulp) from gate-to-gate (from harvesting to final product) as explained in Table 19. With the establishment of the LCI model, all processes are studied and analyzed in depth for the LCI. Only the costs associated with research and development (R & D) of the product can't be derived from the LCA model if the R & D phase is excluded in LCA. Since we completely depend on LCA, we excluded R & D costs from this study. As mentioned shortly above, due to lack of data, we excluded internal costs in the form of CapEx of wood pulp, plywood, pallets and pellets products. However, we included CapEx costs of the sawmill for construction wood.

Table 19: Scope of environmental life cycle costs

Cost elements			
Capital Expenditure (CapEx)		Operational expenditure (OpEx)	
1-	primarily procurement costs plus land acquisition for factory	1-	Maintenance and repair
2-	Interest on total amount of average annual investment including the land cost (price)	2	Energy which includes -Electricity; -fuel which include diesel, gasoline, gas, engine oil, -lubricants
3-	Taxes*	3-	Labor costs this include social security, workmen's compensation, others
4-	Insurance	4-	water

5-	Depreciation on all project assets (Machine, tools, equipment, builds, furniture.....etc.	5-	Steel or others minerals components (For pallet production )
6-	Replacements cost	6-	Chemical materials (For pulp, plywood and pellets production)
		7-	Waste treatment

\* We have two kinds of taxes: tax on pollution (it is within external costs) and tax on capital investment (it is within internal costs)

### 5.6.3. System boundary

Environmental LCC is not considered as a stand-alone technique, as was stated at the beginning of this chapter, but rather as an analysis that supplements environmental LCA. Thus, environmental LCC should be created as an analog to the LCA carried out in the preceding chapter. This means that for environmental life cycle costing, we will use LCI from LCA as the source data for the input and output of the system boundary determined in the study (Gate- To- Gate from harvesting to production) to investigate the internal and external cost for the five studied products pulp, plywood, pallet, pellets and construction wood conducted in the previous chapter and identified via the MFA as the main applications of the maritime pinewood transformation in the Landes Gascogne region according to Chapter3 on their environmental performances and identify the different market shares for each product to minimize environmental impacts in order to guide decision making for the supply chain. Due to the lack of data on the costs of assets for factories of pulp, plywood wood, pallets, and pellets, the calculation of capital costs and operating costs of the factories mentioned above has not been included in economic and environmental performance. The capital costs have been considered for the sawmill only, thanks to the costs of the sawmilling plant from Labrousse sawmill, for evaluating the environmental and economic performance.

### 5.6.4. Function of the system and Functional unit

The function of the system being studied is to harvest and produce maritime pinewood for different uses: roundwood is mainly used in plywood industries and the sawmill industry for constructing and pallet production; industrial wood is used in pulp and paper industries; and residual wood is mainly used as fuel wood. Life Cycle tools require the definition of a functional unit in order to assess systems. For environmental LCC we need to identified the functional unit to allocate the internal and external costs to each product(s) under study based on Chapter 3. The functional unit has to be the same as in the underlying LCA, because it builds on the same product system providing the same function, so the functional unit for LCC will be total cost (€)/m<sup>3</sup>. That means the total internal and external costs to convert one cubic meter of wood to one of the studied products. Because each product has a distinct yield, reference

flows based on the functional unit must be specified for each one as explained in Table 20.

Table 20: Reference flow of studied products based on functional unit (m<sup>3</sup>)

Product	Reference flow	Unit
Construction wood	0,485 (=218,25 kg)	M <sup>3</sup>
Pallets	354,2 (0.708 m <sup>3</sup> )	kg
Plywood	0,681 (=306,45 kg)	M <sup>3</sup>
pulp	167 (0.371m <sup>3</sup> )	kg
Wood pellets (energy)	375 (0.45 m <sup>3</sup> )	kg

### 5.6.2. Objective of environmental life cycle costing

The economic repercussions of alternative products or product designs must eventually be considered in the private sector decision-making circumstances that LCA addresses. Unfortunately, neither the defined LCA methodology nor the currently available LCA technologies adequately address the internal or external economic implications of the decisions. The traditional division between life cycle environmental assessment and economic analysis has limited the influence and relevance of LCA for decision-making and obscured key relationships and trade-offs between the financial and environmental performance of various product design decision scenarios.

The Life Cycle Assessment, on the other hand, compares the environmental performance of several product systems that perform the same purpose. Aiming to take into account all significant causally connected activities, all significant resource and consumption flows, regardless of whether they ultimately have an influence on anyone, this environmental performance is evaluated as holistically as feasible. From the viewpoint of economic decision-makers, such as manufacturing companies or consumers, life cycle cost compares the cost-effectiveness of competing investments or business decisions. Their scope and approach have appropriately varied as a result of these disparities in their purposes. Consequently, this chapter aims to integrating Environmental LCC in life-cycle assessment in order to:

Identify the various eco-costs concerned with every life cycle stage of the product,

Develop a life cycle cost model to assess as well compare the existing product with each other's

Incorporate cost into the eco-design of the products

Find out the total cost of the product environmental costs (External) and CapEx & OpEx (Internal costs).

### **5.6.3. Allocation in Environmental LCC**

Allocating environmental and economic performances to each by-product, which results from multifunctional processes that produce many goods, is a crucial topic for this study. There are other allocation strategies that can be employed, including as partitioning, expansion, and substitution. According to an approach proposed by (Schrijvers, Loubet, and Sonnemann, 2020), the allocation method should be chosen based on the criteria specified in the goal and scope. Partitioning is advised in our situation since we are comparing the environmental effects of various wood products from an attributional standpoint.

Mass and economic allocations are the two dividing techniques that are most frequently utilized. When the price difference between the by-products is significant (>25%), (AFNOR - CEN, 2012) and (The International EPD System, 2017) tend to prefer economic allocation, contrary to the (International Organization for Standardization, 2006) that allows for physical properties and recommendations to use them in mass allocation. (Schrijvers, Loubet, and Sonnemann, 2021) believe that allocation decisions should be made based on target description and supported by the practitioner's long-term objectives.

In our study, allocation is applied at multiple stages. For each forest process there are is specific allocation done. For forest we can use mass and volume, in sawmill we can use mass, volume and proceeds and in industry we can use mass. In life-cycle assessment the mass-based allocation has been used for environmental impact assessment and the same kind of allocation (volumebased allocation) has been used for life cycle costing, so we should multiply the total cost for each product by the share of that product explained in chapter 3) represented by Table 21.

Table 21: Mass allocation table for studied wood products

Level	Item	Mas allocation ratio
Roundwood	Wood packaging	0.15
	Canter Logs	0.10
	Plywood_ no knots	0.9
	Log_ high-quality	0.6
	Log intermediate quality	0.4
Industrial	Pulpwood	0.45
Residual	Residual	0.11
Others	-----	0.1

#### 5.6.4. Information Gathering (Cost category and data acquisition)

In this chapter, we get to know about the different cost categories in an LCC, depreciation, data acquisition from previous studies. This ground-work is an extremely important step in an LCC.

##### Cost Model:

The time value of money and the level of nonlinearity in the relationship between inputs and outputs are two characteristics that define cost modeling. For instance, the LCA model is homogeneous to degree 1 or linearly homogeneous overall, which means that two times the input results in two times the output. Steady-state models, semi-dynamic models, and dynamic models are the three types of cost models. Stable-state models are conceptually the simplest because they have no concept of time and presume that all technologies are constant over time. Substance flow analysis (SFA), inputoutput analysis (IOA), and the majority of LCA applications are steady-state models. The approach employed by environmental LCCs is here thus described according to (Huppel et al., 2004). In contrast, dynamic models describe how variables change over time by using the values of the past to predict those of the future. Macroeconomic models are frequently dynamic time series that are determined exogenously. They represent a middle ground between dynamic and steady-state models. For costs associated with environmental consequences, steady-state is appropriate, but semi-dynamic models are appropriate for internal costs. And in our study, we will also couple steady-state and quasi- dynamic for cost modeling.

## Environmental LCC:

The keeping of cost records for physical assets throughout their entire lifespan is known as lifecycle costing. This implies that choices about the purchase, use, or disposal of assets can be made in a way that maximizes asset utilization while incurring the fewest expenses for the entity. As said before, Environmental LCC is seen as a supplemental analysis to environmental LCA rather than as a stand-alone technique. As a result, in addition to the cost element data of the sawmill from the Labrousse Sawmill, the external costs for an environmental LCC should be generated in a manner similar to the LCA in the preceding chapter. Environmental life cycle costing of a few chosen studied wood products was done in this study, which was based on general ISO 15686-5 standards (ISO 2017) in order to determine the total internal cost of each product, to specify the various eco-costs concerned with each life cycle stage of the product based on the system boundary of this study, as well as to incorporate cost into the eco-design of the products, and to develop a life cycle cost model to compare and evaluate the study products with each other's.

## External costs:

One important aspect in the methodology of environmental LCC (Rebitzer and Hunkeler, 2003) is to have the environmental impacts converted into externalities, that means external costs, in line with the conceptual framework shown in Figure 25.

In the CE Delft Environmental Prices EU28 Handbook (Bruyn, et al., 2018), a monetary value expressed in euros per kilogram of emission is given to damaging the quality of the environment. The amount of environmental impacts is translated into a quantity of euros (2015 prices - €2015) to calculate the social marginal value per emission. It can be said that the CE Delft Handbook is the list of prices of the environmental non-physically existent market. And that it can be used by investors, producers, and consumers to choose or not a product or service. The CE Delft Environmental Prices EU28 Handbook takes the example of a supermarket where every customer can go and compare prices to further decide based on which product or service the client is willing to pay for.

It is possible to use Environmental prices in application of interest for industry and government. The main 3 applications are:

1. Social cost-benefit analysis (SCBA)
2. Corporate Social Responsibility (CSR) and benchmarking
3. Weighting in Life-cycle assessment (LCA)

The environmental prices presented in the Handbook (Bruyn, et al., 2018), have been derived by combining three kinds of models and methods:

1. Characterization models defining physico-chemical relationships between interventions like emissions and midpoint impacts (midpoint characterization) and between midpoint impacts and endpoints (endpoint characterization).
2. Impact pathway models describing the relationships between emissions and endpoint impacts, mapping environmental dispersal of emissions and the impacts of the resultant concentrations on humans, animals, plants and buildings/materials.
3. Valuation techniques establishing a financial relationship between endpoint impacts and the changes in economic welfare resulting from altered availability of the endpoint.

The methodology employed in the Environmental Prices Handbook combines work in all three fields of research. The process adopted to update the former prices is shown schematically in Figure 26, where the main elements of the methodology are shown.

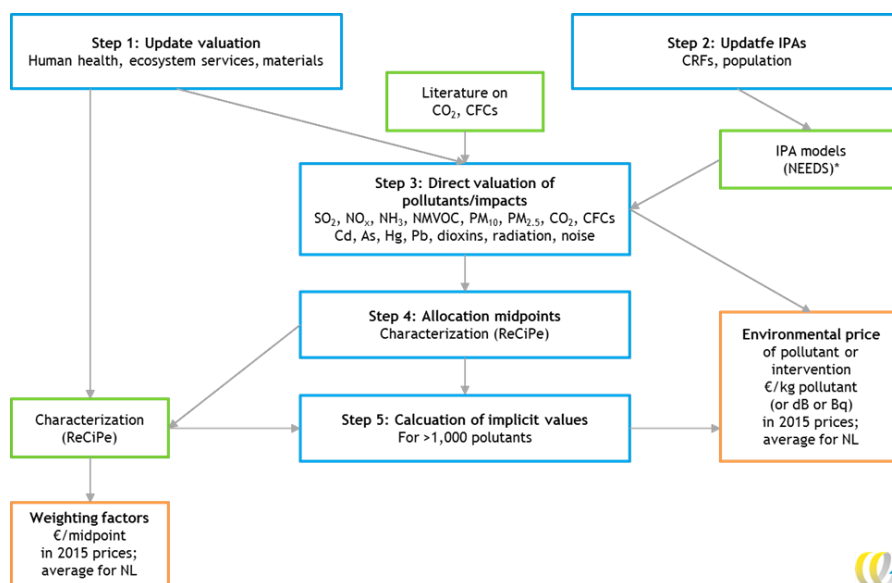


Figure 26: The Environmental Prices Handbook methodology (Bruyn, et al., 2018)

Five steps can be distinguished:

- In step 1, for each of the endpoints adopted here monetary values were established that are in accordance with recent international literature and the



recommendations of the Discount Rate Working Group (Ministerie van Financiën, 2015). This yielded values for human health, biodiversity, agricultural crops and material restoration costs, all in 2015 prices.

- In Step 2, the impact pathway analyses (IPAs) were updated. These specify the relationship between emissions in the EU28 and impacts on endpoints and are built around concentration-response functions (CRFs).
- In Step 3, the updated values and IPAs, combined with the results of literature analyses on CO<sub>2</sub> and CFCs, were used for direct valuation of fifteen pollutants or pollutant groups. These values constitute the environmental prices presented for these substances in the Handbook.
- Step 4 consists of allocating these fifteen pollutants or pollutant groups across the various midpoints.

Most of these pollutants (the exception being PM) have impacts on multiple environmental themes.

- In Step 5, the damage cost of the various pollutants on each environmental theme was weighted using 2015 EU28 emissions (converted to ReCiPe equivalency factors) to arrive at a weighted average value for damage at the midpoint level. This allows the damage due to all the pollutants characterized in ReCiPe calculated and a weighted average midpoint damage factor to be derived. An implicit environmental price is thus calculated for all the pollutants characterized in ReCiPe with ReCiPet to the endpoints adopted here.

It is important to mention that the decision of modelling the costs in SimaPro instead of OpenLCA or GaBi as a LCA software solution was based on the fact that SimaPro has the advantage of providing the external cost directly by using the CE Delft Environmental Prices method described above. In this way the environmental impacts characterized by the ReCiPe method in chapter 4 are here converted into externalities, as described in the steps before using exactly also ReCiPe termediate impact method. The conversion of environmental impacts into external costs is based on multiple methodological and data related assumptions. Evidently, this leads to higher uncertainties as an evaluation done at the life cycle inventory or impact assessment level (Sonnemann et al, 2003)

#### Internal cost Components:

Across the system or project's life cycle, the total costs (internal and external costs) are analyzed using LCC. Internal costs comprised acquisition costs and sustaining costs at the aggregate level in typical life cycle analyses. These expenses can be classified as either recurring (maintenance and repair, salaries, etc.) or non-incurring (depreciation costs, for example). For internal costs, as introduced before, we utilized the terms CapEx and OpEx in This study.

### Capital costs (CapEx):

Capital costs are the costs of the investment capital in the project; these costs are usually fixed and do not change in the analysis with the amounts of goods or services being produced, such as equipment depreciation, insurance, taxes, or interest. We depend on the costs of Labrousse sawmill to calculate the assets of the sawmill (machines, tools, equipment, buildings, water and electricity lines, furniture, computers, and all office furniture). We couldn't access the capital costs for pulp, pallets, pellets, and plywood factories, this is the reason why we didn't consider the CapEx and also maintenance and repair, salaries (elements of OpEx) costs in the economic performance of these product groups. All of the costs have been calculated for one cubic meter of raw wood.

### a-Interest, Insurance and taxes:

Taxes, insurance, and interest are the costs associated with spending money over time. Money for investments might be borrowed or deducted from equity or savings. The lender typically determines the going interest rate when money is lent. Interest rates may change depending on the lending institution and the area. An opportunity cost, or the rate this same money would earn if invested somewhere else (savings bonds or a savings account), should be utilized as the interest rate if the money comes from personal loans or established equity. As a general guideline, interest rates should be between 1 and 10 percent.

Every owner of a piece of equipment is required to pay property or usage taxes on it, and they should also have one or more insurance policies to cover them against damage, fire, and other calamities. Together with location and equipment type, insurance and tax prices vary. whenever possible, use the actual costs.

Even though there is disagreement about what the right discount rate should be, it should, in theory, reflect the opportunity cost of capital for an investor, company, or government. Most of the time, the lending institution sets the real discount rate, which is often 10% in the case of the World Bank. In forestry literature, discount rates are usually between 2% and 10%, but in real life, they are often between 6% and 15% or even higher. Low discount rates will benefit long-term investments like forestry because they will not significantly reduce future values like high discount rates will. Due to the fact that low discount rates give returns to future generations a substantially higher value, they may be deemed appropriate for investments in public goods (Cubbage, F., Davis, R., Frey, G., & Behr, D. C. (2013).

Some analysts and researchers in the fields of forestry and natural resources have argued in favor of lower rates like 4%. (Row et al., 1981). Indeed, according to some recent research, we should use duration-dependent discount rates, which are typically lower for longer investments. The discount rate, according to the Cost-Benefit Analysis textbook (Boardman et al., 2005), should be 3.5% annually.

The choice of the discount rate must take inflation into account as well. Real discount rates that do not account for inflation are typically the simplest to utilize. A nominal discount rate of 8% would result from an additional inflation component of, say, 4% per year added to a real discount rate of 4%. As previously said, the outcome of an analysis will be the same whether one chooses a real discount rate or a nominal discount rate if all costs and prices have the same rate of inflation. If inflation has differing effects on costs and prices, nominal discount rates and nominal input and output costs may be appropriate. Yet, nominal pricing can cloud the research, particularly when dealing with long-term investments like forestry. Therefore, for financial and benefit cost evaluations, it is typically preferable to use real costs, prices, and discount rates. However, actual cash flow, conventional accounting, and tax reporting require the use of nominal costs, prices, and discount rates (Cubbage, F., Davis, R., Frey, & Behr, D. C. 2013). I therefore used 4% as the interest rate in This study research.

#### b-Taxes

Every owner of equipment must pay property or usage taxes on it and should have at least one insurance policy to protect against theft, fire, and other disasters. The cost of insurance and taxes varies based on location and equipment type. Utilize the actual costs whenever possible. There are numerous types of taxes, including property taxes, income taxes, value-added taxes, social insurance taxes, import and export taxes, and others. In several regions of the globe, forest management is eligible for lower tax rates than other land uses.

Based on (Miyata Edwin S.1980), 2 or 3 percent of the average annual investment value may be used for insurance and 2 or 3 percent for taxes. In This study study, I utilized 2 percent for both insurance and taxes. Interest, insurance, and tax fees are typically applied to the average annual investment value. Typically, two approaches are used to compute the annual average value of an investment (AVI). I relied on the straight-line technique to calculate depreciation, so I utilized the first method. This formula is only applicable if the straight-line approach is employed to calculate depreciation) to compute the average annual value of an investment throughout its whole economic life:

$$AVI = \frac{(P-S)(N+1)}{2N} + S$$

(Equation5)

Where: AVI = Average value of yearly investment over its entire economic life

P = Initial investment cost

S = Salvage value

N = Economic life in years.

Now the interest, insurance, and taxes rate as 4, 2, 2 respectively, then the total interest, insurance and taxes in This study study is:

$$4\% + 2\% + 2\% = 8\%$$

b-Depreciation costs:

Depreciation is a way to Figure out how quickly an item loses value because of use, time, or becoming obsolete because of changes in technology and the market. The primary goal of the depreciation schedule is to annually recoup the costs of the initial investment throughout the expected economic life of the asset. Depreciation is typically calculated using one of three methods: (1) a straight line, (2) the sum of the year's digits, or (3) a diminishing balance. Assuming that the value of equipment diminishes at a consistent rate over the course of each year of its economic life, I use the straight-line technique in This study study to determine the depreciation of all project assets. The mathematical calculation is:

$$D = (P - S) / N \text{ ----- (Equation 6)}$$

Where:

D- Yearly depreciation charge

P- initial investment cost of equipment

S- salvage value

N- Economic live in years

Also,  $DR = 1/N$ , where DR is depreciation rate per each y

$$\text{Salvage Value (S)} = P (1 - i)^y \text{ ----- (Equation 7)}$$

Equipment dealers and the Green Guide (1984) provided preliminary estimates of the salvage value in. A standard estimate of 25% of the delivered price was chosen for all equipment due to the wide variety of equipment brands and models and the unpredictability of future market conditions. This represents the tendency of higher used equipment pricing as a result of inflationary price increases for new equipment, but it is slightly more than the 20% frequently used in the past (Werblow, D. A., & Cubbage, F. W. (1986)). The Table 22 represents total capital investment cost of Labrousse sawmill for construction and wood production.

