DEPARTAMENT OF
MECHANICAL AND INDUSTRIAL ENGINEERING

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Bachelor Degree in Engineering Sciences

Residual Agroforestry Biomass Supply Chain Characterization: A Mapping Approach

INTEGRATED MASTER IN INDUSTRIAL ENGINEERING AND MANAGEMENT
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ABSTRACT

Climate change is a critical global problem that has increased the risk of forest fires. The main factors contributing to this risk are global warming, low soil moisture, and the presence of fuel load - woody materials. This problem has attracted increased attention to the residual woody biomass from forests and agriculture since these residues are mainly disposed by setting them ablaze, which increases the risk of forest fires. The valorization of residual agroforestry biomass may represent a solution to reduce the risk mentioned above since it would be possible to reduce the woody fuel. However, this approach is still under research as the low market value of these residues and the high cost of valorization operations, can lead to low efficiency and profitability of the valorization process.

The present dissertation aims to map the supply chains inherent to the valorization of residual biomass from forests and agriculture. The main research objectives are to identify valorization options for residual agroforestry biomass and to characterize the material, information and financial flows of the supply chains that support that valorization. Thus, two case studies regarding the residual forestry biomass valorization were conducted to comprehend the supply chain's implications in a real context. Case study 1 comprises companies located in Figueira da Foz, in the Coimbra district, and its supply chain is solely for energy production from forestry residues. Case Study 2 comprises entities in all municipals of Portugal, and the main valorization of forest residues is renewable energy. Both case studies were mapped to illustrate the entities involved, the supply chain operations, and the information, material and financial flows. Since there are two case studies, a cross-case analysis was carried out. The obtained results demonstrated the potential of forestry residues mainly for energy valorization and the main challenges of the residual biomass supply chain.

Keywords: agroforestry residues, supply chain, mapping, efficiency

RESUMO

As alterações climáticas são um problema global crítico que tem levado a um aumento do risco de incêndios florestais. Os principais fatores que contribuem para este risco são o aquecimento global, a baixa humidade do solo e a presença de combustível lenhoso. Este problema tem atraído cada vez mais atenção para a biomassa lenhosa residual das florestas e da agricultura, pois estes resíduos são principalmente queimados como método de eliminação, representando um risco de incêndios florestais. A valorização da biomassa agroflorestal residual pode representar uma solução para reduzir o risco acima mencionado, uma vez que seria possível remover o combustível lenhoso das florestas. Contudo, esta abordagem ainda está a ser estudada devido ao baixo valor dos resíduos e às operações de valorização de alto custo, o que pode levar a uma baixa eficiência e rentabilidade do processo de valorização.

A presente dissertação tem como objetivo mapear as cadeias de abastecimento inerentes à valorização da biomassa agroflorestal residual. Os principais objetivos da investigação são identificar opções de valorização da biomassa agroflorestal residual e caracterizar os fluxos de materiais, informação e financeiros das cadeias de abastecimento. Assim, dois estudos de caso foram realizados para compreender a cadeia de abastecimento que permite a valorização da biomassa florestal residual num contexto real. O estudo de caso 1 compreende principalmente no concelho da Figueira da Foz, no distrito de Coimbra. O estudo de caso 2 abrange todos os concelhos de Portugal. Ambos são relativos à produção de energia a partir de resíduos florestais. Realizou-se uma análise cruzada dos estudos de caso, em que os resultados obtidos demonstram o potencial dos resíduos florestais para a valorização energética e os principais desafios da cadeia de abastecimento de biomassa residual.

Palavras-chave: resíduos agroflorestais, cadeia de abastecimento, mapeamento, eficiência

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Abbreviations

SC - Supply chain

TCO - Total cost of ownership

CMFF - Municipal Hall of Figueira da Foz

1

INTRODUCTION

1.1 Context and Motivation

One of the biggest challenges to long-term forest and related ecosystems viability is the occurrence of forest fires. In the last 40 years, Portugal had four million hectares of forest burned, which is equivalent to half the continental area (Silva, 2022). The use of fire as a disposal method of forest and agricultural residues is one of the leading causes of forest fires, accounting for 56% of the total number of fires recorded in 2021 (AGIF, 2022). Moreover, high temperatures, the dryness of the soil registered over the years, and the lands' woody fuel are the main contributing factors to forest fires (AGIF, 2022).

The valorization of agroforestry residues (residues from agriculture and forests) would enable the production of energy and other bioproducts, such as biogas and bioplastics, and reduce woody fuel while mitigating the risk of forest fires. In this sense, although there are several types of agroforestry residues, this dissertation focuses on woody agroforestry residues due to their combustion power. These residues have a low monetary value; thus, their valorization process must be efficient along the different operations, starting with the residual biomass harvesting and collection from forests and agricultural fields, transportation, storage, conversion process and, finally, distribution to the end-user. There are several entities involved in the valorization process: forest landowners, loggers, and biomass power plants, among others. This set of entities composes the residual agroforestry biomass supply chain (SC). It consists of the linkage of materials, information, and money between the source and the end-user, whose operations include harvesting and collection, transportation, pretreatment, storage and end-use. Therefore, it allows a global visualization of each operation and its relations (Atashbar et al., 2016).

The dissertation is an output of the *BioAgroFloRes* project, which aims to develop operational solutions to improve the effectiveness and efficiency of the SC, valorizing the agroforestry residues to prevent forest fires and contribute to a greener and circular economy. The project is broken down into five tasks:

- **Task 1**: Development of a database to characterize the residual agroforestry biomass SC
- **Task 2**: Proposal of sustainable business models for residual agroforestry biomass
- **Task 3**: Simulation-based optimization modelling of biomass SC
- **Task 4**: Design and development of a functional prototype of an intelligent web platform
- **Task 5**: Stakeholder engagement and future planning

This dissertation integrates the second task of the project, and it aims at mapping the SC inherent to agroforestry residues. The mapping of the SC allows the visualization of the information, material and financial flows, creating transparency and visibility throughout the process (Carvalho et al., 2012).

Thus, a thorough analysis of the existing literature about agroforestry residues focused on woody residues, their valorization, SC and its mapping was conducted. It was found numerous papers about the valorization of agroforestry residues. For example, Ginni et al. (2021), Nunes et al. (2021), and Yaashikaa et al. (2022) explore the different types of agricultural residues and their valorization. Braghiroli & Passarini (2020) and Maraver et al. (2010) studied the potential of forest residues as a feedstock for energy. Regarding the SC, Atashbar et al. (2016) researched the SC operations individually, addressing the various decision types, and presenting mathematical models mainly to study the SC operations efficiency.

However, information on SC mapping is scarce (Carvalho et al., 2012), and when specifying the mapping of residual agroforestry SC, it is further limited. Moreover, there is a scarcity of graphical elements describing a residual agroforestry biomass SC in the literature studied. To overcome this lack of information, keywords such as "forestry supply chain" were utilized in Google Image Search. The research was limited to images with the domain https://www.sciencedirect.com/, allowing the discovery of one trustworthy publication on the SC mapping of forestry residues (Mansoornejad et al., 2013).

To summarize, the present dissertation studies valorization options and methods, the characteristics of the residual agroforestry biomass SC with a focus on woody residues and its mapping to conduct two case studies. These two case studies intend to provide a realistic understanding of the residual forestry biomass SC mainly for energy production.

1.2 Problems and Objectives

The primary motivation for this dissertation is the following question: "What are the characteristics of the residual agroforestry biomass SC?". This question requires a thorough analysis of the SC under analysis, for which two main objectives have been set:

1. To identify options for the valorization of residual agroforestry biomass.
2. To characterize the material, information and financial flows of the residual biomass SC.

In order to achieve these objectives, the following sub-objectives are envisaged:

- Identification of the residual agroforestry biomass SC entities and understanding their role in the SC.
- Identification of the residual biomass SC operations and the required resources in each operation.
- Characterization of the information, material and financial flows.
- Graphical representation of the residual biomass SC.

1.3 Approach

The work methodology of the present dissertation is structured in three parts:

1. **Theoretical background**: to support the importance of the topic under consideration, an analysis of the global energy and environmental issues was conducted. Then, research was carried out about the potential of biomass as a renewable energy source, narrowing it down to the residual agroforestry biomass. Concepts such as agricultural and forestry residues and the type of valorization were explored. Additionally, a typical agroforestry biomass SC was analyzed, addressing its operations, types of decisions and mapping.
2. **Case Studies**: two case studies are conducted as exploratory research to understand a residual forestry biomass SC in a real-life context. Both case studies focus on the valorization of forestry residues from forest exploitation

and management. Furthermore, a cross cases analysis is conducted to explore the similarities and differences between the case studies.

3. **Conclusions**

1.4 Document Organization

The dissertation is organized into four chapters. The first chapter is the **Introduction**, which presents the purpose of this research, its importance and how it is structured. The second chapter is the **Theoretical Background**, where an intensive literature review on agroforestry residues and the SC inherent to their valorization is carried out. The third chapter is the **Case Studies**: two case studies are described and examined separately and collectively. Finally, in the fourth chapter are the **Conclusions** and suggestions for future work.

2

THEORETICAL BACKGROUND

2.1 The Global Energy Crisis

Since the Industrial Revolution, energy demand has increased dramatically, mainly due to population growth, rapid technological development and more time spent indoors (Cao et al., 2016). In addition, the Russian invasion of Ukraine in February 2022 has led to energy instability as Russia is the world's largest exporter of oil and natural gas to Europe. To weaken the Russian economy and its army to help Ukraine, economic sanctions were imposed on Russia by the United States, the European Union, and others. This conflict has led political leaders to reassess their energy plans since they aim to cut off imports of Russian fossil fuels entirely (Tollefson, 2022).

Therefore, it is crucial to find new sources of energy, ideally renewable ones. Most of the energy produced nowadays emits greenhouse gasses, leading to another severe global problem - climate change (Berndes et al., 2003). As shown in Figure 2.1, energy production is responsible for 73% of worldwide greenhouse gas emissions due to their nonrenewable sources, such as coal, oil and gas (Ritchie et al., 2020a).

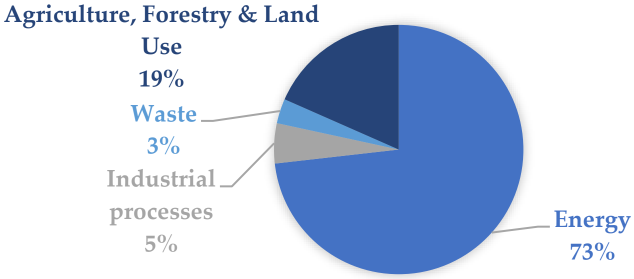


Figure 2.1 - Share of Global Greenhouse Gas Emissions. Adapted from (Ritchie et al., 2020a).

Energy production is proven to be a negative and severe influence on the environment and the evolution of the global energy mix, shown in Figure 2.2, indicates that the use of non-renewable sources is increasing rather than decreasing, representing a serious issue for the present and future society.

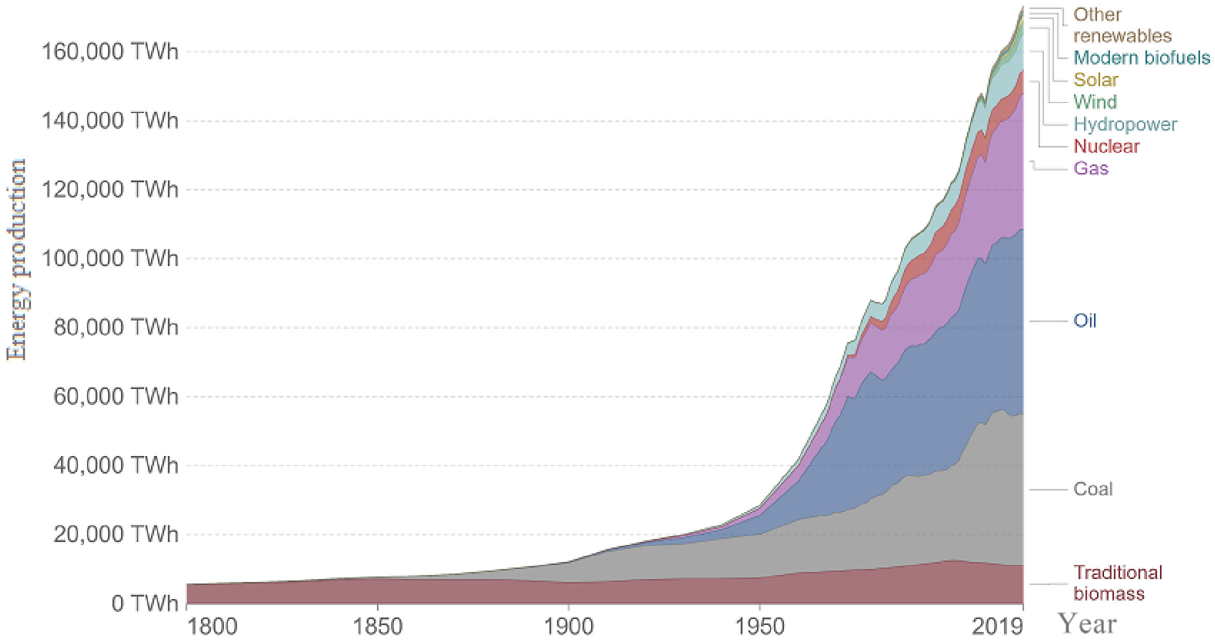


Figure 2.2 - Electricity Production. Retrieved from (Ritchie et al., 2020b).

The discrepancy between the total energy demand and the total renewable energy production has resulted in severe consequences, including increased CO_2 in the atmosphere, global temperature rise, a decrease in snow cover, sea-level rise, ocean acidification and extreme events (such as, intense rainfalls and hurricanes) (Berndes et al., 2003). Hence, climate change has emerged as one of the most pressing environmental issues.

In this sense, renewable energy production plays a critical role in reducing greenhouse gas emissions, ensuring energy sustainability and anticipating the energy demand-supply gap when fossil fuels become scarce (Kumar & Singh, 2019; Mafakheri & Nasiri, 2014). Fossil fuels can be directly substituted if, for example, the installed wind capacity can meet the energy grid's needs or if the yearly hydrological regime can keep the hydroelectric power plant system running. However, this approach can lead to intermittent production due to the constant dependence on meteorological factors. Therefore, dispatchable production points would be required to secure the energy supply when seasonal or daily weather circumstances require it. From this perspective, biomass-based energy production could be a viable solution to the problem (Nunes et al., 2021).

2.2 Biomass as a Renewable Source of Energy

Biomass can be defined as any biodegradable product or residue from agriculture (including vegetal and animal substances), forestry and related industries (such as fishing and aquaculture). From a biochemical view, it is mostly composed of cellulose, lignin, carbohydrates, lipids, and proteins. Moreover, it is regarded as a renewable resource since it is obtained primarily from plants and flora that can be regrown regularly (Bioenergy Europe, 2019; Bonechi et al., 2017; Mafakheri & Nasiri, 2014).

As a feedstock, biomass has several advantages, including its extensive availability, resulting in a more reliable renewable energy supply. It also reduces landfill disposal, creates new jobs and can be a new source of income for farmers (Fernandes & Costa, 2010). Furthermore, plant-based biomass energy production enables a carbon-neutral cycle. When biomass is burned, CO_2 is released into the atmosphere; however, when a plant regrows, it absorbs the same amount of CO_2 by photosynthesis, making this cycle carbon neutral, as seen in Figure 2.3 (VIASPACE, 2022).

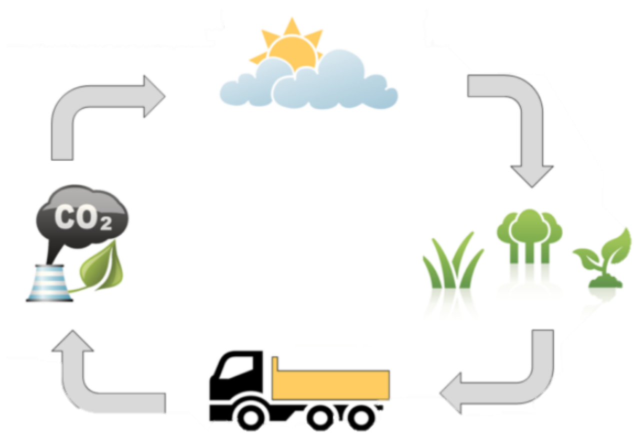


Figure 2.3 - Carbon-neutral Biomass Cycle. Adapted from (VIASPACE, 2022).

It is also important to mention that biomass is a renewable fuel as long as it is derived from sustainable sources, meaning that the source needs to be continuously replanted or managed so that the overall fuel resource is never depleted (Patrick, 2021). Moreover, biomass can be obtained from primary (such as dedicated energy crops), secondary and tertiary sources. Biomass from dedicated energy crops might generate a conflict with food production. However, residual biomass can contribute to the circular economy and energy sustainability without creating that kind of conflict (Andersen, 2021).

2.3 Residual Agroforestry Biomass

The term residual agroforestry biomass can be understood as the residues produced during agricultural and forestry operations. Although these residues are expected to contribute to the future energy mix significantly, they are still traditionally discarded or burned, meaning they are not being exploited to their full potential (Bioenergy Europe, 2019; Casau et al., 2022). In this sense, this section will identify options for the valorization of residual biomass from agriculture and forestry.

In the next two subsections, some examples of the most typical/abundant agricultural and forestry residues will be provided to understand this concept better.

2.3.1 Agricultural Residues

Agricultural residues can be defined as the waste that is left in the production fields after the harvesting of agricultural products (Bioenergy Europe, 2019). Their classification depends on their source. Primary residues are solid vegetal wastes left in the field after harvest or pruning, as well as manure. Secondary residues are those removed during the processing step, such as olive pits and nut shells (Bioenergy Europe, 2019).

Globally, rice is one of the most widely produced crops, so it is regarded as one of the most important food crops for the production of residues. The primary by-products of rice are straw, husk and bran. Rice straw is obtained once the rice seed has been isolated, and it has been recognized as the best source of cellulose for making biomaterials, biofuels, and higher-quality biomolecules. The other by-products, husk and bran, are obtained after husking and polishing the rice seed and the brown rice, respectively, as shown in Figure 2.4.

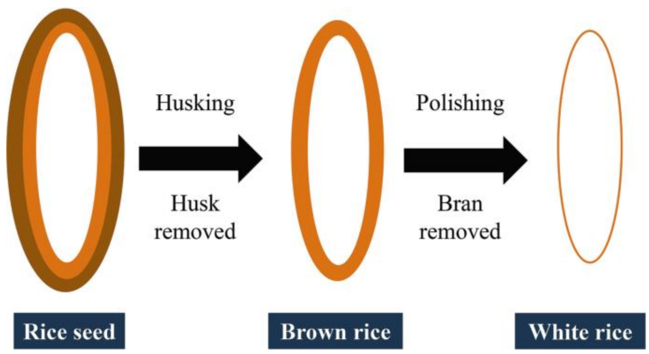


Figure 2.4 - Rice By-products. Retrieved from (Tan & Norhaizan, 2020).

Wheat is the second most important food grain since it is consumed by more than one-third of the world's population and its by-products are straw and bran. Another significant crop is maize, which has several by-products, being maize stover the most important, accounting for nearly half of the total yield. It consists of leaves, stalks, and cobs of maize plants left in a field after being harvested. Cassava is a high-yielding food crop that generates many residues during processing, including cassava peelings, stems, stalks, and rhizomes. The groundnut shell is a remnant usually thrown or burnt after the groundnut seeds have been removed. Sugarcane bagasse is the agricultural residue of cane stem obtained after crushing and extracting juice from sugarcane. Finally, the soybean by-products are soybean straw and pod husk, obtained after the seeds' harvest (Ginni et al., 2021). Table 2.1 is a summary of the main agricultural residues.

Table 2.1 - Most Common of Agricultural Residues Globally. Adapted from (Ginni et al., 2021).

Source	**Type of residues**
Rice	Straw, husk, and bran
Wheat	Straw and bran
Maize	Maize stover and husk
Cassava	Cassava peelings, stems, stalks, and rhizome
Groundnut	Groundnut shell
Sugarcane	Cane stem and bagasse
Soybean	Straw and pod husk

Since agricultural residues are used according to their chemical and physical properties, it is essential to know their composition, which usually varies according to the values shown in Table 2.2 (Ginni et al., 2021). It should be emphasized that agricultural residues have a complex structure and, as a result, pretreatments are required to promote and improve their usage, which will be discussed further.

Table 2.2 - Agricultural Residues Composition. Retrieved from (Ginni et al., 2021).

Component	**Composition**
Cellulose	40-50%
Lignin	15-20%
Hemicellulose	25-35%

Cellulose and hemicellulose are sugar-based macromolecules, while lignin is an aromatic polymer. The cellulose chains are tightly packed, and, as a result, it offers strength to the plant through inter-chain hydrogen connections. Hemicellulose has shorter chains and a more random structure than cellulose, resulting in a less crystalline and resistant structure. As for lignin, its primary function is to provide structural strength, impermeability, and resistance to microbial attack and oxidative stress to plants. The separation of these components enables the production of sustainable products (Ginni et al., 2021).

To analyze the differences and similarities of the agricultural residues mentioned in Table 2.1, the chart in Figure 2.5 presents their relative composition.

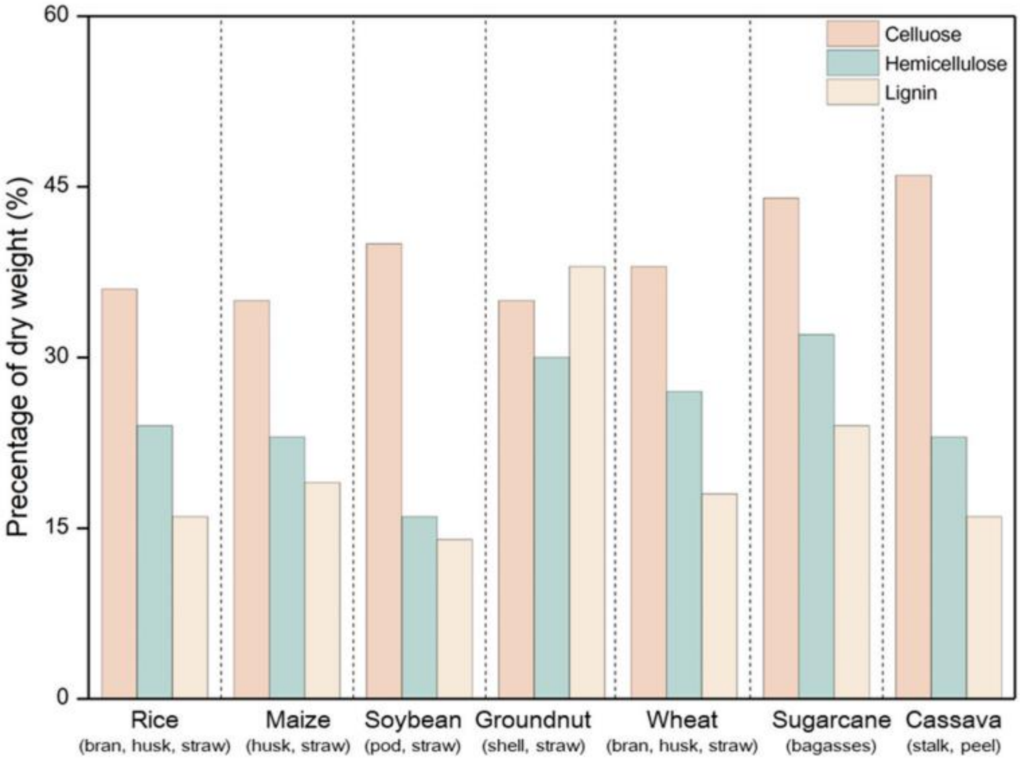


Figure 2.5 - Composition of Agriculture Residues. Retrieved from (Ginni et al., 2021).

It is feasible to conclude that, except for groundnut residues, all other analyzed residues have a similar composition, containing a higher percentage of cellulose, followed by hemicellulose and, finally, lignin. Hence, groundnut residues, especially the shell, can be classified as woody due to their greater lignin content (Esposito & Antonietti, 2015). Therefore, woody residues are characterized by having a higher relative percentage of lignin.

Woody residues from agriculture are usually obtained from orchard pruning operations. Pruning is done every one to three years in all orchards and is a necessary maintenance procedure. In Europe, woody residues are generated, mainly from vine, olive, apple, pear, and hazelnut crops. However, these residues are usually burned on-site, constituting an additional cost and a fire risk (Picchi et al., 2018). Thus, valorizing these residues may be an opportunity to reduce costs for the orchard's exploitation business while contributing to energy production and reducing the risk of fire.

2.3.2 Forestry Residues

The main composition of forest biomass is lignocellulose. Thus cellulose, hemicellulose and lignin are the main components of woody species like broadleaf and needle-leaf trees. When these residues are obtained from forestry operations, they have a heterogeneous composition due to the presence of branches, leaves, treetops, and barks (Braghiroli & Passarini, 2020). Nevertheless, when recovered from the wood processing industry or as end-of-life wood products, they are highly homogeneous and, therefore, more efficient and practical to use in the energy recovery processes (Braghiroli & Passarini, 2020).

Additionally, residues from forest operations are not only treetops, branches, and foliage but also trees that no longer are useful to the wood industry (broken-off or low-quality trees). Examples of forest residues from forestry activities and industry are shown in Table 2.3 to better comprehend the different feedstocks and their origin.

Table 2.3 - Examples of Forestry Residues. Adapted from (Braghiroli & Passarini, 2020).

Source	Type of residues
Forest operations	Branches, leaves, treetops, barks and broken-off or low-quality trees
Wood industries	Sawdust, planer shavings, bark, end-of-life wood products (e.g., plywood and particleboard)

Despite the residues obtained from industries being more homogeneous and, therefore, more attractive for energy conversion or bioproducts, valorizing residues from forestry operations is a priority since they are usually burned on-site increasing the risk of forest fires (Braghiroli & Passarini, 2020).

Moreover, forest residues management are sometimes not retrieved due to various difficulties, such as inaccessibility, geographic distance, and operation costs. The chemical and physical non-uniformity of the residues may also represent another obstacle. Nevertheless, due to recent technological development, collection and harvesting methods are becoming more efficient, which may allow cost-effective management of these residues (Braghiroli & Passarini, 2020).