Table 22: Total capital investment costs of Labrousse sawmill for construction wood production

CAPEX Cost elements		Monetary value €
primarily procurement costs plus land acquisition for factory	Mchine	232,020.33 €
	Vehicales	281,800.23 €
	Office material	42,003.27 €
	Construction- Infrastructuer	1,695,627.74 €
	land	90,547.00 €
	<b>Total capital investment</b>	<b>2,341,998.57 €</b>
Interest on total amount of average annual investment including the land cost (price)		529,153.78 €
Tax on total amount of average annual investment including the land cost (price)		264,576.89 €
Issurance on total amount of average annual investment including the land cost (price)		264,576.89 €
Depreciation costs		552,265.16 €

### The Operating costs

Contrary to capital expenses, operating costs depend on the number of hours or miles used. They fluctuate in accordance with the operating utilization amount. Fuel and lubricant use, maintenance and repair work, and tire or track replacement are the key running expenses. These expenses were determined for one cubic meter of raw wood. We rely on González-García, S., Bonnesoeur, V., Pizzi, A., Feijoo, G., and Moreira, M. T. for harvesting procedures (2014). And for This study sawmill needs, I rely on Labrousse Sawmill and S. K. Diederichs (2014). Also, I took into account manufacturing costs from various references that were provided in Chapter 4 of the LCI as well as other references that would be mentioned in the input-output table. for wood pulp Suhr, M., Klein, G., Kourti, I., Gonzalo, M. R., Santonja, G. G., Roudier, S., & Sancho, L. D. (2015). plywood Wilson, J. B., & Sakimoto, E. T. (2005). Pallets Gascoigne Bois: Technologie, Echologie, Tendance. pellets Reed, D., Bergman, R., Kim, J. W., Taylor, A., Harper, D., Jones, D., ... & Puettmann, M. E. (2012) All of costs have been calculated for one cubic meter of raw wood.

#### a- **Maintenances and repair:**

The most expensive running expenses are typically repair and maintenance costs, which are also the hardest to anticipate. They vary greatly based on the equipment manufacturer, as well as how the operator uses or abuses the equipment, the preventive maintenance schedule, and the intensity of the working circumstances. The cost of repairs and upkeep typically increases as the equipment gets older and decreases in value.

They range from basic upkeep to routine overhauls of the engine, transmission, clutch, brakes, and other important equipment components.

Preventive maintenance and storage charges are also included. The severity of the working conditions, maintenance and repair procedures, operator abuse of the equipment, and the design and quality of the fundamental equipment all have an impact on maintenance and repair expenses. The owner's manual, local labor and part costs, or manufacturer guidance can all be used to estimate the cost of routinely overhauling main components. A good source is another owner's experience with similar equipment and cost records under normal working conditions. We rely on the Labrousse Sawmill for the CapEx and OpEx costs of the sawmill and the production of wood for building.

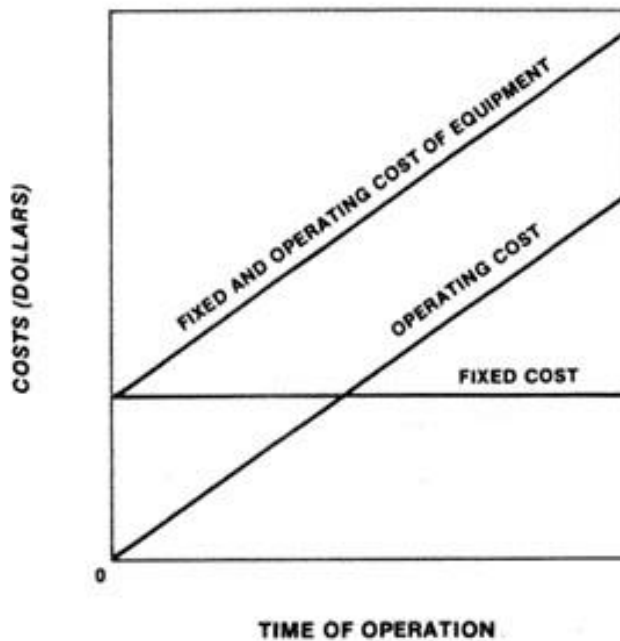


Figure 27- Nature of operating costs and fixed cost as a function of hours of operation and use. (Edwin S. Miyata,1980)

**b- Fuel and lubricant:**

Fuels include diesel and gasoline, and lubricants include engine oil, transmission oil, final drive oil, hydraulic oil, grease, and filters. The fuel consumption rate of a piece of equipment depends on the engine size, load factor, condition of the equipment, the operator's driving habits, environmental conditions, and the basic design of the equipment. (Edwin S. Miyata, 1980)

The prices of diesel fuel or gasoline, engine oil, hydraulic oil, transmission oil, final drive oil, grease, and filters are all included in the category of fuel and lubricants. As these expenses have likely been examined more than any other equipment running costs, predictions can be established with some degree of accuracy. Labrousse Sawmill and

Appendix (5) give the pricing utilized in the fuel and lubricant calculations for sawmill and building timber output.

Labor cost:

For the PhD., labor cost is calculated on a per-unit-of-input basis. Labor costs can be calculated hourly, per unit of input, or as a mix of the two. Employers are also required to contribute to Social Security, Federal Unemployment Insurance, State Unemployment Insurance, Workers' Compensation, and other programs. These costs are collectively referred to as labor costs.

d-Tires cost:

Some cost evaluations incorporate the cost of tires in the initial investment cost, according to Edwin S. Miyata, R. (1980). So, I included the cost of the tires in the original investment cost in This study study as well.

e- Other resources:

Other resources that are needed to produce wood pulp, plywood, pellets, pallets, and solid wood are similarly expensive. These components include:

- Water
- Steel or others minerals components (For pallet production)
- Chemical materials (For pulp, plywood and pellets production)
- Waste treatment

In order to account the life cycle, cost the following formula should be applied:

Life-cycle cost = first cost + maintenance and repair + energy + water + replacement - salvage value ----- (Equation 8)

The present value of Requiring cost (maintenance and repair + energy + water + replacement) should calculate by using annual terminating formula:

$$V_0 = P \left[ \frac{1 - (1+i)^{-n}}{i} \right] \text{----- (Equation 9)}$$

While the present value of salvage value is calculating by the following formula  $V_0 = V_n / (1+r)^n$

The aim of This study study is to assess economic and environmental performance five products from gate to during one year only (2019), so not the recurrent costs nor the residual value have been discounted or compounded and the direct life cycle cost of solid wood has been calculated by use the following formula:

$$LCC = \sum \text{fixed costs (FC)} + \sum \text{variable costs (VC)} \text{-----(Equation 10)}$$

$$\sum \text{fixed costs} = (\text{Depreciation} + \text{interest, insurance, taxes})$$

$$\text{Fixed costs} = \text{Depreciation} + \text{Interest} + \text{Insurance} + \text{Tax} \text{-----(Equation 11)}$$

$$\text{Variable costs} = (\text{Maintenance and repair} + \text{fuel \& lubricant} + \text{electricity} + \text{water} + \text{replacement cost} + \text{Salary and charges} + \text{water} + \text{chemical treatment} + \text{Warping} + \text{raw wood}) \text{----- (Equation 12)}$$

## 5.7. Results and Discussion:

The internal (CapEx and OpEx) and external (environmental impact costs) costs of solid wood, as well as the input-output (related to flow of energy and materials) internal costs of OpEx for plywood, pallets, pellets and pulp were evaluated from an economic and environmental standpoint using a life cycle cost model with SimaPro software to determine the monetary value of twelve environmental impact categories.

### 5.7.1. Construction wood:

The total CapEx of converting one cubic meter of raw maritime pinewood to construction wood using the labrous sawmill database is shown in Table 23. Depreciation and the cost of forgone opportunities account for the majority of capex costs. This is the first study to take into account capital investment costs and include them in the life cycle system boundary of wood products in Landes Gascogne, France, so I couldn't compare the result with pervious study.



Table 23: Capital investment costs of Labrousse sawmill for construction wood production corresponding to % of the MFA presented in chapter 3

CAPEX Cost elements		Monetary value €	Average annual investment	20%FMA
primarily procurement costs plus land acquisition for factory	Mchine	232,020.3300 €	1,670,881.5300 €	
	Vehicales	281,800.2300 €	189,457.6800 €	
	Office material	42,003.2700 €	30,511.0600 €	
	Construction- Infrastructuer	1,695,627.7384 €	11,247,447.1300 €	
	land	90,547.0000 €	90,547.0000 €	
	<b>Total capital investment</b>	<b>2,341,998.5684 €</b>	<b>13,228,844.4000 €</b>	
			<b>cost/m<sup>3</sup>of Raw wood (Input)</b>	
Interest on total amount of average annual investment including the land cost (price)		529,153.7760 €	22.3186 €	4.4637 €
Tax on total amount of average annual investment including the land cost (price)		264,576.8880 €	11.1593 €	2.2319 €
Issurance on total amount of average annual investment including the land cost (price)		264,576.8880 €	11.1593 €	2.2319 €
Depreciation costs		552,265.1600 €	23.2933 €	4.6587 €
Replacment costs		13,413.3300 €	0.5657 €	0.1131 €

In the production stage the raw wood material is the highest cost of input-output followed by salary and charges as shown in Table 24. The research and development phase does itself not cause a share of the overall costs of production process; this is the reason why we didn't include in the R&D cost elements table in general it is between 3-25% of the direct cost of the products manufacturer (Ehrlenspiel et. al. (1998)).

By conducting the life cycle costing, the amount of internal cost of solid wood production has been determined based on LCI in the previous chapter and Labrous sawmill company, the data represented in Table 24 the result shown that the Raw wood cost is the largest amount among all internal cost elements, followed by depreciation while the least cost in the production process is the wat

Table 24: Costs elements of construction production process corresponding to % indicated in MFA

	<b>Operation Expenditure (OPEX)</b>	<b>€/m<sup>3</sup> of Raw wood (allocation 100%)</b>	<b>share of solid wood operation costs corresponding to MFA( 20%)</b>
1-	Maintenance and repair	9.95	1.99 €
2-	Energy which includes		0.00 €
	Electricity	3.3407 €	0.67 €
	fuel(diesel, gasoline,gas,engine oil	2.2857 €	0.46 €
	lubricants	0.1484 €	0.03 €
"-	sallary&charges	24.4286 €	4.89 €
4-	Water	0.0495 €	0.01 €
5-	Chemical Treatments and warping	1.8022 €	0.36 €
6-	Warping	0.1044 €	0.02 €
7-	Capital investment cost(interest, tax, insurance)	22.3200 €	4.46 €
8-	depreciation	23.2600 €	4.65 €
9-	Replacment costs	0.5659 €	0.11 €
10-	Raw wood	49.7100 €	9.94 €
11-	steel nail	0.4100 €	0.08 €
	<b>total operation to convert 1m<sup>3</sup>ofraw wood to cons</b>	<b>137.9658 €</b>	<b>27.5872 €</b>

Direct LCC = 27.60 € Total internal cost to convert 1m<sup>3</sup> of maritime pinewood form harvesting to construction wood corresponding to the MFA %. (50.25/m<sup>3</sup> of construction wood)

### External cost (costs of environmental impacts)

The monetary value of the environmental impact categories obtained from LCA by the SimaPro cost model has been assessed, the results of these assessment shown in Table 25. This table shows that despite the flat topography in Landes Gascogne the environmental cost result from tree harvesting process is the highest costs among all production elements. The global warming potential is higher as well. It is prudent to invest in R&D to tackle the trees harvesting issues.

According to the results of life cycle cost modeling carried out in SimaPro the total amount of external cost resulting from the conversion of one cubic meter of maritime pine raw wood material to 0.549 m<sup>3</sup> of construction wood production corresponding to the MFA% is 0.797 €/m<sup>3</sup> input (Raw wood) (1.452€ /m<sup>3</sup> of construction wood).

Table 25: Environmental impact cost of construction wood production process corresponding to the percentage specified in MFA

C

Percentage indicated in MFA		20%										
Impact category	Unit	Total	Maritime	Diesel.	Light fuel oil	Lubricating	Steel. low-	Tap water	Water.	Wood	Corrugated	Electricity.
<b>Total</b>		<b>0.79788747</b>	<b>0.50338802</b>	<b>0.15611094</b>	<b>0.000274366</b>	<b>0.00348045</b>	<b>0.00618462</b>	<b>2.68588E-05</b>	<b>7.6948E-05</b>	<b>0.00569062</b>	<b>0.00080935</b>	<b>0.1218453</b>
Climate change	EUR2015	0.150819	0.10720755	2.70E-02	4.58E-05	6.88E-04	1.24E-03	5.05E-06	1.58E-05	7.60E-04	1.46E-04	1.37E-02
Ozone depletion	EUR2015	0.00005	4.099E-05	7.9042E-06	1.35151E-07	7.5013E-07	1.1697E-07	7.69E-10	1.76E-08	1.7981E-07	3.2355E-08	3.6879E-06
Terrestrial acidification	EUR2015	0.1218	0.09056292	0.02259569	5.79E-05	5.01E-04	5.32E-04	2.85E-06	8.35E-06	5.69E-04	7.44E-05	0.00687219
Freshwater eutrophication	EUR2015	0.0005	0.00023063	0.00013338	1.29E-07	7.21E-06	1.84E-05	1.23E-07	4.34E-07	1.7425E-05	2.34E-06	0.00012959
Marine eutrophication	EUR2015	0.003	0.00215997	0.00056148	4.78E-07	7.2124E-06	1.3763E-05	9.46E-08	2.67E-07	2.0884E-05	1.3966E-05	0.00037181
Human toxicity	EUR2015	0.036	0.01566357	0.00907155	1.26E-05	0.00034224	0.00086115	5.65E-06	1.49E-05	0.00134407	6.65E-05	0.00873773
Photochemical oxidant formation	EUR2015	0.03	0.02462709	0.00531172	6.64158E-06	0.00030468	0.00010286	3.34E-07	8.06E-07	0.00011456	1.0215E-05	0.00077147
Particulate matter formation	EUR2015	0.2670	0.18081343	0.06629604	9.13E-05	9.39E-04	2.40E-03	7.20E-06	1.92E-05	0.00177726	0.00015698	0.01448978
Terrestrial ecotoxicity	EUR2015	0.00209	0.00092788	0.00065439	1.32E-06	1.31E-05	1.3987E-05	9.30E-08	1.67E-07	0.0001173	2.04E-04	0.0001531
Freshwater ecotoxicity	EUR2015	0.00181	0.00095988	0.0003599	2.46E-07	1.34E-05	4.89E-05	9.04E-08	3.70E-07	3.46E-05	2.65E-06	0.00039085
Marine ecotoxicity	EUR2015	0.000	0.00017421	6.5822E-05	4.41E-08	2.4433E-06	9.6167E-06	1.71E-08	6.87E-08	0.000006	4.86E-07	7.1435E-05
Ionising radiation	EUR2015	0.067	0.00693007	0.00136902	1.80E-05	0.00015505	4.5279E-05	1.46E-06	5.49E-06	0.00010276	1.4903E-05	0.05847169

2019  
2015

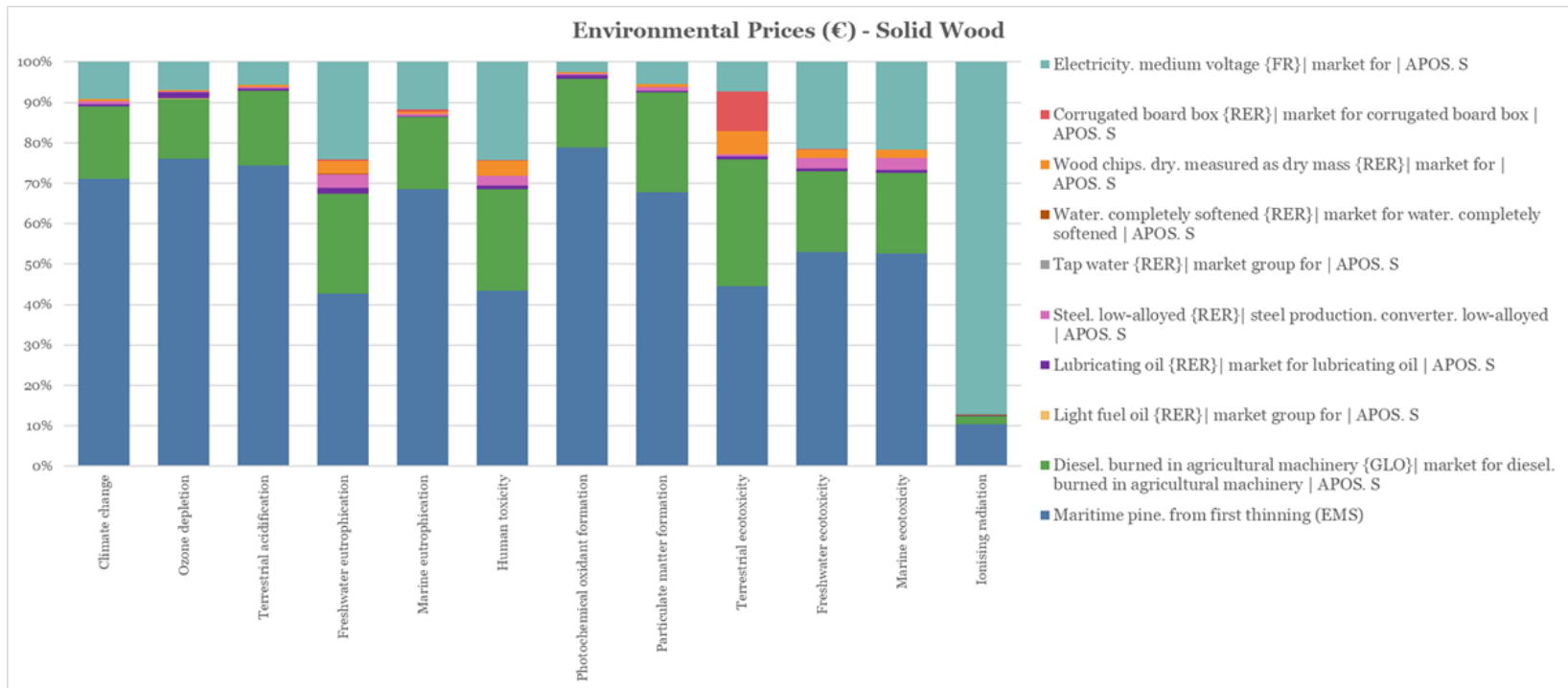


Figure 28: Relative contribution of each production elements of construction wood in environmental impact categories costs.

Figure 28 shows the relative environmental impacts cost contribution of different material and energy flow types in the solid wood production process based on life cycle impact assessment (ReCiPe 2016) results and the LCC cost model (Environmental price, Bruyn et al., 2018) in SimaPro for maritime pine. The first thinning was the most responsible for the environmental impacts cost, with a ratio of 63%, which contributes significantly to the cost results from climate change among the different production elements of construction wood.