2.4 Valorization of Residual Agroforestry Biomass

Since the discovery of fire, biomass has been regarded as the oldest energy source used by humans, mainly for domestic heating and cooking (Casau et al., 2022). Nowadays, due to the technological development of biomass conversion methods, it is possible to valorize biomass for other purposes, which will be addressed in this section (Gil, 2021).

Conversion processes can be classified into three major categories: physicochemical, thermochemical and biological (Casau et al., 2022). This classification may differ depending on the authors. Nevertheless, the selection of the conversion process depends on the desired end-product, environmental conditions, type and quantity of biomass available, project-specific factors and government legislation (Kumar & Singh, 2019). Furthermore, it is worth noting that combining different conversion methods may improve the efficiency of the SC. Therefore, it is crucial to understand which processes or combination of processes improve its efficiency (Casau et al., 2022).

2.4.1 Physicochemical Conversion

Physicochemical conversion is frequently employed as a pretreatment to break the crystalline structure of lignocellulosic biomass and achieve homogeneous physical and chemical properties. Particle size reduction, drying, densification and solvent fractionalization are a few examples of physicochemical conversions used before other conversion steps (Nunes et al., 2021). However, there are other physicochemical conversion methods (Kim, 2018):

- **Steam explosion** destroys the structural integrity of biomass fibers through an abrupt pressure change. This conversion is cost-effective, has a low environmental impact, uses few chemicals, and is a low-energy conversion.
- **Liquid hot water** uses water instead of steam to break the lignocellulosic structure. This process is also cost-effective, minimizes sugar loss, and no additional catalysts or chemicals are needed.
- **Ammonia fiber explosion** uses high pressure and temperature to expand ammonia, breaking down the biomass structure. It is characterized by not needing additional steps to reduce particle size and by the possibility of the ammonia being able to be recycled.

To summarize, physicochemical conversion is considered essential to the efficiency of the SC since it enables more efficient transportation logistics, increased storage capacity and improved combustion qualities compared to the raw biomass (Casau et al., 2022).

2.4.2 Thermochemical Conversion

Thermochemical conversion can be defined as the transformation of biomass into fuels, chemicals or electricity through heat and catalysts. This type of conversion is considered one of the most efficient in terms of the biomass constituents' reaction time and fragmentation capacity (Casau et al., 2022; Zhang & Brown, 2019). Furthermore, thermochemical conversion of biomass can be conducted through combustion, torrefaction, pyrolysis, direct liquefaction, and gasification:

- **Combustion** is the process of burning biomass through air heating in a stove or water heating in a boiler. There is also the combustion of densified biomass (such as pellets and briquettes), which replaces ordinary firewood (Casau et al., 2022; Kumar & Singh, 2019).
- **Torrefaction** removes moisture from biomass and increases its heating value, grindability, and hydrophobicity. It is conducted in the absence of air at temperatures ranging from 200 to 320 °C. This conversion method can be employed as a pretreatment in centralized systems or as a direct conversion method in decentralized systems to produce fuels, such as fertilizers (Kang et al., 2021; Kumar & Singh, 2019).
- **Pyrolysis** is a similar process to torrefaction, although performed with a different temperature range (300–700 °C). The products obtained from pyrolysis are bio-oil, biochar and non-condensable gasses. It is considered a possible substitute for liquid fuels due to its large-scale production potential (Casau et al., 2022; Kang et al., 2021; Kumar & Singh, 2019).
- **Direct liquefaction**, also called hydrothermal, uses high temperatures (300 - 350°C) and a pressurized water environment to break the biomass polymeric structure and produce liquid biofuels. This process does not require dry biomass, reducing overall process costs (Casau et al., 2022; Kang et al., 2021).
- **Gasification** is a process that converts biomass into gaseous products, such as hydrogen, syngas, gaseous hydrocarbons, and condensable compounds (e.g., such as tars and oils). It occurs in a high-temperature environment (800–900 °C) with a controlled oxygen level in gasifiers. In terms of energy recovery, environmental impact, treatment and disposal requirements and waste volumes, gasification is one of the most promising technologies among the others stated above. Nevertheless, it is costly due to the requirement of pretreatments and the blocking of pipelines due to condensed tar, among other challenges (Casau et al., 2022; Monteiro et al., 2017; Y. Zhang et al., 2019).

2.4.3 Biological Conversion

The biological conversion is typically more expensive and time-consuming. Nevertheless, although it generates small amounts of green chemical compounds, this process is still essential since thermochemical conversion cannot produce them (Voloshin et al., 2016).

Anaerobic digestion and fermentation are the main processes for biological conversion:

- **Anaerobic digestion** uses microbial communities in the absence of oxygen to mainly produce biogas and methane. However, the anaerobic digestion process is not feasible due to the complex structure of lignocellulosic biomass. As a result, the biomass must be pretreated, for example, through a hydrothermal process (Casau et al., 2022).
- **Fermentation** is a process that uses yeast or bacteria to convert sugars from biomass into biofuels like bioethanol. This method often uses the hydrolysis of cellulose and hemicellulose as a pretreatment (Casau et al., 2022).

2.5 End-products of the Conversion Processes

Most residual biomass from agriculture and forestry is used in the energy sector; nevertheless, one of the most significant advantages of biomass is its potential to be converted into renewable solid, liquid and gaseous biofuels, among other bioproducts (Nunes et al., 2021). In this sense, examples of the most common end-products will be presented to fully understand the potential of residual agroforestry biomass.

2.5.1 Solid Biofuels

There are three main types of solid biofuels:

- **Biochar or charcoal** is mainly consumed by developing countries for cooking and heating. It is produced through pyrolysis, more specifically, by using a slow heating rate, a low finishing temperature and a long gas residence time. The feedstock for this process is usually woody (such as nut shells) and must have a moisture level of less than 15% (GBS, 2021).
- **Pellets and briquettes** (Figure 2.6) are among the most common densification processes that can turn low-value residues into easily transportable energy products. They can be used as feedstock in coal-fired power plants without considerable modifications due to their similar physicochemical qualities in

terms of heating value and grindability (Nunes et al., 2021). Additionally, these products can serve different purposes. They can be an intermediate product to improve the low quality of residual biomass, or they can be an end-product for residential heating. These solid fuels are primarily obtained from woody residues, such as branches from forest operations and are characterized by their low moisture content, homogeneity and high energy content, which increases combustion efficiency (Bonechi et al., 2017; Monteiro et al., 2017).

Figure 2.6 - Pellets and Briquettes Samples. Retrieved from (MADIPLAC, 2022).

2.5.2 Liquid Biofuels

The primary liquid biofuels consist of:

- **Bio-oil** can be produced through fast pyrolysis, liquefaction, and gasification processes. Fast pyrolysis is the most common process. It consists of biomass conversion at a high temperature and a short vapor residence time, where the outcome is a dark brown mobile liquid. This process is appealing due to the ease of transportation, storage, and combustion of liquid products, such as crude bio-oil, among other benefits. Nevertheless, although it can be used directly for simple heating, it must be catalytically modified to improve its fuel qualities before being utilized as an advanced fuel due to the presence of undesired properties (Xu et al., 2011).
- **Bioethanol**, **bio-methanol**, **biobutanol** and **bio-propanol** are the main bio-alcohols generated, being bioethanol the most common. The latter can be obtained from several sources, including sugarcane sucrose and bagasse, corn starch, and wheat straw, usually via fermentation and distillation processes. In addition, bioethanol is a bio-product with potential, as it can replace gasoline, reducing the release of CO_2 during its combustion (Ginni et al., 2021; Voloshin et al., 2016).

- **Biodiesel** is typically produced through the transesterification process of oil-rich sources, such as rape seeds and soybeans. Although it has a reduced heat capacity in terms of volume, biodiesel has a very similar chemical composition and viscosity to mineral diesel; therefore, it is a good substitute (Voloshin et al., 2016).

2.5.3 Gaseous Biofuels

The three most common gaseous biofuels are:

- **Biogas** is a renewable fuel from cellulosic agroforestry residues, such as almond shells and olive tree pruning. The most suitable process for its production is anaerobic digestion; however, before this process, pretreatments, such as steam explosion, are considered necessary to achieve a higher biomass yield (Ginni et al., 2021).
- **Syngas** is a flammable gas mixture of CO, H_2, CO_2, and CH_3, produced by biomass gasification. It can be used to synthesize fuels and chemicals, like methanol, hydrogen and organic acids, using catalysts or microorganisms, or burned directly to generate electricity (Kumar & Singh, 2019; Zhang & Brown, 2019).
- **Biohydrogen** is a great renewable energy source since water, and a small number of nitrogen oxides are the only components released during combustion. The cellulosic biomass (e.g., wheat straw) must first be hydrolyzed before being subjected to the fermentation process in order to produce this biofuel (Ginni et al., 2021).

2.5.4 Other Bioproducts from Residual Agroforestry Biomass

Besides electricity and biofuels, agroforestry residues can be converted into products such as biopolymers, cosmetics, and dietary supplements.

- **Biopolymers**, such as biofibers from agricultural residues, can be used to produce biodegradable plastics, for example, for food packaging, since they are economical, recyclable, and safe to use. This way, petroleum-based synthetic polymers could be replaced by this sustainable polymer (Mostafa et al., 2018).
- **Cosmetics** can be produced from a variety of agricultural by-products, especially from citrus fruits, such as orange peels. This residue has a high added

value and, therefore, producing essential oils from orange peels is economically attractive (Pascoalino et al., 2021).

- **Dietary supplements** from yeast biomass are a promising product for the pharmaceutical industry since vegans and vegetarians can consume these supplements (Jach et al., 2015).

In conclusion, it is possible to convert residues from agriculture and forestry into several products. However, it is fundamental to analyze specific factors, including the residual biomass's moisture content, size, bulk density, energy content and chemical composition, since the same type of waste can have different characteristics just by being from different locations, for example.

Table 2.4 presents the products and the feedstocks from which they can be obtained.

Table 2.4 - Valorization of Residual Agroforestry Biomass

Agricultural Residues	Products	Observations	Ref.
Corn straw	Bioethanol	Corn straw is the most used biomass to produce bioethanol.	(Yaashikaa et al., 2022)
Rice straw	Bioethanol, Biogas, Bio-oil, Biomethane	Every Kg of grain harvested results in 1–1.5 Kg of straw.	(Ginni et al., 2021)
Rice husk	Biochar, Syngas	Rice husk can also be used for wall and roof insulation.	(Kang et al., 2021; Karimi-Maleh et al., 2022)
Wheat straw	Biodiesel, Biohydrogen	It is estimated that 1 Kg of wheat straw produces almost 108 g of biodiesel.	(Ginni et al., 2021)
Sugarcane bagasse	Electricity, Bioethanol, Biomethane, Heat	Bagasse pretreatment has been claimed to enable up to 90% sugar conversion to ethanol.	(Ginni et al., 2021; Nunes et al., 2021)
Groundnut shells	Biodiesel	Groundnut shells have a high glucose content, which improves fermentation efficiency and yield.	(Ginni et al., 2021)
Flax fibers and Cotton linters	Biodegradable plastics	Flax fibers yielded 81% and cotton linters yielded 54%, respectively.	(Mostafa et al., 2018)
Vineyard and olive tree pruning	Heat, Pellets	Pellets from olive tree leaves have lower hardness value than those from olive tree branches.	(Ferreira et al., 2017; Maraver et al., 2010)

Table 2.4 - Valorization of Residual Agroforestry Biomass (cont.)

Agricultural Residues	**Products**	**Observations**	**Ref.**
Pruning residues of Fruit Trees	Briquettes	The torrefaction process improves the briquettes' compressive strength.	(Kang et al., 2021)
Coconut Shells	Biochar, Electricity	Pretreating coconut shells with extreme torrefaction is not suggested due to significant mass loss and potential difficulties of densifying torrefied goods afterwards.	(Nunes et al., 2021)
Coconut oil cake	Antibiotics	Antibiotics are substances made by microorganisms that, in small amounts, can either kill or stop the growth of other harmful germs.	(Yaashikaa et al., 2022, p.)
Spent coffee grounds	Biobutanol	Since 2010, coffee production has expanded considerably.	(Yaashikaa et al., 2022)
Forest Residues	**Products**	**Observations**	**Ref.**
Wood chips	Pulp and paper	Wood chips account for around 60% of the raw material used in the pulp and paper industry in Canada, with sawdust and shavings accounting for the remaining 5%.	(Braghiroli & Passarini, 2020)
Planer shavings	Particleboard	Planer shavings account for more than half of the wood elements in particleboard in the United States.	(Braghiroli & Passarini, 2020)
Sawdust	Heat, Electricity	Sawmill residues are homogeneous and have a low moisture content.	(Braghiroli & Passarini, 2020)
Bark	Pellets	The burning period of bark pellets is 50% longer than sawdust pellets.	(Braghiroli & Passarini, 2020)
Pine shavings	Biochar	Biochar from forestry wastes indicates up to 70% energy densification.	(Kang et al., 2021)
Eucalypt wood fines	Bio-oil	Eucalyptus species have a fast growth process and high productivity; therefore, are a promising feedstock.	(Kang et al., 2021)
Branches and foliage	Energy	Exploiting eucalyptus, maritime pine, and holm oak allow the valorization of their residues to energy.	(Monteiro et al., 2011)

2.6 Residual Agroforestry Biomass SC

In an increasingly competitive market, in terms of price and timing, new approaches are needed to meet society's demands. Thus, effective and efficient SC management is critical to ensure a constant supply and the economic viability of the valorization process (Mafakheri &

Nasiri, 2014). This section will cover the operations of the SC for the valorization of residual agroforestry biomass, the types of decisions that must be made along and, finally, the mapping, which enables a comprehensive perspective of the SC.

2.6.1 Operations

Despite the growing interest in residual biomass-based products, the performance of the residual agroforestry SC is still unable to compete with the production of fossil-based products. In this regard, analyzing each SC operation, the types of decisions taken in each one, and the network design is essential to make the production of agroforestry-based products efficient and competitive (Atashbar et al., 2016; Mafakheri & Nasiri, 2014).

Thus, this section presents the most common operations of a typical residual agroforestry biomass SC. Moreover, it is essential to mention that a residual agroforestry SC differs according to several factors, which can be very specific, such as climate and road conditions (Mafakheri & Nasiri, 2014; Sarkar et al., 2021). Therefore, the following characterization will not cover all the variations within the operations but rather provide a generic depiction.

2.6.1.1 Harvesting and Collection

The first activity consists of biomass harvesting and collection. These operations can be among the most expensive operations of the SC due mainly to the types of equipment required, which usually depends on the land's slope (Crisóstomo et al., 2003). In agriculture, there are three main methods for harvesting (Atashbar et al., 2016):

- **Multi-pass harvesting** is mostly used on fields of wheat, corn and rapeseed. The grain is separated and kept in a compartment, and the residues are discharged in a windrow or swath on the ground. Later they are collected by a baler that compresses them into bales.
- **Single-pass harvesting** combines a harvester and a baler to harvest and separate grain and plant remains simultaneously. This method is more expensive than the previous one because it requires more robust and expensive equipment.
- **Whole-crop harvesting** method is used to cut the entire crop without being separated into its constituent parts. This is usually used on herbaceous energy crops, such as miscanthus and switchgrass.

The collection methods are determined by the desired moisture level and the product's intended usage, the most common being as follows (Atashbar et al., 2016):

- **Baling** can be done in round bales if the harvested biomass must be kept outside or in rectangular bales if the intention is to transport and store it indoors.
- **Loafing** is a technique for protecting the dry biomass from water in its interior by stacking it into doom-shaped mounds. The resultant stacks are substantially larger than bales; however, their density is lower.
- **Dry chop** is used to cut long stalks into smaller pieces to be stored in a cone shape beneath a farm building or transferred to a biorefinery.
- **Wet chop** is identical to the dry chop, except it is used on wet crops.

As for forestry biomass, it is often obtained from clearcutting on harvesting operations. The most common forestry residues are (Pelkonen et al., 2014):

- Trees that are too small or poorly shaped
- Branches and pecks
- Unwanted tree species by the forest industries.

These residues are usually obtained when the woodland exploitation for forest industries is done. First, the harvester is usually the chosen equipment to cut down the trees, remove the branches and pecks, and cut the trunk into logs. Then, two piles (one of the logs and the other of residual biomass) are made by a forwarder (forest tractor that is used to load and carry the obtained materials) preferably close to the road. Other common forest residues are the stumps and coarse roots that are pulled out by an excavator and piled in a heap on the side of the road (Pelkonen et al., 2014).

Furthermore, the following methods can be used to collect the residual forestry biomass (Crisóstomo et al., 2003; Pelkonen et al., 2014; Vangansbeke et al., 2015):

- **Baling**: Forest residues, usually branches and pecks, are compacted and transformed into cylindrical bales by equipment coupled to a tractor transporter. This equipment is limited when the land is sloping, stoning, or there are rocky outcroppings.
- **Shattering**: The residues are shredded on-site by a chipper, which collects and processes them into chips accumulating them in a pile on the roadside or, if there is enough space, directly into an open container on top.

- **Direct truck loading**: Stumps and coarse roots are directly loaded into a truck due to the high probability of being contaminated by soil, rocks or metal, making it difficult or even impossible to bale or chip them.

Figure 2.7 presents the harvesting and collection of logs, represented by the arrow in brown, and the forest residues (stumps and coarse roots, and treetops and pecks), represented by the green arrows.

Figure 2.7 - Logs, Branches and Pecks and Stumps and Coarse Roots SC. Adapted from (Pelkonen et al., 2014).

2.6.1.2 Pretreatment

The purpose of pretreatment is to improve conversion efficiency while facilitating the handling, storage, and transportation of biomass. Pretreatment is considered as all the procedures performed before the final conversion of biomass. Therefore, depending on the residue, the procedure can be classified as a pretreatment or a conversion method (Gold & Seuring, 2011; Mafakheri & Nasiri, 2014).

Gold & Seuring (2011) addresses five types of pretreatments: ensiling, drying, pelletization, pyrolysis and torrefaction. These pretreatments are considered more relevant since they go beyond simple mechanical operations like crushing or grinding (Shah & Manandhar, 2018; Uslu et al., 2008):

- **Ensiling** is a method of producing silage from wet biomass using anaerobic fermentation without removing the moisture (Gold & Seuring, 2011).

- **Drying** is one of the most common pretreatment methods since specific conversion processes, such as direct combustion, pyrolysis and fermentation, are only feasible if the biomass is dried. Solar drying is the most cost-effective method for drying biomass, although it can be inefficient and time-consuming due to weather conditions (Kumar & Singh, 2019).
- **Pelletization** as a pretreatment is considered a good strategy since it consists of compressed cylindrical pieces that ease handling and transport while reducing biomass moisture content and increasing bulk density (Gold & Seuring, 2011; Kumar & Singh, 2019).
- **Pyrolysis** is still in the development stage due to the high cost associated with the process, it can be used to convert residual biomass into several bioproducts, including char, tar and gases, according to the conversion temperature. These bioproducts can then be used as feedstock to produce energy and bio-oil, for example (Uslu et al., 2008).
- **Torrefaction** is a robust thermal process that produces stable, solid, uniform, carbon-enriched products with shallow moisture content and a high caloric value. The raw biomass is usually chipped to reach a uniform feedstock, which is slowly heated. The raw biomass is typically chipped to generate a uniform feedstock, which is then put in a torrefaction reactor and slowly heated to produce the torrefied biomass. This product can be used to produce torrefied pellets, as shown in Figure 2.8.

Figure 2.8 - Conversion of Raw Biomass to Torrefied Biomass to Torrefied Pellets. Retrieved from (Shah & Manandhar, 2018).

2.6.1.3 Storage

Given the seasonality of biomass, storage is one of the most critical operations in this SC, as it ensures that energy demands met all year round. However, it also represents an additional cost; therefore, careful consideration is required while deciding the location and type of storage facility to meet market demands while still being economically viable (Mafakheri & Nasiri, 2014).

The storage type depends on the type of biomass and its end-use. The storage facilities could be a simple outdoor pile, a covered agricultural shed or more secure storage (Atashbar et al., 2016).

As for the location, some studies have suggested storing biomass in the field to lower the overall expenses (Gold & Seuring, 2011; Mafakheri & Nasiri, 2014). An alternative would be to use intermediate storage sites between biomass fields and the conversion facilities. There is also the possibility of an inter-modal point, where several means of transportation, such as trucks and trains, connect and function as a well-planned storage and distribution point for biomass. Lastly, the storage location can be near/in the conversion facility (Mafakheri & Nasiri, 2014).

Moreover, if storage is done for an extended period, it may present some risks, including degradation of biomass quality and dry matter losses. Therefore, to prevent these situations, effective storage management is essential, including capacity planning and scheduling (Gold & Seuring, 2011).

2.6.1.4 Transportation

Due to the geographical dispersion of biomass, transportation is vital for the SC. Nevertheless, it is essential to remember that this operation adds no value to the product; thus, it should be minimized or eliminated when possible.

There are several transportation modes. Among them, the most common are road, rail and water transportation. The road is considered the most flexible method of transportation since it can reach any biomass production field. Rail is regarded as the most cost-effective when long-distance transport is required, and the conversion facility has a rail connection nearby. Finally, water transportation is considered when the conversion facility is located in an area with a dense waterway network. This mode of transport is the less expensive but the slowest one, and time is an important variable to consider. Moreover, despite the availability of these last two modes of transportation, the assistance of road transport is always required (Atashbar et al., 2016).

The main constraints that must be considered while determining the optimal transportation strategy are biomass availability, transportability, and demand, as well as the condition of the infrastructure's (for example, road quality). Furthermore, to assess the feasibility of the operation, it is necessary to analyze its total cost, meaning both direct and indirect costs, and travel time. The indirect costs are mainly related to the environmental impact since emissions caused by the transport operation can invalidate the carbon-neutral cycle and, consequently, compromise the purpose of energy production from residual biomass (Gold & Seuring, 2011).

According to (Muñoz et al., 2015), for long distances, residual biomass must be compacted or pretreated for the operation to be cost-effective. As for short distances, less than 120 Km, these operations can be eliminated since they have a more significant environmental impact than the transportation itself.

Hence, the efficiency of this operation relies on the quality and quantity of residual biomass transported and the overall expenses incurred, including the equipment's cost, its depreciation, fuel consumption, and staff costs, among others (Gold & Seuring, 2011).

2.6.1.5 Conversion Facility

Several factors must be considered to determine the optimal conversion facility specifications, including geographic location, type of conversion technology, facility capacity and capital and operational planning. The geographic location for the conversion facility is usually related to the transport costs - the location with the lowest overall transportation cost is typically chosen (Mafakheri & Nasiri, 2014).

As for the conversion technologies, these are selected according to the type of residual biomass feedstock available and its properties (e.g., moisture content and particle size), type of pretreatments required, the overall cost and the environmental impact. According to Mafakheri & Nasiri (2014), low-efficiency conversion is more cost-effective in low-cost biomass supply scenarios. A high-efficiency alternative should be chosen for high-cost biomass supply scenarios (Stephen et al., 2010).

Finally, capital and operational planning are essential to meet society's demands as cost-effectively as possible (Mafakheri & Nasiri, 2014).

2.6.1.6 Distribution and End-use

Following residual biomass conversion, distribution is the operation entitled to deliver the finished product to its end-user. The infrastructure chosen for this operation depends on the type of end-product and its physical and chemical characteristics.

In this sense, if the end-product is electricity, it can be directly fed into the grid, eliminating the need for a distribution infrastructure. Moreover, if the composition of biofuels is similar to that of fossil fuels, existing infrastructure can be used to distribute them.

The adoption of renewable energy by the general public is influenced by several factors, including its availability and affordability, technological compatibility, raising public knowledge of the harmful effects of fossil fuels and policy-related actions.

Governmental efforts to incorporate renewable energy into the mix of energy sources currently exist, but they are not yet sufficient. Additionally, the production of renewable energy or bioproducts is still more expensive than fossil fuel-based products. Thus, further research is required to make renewable energy and bioproducts a viable solution (Kumar & Singh, 2019).

2.6.2 Operations' Costs

The profitability of the residual agroforestry biomass valorization process remains one of the main concerns of the process' stakeholders (Mafakheri & Nasiri, 2014). Since the value of the residual biomass is low, it is necessary to reduce the operational costs.

The costs of the SC of residual agroforestry biomass differ primarily according to the following activities (Allen et al., 1998):

- Biomass harvesting
- Handling and transporting biomass on-site to the roadside
- Biomass storage
- Loading and unloading of biomass to transport vehicles
- Transportation
- Processing the biomass to improve its handling and transport efficiency (e.g., chipping and balling)

Allen et al. (1998) studied the SC costs to produce energy from forestry residues by modeling five systems. The results varied between 38€ to 44€ per dry ton of forestry residues. The highest values result from the use of storage since it requires two transport stages. Furthermore, it was concluded that harvesting/baling/chipping and transport operations accounted for more than 50% of the total cost.

Finally, since the transport operation does not increase the product value, it is the subject of several studies. For example, D'Amours et al. (2008) refers only the transportation cost (40% of the total cost) to underline the importance of reducing it.

2.6.3 Strategic, Tactical and Operational Decisions

To better understand the SC of residual agroforestry biomass, the activities above are typically broken down into three major segments: upstream, midstream and downstream. The upstream segment includes harvesting, pretreatment, storage and transportation. The midstream segment comprises the conversion facility, and the downstream segment includes the distribution and end-use. Furthermore, the decisions made in the upstream segment are particular to the SC under study. The midstream and downstream decisions are similar to those in the production and distribution of the petroleum industry; therefore, they will not be addressed thoroughly (Atashbar et al., 2016).

Figure 2.9 illustrates the segmentation of the residual agroforestry biomass SC.