## Discussion:

The finding of the Simapro software life cycle cost model of solid wood production process shows that in addition to the CapEx and OpEx cost there is significant environmental impact cost result during production process from acquisition of raw material to production of final products that should be taken in consideration when we study the life cycle cost of any product or project assets. Somewhat surprisingly, maritime pine from first thinning tends to dominate the overall environmental impact cost of the life cycle cost of solid production processes and has the greatest environmental impacts costs (accounting for 63% of total environmental impact cost of production process), which contributes significantly to the cost result from climate change with about 71% of total climate change impact cost. The consumption of fuel is site specific in harvest process, logging, skidding and assemble logs in the log yard and transportation from log yard to sawmill. Finding of this study contradict those of Liang et al. (2021), whereas main contributor of cost the factory in mentioned while it is the harvesting process in our study, and also the finding of our study is in contradiction to those of Diederichs, S. K. (2014); these differences between our study and previous studies result from the drying method. It is the green dry method versus the kiln- drying method which is the most energy consuming procedure of all saw mill processes. The results confirm the hypothesis about the ability to assess the economic and environmental performance by integrating life cycle cost and life cycle assessment. In general, the limitation of our study was time and access to the data base of most of the wood products factories.

## Conclusion:

The result shows the differences between production steps in economic and environmental costs, raw wood is the greatest contributor in economic and environmental costs. It must be born in mind that this study was only conducted on a small group of wood products, and from that group only the CapEx of the sawmill was obtainable. Further research is hence needed to expansion the system boundary for economic and environmental impact assessment and include the factory capital and operating costs of each product.

### **5.7.2. Plywood:**

As presented in Table 26, the direct life cycle cost results for plywood production process were carried out using input-output analysis based on data from Wilson & Sakimoto (2005). It is evident that cost of chemical raw material is the highest among all input-output materials, followed by heat and raw material costs. The costs of formaldehyde in wastewater due to a general tax on polluting activity (TGAP), where the threshold was not met, is 150 tons per year.

Table 26: Direct life cycle cost results of Plywood production.

	Category	Category elements	Amount of 1m <sup>3</sup> of wood input	Price €/ unit	Cost for 1m <sup>3</sup> wood input €/unit	Share of plywood from 1m <sup>3</sup> wood input corresponding to percentage indicated in MFA 9%
products		Plywood(h)	0.48 m <sup>3</sup>	889.2 €/m <sup>3</sup>	379.44 €/m <sup>3</sup>	34.14€
Inputs	water	Water(a)	0.68 m <sup>3</sup>	0.073 €/m <sup>3</sup>	0.044 €/m <sup>3</sup>	0.004 €
	chemicals Raw material	Resin(b)	30.80 kg	4.1 €/kg	112.26€/ <sup>3</sup>	10.10 €
		Pin maritime pine.EMS	1.00 m <sup>3</sup>	56.69€/m <sup>3</sup>	50.40 €/m <sup>3</sup>	4.536€
	Energy	Diesel(c)	0.03 l	0.04 €/mj	0.047€/m <sup>3</sup>	0.004 €
		Electricity(d)	113.00 kwh	13.203 €/Mwh	1.49 €/m <sup>3</sup>	0.134 €
		Heat(e)	2400.00MJ	.0.007 €/kWh	4.00€	0.36 €
Outputs	Emission to air	Formaldehyde	0.03 kg	The general tax on polluting activity threshold was not met		
		Water	0.26 m <sup>3</sup>	No tax		
	Outputs to technosphere: waste treatment	Wastewater(g)	0.68 <sup>3</sup>	Pollution fee thresholds are not reached		
Total costs to convert 1m <sup>3</sup> of raw wood and all complementary material to plywood					168.1 €	

The following ecoinvent inventory flows were used: (a) Water-cooling, unspecified origin. RER; (b) Resin- Burned in building machine {GLO} | market for | APOS. U; (c) Diesel- Burned in building machine {GLO} | market for | APOS. U; (d) Electricity medium voltage {RER} | market group for | APOS. U; (e) Heat medium voltage {RER} | market group for | APOS. U; (g) Wastewater from plywood production {GLO} | market for | APOS. U; (h) Plywood for outdoor use {RER} | production | APOS.

The indirect LCC of plywood production process has been analyzed by the SimaPro LCC model using the inventory data mentioned, and the result is presented in Table 27. The results show that the environmental impacts costs of melamine formaldehyde are the highest among all elements of the plywood production process followed by heat with €3.55 and €2.79 respectively. While the smallest cost result from diesel. From all environmental impact categories, particular mater formation has the highest share of total environmental impact categories cost which mostly results from melamine formaldehyde and heat, followed by climate change which result from melamine and heat also.



Table 27: Costs of environmental impact of plywood production process corresponding to the percentage indicated in chapter three (MFA).

Percentage indicated in MFA		9%								
Impact category	Unit	Total	Maritime	Diesel.	Melamine	Wooden	Electricity.	Heat.	Wastewater	
<b>Total</b>		<b>7.1273663</b>	<b>0.2265246</b>	<b>0.0034174</b>	<b>3.5469218</b>	<b>0.0236889</b>	<b>0.5163195</b>	<b>2.7933763</b>	<b>0.0171178</b>	2019
<b>Total</b>		<b>6.09250</b>	<b>0.19363</b>	<b>0.00292</b>	<b>3.03192</b>	<b>0.02025</b>	<b>0.44135</b>	<b>2.38779</b>	<b>0.01463</b>	2015
<b>Total</b>	EUR2015									
Climate change	EUR2015	1.1	0.0482	0.00055	0.871411	0.0042867	0.0580	0.128	0.0049688	
Ozone depletion	EUR2015	0.00019	0.00002	2.05E-07	0.0001381	6.18E-07	0.00002	0.000020	2.66E-07	
Terrestrial acidification	EUR2015	0.86	0.0407533	0.00058	0.5408326	0.0035253	0.0291209	0.244	0.0017623	
Freshwater eutrophication	EUR2015	0.011	0.00010	5.46E-07	0.00753	4.684E-05	0.0005	0.002	0.0000850	
Marine eutrophication	EUR2015	0.021	0.000972	1.44E-05	0.01127	0.0001224	0.0015755	0.0066051	5.143E-05	
Human toxicity	EUR2015	0.67	0.0070486	3.352E-05	0.401250	0.0027206	0.0370261	0.219	0.0017075	
Photochemical oxidant formation	EUR2015	0.14	0.0110822	0.0001561	0.0532703	0.0003759	0.0032691	0.0755155	0.0002830	
Particulate matter formation	EUR2015	2.9	0.0814	0.0015579	1.090032	0.0087166	0.0614004	1.687	0.0053765	
Terrestrial ecotoxicity	EUR2015	0.027	0.0004	3.65E-06	0.013217	0.0001221	0.0006488	0.0123856	0.0001256	
Freshwater ecotoxicity	EUR2015	0.020	0.0004	9.01E-07	0.01538	9.914E-05	0.002	0.0027	0.0000583	
Marine ecotoxicity	EUR2015	0.0036	0.0001	1.76E-07	0.002704	1.786E-05	0.0003027	0.0005206	0.0000107	
Ionising radiation	EUR2015	0.29	0.0031	2.826E-05	0.024887	0.0002151	0.248	0.0095	0.0002030	

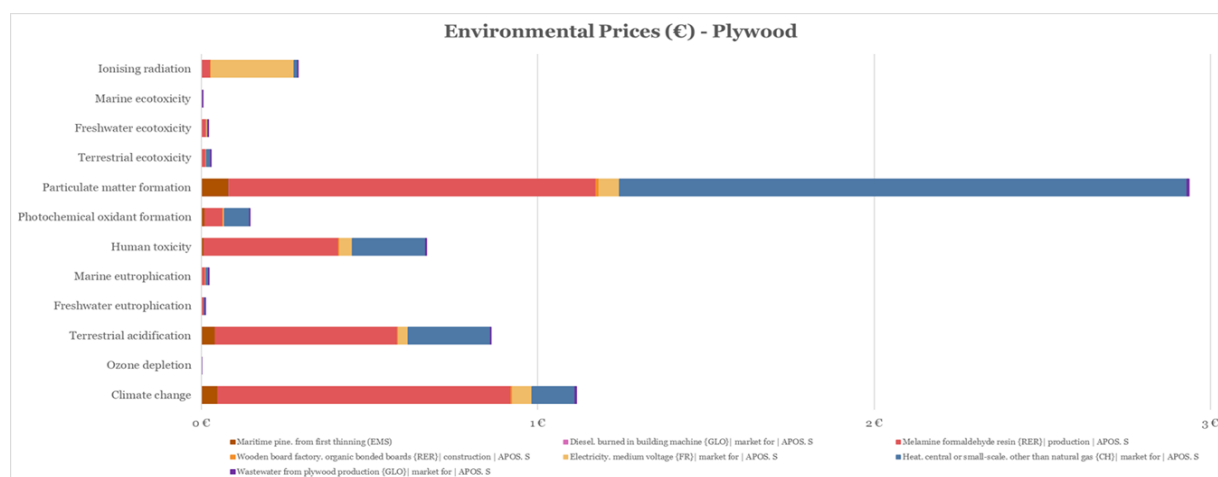


Figure 29: Relative contribution of each production elements of plywood in environmental impact categories costs.

Figure 29 represents the relative contribution of each production element in environmental impact categories costs, the Figure shows that the cost of particular matter formation is the highest cost among all impact categories followed by climate change with (48%, 18% respectively). Most amount of particulate matter formation results from the heat process. Therefore, investing in R&D to develop a more efficient heat method is advisable.

## Discussion:

The environmental impacts cost (external costs) has been identified for plywood production process by the SimaPro environmental LCC model. In the new global economy, determination of environmental impacts value has become a central issue for a decision-maker to take a sound decision to select between various projects (Pearce and Barbier, 2000). The result identifies melamine formaldehyde and heat as key elements of environmental impact cost with a contribution of 50% and 39% respectively. By comparing external cost and internal cost we could assess economic and environmental performance of plywood production process and partially solve market failure in determining the real cost of plywood products consequently specified by the precise price of products. The result of this study agrees with the study of Jia, L., Chu, J., Ma, L., Qi, X., & Kumar, A. (2019) in terms of the production elements that represent the highest environmental cost (Resin application and pressing hot press which means melamine and heat). This result is also in agreement with the result of Puettmann, M., Kaestner, D., & Taylor, A. (2020), in term of the plywood production process that is the key factor of environmental impact and consequently is costlier than raw wood harvesting and transportation.

Pyrolysis of bio-oil can be used to produce green resin to replace traditional phenolic formaldehyde (PF) resin to decrease the impacts of most of impact categories and consequentially the cost results from those. This result could serve as the foundation for a comparative study with a more extended system boundary. In general, our study was limited by time and access to the data bases of most wood products factories.

## Conclusion:

This chapter focuses on the costs of the environmental impact of plywood production in Landes-Gascogne, France. All production elements that contribute to the plywood production process. were assessed to obtain results and serve as decision-making indicators to help the wood-based panel industry develop and introduce alternatives in plywood processing to improve the environmental performance of production. Funding, time and access to the data bases of most wood products factories was the most limitation of This study study. This result could serve as the foundation for other studies with more comprehensive system boundaries to compare with alternative solutions

### **5.7.3 Unbleached Pulp:**

The cost input output elements of unbleached wood pulp production process have been estimated based on Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board data produced by Michael, S. U. H. R., Gabriele, K. L. E. I. N., Ioanna, K. O. U. R. T. I., Miguel, R. G., German, G. S., Serge, R. O. U. D. I. E. R., & Luis, D. S. (2015) .It appears from the Table 27 that the calcium oxide (quicklime, CaO) represents the highest costs followed by the wood raw material (46.56€/m<sup>3</sup> and 19.93€/ m<sup>3</sup> respectively). Water consumption is the smallest cost contributor in pulp production process.

Table 28: Input-output table of unbleached pulp production process.

		product	UB	Unit	Price/unit	B-Cost €/m <sup>3</sup> wood as input	Date	Cost I 2019	ost €Corresponding to MFA 45%	
Input	Raw material	wood	1.00	m <sup>3</sup>	22.42€/m <sup>3</sup>	22.42	2022	19.93€	8.97	
		water	13.33	m <sup>3</sup>	0.0118€/m <sup>3</sup>	0.16	2022	0.14€	0.063	
	chemicals	Caustic soda/sodium hydroxide(NaoH)	3.33	kg	0.73€/kg	2.43	2021	2.24€	1.00	
		Calcium oxide (quicklime, CaO)	1.67	kg	31.36€/kg	52.37	2022	46.56€	20.95	
	Energy	Total electricity	270	kWh	9.46€/MWh	2.55	2018-2019	2.55€	1.14	
	Soild waste	Other ashes	2.33	kg	200€/ton	0.466 €/kg	2017	0.5€	0.23	
		Fiber	0.83	kg	reintro- duced into the process / low quality paper					
		Wood waste	1.00	Kg	*					
		Dregs, grit and green liquor sludge	3.33	kg	**					
		Lime (with non-process elements)	3.33	kg	***					
		Hazardous waste	0.03	kg	****					
		Wastewater sludge treatment cost treatment sludge	1.67	kg	*****					
	Waste water	Nitrogen	0.17	g	0.33€/kg	0.000056			0.000056	0.000025
		Phosphorus	8.33	g	0.44 €/kg	0.003667			0.003667	0.0017
		Suspended solids	0.54	g	0.13 €/kg	0.0000702			0.0000702	0.0000315
		Cd	0.01	g						
		Pb	0.05	g	0.77 µg/l :					
		Cu	0.08	g	METOX					
		Cr	0.03	g	(µg/l) : 10 x					
		Ni	0.07	g	[As] + 10 x					
		Zn	0.83	g	[Pb] + 50 x	0.000104			0.000104	0.000047
	Air emissions	Nox	0.37	kg	175.48€/ton	free quotas	2021			
		Sulfur	0.27	kg	145.38€/ton	by the State	2021			
		VOC	0.37	kg	145.38€/ton	(gascony)	2021			
	By-product (sold )	Cured tall oil	12.50	kg	0.99€/kg	12. 375	2021	11.44€	5.15	
Crude sulfate turpentine		2.50	kg	3.86€/kg	9.655169428	2021	8.93€	3.73		
Main product	Kraft pulp	0.17	t	873.11€/ton	145.5189254	2018-2019	148.43€	66.79		

\* with classic process wood waste are bark and sometimes are used as biofuel for factory with wood waste from other factories

\*\* the green liquor is regenerated into white liquor (see water sheet diagram for Gasconne)

\*\*\*Gasconne papier valorizes lime for lime kiln Figures on their annual reports

\*\*\*\*Are sorted by factories, then collected and eliminated by waste gestion installations.

\*\*\*\*\* probably treated by external installations as sludge is an “ultimate dechet” so won't be valorized but burned or buried.

The environmental impact costs of 12 impact categories resulting from input and output elements of the unbleached pulp production process were assessed again using the SimaPro software's life cycle cost model, the results are presented in Table 29 and show that heat is the most significant contributor to the environmental impact cost (23.96 € to convert 1 m<sup>3</sup> raw wood to unbleached pulp) followed by maritime pine (raw wood) (1.13 €). The total environmental impact cost results from converting 1m<sup>3</sup> of maritime pine to unbleached pulp is (27.19€) (159.94 €/ton).

Table 29: Costs of environmental impact of un bleached pulp production process corresponding to the percentage of MFA

Percentage indicated in MFA		45%												
Impact category	Unit	Total	Maritime	Sodium	Quicklime.	Heat. from	Electricity.	Wastewater	Wood ash	Ash from	Waste	Green liquor	Hazardous	
Total		27.1933603	1.13262304	0.54881057	0.08816994	23.9640122	0.38425595	0.11662762	0.68869865	0.12425053	0.05506666	0.09012609	0.00071914	2019
Total		23.2450	0.9682	0.4691	0.0754	20.4845	0.3285	0.0997	0.5887	0.1062	0.0471	0.0770	0.0006	2015
Total	EUR2015													
Climate change	EUR2015	10.3	0.24121699	0.10974067	0.04930429	9.74381265	0.05900243	0.02610484	0.00088119	0.00066164	0.00318613	0.02821544	0.00015903	
Ozone depletion	EUR2015	0.00281	9.2228E-05	0.000146	5.19E-06	0.00253542	1.54E-05	7.44E-06	3.15E-07	4.35E-07	1.02E-07	2.99E-06	1.53E-08	
Terrestrial acidification	EUR2015	3.59	0.20376657	0.06166982	0.0061531	3.25	0.04885673	0.01040258	0.00057697	0.00055095	0.00132786	0.00931325	6.4178E-05	
Freshwater eutrophication	EUR2015	0.106	0.00051891	0.001803	3.17E-05	0.03	0.001166	0.00098206	0.004883	0.06457662	1.13E-05	0.00025775	2.04E-06	
Marine eutrophication	EUR2015	0.083	0.00485994	0.00174764	7.9809E-05	0.03754449	0.00164571	0.01122351	2.49E-05	0.02067812	0.00489047	0.00021002	1.90E-06	
Human toxicity	EUR2015	2.13	0.03524302	0.07424644	0.00252352	1.35	0.04809636	0.01030712	0.56989962	1.80E-02	0.00323271	0.01358897	8.1364E-05	
Photochemical oxidant formation	EUR2015	0.399	0.05541096	0.00701472	0.00099549	0.32325599	0.00841921	0.00181258	8.9038E-05	1.16E-04	0.00051977	0.00161267	1.38E-05	
Particulate matter formation	EUR2015	6.2	0.40683022	0.19609056	0.01516431	5.30	0.15099975	0.03374516	0.00135734	0.00133364	0.03309993	0.02250086	0.00028039	
Terrestrial ecotoxicity	EUR2015	0.096	0.00208772	0.00171137	0.0002253	0.08	0.00346751	0.00308365	0.00870943	2.10E-05	0.00071466	0.00024619	4.04E-06	
Freshwater ecotoxicity	EUR2015	0.0272	0.00215973	0.00231262	2.67E-05	0.02	0.00199291	0.0004748	0.00185805	0.00020045	6.1408E-05	0.0003211	2.99E-06	
Marine ecotoxicity	EUR2015	0.0057	0.00039198	0.00042032	8.31E-06	0.00	0.000367	8.842E-05	0.00034776	3.76E-05	1.11E-05	6.1068E-05	5.85E-07	
Ionising radiation	EUR2015	0.38	0.01559265	0.01222238	0.00085031	0.35	0.0044349	0.00146162	7.5201E-05	6.4677E-05	1.58E-05	0.00070984	4.44E-06	

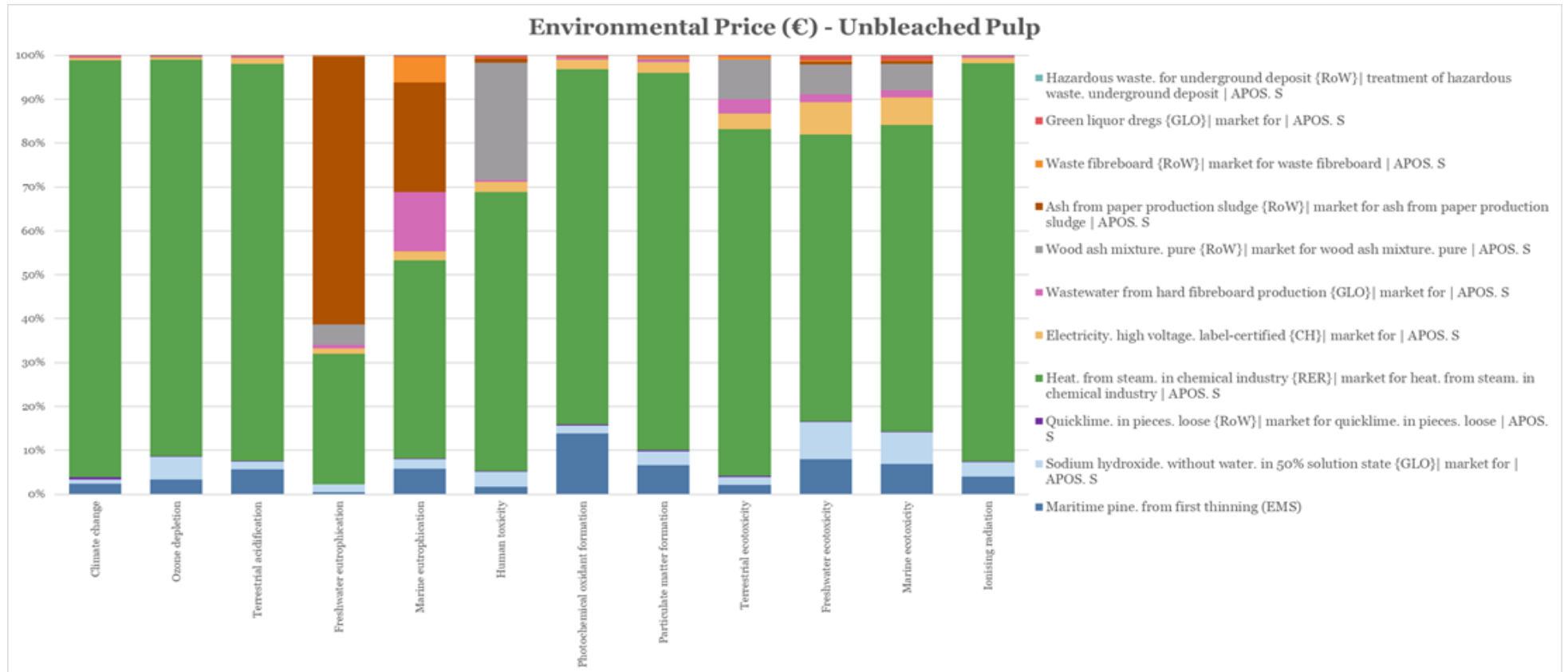


Figure 30: relative contribution of unbleached pulp production process elements in environmental impact costs.

The environmental impact costs of unbleached pulp production process elements of twelve impact categories” has been assessed using the SemaPro software’s life cycle cost model and presented in Figure 30. The Figure shows that heating has the highest environmental impact cost, accounting for 85% of the total environmental impact cost, followed by maritime pine raw wood at 4%. And climate change and particular matter formation were having the highest cost among all impact categories which represent (44%, 27%) respectively both of them results from heat in production process.

According to the results of the applied SimiPro software life cycle cost analysis model, the production of unbleached pulp resulted in varying amounts of emissions, which created environmental costs in different types of environmental impact categories that were determined in this study. The key environmental impact cost element is heat as a result of an intensive user of energy in heating, which accounts for 85% of the total environmental impact cost. In agreement with other related articles focused on pulp (Jawjit et al., 2006; Gonzalez-Garcia et al., 2009b), this situation is unsustainable and contributes to economic and political vulnerability (Sammons et al., 2007). Raw wood, which includes forest activity, is the next highest contributor to the environmental impact cost of the pulp production process, accounting for 4% of the total. This finding contradicts the findings of previous studies such as Jawjit et al. (2006), Gonzalez-Garcia et al. (2009a), Lopes et al. (2003), and Dias et al. (2007). This finding has the potential to become the basis for a comparative investigation of a system boundary that is more extensive. In general, time constraints and a lack of access to the databases of most wood product firms hampered an intense work environment during this research.

#### Conclusion:

The results indicate that the heat is the greatest contributor of environmental impact cost among all of pulp production elements. This chapter not only investigates the environmental impact cost of pulp production input and output elements, but it also raises the issue of the pulp factory’s CapEx and OpEx to conduct a comprehensive evaluation. It should be noted that this study only looked at the environmental impacts of the input and output costs of unbleached pulp production from harvesting to final products, excluding pulp factory CapEx and OpEx. That means more work is needed to extend the system boundaries of the product studied with regard to forestry and alternatives and to include all CapEx and OpEx data and related calculations in the evaluation process.



#### **5.7.4. Pellets:**

This chapter will start with a table of the inputs and outputs of the pellet production process. This will show the amount of input materials and their prices, as well as the types, amounts, and prices of outputs that have a negative impact on the environment (emissions and waste), as well as the amount of final product that can be made from one cubic meter of raw maritime pinewood. The negative environmental impact of the pellet production process will then be assessed for the 12 impact categories specified in this study using the LCC model in SimaPro software. For the life cycle inventory for this wood products this study depends on the data from Reed, D., Bergman, R., Kim, J. W., Taylor, A., Harper, D., Jones, D., ... & Puettmann, M. E. (2012) and the data has been adjusted to maritime pinewood in Landes Gascogne, France in 2019. The results, as shown in Table 30, indicate that the greatest costs are represented by Maritime pinewood (logs + by-products), and followed by the amount of electricity consumed during the production process (27€, 5.67€) respectively. Most of the air emission outputs from the production process doesn't reach the thresholds established of the general tax on polluting activities (TGAP).

Table 30 Input-output table of pellets production process

	Material	For 1 ton of woods pellets		For 1m <sup>3</sup> of wood as input-UF)		Price	cost for 1 ton of wood pellets	cost for 1m <sup>3</sup> of wood as input
		Amount	Unit	Amount	Unit			
Daniel Reed et al.								
Inputs	Maritime pinewood (logs + by-products)	1.20E+00	t	1.00E+00	m <sup>3</sup>	27.0€/m <sup>3</sup>	32.50€	27.0€
	Polyethylene (for 50kgbags)	3.57E-04	kg	1.34E-04	kg	1.87€/kg	0.00067€	0.00025€
	Electricity	1.58E+02	kWh	5.93E+1	kWh	95.68€/MWh	15.12€	5.67E+00€
	Diesel	8.60E-01	liters	3.23E-01	l	0.04Mj	1.31€	0.49€
Air emission	CO	2.43E-03	kg	9.11E-04	kg	No Tax	No tax	
	CO <sub>2</sub> Fossil	2.73E+00	kg	1.02E+00	kg	24.0 tons	**	**
	NO <sub>x</sub>	3.09E-01	kg	1.16E-01	kg	175.48€/ton		
	SO <sub>2</sub>	4.00E-02	kg	1.50E-02	kg	145.38€/ton		
	CH <sub>4</sub> biogenic	3.60E-03	kg	1.35E-03	kg	600.00€/ton		
	CH <sub>4</sub> Fossil	5.53E-05	kg	2.07E-05	kg	600.00€/ton		
NM <sub>VOC</sub>	2.72E-02	kg	1.02E-02	kg	145.38€/ton			
Waste	Ashes to landfill	2.14E+00	kg	8.03E-01	kg	200.00€/ton	0.43€	0.16€
Products	Pellets	1.00E+00	t	3.75E-01	t	203.63€/ton	203.63€	76.36€

\*\* Threshold of general taxation on polluting activities doesn't reach

The environmental impact costs of the twelve impact categories specified in this study and the results during the pellet production process from gate to gate (from harvesting to final products) have been assessed using the LCC analysis model in SimaPro software. The results are represented in Table 31, and they indicate that the largest amount of cost results from electricity, followed by maritime pine (from first thinning) to final harvesting) (0.276, 0.33€, respectively), and that ionizing radiation and climate change are the two greatest environmental impact categories among those considered in this study.

Table 31: Costs of environmental impact of pellets production process corresponding to the percentage of MFA described in chapter 3

Impact category	Unit	Total	Maritime pine. from	Diesel. burned in	Packaging film. low	Electricity. medium	Wood ash mixture.	
<b>Total</b>		<b>0.75350739</b>	<b>0.27686341</b>	<b>0.05592047</b>	<b>8.4582E-06</b>	<b>0.33088616</b>	<b>0.08982889</b>	<b>2019</b>
<b>Total</b>		<b>0.64410</b>	<b>0.23666</b>	<b>0.04780</b>	<b>0.00001</b>	<b>0.28284</b>	<b>0.07679</b>	<b>2015</b>
<b>Total</b>	<b>EUR2015</b>							
Climate change	EUR2015	0.11	0.05896415	0.00967789	2.38E-06	0.03717835	7.97E-05	
Ozone depletion	EUR2015	3.55E-05	2.2545E-05	2.83E-06	1.33E-10	1.00E-05	7.03E-08	
Terrestrial acidification	EUR2015	0.077	0.04980961	0.008094	1.04E-06	0.01866228	6.64E-05	
Freshwater eutrophication	EUR2015	0.0012	0.00012685	4.7779E-05	2.34E-08	0.00035193	6.40E-04	
Marine eutrophication	EUR2015	0.0024	0.00118799	0.00020113	2.60E-08	0.0010097	1.11E-06	
Human toxicity	EUR2015	0.11	0.00861496	0.00324952	8.71E-07	0.02372841	0.07442247	
Photochemical oxidant formation	EUR2015	0.018	0.0135449	0.00190271	1.98E-07	0.00209503	1.05E-05	
Particulate matter formation	EUR2015	0.16	0.09944739	0.02374789	2.43E-06	0.03934881	0.00014739	
Terrestrial ecotoxicity	EUR2015	0.0023	0.00051033	0.00023441	1.93E-08	0.00041578	0.00112458	
Freshwater ecotoxicity	EUR2015	0.0020	0.00052793	0.00012892	2.41E-08	0.00106139	0.00024227	
Marine ecotoxicity	EUR2015	0.00036	9.5818E-05	2.3578E-05	4.42E-09	0.00019399	4.535E-05	
Ionising radiation	EUR2015	0.16	0.00381154	0.00049039	2.12E-07	0.1587872	6.30E-06	

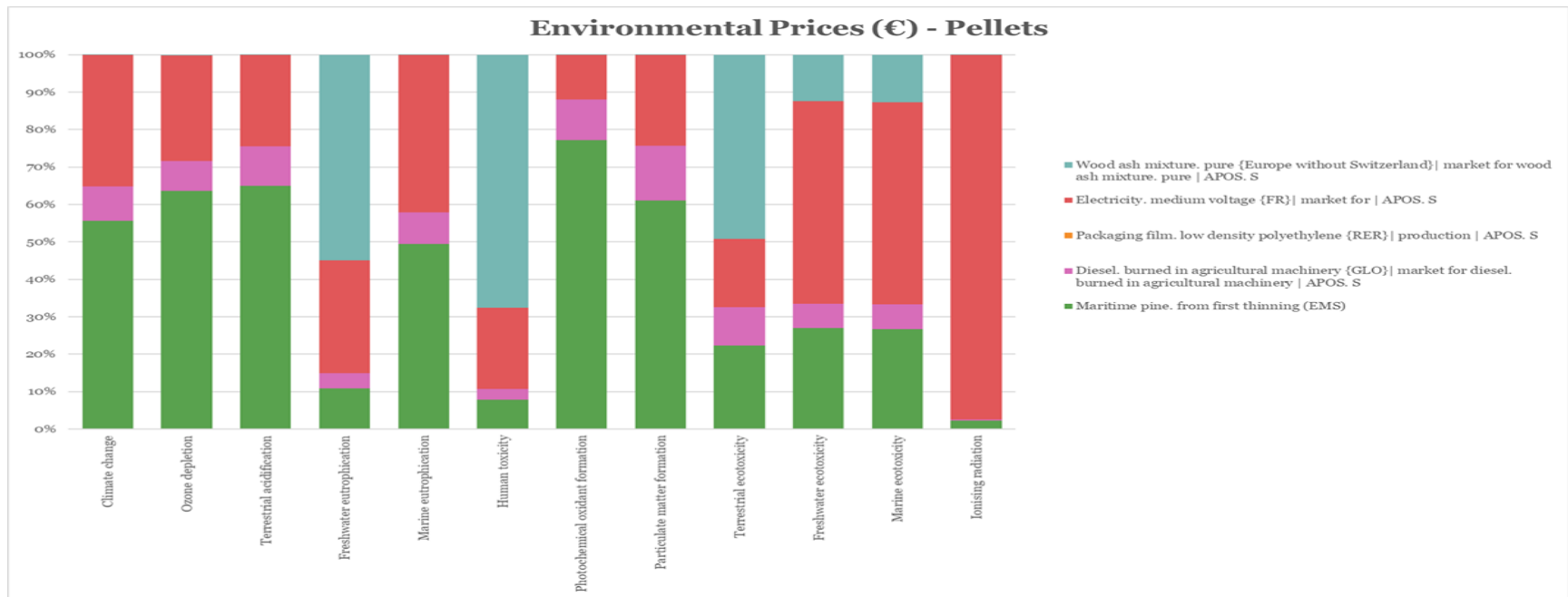


Figure 31: Relative contribution of pellets production process elements in environmental impact costs.

The cost of twelve impacts categories result from pellet production have been assessed using life cycle cost analysis model in SimaPro software represented in Figure 31. The cost of maritime pine, from first thinning is the most significant environmental impact category cost. It is responsible for 36% from the total cost of environmental impact categories among production elements and which is the main cause of climate change. The second contributor in the cost environmental impact is electricity which represent 19% and it is the cause of ionizing radiation impact category.

## Discussion:

This study found that the manufacture of pellets resulted in varied levels of emissions, which resulted in environmental costs in various sorts of environmental impact categories. The biggest expense in the environmental effect category is the cost of maritime pine, from first thinning. It is the dominant driver that contributes to climate change and is responsible for 36% of the total cost of environmental impact categories that are associated with production aspects due to the amount of fuel consumption in thinning and final harvesting. Electricity is the second largest contributor to the cost of environmental impact, accounting for 19% of the total, and it is the primary factor responsible for the category of ionizing radiation impact, the large consumption of electricity is due to grinding and pelletizing (press with heating).

Despite the difference between the kind of wood raw materials, the study results are in agreement with the Pergola, M., Gialdini, A., Celano, G., Basile, M., Caniani, D., Cozzi, M., ... & Ripullone, F. (2018) study from where the electricity is the one of the main of environmental impact cost contributor among the pellets production elements. The environmental impact result from pellets production in our study is less significantly compared with the mentioned previous study due to the kind of raw wood used in the production process. In the study of Pa, A., Craven, J. S., Bi, X.T., Melin, S., & Sokhansanj, S. (2012) harvesting is the second highest impacting process and consequently harvest is the second highest costing process. More time and funding for this study to include capital and operation constant to extend the system boundaries to include all stage of pellet life cycle from cradle to grave are the most important to get a more comprehensive picture This study can serve as a link to other procedures related to this study, whether in the background or foreground, in order to cover the environmental impact and environmental cost of all pellet life cycle stages.

## Conclusion:

The purpose of this section was to analyze the costs associated with the twelve different types of environmental impacts caused by the various aspects of pellets production. The findings show that, out of all the pellets manufacturing steps, the maritime pine from initial harvesting is the largest contributor of environmental impact cost. In addition to assessing the environmental costs associated with producing pellets, this chapter also raises the question of the pellets factory's CapEx and OpEx in order to undertake an extensive economic and environmental performance of pellets production process in Landes Gascogne, France. Based on these results, researchers should think about expanding the pellet production system's boundary and taking both CapEx and OpEx into account during the evaluation process.

### **5.7.5. Pallet:**

This chapter will begin with a table of the pallets production process's inputs and outputs. This will indicate the amount of input materials and their prices, as well as the types, amounts, and prices of outputs with an environmental impact (emissions and waste), as well as the amount of final product that can be made from one cubic meter of raw maritime pinewood. The negative environmental impact of the pallets production process will next be examined using the LCC model in SimaPro software for the 12 impact categories indicated in this study. This study's life cycle inventory for these wood products is based on data from the statistics of pallet production inputs and outputs shown in Table 32. As indicated in Table 32, the cost of Maritime pinewood from first thinning is the highest among all input/output materials followed by steel nails (46.7€), (28.9€) respectively.

Table 32: Input output table of pallet production

4.Pallets	Material	Amount of 1m <sup>3</sup> of wood as input)		Price	Price for 1m <sup>3</sup> of wood as input(UF)	Cost amount in €(2019) share of construction wood wood corresponding to MFA %
		Amount	Unit			
Inputs	Sawn timber	1.00E+00	m <sup>3</sup>	169.00€/m <sup>3</sup>	46.7€	7.01€/m <sup>3</sup> (ub)
	Steel nails	6.37E+00	kg	800.00€/ton	28.9€	4.33
	Alkyd paint	4.07E-01	l	1.64€/l	0.82€	0.12
	Light fuel oil	0.0	-	-	-	
	Electricity	2.94E+01	kWh	1.26E02€/MWh	3.70€	0.56
	Gas	1.58E+01	KWh	0.05€/KWh	0.79 €	0.46
Outputs and by-products	Wood Pallet	3.54E+02	kg	0.42€/kg	255.9€	
	Wood waste*	1.33E+01	kg	internal valuation *	Internal valuation	
	Sawdust	2.57E-03	t	42.64€/ton	0.13€	0.019
	Planches	1.07E-02	t	32.43€/ton	0.41€	0.06
Products	Nb.of pallets	1.54E+01	p	16.62 €/piece	255.9	

\* With the classic process, wood waste is mostly bark and sometimes used as biofuel for factories with wood waste from other factories.<https://www.georisques.gouv.fr/risques/installations/donnees?page=1> ICPE reports from factories sometimes give this information



Using the LCC analysis model in SimaPro software, the environmental impact costs of the twelve impact categories indicated in this study, and the input output data during the pallet production process from gate to gate (harvesting to final products) have been evaluated. The results are summarized in Table 33, which reveals that steel results the greatest cost, followed by maritime pine from first thinning (EMS) to final harvesting (0.57 €/m<sup>3</sup>, 0.377€/m<sup>3</sup> respectively) of raw material, and that particulate matter formation and climate change are the two environmental impact categories with the greatest magnitude among those considered in this study, the most amount of them released for steel consumption

Table 33: Environmental impact cost of pallet production corresponding to the percentage of MFA described in chapter 3

Percentage indicated in MFA		15%							
Impact category	Unit	Total	Maritime pine. from	Electricity. medium	Natural gas. burned in	Alkyd paint. white.	Steel. low-alloyed	Waste wood.	
<b>Total</b>		<b>1.37394488</b>	<b>0.37754101</b>	<b>0.22373844</b>	<b>0.05281528</b>	<b>0.1163033</b>	<b>0.57329401</b>	<b>0.03025283</b>	2019
<b>Total</b>		<b>1.17445</b>	<b>0.32272</b>	<b>0.19125</b>	<b>0.04515</b>	<b>0.09942</b>	<b>0.49005</b>	<b>0.02586</b>	2015
<b>Total</b>	<b>EUR2015</b>								
Climate change	EUR2015	0.28	0.08040566	0.02513924	0.03162729	0.01979114	0.11530443	0.00541278	
Ozone depletion	EUR2015	0.000057	3.0743E-05	6.77E-06	5.19E-06	2.97E-06	1.08E-05	8.17E-07	
Terrestrial acidification	EUR2015	0.16	0.06792219	0.01261905	0.00371434	0.02206485	0.04934446	0.00222295	
Freshwater eutrophication	EUR2015	0.0023	0.00017297	0.00024	8.07E-06	0.00019197	0.001709	2.2714E-05	
Marine eutrophication	EUR2015	0.0071	0.00161998	0.00068274	5.0086E-05	0.00108269	0.00127583	0.00241452	
Human toxicity	EUR2015	0.127	0.01174767	0.01604466	0.00199758	0.00791443	0.07982603	0.00914001	
Photochemical oxidant formation	EUR2015	0.032	0.01847032	0.00141662	0.00076133	0.00132514	0.00953511	0.0005951	
Particulate matter formation	EUR2015	0.43	0.13561007	0.02660686	0.00650444	0.03574374	0.22	0.00569252	
Terrestrial ecotoxicity	EUR2015	0.0125	0.00069591	0.00028114	0.00031567	0.00977695	0.00129655	0.00014205	
Freshwater ecotoxicity	EUR2015	0.0064	0.00071991	0.00072	9.2262E-05	0.00030244	0.00453046	7.1287E-05	
Marine ecotoxicity	EUR2015	0.00123	0.00013066	0.00013117	6.07E-06	5.5318E-05	0.00089143	1.34E-05	
Ionising radiation	EUR2015	0.118	0.00519755	0.10736865	6.4411E-05	0.0011649	0.00419721	0.00013208	