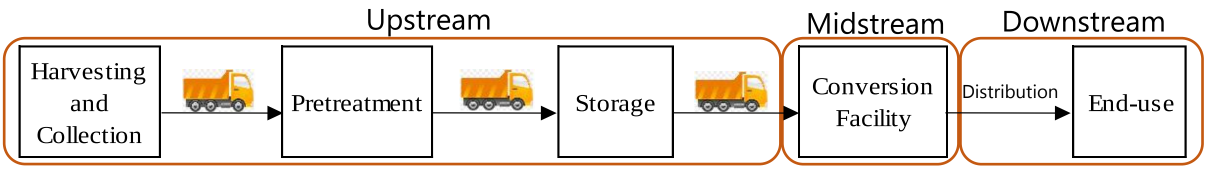


Figure 2.9 - Segments of the Residual Agroforestry Biomass SC

These operations are segmented this way to better understand the SC and because different actors are involved in each segment. The entities of the upstream segment are the forest landowners and the loggers, and, in this dissertation, the customers are part of the midstream and downstream.

Regarding the decisions of the SC, these can be classified as (Yue et al., 2014):

- **Long-term decisions** that impact the project for at least a year and are presented at the strategic level.
- **Medium-term decisions** are represented at the tactical level and affects the project within weekly or monthly.
- **Short-term decisions** are made daily or hourly and are presented at the operational level.

2.6.3.1 Strategic Decisions

Strategic decisions establish how a specific objective will be accomplished over the long term. Thus, once these are made, they rarely change (Yue et al., 2014).

The definition of the SC network involves several strategic decisions, including selection of residual biomass suppliers, location of conversion facility, types of equipment required and the identification of transportation links that connect different facilities and deliver residual biomass across the SC network. These decisions have a direct impact on financial investment; therefore, it is essential to analyze the market and its trends and how the overall investment will fit into the SC (Atashbar et al., 2016; Yue et al., 2014). Thus, strategic planning encompasses decisions at all SC stages, from the upstream segment to the downstream segment.

2.6.3.2 Tactical Decisions

Following strategic planning, the next level of the hierarchy is tactical or medium-term planning. It assesses the amount of residual biomass harvested, processed, transported and stored over a given period. These operations need to be planned mainly due to the seasonality of biomass, which significantly impacts the procurement stage (Atashbar et al., 2016).

In contrast to strategic decisions, tactical decisions can be changed, as the type and number of equipment, staffing, and inventory, among others, can be adjusted according to the dynamics of the SC (D'Amours et al., 2008).

Furthermore, tactical planning acts as a link between long-term strategic planning and short-term operational planning. Thus, tactical planning must ensure that subsequent operational planning follows the instructions issued during the strategic planning phase to align all decision types (D'Amours et al., 2008).

2.6.3.3 Operational Decisions

The operational level focuses on short-term decisions. These decisions involve a high level of detail and a significant amount of data that needs to be adequately analyzed; thus, the information is divided between the facility units to ease the process (D'Amours et al., 2008).

Operational decisions are adjusted more frequently since they depend on the present internal and external circumstances, such as workers and equipment availability (D'Amours et al., 2008). Typical operational decisions in the residual biomass SC include the allocation of operators to harvesting equipment and others, the scheduling of work shifts, the assignment of harvesting operation areas, and the conveyance of collected biomass to storage units (Yue et al., 2014).

Figure 2.10 is a schematic illustration that provides examples of decisions made in each level and operation.

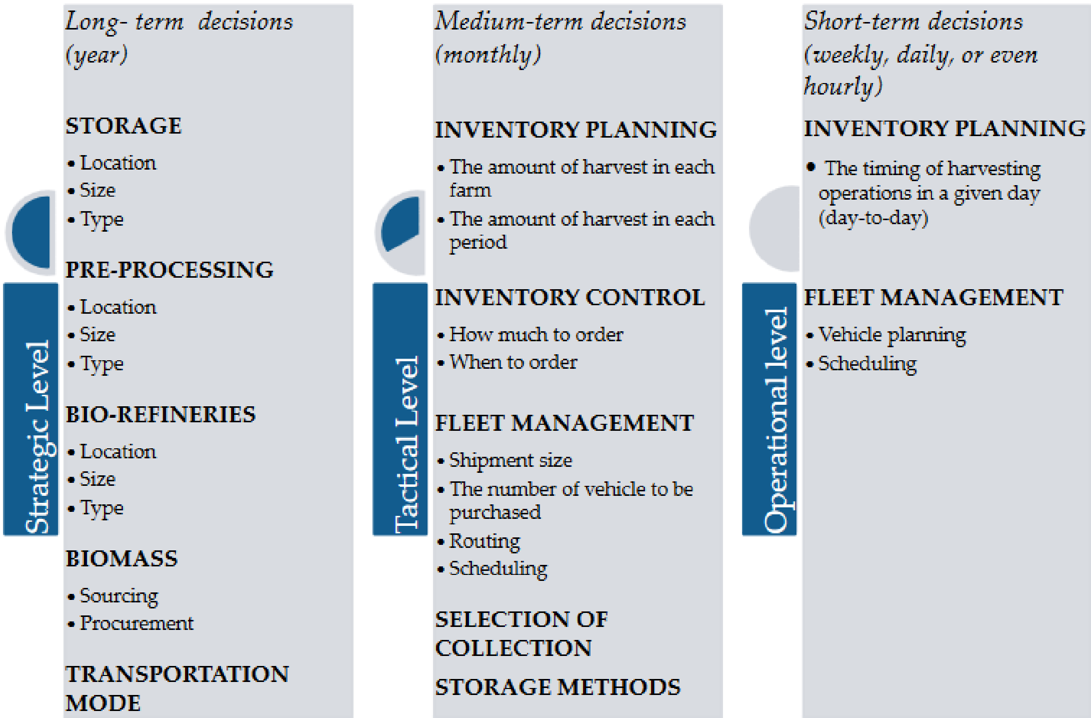


Figure 2.10 - Residual Agroforestry SC Decision's Categorization. Retrieved from (Atashbar et al., 2016).

2.6.4 SC Mapping

The term "supply chain mapping" can be defined as the connection between activities, entities, resources (e.g., human and financial resources) and location, allowing the flow of products and information to be visible across the three streams (upstream, midstream and downstream) (Mubarik et al., 2021). The mapping provides a snapshot of the system state for flexible management and overcoming unpredictable events or risks, such as feedstock and labor capacity shortages (Sarkar et al., 2021). It also helps predict the time and costs of the overall SC to manage the network efficiently and deliver the right products at the right time and place (Carvalho et al., 2012). SC mapping has a significant impact on an organization's performance since it allows the decision-makers to respond promptly to unexpected disruptions (Mubarik et al., 2021).

There are not many graphical elements in the literature that describe a residual agroforestry SC. Nevertheless, Mansoornejad et al. (2013) presents the mapping of a SC of residual agroforestry biomass as shown in Figure 2.11. This SC mapping focuses on the material flow and the participating entities. It is important to note that it also separates the SC echelons by operations.

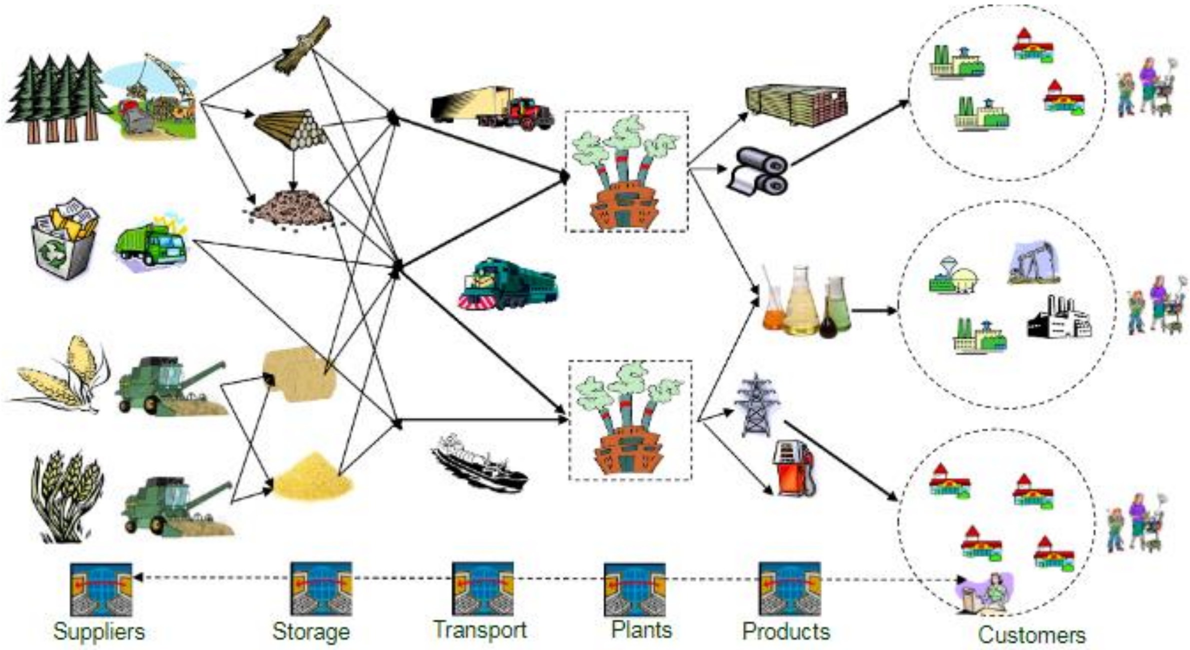


Figure 2.11 - Residual Agroforestry Biomass SC Mapping. Retrieved from (Mansoornejad et al., 2013)

Furthermore, the SC is not a static event but a continuous process that evolves as new information is gathered, and SC entities change. To characterize it, mapping dimensions, such as the involved entities, their relationships, the flow of materials, information, and money, as well as management policies and lead times, can be used. According to Carvalho et al. (2012), these mapping dimensions can be then translated into SC state variables (Carvalho et al., 2022), as shown in Table 2.5.

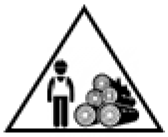
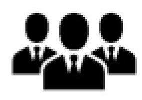
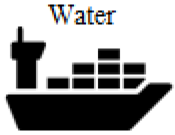
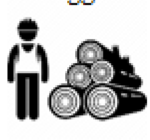
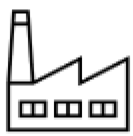
Table 2.5 - State Variables of the SC. Adapted from (Carvalho et al., 2012).

SC mapping dimension	State variables
SC entities	· Type and number · Geographic localization
Relational links	· Type of relationship between entities (vertical and horizontal relations between forest landowners, loggers and consumers)
Material flow	· Volume and delivery frequency · Transport mode · Stock location · Number of customers
Information flow	· Frequency · Type of communication (word of mouth, electronic devices, etc.)
Management policies	· Stock type and level · Management strategy · Number of operations
Lead times	· Production and transit lead times

The state variables stated in Table 2.5 can be used as observable items to assess SC mapping (Carvalho et al., 2022). Moreover, decision-supporting tools and models utilize them to predict the system behavior, integrate knowledge and understanding, and help determine the appropriate management strategies (Jose & Gordon, 2008).

Finally, to map a SC it is necessary to specify the symbols/icons to be used as representation of the entities, means of transportation and links of the SC. Although there are no conventional symbols, (Gardner & Cooper, 2003) proposed conventions, which were adapted to the SC under study, as seen in Table 2.6.

Table 2.6 - Residual Forestry Biomass SC Mapping Conventions

SC Entities	Mean of Transportation	Links	Others
Suppliers 	Road 	Information flow - - - - - - - -▶ Material flow ———————▶	Logger's open-air park 
Thrid parties 	Water 	Monetary flow -·-·-·-·-·-▶	
Logger 	Trail 		
Customer 			

In the residual forestry biomass SC context, the entities or SC actors are:

- **Suppliers**: Forest landowners. They can be private landowners, the state and municipal halls.
- **Third parties**: A company, organization or individual that is involved in the SC, but it is not one of the main entities. They are usually included in the residual biomass SC, when the logger needs services such as transportation, warehouse services and machinery (e.g., bash baler and chipper) (Jayaram & Tan, 2010).

- **Logger**: Entity whose work is logging trees. It is the focal entity in the residual forestry biomass SC.
- **Customer**: Entity to whom the logger delivers the forest residues. It is the end-user in the residual forestry biomass SC.

3

CASE STUDIES

3.1 Case Study Methodology

A case study is a research strategy used to understand complex issues by gathering detailed and systematic information to represent the dynamics of the past or current context (Crowe et al., 2011). It allows to understand the complexities of a particular organizational phenomenon, and it can be used for different purposes, including exploratory, theory building, testing a theory or refining a theory (Martins, 2008).

According to Yin, there are four types of case studies (Yin, 2015):

- The **single case study** is typically used to test a theory when the cases are rare or extreme, resemble other cases, the phenomenon is not reachable or if the single case is studied at different moments.
- **Multiple cases** require more resources and time; nevertheless, they are more consistent and enable broader generalizations.
- The **embedded approach** is a case study that analyses more than one unit.
- The **holistic approach** is a global analysis of the nature of the program or organization.

It is possible to combine different case studies: a single case with a holistic approach, a single case with an embedded approach, and multiple cases with the same approaches (Martins, 2008).

The present dissertation uses the case study methodology as an exploratory study to understand the characteristics of the residual agroforestry biomass SC and achieve the objectives mentioned in section 1.3. Thus, two case studies (this is, multiple cases) with an embedded approach will be conducted by defining and planning the case, collecting data, analyzing and interpreting it, and presenting the results (Crowe et al., 2011; Freitas & Jabbour, 2011).