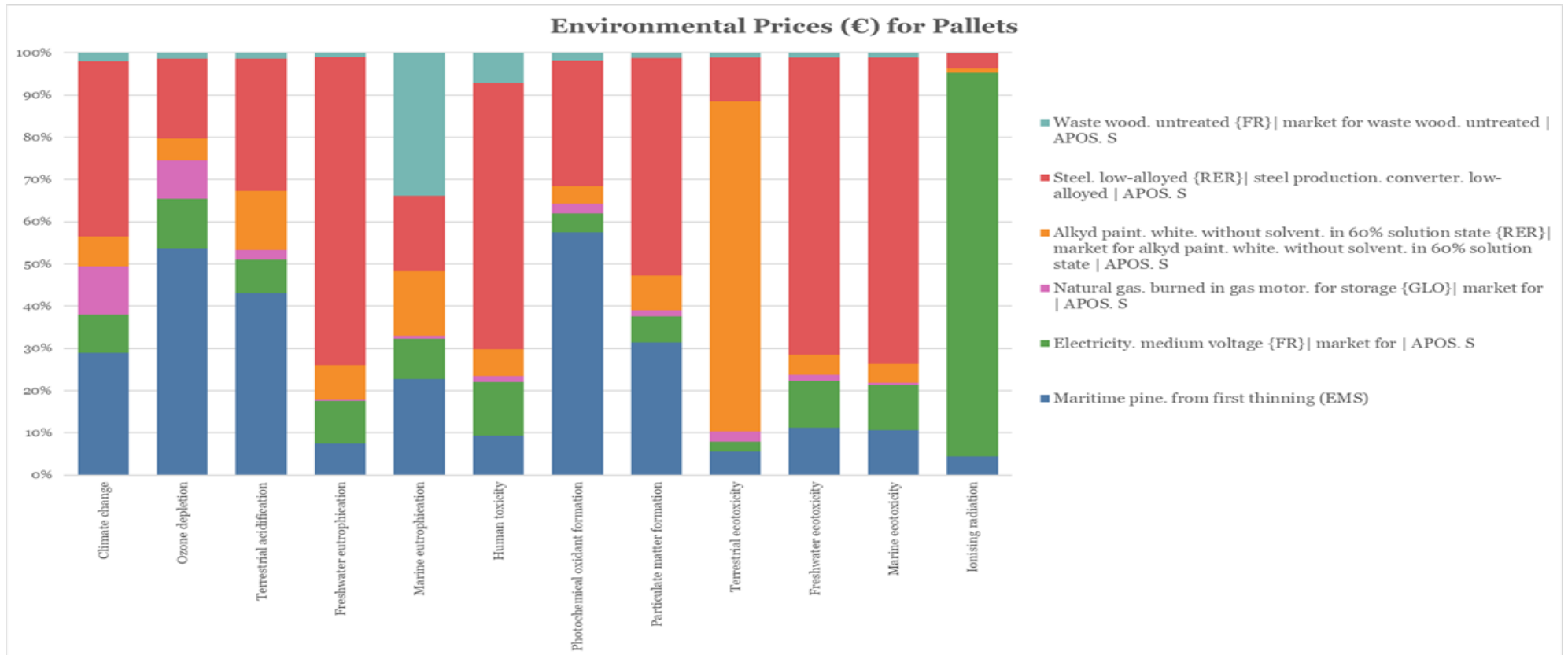


Figure 32: Relative contribution of pallet production process elements in environmental impact costs.

Using the SemaPro software’s life cycle cost model, the relative contribution of the environmental impact costs of pallet production elements in each of the twelve impact categories was calculated and shown in Figure 32. The graph shows that steel has the highest cost to the environment, at 42% of the total cost. The next highest cost is raw maritime pinewood, at 27%. And particulate matter formation and climate change have the highest costs of all the different types of impact categories.

### Discussion:

The results of the Simapro software life cycle cost model of the pallet production process show that, in addition to the CapEx and OpEx costs, there are also significant environmental impact costs that should be taken into account when we look at the life cycle cost of any product or project asset. The greatest expense in the category of environmental effects is the cost of steel. It is the leading contributor to particular matter formatting and climate change and accounts for 42 percent of the overall cost of environmental impact categories linked with production aspects. The maritime pinewood from first thinning is the second largest contribution to the cost of environmental effect, accounting for 28 percent of the total cost. This study is in agreement with the study of García-Durañona et al. (2016) from where the steel is the largest contributor in environmental impact cost among all pallet production elements categories. The most crucial factors for a further development of this study are again time and funds for the inclusion of capital and operating costs as well as its extension of the system boundary to cover the entire pallet life cycle from cradle to grave. In order to cover the environmental cost and impact of every stage of the pellet life cycle, this study can be used as a link to other processes that are associated with it, whether they are carried out in the foreground or the background.

### Conclusion:

This section wraps up the research project by giving a summary of the most important findings in terms of the research questions and goals. It will also discuss the study's limitations and offer suggestions for further research. This chapter's objective was to assess the monetary value of the twelve distinct environmental consequences resulting from the production of pellets. The research revealed that steel is the component with the greatest cost-related environmental impact of all those used in pallet manufacturing. In order to conduct a complete economic and environmental performance analysis of the pallet production process in Landes Gascogne, France, this chapter does not only evaluate the environmental costs involved with creating pallets but also raises the issue of the pallet factory's CapEx and OpEx. Based on these findings, researchers ought to consider broadening the scope of the pallet production system and considering both CapEx and OpEx throughout the evaluation

process in order to address the market failure caused by the neglecting external cost of the products studied.

Scholars usually use LCA and LCC (e.g., Rebitzer 2002; Kloepffer and Renner 2008) to measure and compare the environmental and economic sustainability of product systems (Kloepffer 2008). LCA is a non-financial tool that involves putting together and evaluating the inputs, outputs, and possible environmental effects of a product system over its entire life cycle. These effects cannot be easily internalized as costs in the frame of ISO 14040, 2006), while LCC according to ISO/DIS 15686-5.2: 2016, is a financial tool for the systematic economic evaluation of life-cycle costs throughout an analysis period. According to the study's scope, it encompasses (a) real internalized costs and revenues (traditional LCC) and (b) predicted external costs and revenues paid for by third parties and relevant to decisions over the planning horizon (environmental LCC).

To increase the transparency of resource flows and to modify the flow structure of LCA and LCC through its categorization technique, another monetary instrument called MFCA should be applied. In order to accomplish this, MFCA classifies all product system input and output flows by material, energy, waste, and system flows and finds internalized cost drivers not just for desired product output but also for undesirable non-product output (ISO 14051: 2011). Thus, MFCA can act as a bridge between LCC and LCA (Bierer et al., 2015: 1289) in order to improve the evaluation of resource productivity and economic-environmental performance. This will be done in the sixth chapter.

This chapter will include part of the study (monetary value of environmental impacts) by summarizing the key research findings in relation to the research questions, as well as the value and contribution thereof. It will also review the limitations of the study and propose opportunities for future research.

This chapter aimed to investigate the monetary value of the environmental impact of twelve impact categories resulting from converting 1 m<sup>3</sup> of raw wood material to each of the five studied products (Unbleached pulp, plywood, pallets, pellets, and construction), in addition to Capex and Opex of construction wood with the system boundary specified in this study. Further, findings show that construction wood has the lowest environmental cost. While plywood was the most environmentally expensive product among the five studied products, System boundaries and data

availability were the main limitations of this study. Whereas the study was limited by the system boundary of Alliance forests Boi Company as mentioned in Chapter 3 (materials follow analysis) and focused on the first wood transformation and didn't go to the second and third stages, On the data availability side, there is a lack of capital and operation cost data for Unbleached pulp, plywood, pellets, and pallets. Furthermore, because ambiguity can arise, extra extensions must be made to system boundaries, assumptions, and methodological concerns, which in turn cloud the Capex and Opex of unbleached pulp, plywood, pallets, and pellets. The results of this study could be relevant in making decision strategies, particularly for forest-based companies using maritime pine as the primary raw material.



## **CHAPTER 6**

# **Integrating Material Flow Cost Accounting and Life-cycle assessment of five wood products industries in Landes Gascogne, France**

### **6.1. Introduction**

According to the United Nations Environment Programme (2010) and the Commission of the European Communities (2011), our consumption and production habits have a negative influence on the environment, and the earth can no longer absorb the impacts of human activity indefinitely. However, natural resources are essential to industrial production and are required for value generation (Gutenberg 1983).

Numerous goods and services that are either traded in markets or not, but have a considerable value to people's well-being, are provided by forestry to society. Through the sustainable management of forest resources, forest science enables forest groups or the Public Forest Service to offer these goods in an economically viable manner. Through the sustainable management of forest resources, forest science enables forest groups or the Public Forest Service to offer these goods in an economically viable manner. However, more than 300 years ago, von Carlowitz described sustainability for the first time in this field (1713). Through the years, von Carlowitz's idea of "timber-maintained yield" has grown into an integrated approach to sustainability that encourages the prudent use of natural resources (Pearce & Atkinson, 1993). In order to achieve this goal, forest organizations must assess both the goods' and services' positive and negative social and environmental impacts throughout the entire production chain.

The analysis of material flows and the accompanying environmental impacts of goods and services over their life cycles is made possible by life cycle management, which is a significant strategy used by businesses to meet this challenge (Hunkeler et al., 2003; Power, 2009; Sonnemann & Margni (Eds.), 2015). As a result, it can significantly ease the tension between economic and environmental trade-offs, while promoting resource security, sustainable innovation, and



even competitive advantages (Porter & Van der Linde, 1995; Hunkeler et al., 2003; Power, 2009).

For quantifying the detrimental effects of production processes in operations and organizations, a number of approaches have been put forth. The material and energy flows and their effects on sustainability are revealed by methodologies like life cycle costing (LCC), life-cycle assessment (LCA), material flow analysis (MFA), and environmental management accounting (EMA) (Jasch, 2003).

Integrated economic and ecological decision making is gaining in significance. LCA and LCC are promising tools for the modeling and calculation of the respective consequences. Scholars often recommend life-cycle assessment LCA and life LCC for simultaneous environmental and economic performance evaluations (Rebitzer 2002; Klopffer and Renner 2008). The first is a non-monetary instrument for visualizing environmental impacts that are difficult to embody as costs (ISO 14040: 2006), whereas the latter is a monetary tool for assessing internalized and, if relevant, external costs and revenues incurred by third parties (Hunkeler et al., 2008).

MFCA is proposed as a link between LCC and LCA (Bierer et al., 2015) to enhance their flow viewpoint. MFCA identifies internalized cost drivers for desired product outputs and undesirable non-product outputs (ISO 14051:2011) and functions at the nexus of production technology, the environment, and cost accounting and management (Burrill et al., 2002; Nakajima 2011; Guenther et al., 2017). A linkage of all three instruments is interesting for high-end integrated evaluations over the whole supply chain and life cycle.

The method appears to lack application on primary products, such as forestry products. This chapter therefore attempts to tie life-cycle assessment and life cycle costing by material flow cost accounting as a modern accounting tool to allocate and calculate the costs of all input-output of the production process during the specified system boundary of the studied products.

## **6.2. Methodology:**

Because the method appears to lack application on primary items such as forestry products, the current study investigated current trends in MFCA and applied it to woodland products and services. It is to be demonstrated

through an MFCA study and forestry examples that MFCA may be a beneficial tool for forest managers, whether in public forest service or other forestry organizations. As a result, the study question may be stated as follows: how can the forestry sector adapt MFCA and assist forest managers in improving decision-making and producing forest products in a sustainable manner?

In line with Papaspyropoulos et al. (2016), the proposed framework for applying material flow cost accounting in forestry is shown in Figure 33. The seven-step summary of the framework includes the three-step process for implementing MFCA outlined by Schmidt et al. (2015).



Figure 33: Forestry MFCA framework proposal. (Papaspyropoulos et al., 2016).

### 6.2.1. The boundary of the production process

The boundaries for the application of MFCA must be determined in Step 1. The cost centers of forest management include logging of natural stands, nursery production of forest plants, breeding of quarry species, management of public hunting lands, and engineering of forests. The use of MFCA can be made simpler by defining the limits of each cost center and its production process. Utilizing MFCA may be more challenging if all forest operations are viewed as a single process, although this is not always a bad thing.

### **6.2.2. The flow structure**

The flow structure needs to be modeled in Step 2. This entails tracking the locations and timing of material and energy inputs, as well as the timing and nature of desired and undesirable outputs. The flow structure modeling includes quantity center and flow. They can be regarded either as spatial or functional units that store, process, or otherwise alter materials, or, more simply, as operations such as receiving, machining, assembling, and storing (ISO, 2011; Strobel & Redmann, 2002). The frequent exchanges of materials between the quantity centers during the specified time are referred to as flows. In the flow structure modeling phase, material flows are determined in terms of the material(s) they contain, the quantity centers that constitute their source and sink, and their fundamental nature, desired or undesirable. A so-called flow structure model, which describes the investigated system by quantity centers, desired and undesired flows, and system boundaries, is the end result of the first stage of MFCA.

### **6.2.3. The Environmental Performance Indicator for monitoring the process**

The Environmental Performance Indicator (EPI) is any of the ways in which environmental outcomes and/or impacts can be assessed. Life cycle impact assessment methodology has been applied here using SimaPro software analysis to estimate environmental impact of five wood products specified in this study, as described in chapter 4. It will help forest managers and also the ownership of factories in step four to measure the materials and energy consumed in the process in terms of physical quantity. Step 3 will help measure the four costs categories of Step 5.

### **6.2.4. Measuring material and energy used in physical amount**

In Step 4, the measurement of flows, for each quantity center, all material inputs and outputs (flows) in addition to potential (stock) changes for the underlying time period are quantified. To ensure consistency, an input-output balance is produced for each quantity center, taking stock changes into account. This, in turn, necessitates the employment of suitable physical units. In this case, MFCA literature advises

using mass units or, at the very least, units that can be converted into mass units, such as length or the number of parts (ISO, 2011; Strobel and Redmann, 2002). Step 4 outputs are added to the flow structure model, which is then improved to become a flow quantity model.

#### **6.2.5. Measure material, energy, system and waste management cost**

The flow system is valued in monetary terms during Step 5 of MFCA, the cost assessment. The following common categories are distinguished by ISO 14051 (ISO, 2011) in this case:

##### **-Material Cost**

Each “substance that enters and/or departs a quantity center” has a cost, which is known as a material cost (ISO, 2011, p. 15). These are the only direct costs of MFCA and are calculated by multiplying a fixed material price by the flow and stock quantities. Cost related to materials includes material purchase cost and selling cost of scrap.

##### **-Energy costs**

Purchase costs of “electricity, fuels, steam, heat, compressed air, and other similar media” are referred to as “energy costs” (ISO, 2011). Each quantity center’s energy expenses should be determined based on the actual or expected energy use. The utilization of their mass ratio is suggested for allocation (indirect assignment) to the outgoing desired and undesired material flows.

##### **-Waste management costs**

Waste management expenses, which includes the cost of handling the waste, are the “costs of addressing material losses created in a quantity center” (ISO, 2011) and include actions such as reworking rejected items and recycling, tracking, storing, treating, or disposing of air pollutants, waste water, and solid wastes. They are exclusively assigned to substantial losses. If many undesirable material flows exit, a quantity center mass ratio is employed as the basis for allocation.

- System costs

The costs associated with managing internal material flows, excluding those for materials, energy, and trash, are represented by system costs. Depreciation, labor and maintenance costs, for instance, are included. System cost includes labor cost, depreciation cost, transportation, and maintenance cost. Cost categories are represented in Figure 34.

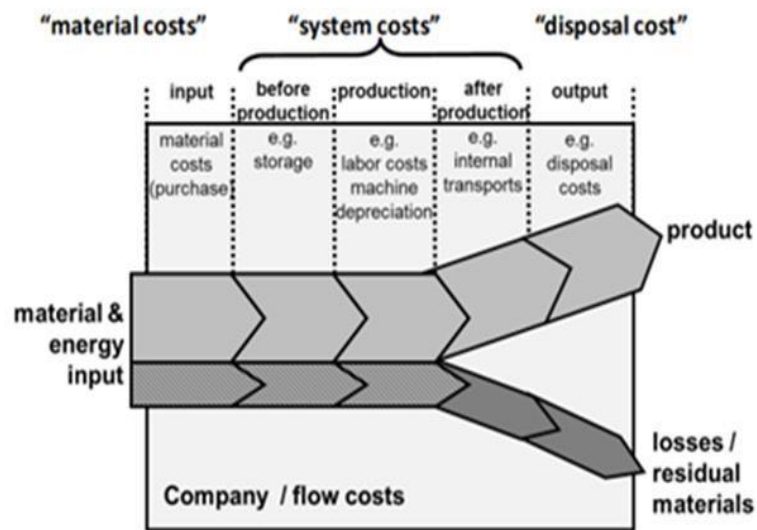


Figure 34: Division of the various costs associated with product and waste flows (Strobel, M., & Redmann, C. F. (2002).

**6.2.6. Suitable cost accounting techniques to allocated cost to desired and undesired products.**

During Step 6 an MFCA calculation model is created and the acquired data is entered. Positive and negative product costs can be apportioned using the mass balancing approach. The cost of positive product is the cost of process product that is released to the next process, whereas the cost of negative product is the cost of discarded or recycled products. The MFCA calculation results are checked and examined to identify negative product costs and their causes by the process.

### **6.2.7. Interpretation and evaluation**

In the interpretation and evaluation step the cost drivers and environmental implications are explained, the data's completeness is assessment and sensitivity analyses are carried out.

## **6.3. Results**

As indicated before, this chapter aims to tie life-cycle assessment and life cycle costing by material flow cost account to increase the transparency of material use practices through the development of a material flow model that traces and quantifies the flows and stocks of materials within an organization in physical and monetary units. This serves again the overall goal of the PhD thesis to find both economic and environmental performance of the production processes of the selected wood products pallet, plywood, pellets, construction wood and unbleached pulp within the defined system boundaries of this study from gate-to gate to help producers and other stakeholders to take sound decisions and produce forest products considering sustainability. This is done following the steps of MFCA defined above:

- 1- Define the system boundary of production process and of the unit function

As part of Step 1 on goal and scope definition we define the system boundary and unit function for all studied products (construction wood, plywood, palette, pellets and unbleached pulp) in line with chapter four and five, where the system boundaries for gate-to-gate etc. have been described for LCA and LCC: from first thinning to final harvesting and the functional unit is 1m<sup>3</sup> of maritime pine (ub) raw wood.

- 2 - Model the structure of flow

The flow structure must be modeled in Step 2. This includes tracing where and when material and energy inputs are used, as well as when and what outputs are desired and undesirable. All of these steps have been done in life cycle inventory in chapter 4 on LCA, and the physical inputs and outputs are the same in LCA and MFCA. The reference of the life cycle inventory for each studied wood products are mentioned in Chapter 4 and included in the appendix (5-1 to 5-5).

3-Construct and quantify environmental performance indicators for monitoring the process.

As explained in Chapter 4, the LCIA methodology was used to examine several environmental impact categories resulting from the five studied wood products production from gate-to-gate using SimaPro software version 9.3.0. Using the ReCiPe method this study examines twelve environmental effect categories (CC, OD, TA, FE, ME, HT, POF, PMF, TET, MET, and IR) and displays each input's contribution to environmental impacts in order to investigate the environmental performance for each product.

4-Measure material and energy used in in physical amounts

This step gathers relevant physical and monetary data, and the same physical amount determined in Chapter 4 during the life cycle inventory. That means material and energy flow results of the life-cycle assessment have been taken into account here for the material flow cost accounting.

5-Measure material, energy, system and waste management costs and environmental impacts

Material, energy and waste management as well as system costs, in addition to the external costs of the twelve environmental impact categories considered in this study, are found in Chapter 5 on life cycle costing and are in accordance with previous work presented in this manuscript and the appendix (5-1 to 5-5). They have been calculated using the SimaPro software life cost model based on the Environmental prices handbook for the twelve environmental impact categories resulting from the production processes and combined with internal costs, for which data could be collected.

6- Use suitable cost accounting technique to allocated cost to both desire and undesired products

The mass allocation process based on market share specified in Chapter 3 on MFA has influenced the cost allocation in this study, which are roundwood lumber (43%), industrial wood in the form of pulp (45%), construction wood (20%), pallet (15%) and pellets (11%).

## 7-Carry out cost accounting and allocation

The material cost accounting has been applied as modern cost accounting tool for economic and environmental cost accounting to quantify the flow and stock of materials in the production of wood products in both physical and monetary terms (ISO14051:2011). This accounting tool assists forest manager in realizing that the process' desired output (1 m<sup>3</sup> of wood ub) does not actually cover all the costs of production and hence allows reducing costs and increasing profits by implementing the lessons learnt.

### **6.3.1. Construction wood:**

In this chapter, life cycle cost accounting has been utilized to measure and cost material flow, allocate it to accountable products, and provide chances for negative impact reduction and cost savings. The results for the construction wood production are represented in Table 34. Because of the variation and difficulty in using the actual weights of each input material, the cost allocation procedure in MFCA relies on the mass-based allocation outlined in Chapter 3. The quantified percentage of construction wood is 20% of the total amount of stock specified in Chapter 3 (Gascogne, 2019). It is appearing from Table 34 that acquisition of raw wood is the highest cost contributor among all production elements of the construction wood production process (€9.80, €0.50) economically and environmentally representing 35% and 63% of total economic and environmental cost respectively, as presented in Table 34.



Table 34: Flow cost model of MFCA based on LCC and LCA for construction wood production

Cost categories		€/ m <sup>3</sup> of Raw wood of construction wood (allocation 100% to construction wood)	Cost amount in € (2019) share of construction wood corresponding to MFA 20%
Materials	Raw wood	49€	9.8€/m <sup>3</sup> (ub)
	water	0.05€	0.01/m <sup>3</sup>
	Steel nails	0.41€	0.082€
Energy	Electricity	3.34€	0.67€
	Fuel (diesel, gasoline, gas, engine oil)	2.29€	0.46€
	lubricants	0.15€	0.03€
System cost	Chemical treatment	1.80€	0.36€
	Warping	0.10€	0.02€
	Capital investment cost (interest, tax, insurance)	22.32€	4.46 €
	Depreciation	23.26€	4.65 €
	Replacement cost	0.57€	0.11€
	Maintenance	9.95€	1.99 €
	Salary and charge	24.43 €	4.89€
Environmental impact cost (LCIA)	Impact for twelve impact categories	0.798 €	0.156 €
Total cost		57.14€	11.42€
Amount of construction wood produced from 1m <sup>3</sup> raw wood		9m <sup>3</sup> (418€/m <sup>3</sup> ) =229.48€	45.89
Profit = Total proceeds – Total cost*		=229.48-57.14=171.54€	34.45 € realized profit from 1m <sup>3</sup> of wood as input correspond to the MFA 20%

\*Total costs include Capital investment cost CapEx, and Depreciation, Replacement cost, Maintenance, Salary and charge

Figure 35 presents the relative contribution of production factors to the construction wood. The Figure shows that the raw wood is the greatest cost contributor among all production factors representing 35% of total cost followed

by salary and charge represent 18%. The warping is the smallest cost contributor among all production factors

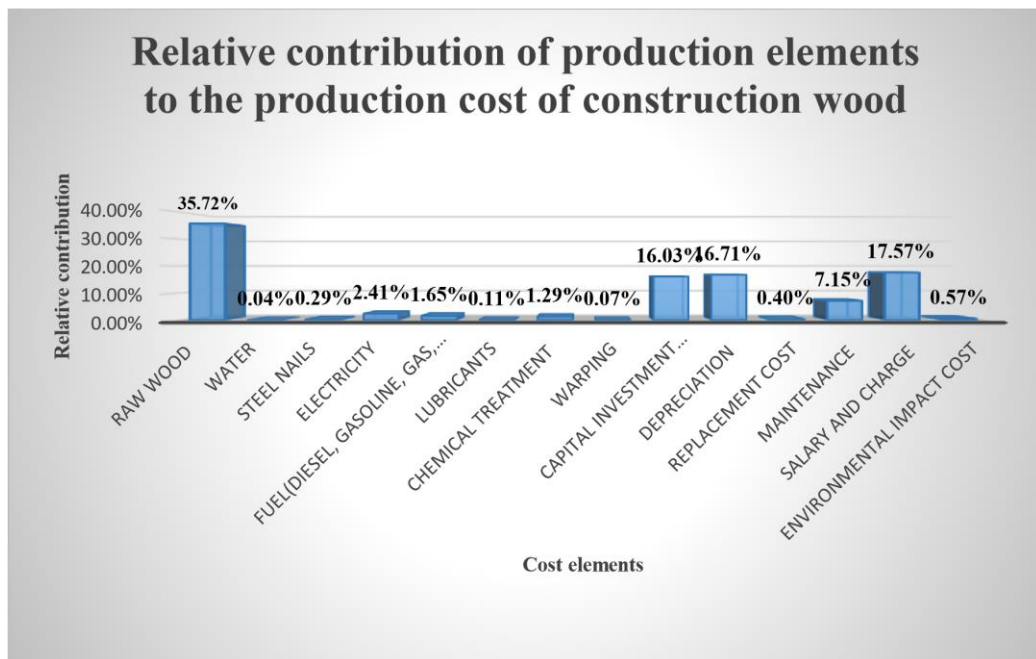


Figure 35: Contribution of production factors to the production cost of construction wood corresponding to MFA%

### 6.3.2. Pallet

Material flow cost accounting quantified the costs of desired and undesirable output from the pallet production process. Table 35) represents the cost of each production process element and the desired and undesired product costs for pallet production. The table shows the greatest cost contributor in the pallet production process economically is raw wood cost (€7.01) which represents 56% form the total economic cost of pallet shares corresponding to the MFA %, and the greatest cost contributor environmentally is steel cost (€0.57), which represents 42% of total environmental cost of pallet share corresponding to the MFA %, as presented in Figure 36.

Table 35: Flow cost model of MFCA based on LCC-LCA for pallet production

Cost categories		€/ m <sup>3</sup> of Raw wood (allocation 100% to pallet)	Cost amount in € (2019) share of construction wood wood corresponding to MFA %
Materials	Raw wood	46.7€	7.01€(ub)
	Nail steel	28.9	4.33
	Alkyd paint	0.82	0.12
Energy	Electricity	3.70€	0.56€
	Gas	0.79€	0.12€
	Capital investment cost (interest, tax, insurance)	The data is not available Now	
	Depreciation		
	Replacement cost		
	Maintenance		
Salary and charge			
Environmental impact cost (LCIA)	Impact for twelve impact categories	9.16€	1.37€
Output and by products	Wood pallet	255.9€ (15.4*16.62)	38.39€
	Wood waste	Internal valuation	-----
	sawdust	0.13€	0.02 €
	planches	0.41€	0.06€
Product	Number of pallets	1.54E+01€	2.31 piece
Total cost		89.25	13.39
Net profit		(255.95+0.13+0.41)- 89.25=167.24€	(38.39+0.02+0.06) - 13.51= 24.96€

\*Due to unavailability of data, total costs in case of pallet don't include CapEx and depreciation, replacement cost, maintenance, salary and charges (OpEx).

The results obtained from MFCA are shown in Figure 36. As can be seen from this Figure, raw wood was the most significant cost contributor with 51% of total cost of pallet share, corresponding to the MFA % (15%). This is followed by steel nail, while the smallest cost contributor is alkyd paint.

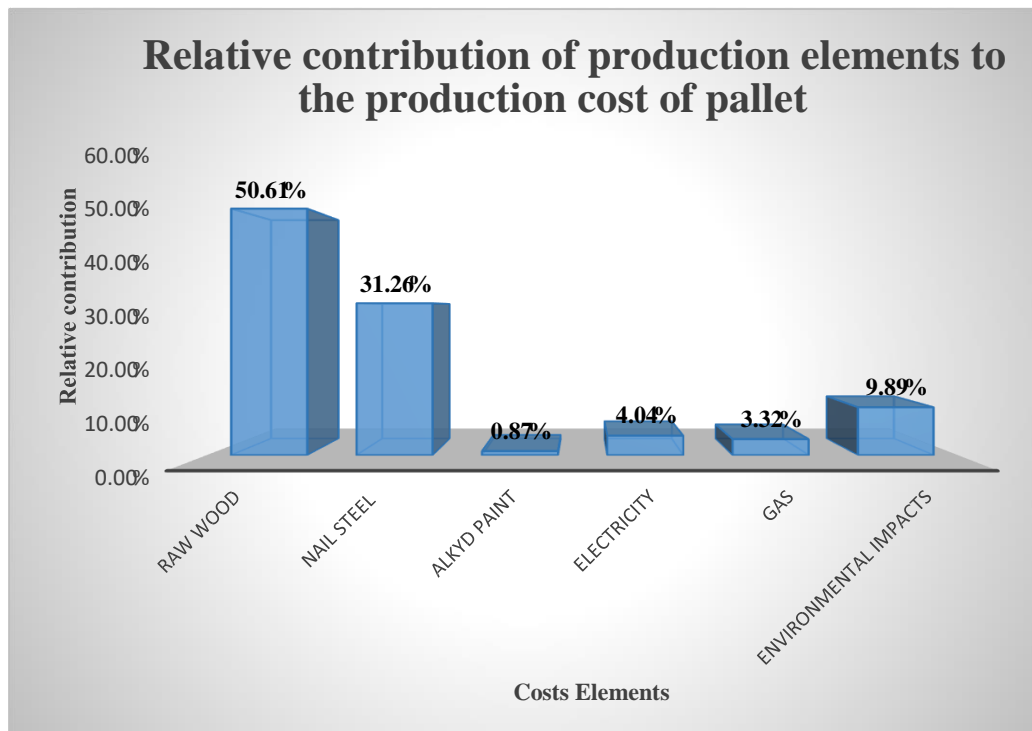


Figure 36: Relative contribution of production factors to the production cost of pallet production corresponding to MFA%.

### 6.3.3. Plywood:

To assess economic and environmental costs of plywood production process again material flow cost accounting has been applied. The results are presented in Table 36. As the table shows the greatest economic cost contributor is chemical raw material (resin) (10.10€) followed by chemical raw material (4.53€) which represents 66.71%, and 30% from total economic value of plywood share corresponding to the MFA % respectively. The greatest cost contributor environmentally is melamine cost (3.55€), which represents 50% of total environmental cost of plywood share corresponding to the MFA %. Table 36: Flow cost model of MFCA based on LCC-LCA for plywood production

	Categories		Amount for 1m <sup>3</sup> of wood input	Cost for 1m <sup>3</sup> of wood as input	Cost Corresponding to MFA 9%
product		Plywood(h)	0.48 m <sup>3</sup>	379.44€	34.14€
Inputs	water	Water(a)	0.68m <sup>3</sup>	0.044€	0.004€
	chemicals. raw material	Resin (b)	30.80kg	112.26€/m <sup>3</sup>	10.10€
		Pine maritime EMS	1.00 m <sup>3</sup>	50.40€/m <sup>3</sup>	4.536€
	Energy	Diesel(c)	0.03 L	0.047€	0.0042€
		Electricity	113.0kW/h	1.49€/m <sup>3</sup>	0.134€
		Heat(e)	2400.0 MJ	4.00 €	0.36€
Outpost	Emission to air	Formaldehyde	0.03kg	The general tax on polluting activity threshold was not met	
		water	0.26	No tax	
Environmental impact	LCIA results	Twelve impacts categories		79.2€	7.13 €
	Outputs to technosphere: waste treatment	Wastewater(g)	0.68 m <sup>3</sup>	Pollution fee thresholds are not reached	
Total costs to convert 1m <sup>3</sup> of raw wood and all complementary material to plywood				247.24 €	22.27€
Profit = Total proceeds - Total cost*		=379.44-247.44=132€			11.87€ realized profit from 1m <sup>3</sup> of wood as input correspond to the MFA 9%

Inventory data use are: (a) Water-cooling. unspecified origin. RER; (b) Resin- Burned in building machine {GLO}| market for | APOS. U; (c) Diesel-durned in building machine {GLO}| market for | APOS. U; (d) Electricity medium voltage {RER}| market group for | APOS. U; (e) Heat medium voltage {RER}| market group for | APOS. U; (g) Wastewater from plywood production {GLO}| market for | APOS. U; (h) Plywood for outdoor use {RER}| production | APOS. U (a) Water-cooling. unspecified origin. RER; (b) Resin- Burned in building machine {GLO}| market for |

APOS. U; (c) Diesel- Burned in building machine {GLO}| market for | APOS. U; (d) Electricity medium voltage {RER}| market group for | APOS. U; (e) Heat medium voltage {RER}| market group for | APOS. U; (g) Wastewater from plywood production {GLO}| market for | APOS. U; (h) Plywood for outdoor use {RER}| production | APOS. U;

From the data in Figure 37, it is apparent that the resin is the largest contributor to the total cost of the plywood production process, accounting for 32% of the total cost of plywood production. Some of the outputs that have an environmental impact are exempted from tax because they did not reach the level of pollution for which the tax is imposed (e.g., formaldehyde and waste water), and others have no tax on them (water).

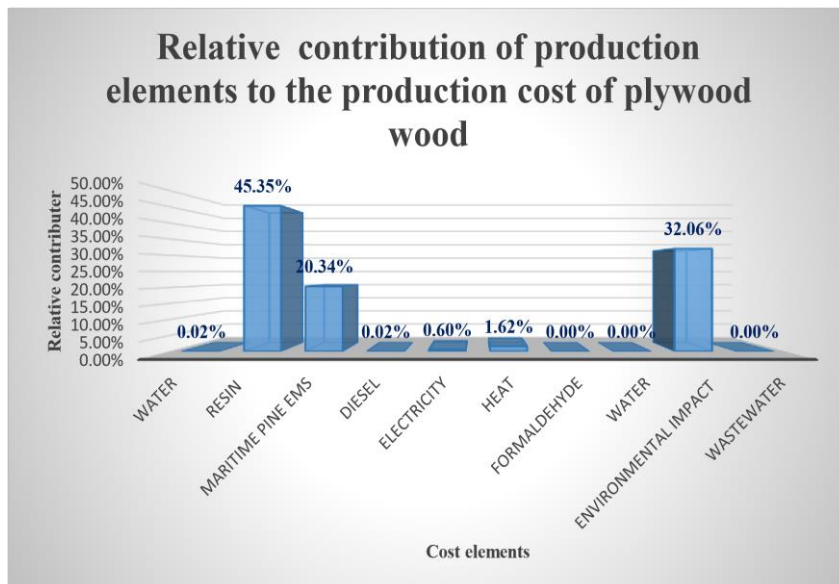


Figure 37: Relative contribution of production factors to the production cost of plywood production corresponding to MFA%

#### 6.3.4. Unbleached pulp:

Next, material flow cost accounting has been used to evaluate the financial and environmental impacts cost of the pulp production process. The outcomes are shown in the Table 37. As indicated in the table, calcium oxide (\$20.95) is the largest economic cost contributor, which account for 64% of the entire economic value of pulp and equate to the MFA%. Cost of heat (23.96€) accounts for 88% of the overall environmental cost of the pallet shares and corresponds to the MFA% (45%) as the largest cost contributor.

Table 37: Flow cost model of MFCA based on LCC-LCA for unbleached pulp production

Categories					
		Material carries	Amount 1m <sup>3</sup> of input	Cost for w1m <sup>3</sup> wood as input	Cost € Corresponding to MFA 45%
Input	Raw material	wood	1m <sup>3</sup>	19.93€/m <sup>3</sup>	8.97
		water	13.33 m <sup>3</sup>	0.14 €/ m <sup>3</sup>	0.063
	Chemical	Caustic soda/ Sodium hydroxide (NaOH)	3.33 kg	2.24€/ m <sup>3</sup>	1.00
		Calcium oxide (Quicklime, CaO)	1.67kg	46.56€/m <sup>3</sup>	20.95
	Energy	Electricity	270 kWh	2.55€/ m <sup>3</sup>	1.14
Output	Solid waste	Other ashes	2.33 kg	0.5	0.23
		Fiber	0.83	reintroduced into the process / low quality paper *	
		Wood waste	1.00 kg	**	
		Dregs, grit and green liquor sludge	3.33kg	***	
		Lime (with non-process elemen ts)	3.33kg	****	
		Hazard waste	0.03 kg	*****	
		Wastewater sludge treatment	1.67 kg	*****	
			cost treatme nt sludge		
	Nitrogen	1.7 g	0.000056€	0.000025	
	Phosphorus	8.33g	0.003667 €	0.0017	

Categories					
	Material ca	t	Amount	Cost for	Cost € Corresponding to MFA
	ries		1m <sup>3</sup> of	w1m <sup>3</sup> wood	45%
			input	as input	
Waste water	Suspended solids		0.54 g	0.0000702 €	0.0000315
	Cd		0.01g	0,77 µg/l :	0.000047
	Pb		0.05	METOX	
	Cu		0.08	(µg/l) : 10 x	
	Cr		0.03	[As] + 10 x	
	Ni		0.07	[Pb] + 50 x	
	Zn		0.83	[Cd] + 1 x	
	Sulphur		0.33	[Cr] + 5 x	
				[Cu] + 50 x	
				[Hg] + 5 x	
			[Ni] + 1 x		
			[Zn]		
Air emission	NOx		0.37 Kg	175.48 €/ton	free quotas by the State (Gascony)
	Sulfur		0.27 Kg	145.38 €/ton	
	VOC		0.37 Kg	145.38 €/ton	
By prod- ucts(sold)	Crude tall oil		12.50 kg	11.44€	5.15
	Crude sulfate turpentine		2.50 kg	8.93	3.73
Environmental impact s (LCIA)	Twelve impacts categories			60.48€	27.22
Total cost				132.4	60.1
Main prod- uct	Kraft pulp		0.17 t	148.43	75.67
Profit = Total proceeds – Total cost*			=148.43+11.44+8.51 - 132.4=36.4		15.86€ realized profit from 1m <sup>3</sup> of wood as input respond to the MFA 45%

\*Reintroduced into the process / low quality paper

\*\*with classic process wood waste are bark and sometimes are used as biofuel for factory with wood waste from other factories

\*\*\*the green liquor is regenerated into white liquor (see water sheet diagram for Gascogne)



\*\*\*\*Gascogne papier valorizes lime for lime kiln Figures on their annual reports

\*\*\*\*\*Are sorted by factories, then collected and eliminated by waste gestion installations.