3.1.1 Case Defining and Planning

The focus of both case studies is the residual woody biomass from forest management and exploitation, as it is considered more relevant for forest fire prevention. When these residues are removed from forest land, the pace at which the forest fire spreads can be slowed down or even prevented. The valorization process can contribute to preventing these types of catastrophes and promote a sustainable economy by reducing the dependency on fossil fuels.

Hence, two case studies were performed to study their SC. The role of each entity, and the material, information and financial flows. The case studies present similar activities since both refer to the residual forestry biomass SC. Case Study 1 covers the Figueira da Foz municipal of the Coimbra district with a focus on Logger X. Case Study 2 focuses on Logger Y, which presents a more significant geographic dispersion - Portugal, enabling the comprehension of a potential scale economy for the valorization of woody residues.

Table 3.1 - Characterization of the Entities of each Case Study

	Entity	Description	Location	Role in the SC
Case study 1	Forest Landowners	Small owners of forestry lands	Figueira da Foz	Supplier
	Loger X	Forestry company	Figueira da Foz	Logger
	Altri Florestal, S. A	Pulp and biomass energy company	Figueira da Foz (Celbi)	Customer
Case study 2	Forest Landowners	Small owners of forestry lands	Municipalities of Portugal	Supplier
	State	State forests from public auctions	Municipalities of Portugal	
	Municipal Hall of Figueira da Foz (CMFF)	Responsible entity for enforcing the legislations concerning the municipality's forest lands	Figueira da Foz	
	Logger Y	Forestry company	Monte Redondo	Logger
	Altri Florestal, S. A	Pulp and biomass energy company	Constância (Caima) Figueira da Foz (Celbi) Mortágua (Celtejo) Vila Velha de Ródão (Celtejo/Biotek)	Customer
	The Navigator Company	Pulp and paper company	Setúbal Figueira da Foz	

			Aveiro	
	Casal & Carreira - Biomassa, S. A	Lumber Sawmill Company	Porto de Mós	

In this dissertation the following research phases were carried out:

1. **Case Studies Framework:** background of the legislation regarding land cleaning and management in Portugal, characterization of each case study's geographical area and equipment, and identification of the biomass power plants in Portugal are conducted.
2. **Case study 1**: identification of the SC entities with focus on Logger X, followed by the information material and financial flows and description and mapping of its SC.
3. **Case study 2**: identification of the SC entities with focus on Logger Y, followed by the information material and financial flows and description and mapping of its SC.
4. **Cross Cases Analysis**: understanding the case studies' differences and similarities.

3.1.2 Data Collection

The collected data is classified as primary or secondary, depending on whether the researcher collected the data himself or received it as supporting documentation from a third party. The secondary data sources in Table 3.2 are documents that allowed a thorough comprehension of the case studies.

Table 3.2 -Secondary Data Sources

Documents	Data	Source
"Diário da República, 1.ª série"	Description of the integrated management system for rural fires in the continental territory and the operating rules.	Decree-Law No. 82/2021
"Custos da Exploração da Biomassa"	Description of the power plant operations and its costs	Altri Florestal, S. A

The primary data was collected mainly through semi-structured interviews. A list of questions was prepared, but the interview was not strict, allowing for a more candid conversation. Table 3.3 depicts the primary data sources and objectives.

Table 3.3 - Primary Data Sources

Objective	Type	No of occurrences	Entity
SC stakeholders' identification	Semi-structured interview	1	CMFF
	Phone interview	1	
SC operations' identification	Semi-structured interview	1	Logger X
	Field visit	1	
	Semi-structured interview	1	Logger Y
	Semi-structured interview	1	Altri Florestal, S. A
Mapping of the SC	Questionnaire about the SCs operations and financial, information and material flows (Appendix A)	1	Altri Florestal, S. A
	Semi-structured interview	1 per entity	Logger X, Logger Y

Each company selected the interlocutor most suitable to provide the data. The interviewed experts are listed in Table 3.4. All of them were knowledgeable on the topic of residual agroforestry biomass valorization.

Table 3.2 - Interviewed Experts

Entity	Expert	
	Role	Experience time (years)
CMFF - Forest Technical Office	Environmental Engineer	2
Logger X	Executive Director	7
Logger Y	Executive Director	46
Altri Florestal, S. A	Forestry Engineer	10

It was not easy to obtain data from the various stakeholders for different reasons. The experts are very busy, and the interviews were carried out between 31/05/2022 and 02/09/2022, which corresponds to a period of overwork. Moreover, not all experts were willing to reveal data about their operations for confidentiality reasons. For example, in Case Study 1, it was not possible to collect data on operational costs and, in Case Study 2, it was difficult to collect detailed information on the operations and resources.

3.2 Case Studies Framework

3.2.1 Legislation regarding Land Cleaning and Management

Portugal has experienced a significant increase in forest fires in the last years; therefore, the government established the National Forest Fire Defense Plan (PNDFCI) to mitigate this risk. The PNDFCI promotes the prevention of forest fires by coordinating efforts among all parties, from small and medium-sized forest owners to Public Administration institutions. The mandatory land cleaning and management through Decree-Law No. 82/2021 is one of the adopted policies. According to this law, all landowners, tenants, leaseholders, and entities possessing lands for any purpose must take several precautionary measures yearly to mitigate fire risk. The legislation states (Canas, 2022; ICNF, 2006):

- The clearing of vegetation, such as weeds and bushes, around houses in rural or forest regions in a strip no less than 50 meters wide and in a 100-meter zone surrounding residential, camping, and industrial areas.
- Trimming tree branches to a height of four meters above the ground.
- Trees should be spaced apart by four meters (10 meters for pine or eucalyptus trees, which are both highly combustible species).
- Trimming vegetation less than five meters from buildings.

The Municipal Halls are responsible for ensuring that the law is being followed and, in case of non-compliance, this entity will proceed with the cleaning of the land, but the defaulter will bear the costs (Canas, 2022).

3.2.2 Characterization of the Geographic Area Under Study

Case study 1 is mostly situated in the municipal of Figueira da Foz - Coimbra district, as shown in Figure 3.1.

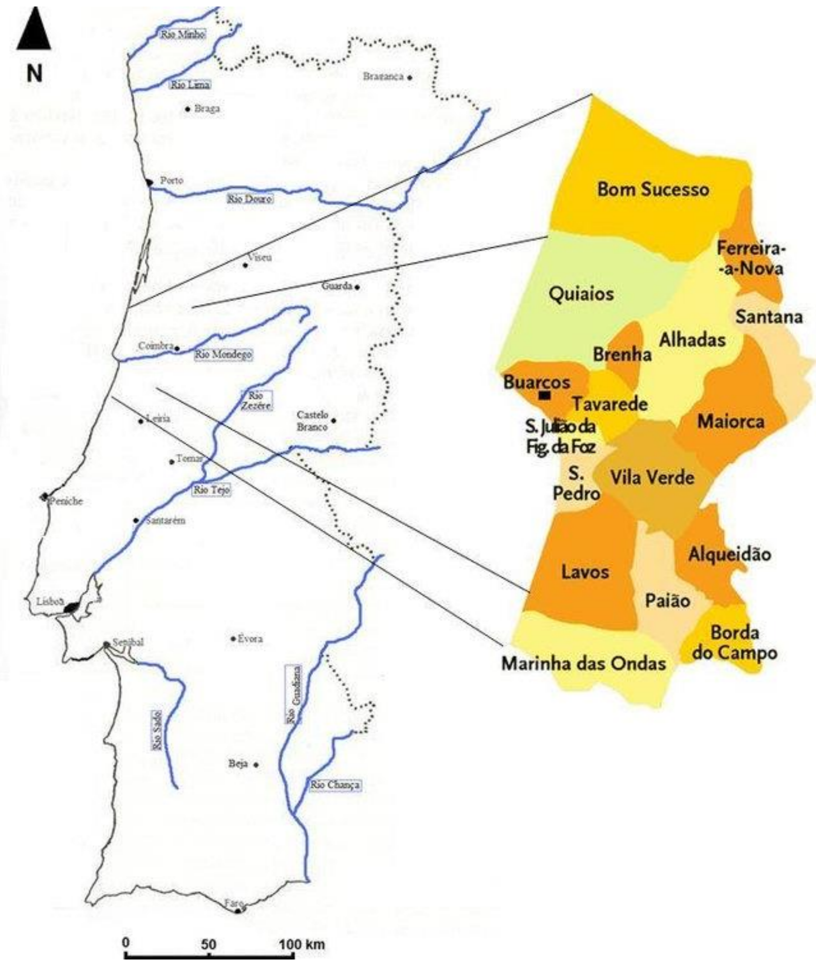


Figure 3.1 - Location of Figueira da Foz in Portugal. Retrieved from (Figueiredo & Rosina, 2015).

The municipal of Figueira da Foz presents an area of 379.05 km^2. It is mostly covered by forest land and maritime pine and eucalyptus being the predominant species. Agricultural land represents the second most significant area of the municipal, as shown in Figure 3.2, in yellow, due mainly to rice and corn production (GTF, 2018).

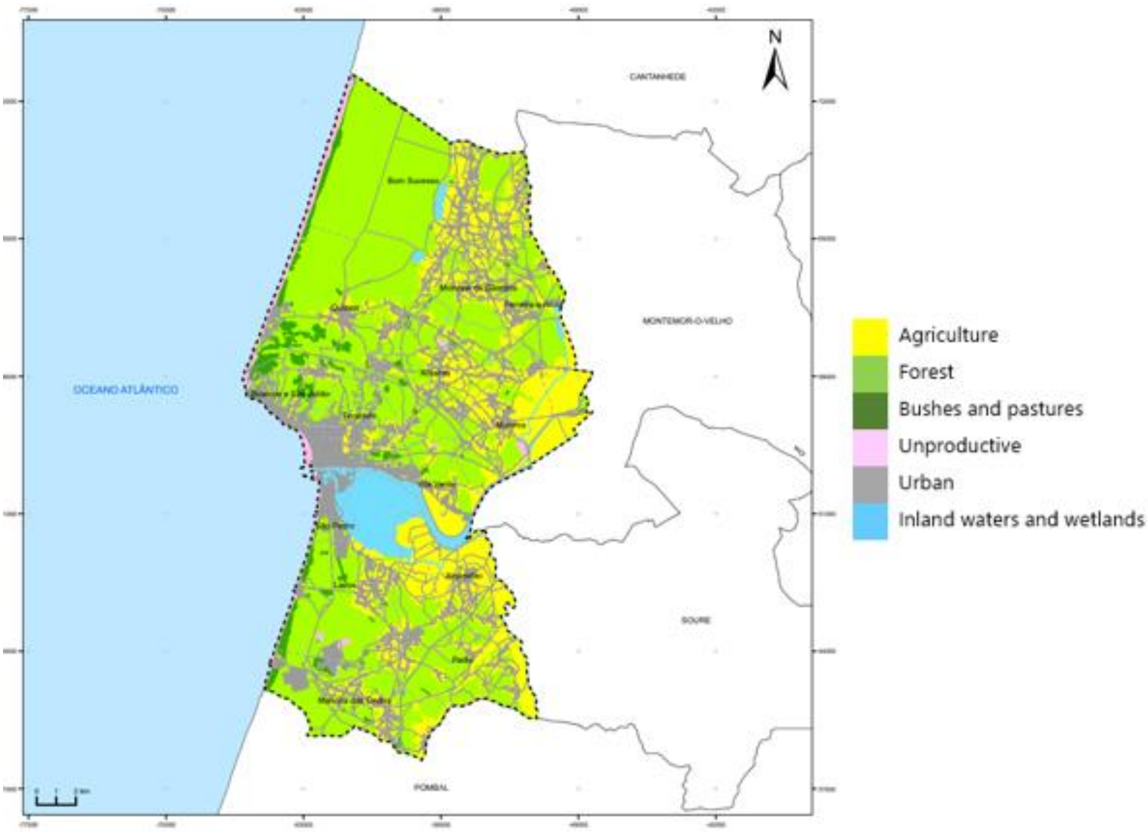


Figure 3.2 - Figueira da Foz Forest Distribution. Adapted from (GTF, 2018).

Case Study 2 has a wider geographic distribution, operating across continental Portugal (Figure 3.3), which presents an area of 89 015,00 Km^2. It was not possible to determine the precise number of Logger Y's suppliers and the corresponding forest area; thus, it was assumed that the suppliers' area corresponded to continental Portugal.

In continental Portugal, the residual biomass is mainly obtained from forestry exploitation (Almeida et al., 2020). Forests represent around 38% of the continental national area, having as dominant species the maritime pine, the cork oak and the eucalyptus. Approximately 75% of the forest belongs to private owners whose lands are less than 5 hectares, meaning that their exploitation has low profitability and disables scale economies. (Ibero Massa Florestal, Lda, 2014).

As for the agricultural land, it occupies about 34% of the Portuguese territory, being more predominant in the south of the country. Considering that agricultural land can be divided into permanent and temporary crops, it is estimated that cereal crops, such as potato and corn crops, occupy 53 % of the temporary crops and olive groves and vineyards occupy 90 % of the permanent crops.

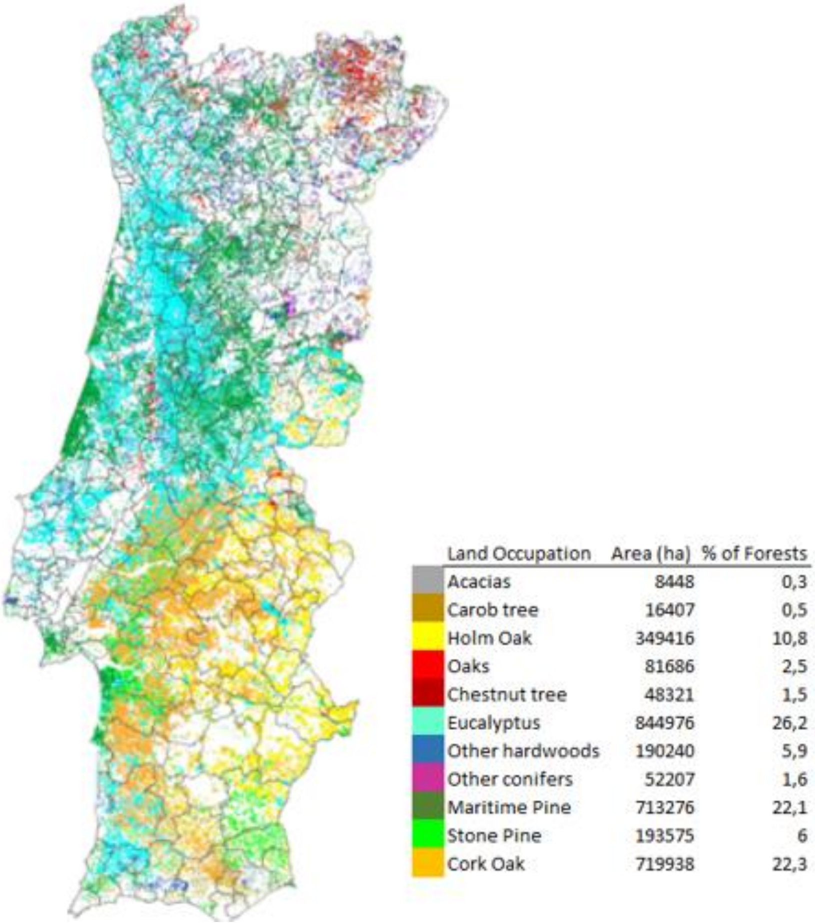


Figure 3.3 - Continental Portugal Forest Distribution. Adapted from (*ICFN*, 2015).

As a result, the expected production of residues is 2,835 and 1,172 million tons per year from forests and agriculture, respectively (*Grupo de Trabalho de Biomassa*, 2013; Ibero Massa Florestal, Lda, 2014).

3.2.3 Biomass Power Plants in Portugal

The installation of biomass power plants is relatively recent in Portugal. In 2005 there were only two plants, EDP in Mortágua and Centroliva in Vila Velha de Ródão. Later, public tenders were launched for the construction of more biomass power plants as an incentive to remove the residual forest biomass from forest areas. This project was initially unsuccessful due to high costs and lack of efficiency in the SC (bad location, lack of raw material, among others). Nonetheless, in 2016 and 2017, new licenses were given, and, in 2022,Portugal accounts for 23 power plants essentially located in the center and north of the country (*A Biomassa Em Portugal*, 2021). Table 3.3 depicts the power plants, installed power and the estimated feedstock demand. The values in the fourth column were obtained through a direct proportionality method using the total installed energy value of 523.79 MW and the estimated amount of residual forest biomass available for energy of 2 835 700 tons per year.

Table 3.3 - Portugal Biomass Power Plants. Adapted from (Florestas.pt, 2021).

Biomass Power Plant	Location (District)	Installed Power (MW)	Estimated Biomass Demand (t. yr-1)
Cogeração Amorim	Aveiro	1	5 413,81
Cogeração de Cacia	Aveiro	35,1	190 024,76
Termoelétrica de Cacia	Aveiro	12,5	67 672,64
Termoelétrica Terras de Sta. Maria	Aveiro	10,75	58 198,47
Central a Biomassa de Vila Nova de Famalicão	Braga	10,8	58 469,16
Central de Biomassa de Corga de Fradelos	Braga	10	54 138,11
Cogeração Celtejo	Castelo Branco	23,69	128 253,18
Termoelétrica Centroliva	Castelo Branco	5,63	30 479,76
Termoelétrica da Palser	Castelo Branco	3,3	17 865,58
Termoelétrica de Belmonte	Castelo Branco	2,53	13 696,94
Termoelétrica de Rodão	Castelo Branco	12,5	67 672,64
Cogeração Celbi	Coimbra	70,96	384 164,02
Cogeração da Figueira da Foz (Lavos)	Coimbra	95	514 312,03
Termoelétrica Celbi	Coimbra	6,26	33 890,46
Biomassa Caima	Santarém	7,04	38 113,23
Cogeração Caima	Santarém	8	43 310,49
Termoelétrica de Constância	Santarém	13,23	71 624,72
Cogeração de Setúbal	Setúbal	53,9	291 804,41
Termoelétrica de Setúbal	Setúbal	12,5	67 672,64
Cogeração Europac Energia Viana	Viana do Castelo	103,7	561 412,19
Cogeração SIAF	Viseu	3,8	20 572,48
Mangualde	Viseu	12,6	68 214,02
Termoelétrica de Mortágua	Viseu	9	48 724,30
	Total	**523,79**	**2 835 700,00**

Thus, to produce 523.79 MW approximately 2 835 700,00 tons of residual biomass is required per year (INE, 2020).

Figure 3.4 presents the location of the biomass power plants listed in Table 3.5. The green triangles correspond to dedicated biomass power plants and the red circles to biomass cogeneration plants. Cogeneration consists in the simultaneous generation of heat and electrical energy.

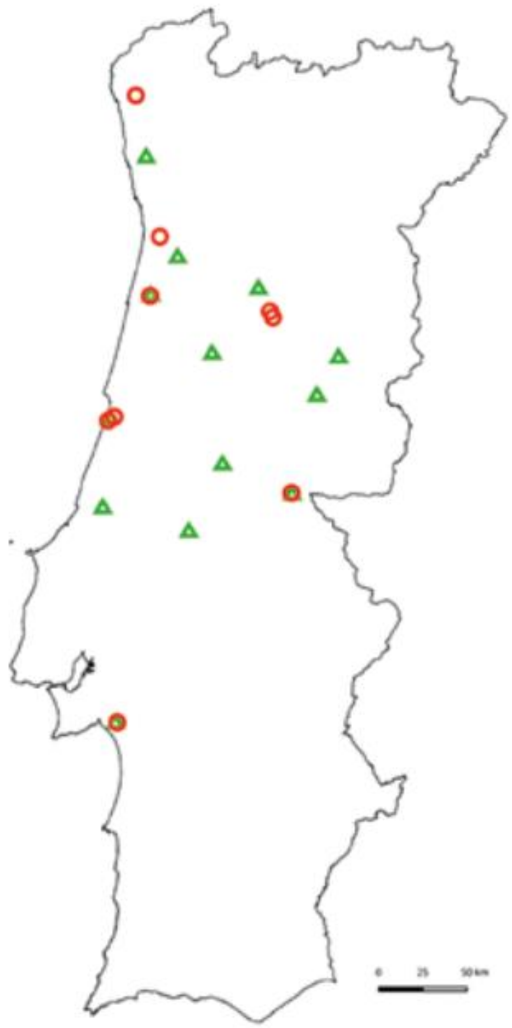


Figure 3.4 - Portugal's Biomass Power Plants. Retrieved from (Almeida et al., 2020)

3.2.4 Equipment used on Residual Biomass Valorization

Both case studies focus on companies with similar activities, which are related with the valorization of woody residues from forests. Thus, the used equipment is mostly the same. Table 3.4 characterizes the equipment utilized by companies under study.

Table 3.4 - Equipment utilized for the exploitation of Agroforestry Residues

Equipment		Features
Harvester		The harvester cuts the tree, removes the bark, branches and foliage, and traces it into logs.
Forwarder		Tractor with a forest crane and a trailer transports the logs/residual biomass and stack them on the roadside, separated.
Chipper		Chippers consist of sharp knives or hammers for cutting woody residues.
Brash Baler		The procedure consists of inserting the residual biomass using a gripper, compressing it, wrapping it with wires, and finishing by cutting the bale with a blade. The equipment is inert-resistant.

Table 3.5 - Equipment utilized for the exploitation of Agroforestry Residues (cont.)

Equipment		Features
Walking floor	* 	The chipped woody residues are placed on top of the truck, and when delivered, the walking floor allows unloading without needing other equipment. Capacity: 93m^3 (28-ton net)
Truck		The bales are placed on the truck with the truck's claw. Capacity: 93m^3 (20 - 30-ton net)

*Retrieved from (Steele, 2013)

The equipment selection is based primarily on the logger's experience and considers the accessibility, size and type of land being exploited. Additionally, the forestry lands exploitation is often associated with land cleaning, therefore, other equipment, including brush cutter and backhoe may be also necessary.

The total cost of ownership (TCO) of each equipment consists of the purchase price of an asset plus the operation costs, is around six digits. Thus, a considerable investment is required to acquire all the necessary equipment for forest exploitation. Considering this, while Logger Y has all the equipment listed, Logger X has to rent the brash baler and the chipper.

3.3 Case Study 1

The focal entity of Case Study 1 is Logger X. Therefore, the entities involved in the case study will be introduced, starting with Logger X. Then, the suppliers and the customer. Afterwards, the characterization of the information, material and financial flows will be carried out, as well as, the presentation of the valorization process, finalizing with the mapping of the valorization process.

3.3.1 Entities of the SC

3.3.1.1 Logger X

Table 3.5 depicts the demographic information of Logger X to contextualize and understand its background, which is engaged in various activities and has forest lands of its own. It was not possible to quantify Logger X's forest lands.

Table 3.6 - Demographic Information of Logger X

Logger X
Activity: Wood trade, cutting, hogging, forest clearing, wood and wood products sale, biomass, forest nurseries and tree plantations.
Legal status: Private Limited Company
About the company: The company is seven years old, having been established on 30/01/2015. Its headquarters is located in Figueira da Foz. The share capital is 1 000.00 €. It develops its main activity in the field of raw wood.
Core CAE: 46731 - Wood in the rough
Secondary CAE: 02100 - Silviculture and other forestry activities
Sales volume: <10 million €
No. of employees: >10 and <50
Geographic dispersion of the main suppliers: Figueira da Foz municipal
Years of experience in the residual biomass business: 7 years
Customers in the residual biomass business: Altri Florestal, S. A

Although the company was founded in 2015, it is a family-run company with extensive experience in the sector. Furthermore, the Logger X is a small size company since it employs between 11 to 50 workers and its annual turnover does not exceed 10 million euros.

3.3.1.2 Suppliers

It was not possible to assess the number of suppliers of Logger X. Nevertheless, they are mainly private forest landowners' from Figueira da Foz, whose land area is usually less than 1 hectare. This type of dimension hinders the profitability of forest residues valorization.

These suppliers usually do not exploit the forest land since they do not have the necessary equipment or lack of knowledge and interest, leaving the land exploitation and management to Logger X.

Finally, Logger X is also considered a supplier since it has also forest lands of its own.

3.3.1.3 Customer

Logger X only has one customer in the business of the residual forestry biomass valorization - Altri Florestal, S. A (Table 3.6).

Table 3.7 - Demographic Information of Altri Florestal, S. A

Altri Florestal, S. A
Activity: Forestry exploitation
Legal status: Private Limited Company
About the company: Altri Florestal has its head office in Figueira da Foz. The share capital is 63 150 000.00 €. It develops its main activity in the field of Forestry.
Core CAE: 2100 - Forestry
Secondary CAE: 72190 - Other research and development in natural and physical sciences

This company is part of the Altri Group, which comprises five companies, as shown in Figure 3.5.

Figure 3.5 - Altri Group Companies. Retrieved from (Altri, 2022)

Altri Florestal is responsible for supplying biomass power plants located in Mortágua, Ródão (Biotek), Constância (Caima) and Figueira da Foz (Celbi).

Logger X only delivers the residual biomass to Altri - Celbi Cogeneration Plant. The electrical energy produced satisfies the needs of the pulp factory (Celbi) and since the plant's electrical energy distribution system is interconnected permanently with the national electrical grid, it allows energy exchanges (buying and selling) with it.

3.3.2 SC's Information, Material and Financial Flows

3.3.2.1 Information Flow

The complexity of the SC creates the necessity for efficient management of the information flow since it enables communication improvement and continuous relationships between the SC entities (Madenas et al., 2014).

The information flow of Case Study 1 begins when the forest landowners contact Logger X by cell phone or word-of-mouth to ask about the price Logger X would pay for the woodland. Logger X records the request on a physical diary/calendar. When Logger X evaluates the woodland, contacts the forest landowner to communicate the woodland price by cell phone or word-of-mouth. If the offer is accepted, a self-billing and a contract are made, and the exploitation of the forest land can begin. It is important to note that the value of the forest residues is not included in the price, only the wood is considered.

Logger X does not own a brash baler or a chipper, so it has to rent the equipment from third parties. Therefore, there is also an information flow between Logger X and third parties, usually by cell phone.