\*\*\*\*\* probably treated by external installations as sludge is an “ultimate dechet” so won’t be valorized but burned or buried

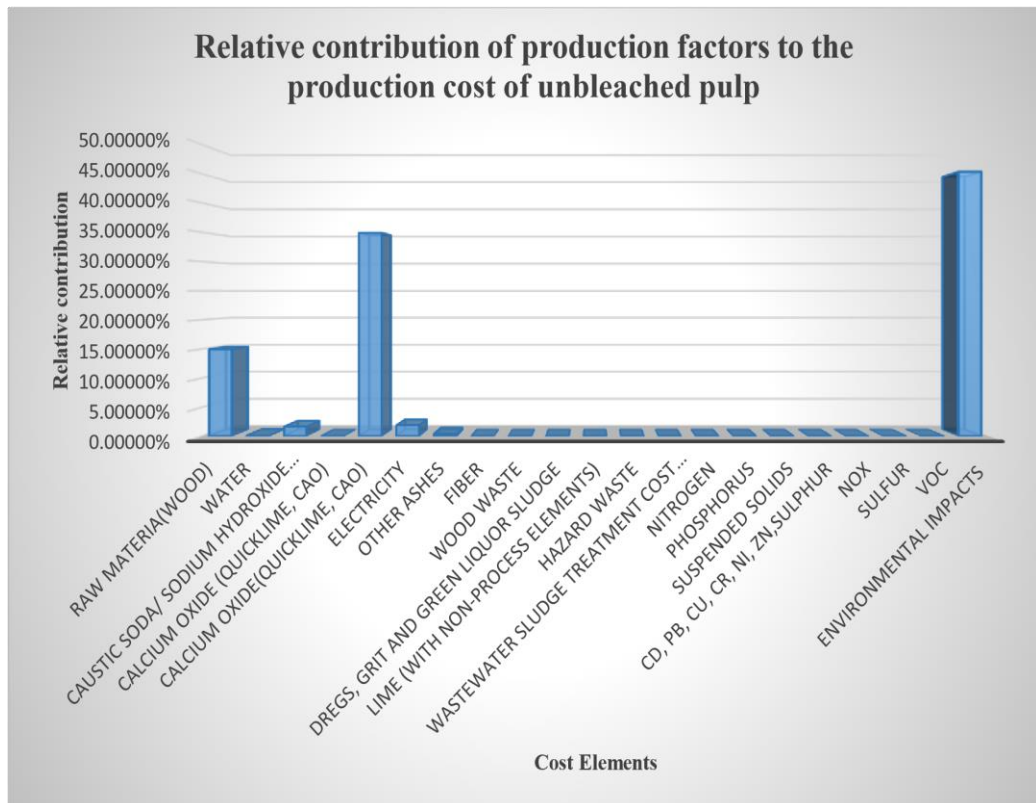


Figure 38: Relative contribution of production factors to the production cost of unbleached pulp production correspond to

MFA %

The information in Figure 38 makes it clear that the environmental impacts account 46% of the entire cost of unbleached pulp manufacture, which is the largest contributor of pulp production process as whole, followed by calcium oxide representing 35% of the total cost.

### 6.3.5. Pellets

Finally, material flow cost accounting is used to quantify the costs of input and desired and undesirable output from the pellets production process. The Table 38 represents the cost

of each production process element and the desired and undesired product costs. The table shows the greatest cost contributor in pellets production process economically is raw wood cost (2.79€) which represent 79% form total economic cost of pallet share corresponding to the MFA %, and the greatest cost contributor environmentally is raw wood cost (0.27€) which represents 36% of total environmental cost of pallet share corresponding to the MFA % as presented in Figure 39.

Table 38: Flow cost model of MFCA based on LCC-LCA for pellets production

	Material	For 1m <sup>3</sup> meter of wood as input	Cost for 1m <sup>3</sup> of wood as input	Cost € Corresponding to MFA 11%
Inputs	Maritime pinewood (logs + byproducts)	1.00E+00 m <sup>3</sup>	27.0€	2.97 €
	Polyethylene (for 50kg-bags)	1.34E-04kg	0.00025 €	0.000028 €
	Electricity	5.93E+01kWh	5.67€	0.62€
	Diesel	3.23E-01 L	0.49	0.054
Air emission	CO	9.11E-04 kg	Threshold of general taxation on polluting activities doesn't reach	*
	CO2 fossil	1.02E+00 kg		
	Nox	1.16E-01 kg		
	SO2	1.50E-02 kg		
	CH4 biogenic	1.35E-03 kg		
	CH4 fossil	2.07E-05 kg		
NMVOC	1.02E-02 kg			
Environmental impacts (LCIA)	Twelve impacts categories		0.754€	0.083
waste	Ashes to landfill	8.03E-01 kg	0.16€	0.018
Total cost			34.1	3.75
product	pellets	3.75E-01 t	76.36	8.399
Profit = Total proceeds – Total cost*		= 76.36-34.1= 42.26		4.65 realized profit from 1m <sup>3</sup> of wood as input correspond to the MFA 11%

\* Threshold of general taxation on polluting activities doesn't reach.

As shown in Figure 39, Raw wood material contribute the greatest percentage among all pellets production factors with 82% from total pellets production costs, whereas, some production factors no have cost despite they were contribute in production process such as CO, CO2fossil, Nox, CH4 biogenic, CH4 fossil, NMVOC because they weren't reaching the threshold of general taxation on polluting activities

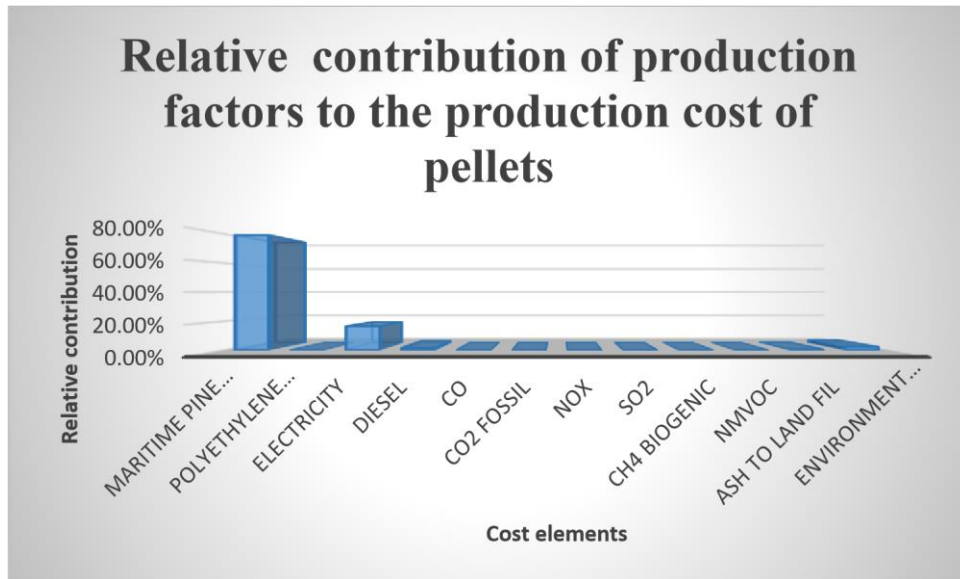


Figure 39: Relative contribution of production factors to the production cost of pellets production correspond to MF

The economic and environmental costs of the studied products were compared without taking into account co-products, and all costs were applied to the study products (100%). The results are shown in Table 39 and Figure 40 for the five products (construction wood, pallet, plywood, un-pulp and pellets) without taking the CapEx and some of OpEx elements costs into consideration. Pellets are second in cost after plywood from an economic perspective, while pulp is second in cost after plywood from an environmental perspective. In general, we can conclude that using wood in construction is the best use of wood in terms of environmental impact because of the small amount of environmental impact resulted from the construction wood production process and the long period of carbon stock in construction as wood. These results are agreement with the study of (Oliver, C. D., Nassar, N. T., Lippke, B. R., & McCarter, J. B. (2014); Bowyer, J., Howe, J., Stai, S., Trusty, W., Bratkovich, S., & Fernholz, K. (2012).

Table 39: Comparison of economic, environmental and net profit between studied products (100%) without CapEx, & some of OpEx costs elements.

Products	Economic costs €	Environmental costs €	Net profit €
Construction wood	57.14	0.797	171.54
Pallet	81.28	9.16	165.96
Plywood	168.04	79.2	132.2
UB-pulp	71.92	60.48	69.27
Pellets	33.35	0.754	42.26

All of products excluded CapEx (Depreciation, replacement, Tax, Interest and insurance), OpEx (salary charge, maintenance).

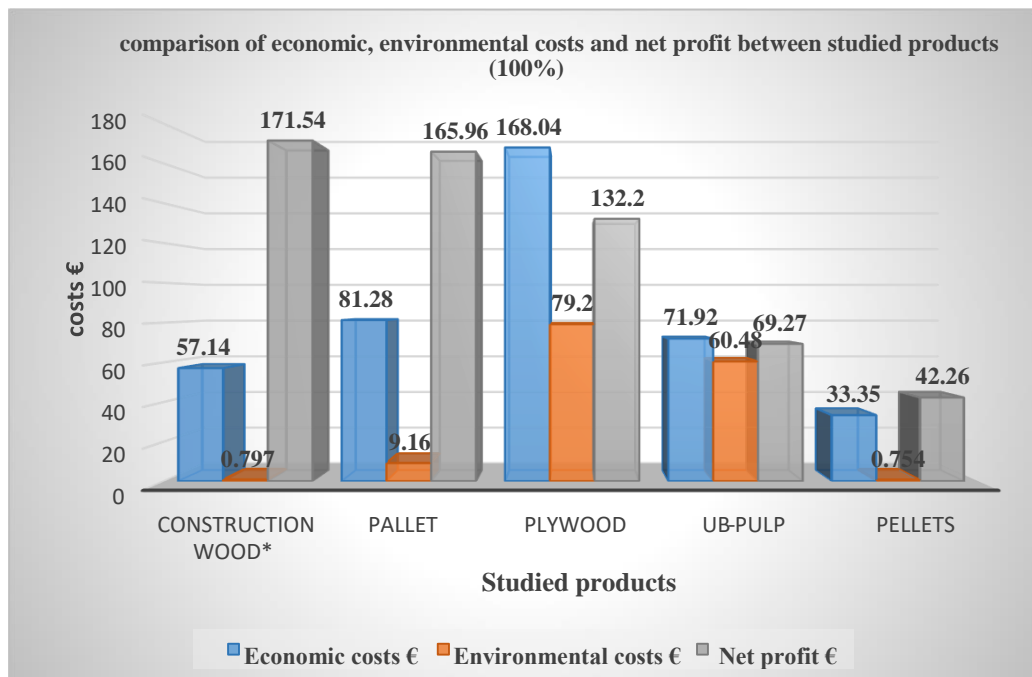


Figure 40: Comparison of economic, environmental costs and net profit between studied products (100%)

Economic and environmental costs and net profits of the studied products corresponding to market share specified in Chapter 3 are presented in the Table 40 and Figure 41. It is

apparent from the Table 40 and Figure 41 that economic and environmental cost have been allocated depending on the products percentage determined in the flow structure in chapter (3) Chapter 3ulp 45%, construction wood 20%, pallet 15%, pellets 11% and plywood 9%.

Table 40: A comparison of the economic and environmental performance of the studied products and the realized net profit, using environmental technical tools corresponding to the MFA%.

Products	Economic costs €	Environmental costs €	Net profit €
Construction wood*	11.57	0.16	34.45
Pallet	12.48	1.37	24.54
Plywood	15.13	7.14	11.87
UB-pulp	32.36	27.22	16.91
Pellets	3.667	0.083	4.65

- All of products excluded CapEx (Depreciation, replacement, Tax, Interest and insurance), OpEx (salary charge, maintenance).

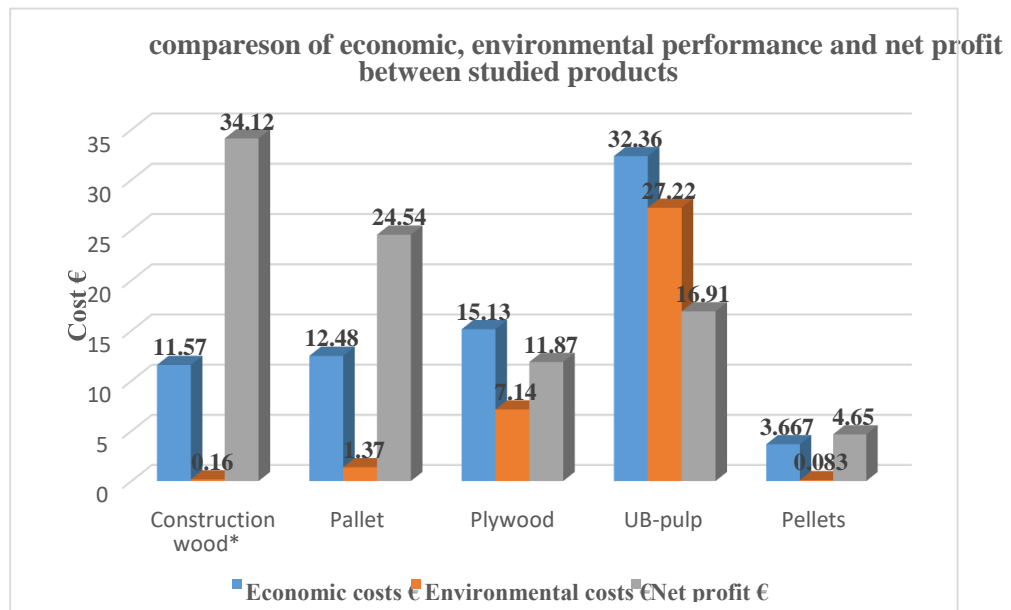


Figure 41: Comparison of economic, environmental costs and net profit between studied products corresponding to MFA%.

#### **6.4. Discussion and conclusion**

This chapter has the aim of improving the sustainability of the wood products and address the market failure in the pricing of forest products by taking into account the production costs of undesirable outputs such emissions to air, water, and land coming from the production process, and to expand existing knowledge in this field in order to support decisions makers to encourage the wood industry, to support more systematic, consistent, and transparent assessments of costs alongside scarce resources and environmental impacts and to understand how to construct a reliable flow structure model. To achieve these aims material flow costs accounting (MFCA) has been applied in this chapter.

The results of this chapter show the significant amount of cost related to the undesired products resulting from production process from some of studied products such as pulp and plywood that represent (46%, 32% from the total cost of production process) respectively. They should be taken into account in economic valuation and feasibility studies in forest projects and all others economic sectors to obtain precise results and addressing the problem of market failure in pricing all forest products and others goods and service from other industry sectors. As far as we know there is no previous study applied MFCA to assess economic and environmental performance of wood products production process. However, the results of the raw wood acquisition part are consistent with those of other studies by Buonocore, E., Häyhä, T., Paletto, A., & Franzese, P. P. (2014). We assess the environmental cost and impacts of forest activities that represent high percent of total cost in case of

s with 82% from total pellets production costs, in pallet raw wood acquisition (first thinning and harvesting) contribute with 51% of total cost of pallet production costs, and construction wood and in construction wood represent 36% of total cost.

These results could be used as a foundation to extend the system's boundaries both forward and backward of studied products to allow for the economic evaluation of the entire life cycle of the selected wood products. In addition, this study will contribute partially to achieve what was recommended by Papaspyropoulos, K. G., Karamanolis, D., Sokos, C. K., & Birtsas, P. K. (2016) by considering twelve environmental indicators, not only greenhouse gas which cause climate change. These results can contribute to production process improvement, by creating cost saving and new usable products and thus at the end to enhancing sustainability in the forest sector due to greater resource efficiency. Consequently, we help decisionmaker to take sound decisions.

The lack of funding, time, and availability of data are the most important limitations of this study to cover the entire life cycle of the studied products. This is the reason why we couldn't base our final recommendations on more complete results of this study about the studied products. Hence, more research on this topic needs to be undertaken to include all types of internal and external cost of each product group and cover the entire life cycle of the products.





# **CHAPTER 7: OVERALL DISCUSSION and CONCLUSION**

## **7.1 Overall Discussion**

The aim of this dissertation is to build an integrated methodology to join the environmental and economic performance of different kind of wood products. The first research question is “How can we measure the total value (internal costs, external costs and added value during a certain period and stages of its life cycle as well as the related externalities) of wood products for each wood industry specified in the system boundaries of a specific study by integrating material flow analysis, material flow cost accounting, life-cycle assessment and life cycle costing?”. The second research question is “How can we assess the economic and environmental performance performances for selected wood industries in the Landes de Gascogne Forest, France, to get an insight into their overall resource productivity?”. Coherently, the research hypothesis is “Life cycle management is the adequate concept and life cycle assessment, life cycle costing, material flow analysis and material flow cost accounting are the most appropriate tools for calculating the value of wood products including the internal and external costs as well as the added value and the externalities of the production processes”. These methodologies can be linked to assess economic and environmental performance for the wood industries specified in this study and adequate data are available in the Landes de Gascogne Forest, France. Four sub-objectives are identified in Chapter 1.

The first sub-objective to estimate the volume of wood products for each wood industry specified in Landes de Gascogne, France, through conducting material flow analysis as an adequate tool for materials management with a view to sustainable development is addressed in Chapter 3. The upstream supply chain of wood-based products in the Landes de Gascogne area in 2019 are quantified with a focus on maritime pine (*Pinus pinaster*) in this Chapter 3.

The second sub-objective to estimate the environmental impacts by considering 12 impact categories within the system boundary gate-to-gate of specified wood products is addressed in Chapter 4. Many environmental studies utilizing the life-cycle assessment (LCA) method to identify the environmental impacts of specified industrial forest systems are found in scientific literature, but this study

differs from the literature review because it goes beyond using the life-cycle assessment method to determine the environmental impacts of the production gate-to-gate systems boundaries for five wood-based products (construction wood, plywood, pulp, pallets, and pellets) in the following chapters, where the results of the life-cycle assessment method have been used to find the economic value of the negative effects of externalities one reason why the market is not good at estimating true costs and compare these externalities with the market costs.

The third sub-objective is to estimate wood products' internal (CapEx and OpEx) and external costs (environmental impact costs or externalities) within the system boundary (gate-to-gate) of wood products' life cycles is addressed by applying life cycle costing and converting LCA results in environmental prices in Chapter 5. Many environmental studies utilize life cycle cost methodology to assess the environmental cost of all product production process steps, but this study goes beyond using life cycle cost in order to minimize costs, improve environmental performance, and increase economic and environmental efficiency in order to make strategic decisions toward sustainable development in the forest industry. On a more pragmatic note, this study provides the total internal (CapEx and OpEx) and external (environmental) costs for construction wood and the input, output, and environmental costs for plywood, pallet, pellets, and unbleached pulp (the five most significant wood products based either on a life cycle inventory of the literature or on specialist data collection).

The fourth sub-objective is to support decision-makers by encouraging the wood industry to back more systematic, consistent, and transparent assessments of costs alongside scarce resources and environmental impacts, and to understand how to construct a reliable flow structure model by applying material flow cost accounting (MFCA) is addressed in Chapter 6. This chapter helps to further improve sustainability and address the market failure in the pricing of forest products, by expanding existing knowledge in this field to the production costs of undesirable outputs (such as emissions to air, water, and land coming from the production process) and to compare with material flow costs.

The results of the material flow analysis of the maritime pine supply chain in France presented in Chapter 3, considering a cradle-to-gate approach, indicated that in 2019 the difference between lumber and industrial wood allocation was almost balanced and equal, with 43% of timber allocated

to lumber and 45% allocated to industrial wood. From the total harvest, 45% was dedicated to pulp production, because softwoods, like maritime pine, are better for paper pulp because the increased fiber length usually translates into more inter-fiber bonding. This increase in bonding generates stronger paper. Furthermore, softwood pulps impart greater strength to the products into which they are made, compared to hardwood pulps manufactured in the same process. Only 14% of the total harvest was dedicated to the construction sector in the form of high-quality logs (6%) and plywood (8%). High-quality logs are further processed into flooring, siding and joinery. The limited use for higher quality applications is due to the high number of knots and the general slope of the grain; therefore, it is not considered as standard wood for timber. Fuelwood represented a total of 11% of the flow, with a majority of this being shredded fragments and grey soft-wood.

The results of the LCA study presented in Chapter 4 indicate that remarkable differences of environmental impacts (calculated using the ReCiPe method) exist among the five studied wood products (from first thinning to final product). It is interesting to note that unbleached wood pulp production has the highest environmental impact due to the large amount of undesirable releases to the water, soil and atmosphere from pulp production processes. This is in agreement with the results presented in literature. In addition, the practice of clear cutting, or removing all trees in a specified sector, is a particularly sensitive issue due to the process being highly visible. Reforestation, or the planting of tree seedlings on logged areas, is also criticized for decreasing biodiversity because reforested areas are monocultures. Furthermore, the logging of old growth forest accounts for 10% of wood pulp. However, these are some of the more controversial issues in forest harvesting and not directly addressed through the results of an LCA study. Construction wood has the smallest amount of environmental impacts due to the low input-output of production process in addition to the long period extent of carbon sequestration in construction wood and long period of rotation cut required to produce suitable quality of log for construction purposes.

The environmental impact costs (external costs or externalities) have been estimated for five of the same studied product groups by LCA software SimaPro 9.3 using the environmental prices method based on the environmental impacts calculated by the ReCiPe method. The environmental LCC model is presented in Chapter 5, covering both internal market costs and external costs. In the new global economy

study, determination of environmental impacts value has become a central issue for decision-makers to take sound decisions when select between various projects. The result identifies that pulp production process is the highest environmental cost among the studied products, due to the various production elements and the large amount of energy used in the heating step. Construction wood represents the smallest amount of environmental cost among the studied products. due to the small numbers of production elements and steps compared with the others studied products.

To increase the transparency of resource flows and to modify the flow structure of LCA and LCC through its categorization technique, another monetary instrument called MFCA has been be applied in Chapter 6. This study finds that construction wood has the largest amount of net profit value, excluding CapEx (depreciation, replacement, tax, interest and insurance) and OpEx (salary charges and maintenance) from the production process of all studied products. Pellets achieved the smallest amount of net profit, which indicates that use of wood for heating purposes does not provide much added value to the region where the production is taking place.

The results of this study could be taken into account when considering how to extend the system boundaries to find negative environmental impacts for the total life-cycle assessment from cradle-to-grave of all wood-based products studied, as well as to find the related monetary values of environmental impacts. Time, funding, and unavailable data were constraints on this thesis in covering the environmental impacts of the entire life cycle of the studied products. Advanced technology and substitution materials (e.g., green materials in the case of plywood production) can be employed instead of traditional techniques to improve environmental performance. These would interesting scenarios to include in a future study. Moreover, factory location near a rich supply of quality wood resources could help to control the environmental impacts substantially. Further research should be done in this field and should include the capital costs (depreciation, replacement, tax, interest and insurance) and the operating costs (salary charges and maintenance), along with environmental and direct factory production costs, for all the product groups studied.

## 7.2. Conclusion

This section summarizes the most important findings in terms of this study's goals and research questions and approve research hypothesis, as well as their value and contribution. It also examines this study's weaknesses and suggests areas for future investigation. Five wood products (construction, pallets, plywood, pellets, and unbleached pulp) produced from maritime pinewood in the Landes de Gascogne have been analyzed and compared in order to assess economic and environmental performance and identify the most economically and environmentally troublesome wood products made from maritime pinewood.

The study points out the importance of calculating the internal and external costs of any product to get transparent and accurate evaluation results that will help decision-makers take sound decisions and partially solve the market failure resulting from ignoring external costs in the production cost calculation of goods and services. It must be kept in mind that this study was only conducted on the mentioned small group of wood products and, though OpEx was available for life cycle costing for all these products, but CapEx was only available for sawmill. The results indicated that, within the system boundaries considered in this study, unbleached pulp and plywood are the most expensive among the studied products, both economically and environmentally. Heating and formaldehyde were identified as the hotspots in the pulp and plywood production steps, respectively. The findings show that unwanted material costs resulting from the production process of some products, such as pulp and plywood, account for a significant portion of the total cost of the production process.

In this study, life-cycle assessment and life cycle costing have been connected by material flow cost accounting in order to include the environmental cost, which cannot be done by traditional accounting methods and, as a result, address the market failure in determining the real price of wood products and support decision-makers in making sound choices and, consequently, achieve transparent, concise, and precise results.

The results that were obtained provide valuable information that can assist both forest-based and other kinds of industries to improve their economic and environmental performance, in addition to following and controlling material flow (of raw wood) to increase sustainability. Further research

is needed (e.g., to conduct system boundary expansion to cover the entire lifespan of wood products cradle-to-grave) and include all capital and operating costs of all product groups. This will add components towards the direction of having a complete perspective of the forest-wood chain from the forest up to all wood products.

Forest engineering still does not broadly employ or adopt LCA. The examined systems' limits are frequently too small. The majority of research pertaining to forests only considers the energy input into the primary process and disregards the environmental costs and benefits of upstream processes like seeding trees and their growth in forests. Truncated LCAs have the tendency to underestimate environmental damage or overestimate environmental performance because they ignore the embodied costs of road infrastructure and forest equipment. Moreover, environmental services, and thus benefits provided by forests, are not taken into account. The community of forest operations must improve its life cycle capability, and as a result, studies related to forests should become more thorough, and similar to those of the core LCA community. Academics also need to work on a better integration of environmental services into LCA and related hybrid studies, while also using MFA and LCC like this one.

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## **Annex-Context**

### **Chapter 5:**

**Annex 5-1- Price Reference for Input Output of Plywood Production Process**

**Annex 5-2- Price Reference for Input Output of Kraft Production Process**

**Annex 5-3- Price Reference for Input Output of Pellets Production Process**

**Annex 5-4- Price Reference for Input Output of Pallets Production Process**

**Annex5-5- Price Reference for Input Output of Construction Wood Production Process**

**Annex 5-1: Price reference for input output of plywood production process**

<b>Materials</b>	<b>Link to website</b>
Revendeurs tebopin	<a href="https://www.smbois.com/contreplaque-resineux.html">https://www.smbois.com/contreplaque-resineux.html</a> ; <a href="https://www.dispano.fr/p/panneaux/contreplaque-tebopin-elite-pin-maritime-exterieur-collage-ctbx-A1849006">https://www.dispano.fr/p/panneaux/contreplaque-tebopin-elite-pin-maritime-exterieur-collage-ctbx-A1849006</a>
(2) Price of water (Landes)	<a href="https://www.services.eaufrance.fr/donnees/commune/40303">https://www.services.eaufrance.fr/donnees/commune/40303</a>
(4) Price of maritime pine	<a href="https://www.groupementforestier.org/indicateur-2021-du-prix-de-vente-des-bois-sur-pieden-foret-privee/">https://www.groupementforestier.org/indicateur-2021-du-prix-de-vente-des-bois-sur-pieden-foret-privee/</a>
(7) Diesel-oil L to MJ	<a href="https://deepresource.wordpress.com/2012/04/23/energy-related-conversion-factors/">https://deepresource.wordpress.com/2012/04/23/energy-related-conversion-factors/</a>
(8a) Elec. prices. according to 2021 dispositive « <i>Accès Régulé à l'Electricité Nucléaire Historique</i> » (ARENH)	<a href="https://lelab.bpifrance.fr/thematiques/tendances-economiques-et-sectorielles/les-entreprisesface-a-la-hausse-des-prix-du-gaz-et-de-l-electricite">https://lelab.bpifrance.fr/thematiques/tendances-economiques-et-sectorielles/les-entreprisesface-a-la-hausse-des-prix-du-gaz-et-de-l-electricite</a>
(8b) Electricity prices 2020	<a href="https://www.statista.com/statistics/595816/electricity-industry-price-france/">https://www.statista.com/statistics/595816/electricity-industry-price-france/</a>
(9) US Inflation	<a href="https://www.usinflationcalculator.com">https://www.usinflationcalculator.com</a>
(10) USD to EUR in 2020	<a href="https://www.exchangerates.org.uk/USD-EUR-spot-exchange-rates-history-2020.html">https://www.exchangerates.org.uk/USD-EUR-spot-exchange-rates-history-2020.html</a>

**Annex 5.2. Price reference for input output of Kraft production process**

<b>Materials</b>	<b>Link to website</b>
(1) O2 price (pure)	<a href="https://www.researchgate.net/publication/303968663_High-Purity_Oxygen_Production_Using_Mixed_Ionic-Electronic_Conducting_Sorbents">https://www.researchgate.net/publication/303968663_High-Purity_Oxygen_Production_Using_Mixed_Ionic-Electronic_Conducting_Sorbents</a>
(2) Price of water (Landes)	<a href="https://www.services.eaufrance.fr/donnees/commune/40303">https://www.services.eaufrance.fr/donnees/commune/40303</a>
(4) Price of maritime pine	<a href="https://www.groupementforestier.org/indicateur-2021-du-prix-de-vente-desbois-sur-pied-en-foret-privee/">https://www.groupementforestier.org/indicateur-2021-du-prix-de-vente-desbois-sur-pied-en-foret-privee/</a>
(6) US\$ to € Dec. 2020	<a href="http://currencyconverter.io/1.35-usd-eur">http://currencyconverter.io/1.35-usd-eur</a>
(9) CTO (Crude Tall Oil)	<a href="https://www.upmbiofuels.com/siteassets/documents/other-publications/ecofys-crude-tall-oil-low-iluc-risk-assessment-report.pdf">https://www.upmbiofuels.com/siteassets/documents/other-publications/ecofys-crude-tall-oil-low-iluc-risk-assessment-report.pdf</a>
(10) Caustic Soda (NaOH)	<a href="https://www.chemanalyst.com/Pricing-data/caustic-soda-3">https://www.chemanalyst.com/Pricing-data/caustic-soda-3</a>
13)EDTA	<a href="https://rawchem2021.en.made-in-china.com/product/LdktEgiYYbVI/ChinaEDTA-Ethylene-Diamine-Tetraacetic-Acid.html">https://rawchem2021.en.made-in-china.com/product/LdktEgiYYbVI/ChinaEDTA-Ethylene-Diamine-Tetraacetic-Acid.html</a>
14)CaO	<a href="https://jfuturechemical.en.made-in-china.com/product/kZot-qHQjZupV/China-CAS-1305-78-8-Calcium-Oxide-with-Metallurgical-FluxIndustry-Grade.html">https://jfuturechemical.en.made-in-china.com/product/kZot-qHQjZupV/China-CAS-1305-78-8-Calcium-Oxide-with-Metallurgical-FluxIndustry-Grade.html</a>
16) Ozone	<u>BAT Pulp, Paper, Board (page 303)</u>
17) Wastewater Sludge Treatment	<a href="https://ec.europa.eu/environment/archives/waste/sludge/pdf/sludge_disposal4.pdf">https://ec.europa.eu/environment/archives/waste/sludge/pdf/sludge_disposal4.pdf</a>
18) Wood waste prices	<a href="https://www.letsrecycle.com/prices/wood/wood-prices-2019/">https://www.letsrecycle.com/prices/wood/wood-prices-2019/</a>

### Annex 5-3- Price Reference for Input Output of Pellets Production Process

Materials	Reference
Maritime pinewood (logs + byproducts)	<a href="https://nouvelle-aquitaine.cnpf.fr/n/le-prix-des-bois/n:2396#p5507">https://nouvelle-aquitaine.cnpf.fr/n/le-prix-des-bois/n:2396#p5507</a> <a href="https://www.europeansa-online.com/bois_sur_pied.php">https://www.europeansa-online.com/bois_sur_pied.php</a> <a href="https://www.allianceforetsbois.fr/proprietaires-forestiers/exploitation-achat-de-bois/estimation-bois-pied/">https://www.allianceforetsbois.fr/proprietaires-forestiers/exploitation-achat-de-bois/estimation-bois-pied/</a>
Polyethylene (for 50kg-bags)	<a href="https://serpbio.fr/wp-content/uploads/Archives%20Infos%20SERPBIO/2015/153%2020%20juin%202015.pdf">https://serpbio.fr/wp-content/uploads/Archives%20Infos%20SERPBIO/2015/153%2020%20juin%202015.pdf</a>
Electricity	tarif vert A5 – TLU - EDF <a href="https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2021-06/datalab_essentiel_248_prix_de_l_electricite_en_france_et_dans_l_union_europeenne_en_2020_juin2021.pdf">https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2021-06/datalab_essentiel_248_prix_de_l_electricite_en_france_et_dans_l_union_europeenne_en_2020_juin2021.pdf</a>
Diesel	<a href="https://www.prix-carburants.gouv.fr/">https://www.prix-carburants.gouv.fr/</a>
CO	“ <a href="https://www.legifrance.gouv.fr/download/pdf/circ?id=44043">https://www.legifrance.gouv.fr/download/pdf/circ?id=44043</a>
CO2 fossil	<a href="https://fr.wikipedia.org/wiki/Protocole_de_Kyoto">https://fr.wikipedia.org/wiki/Protocole_de_Kyoto</a>
Nox	<a href="https://fr.wikipedia.org/wiki/Syst%C3%A8me_communautaire_d%27%C3%A9change_de_quotas_d%27%C3%A9mission">https://fr.wikipedia.org/wiki/Syst%C3%A8me_communautaire_d%27%C3%A9change_de_quotas_d%27%C3%A9mission</a>
SO2	<a href="https://fr.wikipedia.org/wiki/Cr%C3%A9dit-carbone">https://fr.wikipedia.org/wiki/Cr%C3%A9dit-carbone</a>
CH4 biogenic	<a href="https://fr.wikipedia.org/wiki/M%C3%A9canisme_de_d%C3%A9veloppement_propre">https://fr.wikipedia.org/wiki/M%C3%A9canisme_de_d%C3%A9veloppement_propre</a> <a href="https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Carbon_dioxide_equivalent/fr">https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Carbon_dioxide_equivalent/fr</a>
CH4 fossil	Décret n°99-508 du 17 juin 1999 pris pour l’application des articles 266 sexies à 266 duodecimes du code des douanes instituant une taxe générale sur les activités polluantes”
Ashes to landfill	<a href="https://cibe.fr/wp-content/uploads/2017/01/20151208_CendresPlenieresV2.pdf">https://cibe.fr/wp-content/uploads/2017/01/20151208_CendresPlenieresV2.pdf</a> <a href="https://cibe.fr/wp-content/uploads/2017/09/Valorisation_cendres.pdf">https://cibe.fr/wp-content/uploads/2017/09/Valorisation_cendres.pdf</a> <a href="http://paysdefayence.free.fr/incinerateur-Fos/memoire-incineration.pdf">http://paysdefayence.free.fr/incinerateur-Fos/memoire-incineration.pdf</a>
Pellets	<a href="https://www.proxi-totalenergies.fr/prix-pellets#:~:text=Aujourd'hui%2C%20le%2017%2F,0%2C33%20%E2%82%AC%20au%20kg.">https://www.proxi-totalenergies.fr/prix-pellets#:~:text=Aujourd'hui%2C%20le%2017%2F,0%2C33%20%E2%82%AC%20au%20kg.</a>

**Annex 5-4: Price reference for input output of Pallets production process**

<b>PALLETS</b>	<b>Material</b>	<b>Reference</b>
<b>INPUTS</b>	Sawn timber (planches et chevrons)	Labrousse et fils
	Steel nails	<a href="https://bostitch.fr/produits/details-sur-les-appareils-de-fixation/f300r40bbq/">https://bostitch.fr/produits/details-sur-les-appareils-de-fixation/f300r40bbq/</a> <a href="https://bois.fordaq.com/catalog/rouleaux-de-pointes-pour-palettes-bostitch-et-frac-18376078">https://bois.fordaq.com/catalog/rouleaux-de-pointes-pour-palettes-bostitch-et-frac-18376078</a> <a href="https://www.ftfi.fr/bois/articles/consommables/">https://www.ftfi.fr/bois/articles/consommables/</a>
	Alkyd paint	douanes françaises
	Light fuel oil	<a href="https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/202106/datalab_essentiel_248_prix_de_l_electricite_en_france_et_dans_l_union_europeenne_en_2020_juin2021.pdf">https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/202106/datalab_essentiel_248_prix_de_l_electricite_en_france_et_dans_l_union_europeenne_en_2020_juin2021.pdf</a>
	Electricity	“Eurostat – France – Prix du gaz pour client non résidentiel – Hors TVA et prélèvement récupérables <a href="https://www.edf.fr/sites/default/files/contrib/entreprise/electricite-et-gaz/gaz/contratprix-fix/contrat-prix-garanti/2022/edf_fiche_cre-ent-contrat_garanti_gaz_naturel_janvier_2022.pdf">https://www.edf.fr/sites/default/files/contrib/entreprise/electricite-et-gaz/gaz/contratprix-fix/contrat-prix-garanti/2022/edf_fiche_cre-ent-contrat_garanti_gaz_naturel_janvier_2022.pdf</a> <a href="http://developpement-durable.bsocom.fr/Statistiques/TableViewer/tableView.aspx?ReportId=13176">http://developpement-durable.bsocom.fr/Statistiques/TableViewer/tableView.aspx?ReportId=13176</a> ”
	Gas	Eurostat – France – Prix du gaz pour client non résidentiel – Hors TVA et prélèvement récupérables <a href="https://www.edf.fr/sites/default/files/contrib/entreprise/electricite-et-gaz/gaz/contratprix-fix/contrat-prix-garanti/2022/edf_fiche_cre-ent-contrat_garanti_gaz_naturel_janvier_2022.pdf">https://www.edf.fr/sites/default/files/contrib/entreprise/electricite-et-gaz/gaz/contratprix-fix/contrat-prix-garanti/2022/edf_fiche_cre-ent-contrat_garanti_gaz_naturel_janvier_2022.pdf</a> <a href="http://developpement-durable.bsocom.fr/Statistiques/TableViewer/tableView.aspx?ReportId=13176">http://developpement-durable.bsocom.fr/Statistiques/TableViewer/tableView.aspx?ReportId=13176</a>
<b>OUTPUTS AND BY-PRODUCTS</b>	Wood pallet	enquête SDES/ masse d'une palette (kg)
	Wood waste	internal valuation / Mercuriales de la CEEB
	Saw dust	Mercuriales de la CEEB
	Planches	Mercuriales de la CEEB
	Nb. of pallets	<a href="https://fr.lets-rebuild.com/price-of-euro-pallet-depends-on-condition-4690">https://fr.lets-rebuild.com/price-of-euro-pallet-depends-on-condition-4690</a> <a href="http://franceboisforet.com/wp-content/uploads/2014/06/Synthese-Etude-structurelledonnees-2015.pdf">http://franceboisforet.com/wp-content/uploads/2014/06/Synthese-Etude-structurelledonnees-2015.pdf</a>

**Annex 5-5: Price reference for input output of construction wood production process**

<b>Constructi on wood</b>	<b>Materials</b>	<b>Reference</b>
	Raw wood	Labrousse sawmill
Input	Diesel	<a href="https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2020-04/datalab-essentiel-209prix-produits-petroliers-2019-avril2020.pdf">https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2020-04/datalab-essentiel-209prix-produits-petroliers-2019-avril2020.pdf</a>
	Electricity	<a href="https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2019-06/datalab-essentiel-180prix-electricite-france-ue-2018-juin2019.pdf">https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2019-06/datalab-essentiel-180prix-electricite-france-ue-2018-juin2019.pdf</a>
	Water	<a href="https://chiffrecl.e.oieau.fr/1634/">https://chiffrecl.e.oieau.fr/1634/</a> Memento FCBA 2020-19-18 page 25
	Engine oil	<a href="https://www.44tonnes.com/tarif-vidange-poids-lourds190#:~:text=Huile%20C3%A0%20moteur%20Direct%20Lub,42%20euros%20TT C%20par%20litre.">https://www.44tonnes.com/tarif-vidange-poids-lourds190#:~:text=Huile%20C3%A0%20moteur%20Direct%20Lub,42%20euros%20TT C%20par%20litre.</a>
	Surface water	<a href="https://chiffrecl.e.oieau.fr/1634">https://chiffrecl.e.oieau.fr/1634</a>
	Drinking water	
	CapEx & OpEx	Labrousse/ memento FCBA_2020
	Polymers	<a href="https://www.uline.com/Product/Detail/S-3001/Polyester-Strapping/Polyester-Strapping-Green-1-2-x-028-x-6500">https://www.uline.com/Product/Detail/S-3001/Polyester-Strapping/Polyester-Strapping-Green-1-2-x-028-x-6500</a>
	Wood	
	Paper	
Steel		
Output	Constructi on wood	Labrousse saw mill
	Wood for pallet	
	Bark	
	Dust cutting	
	chips	