Finally, Altri Florestal, S.A. sends a weekly e-mail to Logger X to inform the quantity and period of time that Logger X has to deliver the residual forestry biomass agreed in the annual contract. When Logger X delivers the residual biomass, an entry form is created to register the quantity and quality of biomass. At the same time, this information is registered in Altri Florestal, S. A's digital platform.

The SC's information flows of Case Study 1 are illustrated simplistically in Figure 3.6.

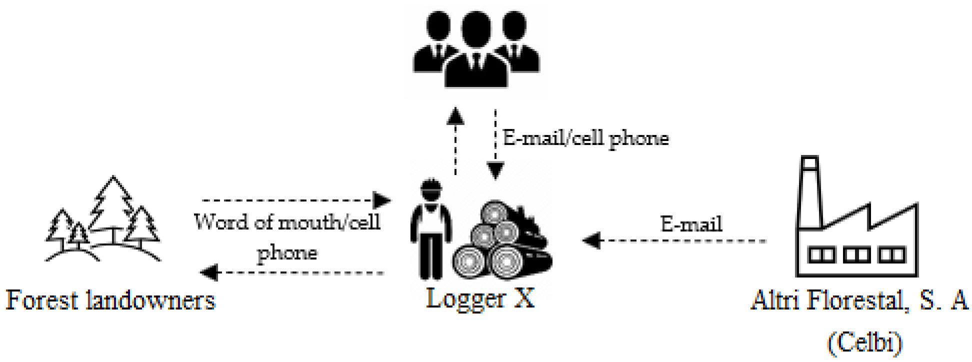


Figure 3.6 - Information Flow of Case Study 1

3.3.2.2 Material Flow

The material flow begins on the forest land, where the logs and forest residues (branches and pecks) are obtained and separated. The forest residues can be chipped, baled, or collected in bulk. The residues are chipped when their volume exceeds around 100 m^3; baled when there are enough forest residues to complete a truck with bales; and collected in bulk when there is an insufficient quantity to complete a truck of bales. Nevertheless, whether to chip, bale or collect in bulk depends on the available equipment since the company has to rent the chipper and the bash bales from third parties.

The stumps and the coarse roots, which are usually uprooted every 24 years to replant the forest, are transported in bulk directly to the end-user - Altri Florestal, S.A (Celbi), due to their hardness and high quantity of inert.

When the residues (branches, pecks, stumps and coarse roots) do not complete the truckload (93 m^3), they are taken to Logger X's open-air park, where they are stored until there are enough quantity to load the truck entirely.

Finally, Logger X delivers the forest residues to Altri Florestal, S. A (Celbi). The average distance travelled to deliver the forest residues to the end-user is less than 50 km.

Figure 3.7 is a schematic illustration of the SC's material flow.

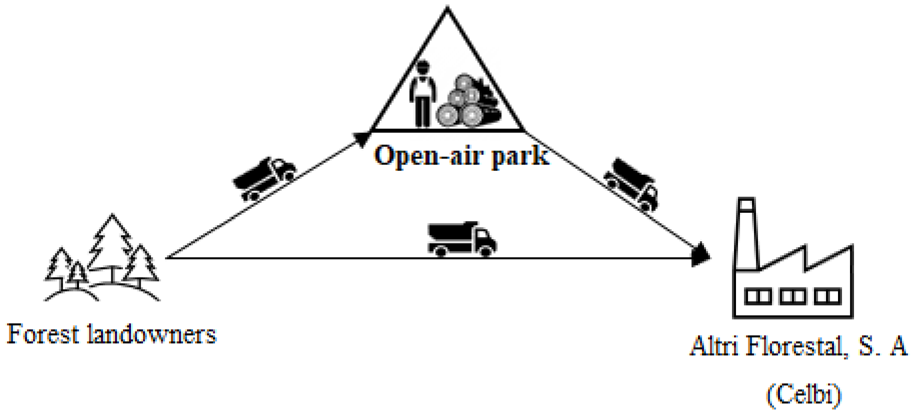


Figure 3.7 - Material Flow of Case Study 1

3.3.2.3 Financial Flow

When the forest landowner accepts Logger X's purchase price of the woodland, Logger X pays the forest landowner the agreed amount before the wood is harvested. However, because Logger X does not pay for the forest residues, the SC's financial flow only starts when Logger X rents the chipper or the brash baler to third parties. The usage time and type of equipment determine the paid amount, which is done at the time of the leasing.

Lastly, the residues are sold to Altri Florestal, S. A (Celbi), which pays Logger X every two weeks.

Figure 3.8 illustrates the financial flow of Case Study 1.

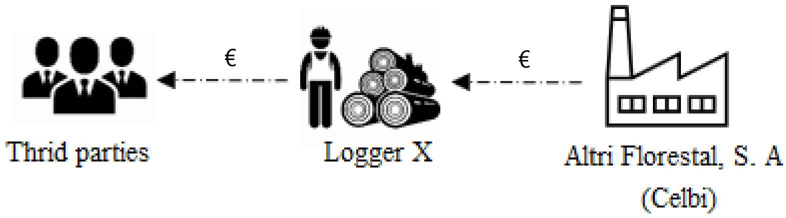


Figure 3.8 - Financial Flow of Case Study 1

3.3.3 SC Characterization of Case Study 1

The SC of Case Study 1 has four main entities: forest landowners, Logger X, third parties, and Altri Florestal, S. A (Celbi). The forest landowners contact Logger X to sell the wood of their land and clean it as stipulated in the legislation. Since the forest landowners do not know the value of their wood, Logger X evaluates it and gives them the purchase price, which the landowner can accept or not. This evaluation has the average diameter, height, quality, and number of trees as criteria. However, it is subjective because the criteria mentioned are determined based on the experience of Logger X. If the landowner accepts the given purchase price, the payment is made, and the exploitation of the land can begin.

The first operation consists of cutting the trees with the harvester, obtaining the wood logs separated from the branches and pecks, as shown in Figure 3.9.

Figure 3.9 - Logs, branches and pecks from Harvesting

Then, the forwarder gathers the logs and stacks them on the roadside, doing the same for the branches and pecks (Figure 3.10).

Figure 3.10 - Pile of branches and pecks

While the logs can be directly loaded into a truck and transported to the customer, the residual biomass (branches and pecks) must go through another process - baling or chip production - to make biomass transportation efficient. As for the stumps and coarse roots, they can be directly loaded into the truck.

Logger X does not own a brash baler or a chipper; thus, the company must rent this equipment from third parties, being subject to their non-availability, which can result in work delays. Additionally, no set rule determines whether to bale or chip. The company usually bales (Figure 3.11) the residual biomass because it does not need as many resources and time as chipping, but when the residual biomass is considerably large, the company prefers chip production since the transportation is more efficient than the bales transportation.

Figure 3.11 - Baling Process of Forest Residues

Ideally, the residual biomass is transported directly to the customer after the truck is entire; however, if there are just some residues left, which are not enough to complete the truckload, these are placed at Logger X's open-air park until there are enough residues to complete the truckload and do the delivery.

In Altri Florestal, S. A (Celbi)'s reception park, an entry form is made to identify the cargo, quantity, and quality (percentage of aggregates and moisture). The percentage of aggregates is established by examining samples of each cargo in a lab, and the moisture percentage is verified with moisture measuring equipment. There is a base price that can increase or decrease depending on the characteristics of the residual biomass.

To better understand the relationships between the entities of Case Study 1, the SC was mapped using the symbology described in chapter 2.6.3, in Figure 3.12.

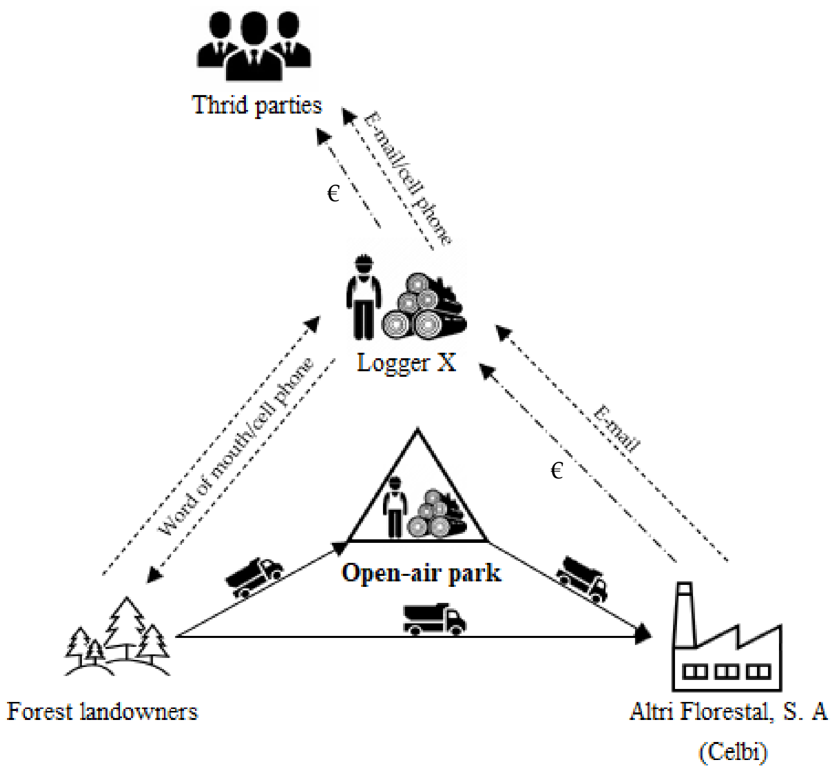


Figure 3.12 - Mapping of the Residual Forestry SC of Case Study 1

3.4 Case Study 2

The focal company of Case Study 2 is Logger Y. The entities involved in the case study will be introduced, starting with Logger Y, followed by the suppliers and, finally, the customers. Afterwards, the characterization of the information, material, and financial flows will be carried out, as well as the presentation of the valorization process, finalizing with its mapping.

3.4.1 Entities of the SC

3.4.1.1 Logger Y

Table 3.7 depicts the demographic information of Logger Y to contextualize and understand the background of Logger Y. The company is engaged in various activities and has forest lands from which woody residues are also explored. It was not possible to quantify Logger Y's forest lands.

Table 3.8 - Demographic Information of Logger Y

Logger Y
Activity: Purchase and sale of wood and firewood; Exploration and sale of resins; Sawmilling of wood; Manufacture of wooden packaging; Manufacture of other builders' carpentry; Manufacture of other woodwork; Wood impregnation; Cereal farming; Production of electricity from wind, geothermal and solar sources etc.;
Legal status: Private Limited Company
About the company: The company is 46 years old, having been established on 28/04/1976. Its head office is located in Leiria. It develops its main activity within the scope of Services for forestry and logging.
Core CAE: 02400 - Service activities related to forestry and logging
Secondary CAE: 16240 - Wooden packaging - manufacturers 16101 - Wood sawmill 35113 - Production of electricity from wind, geothermal and solar sources
Sales volume: < 10 million euros
No. of employees: Around 150 employees
Geographic dispersion of the main suppliers: All municipals of Portugal
No. of years of experience in the forestry residues valorization business: Around 15 years
Customers: Altri Florestal, S.A, The Navigator Company, Casal & Carreira - Biomassa, S. A

The company is characterized as a medium size company since it employs between 50 to 249 workers and its annual turnover does not exceed 10 million euros. It was founded in 1971, so it has vast experience in its field of business, which also explains why it has suppliers and customers across the country.

3.4.1.2 Suppliers

Logger Y's suppliers are mainly private forest landowners from all municipals of Portugal. However, it was not possible to characterize the exact geographic dispersion of these suppliers, hence the characterization of forest land in the national territory of Portugal in its entirety in subsubsection 3.3.2. Forest landowners usually do not own more than five hectares of forest land and are typically elderly, less mobile, and unaware of the woodland's worth, so they are subject to the loggers in their region. Furthermore, the person who estimates the worth of the wood is the buyer (Logger Y) and not the vendor (forest landowners), due to lack of information regarding the prices in this business.

The Portuguese state is also a supplier of Logger Y since the company attends public auctions held by Instituto da Conservação da Natureza e das Florestas (ICNF) for managing and cleaning the state's forest land for a specific period of time.

Similarly, the Municipal Hall of Figueira da Foz (CMFF) has established an agreement with Logger Y for the collection of forest residues when they exceed $3m^3$. CMFF is responsible for the forest lands inspection and answering complaints/requests from the municipal's population regarding land management and cleaning. When a considered amount of forest residues (this is, $3m^3$) is identified, CMFF contacts the forest landowner in non-compliance and allows ten working days to solve the situation. If the situation is not solved within the given time, CMFF identifies the location of these residues in an app developed by CMFF and Company Y, so the latter collects them without the need of direct contact between the entities.

Finally, Logger Y is also considered a supplier since it also has forest lands, which are also explored for wood and residue valorization.

3.4.1.3 Customers

Logger Y has three major customers in the residual forestry biomass business: Altri Florestal, S. A, The Navigator Company, S. A, and Casal & Carreira - Biomassa, S. A.

As **Altri Florestal, S. A** is also a customer of Logger X, it has already been characterized in Case Study 1.

The Navigator Company is a cellulose pulp and paper company, which has invested in biomass power plants to reduce natural gas consumption and contribute to the production of renewable energy. The biomass used is derived from:

- Forestry residues from the pulp and paper operations, sawing, and screening of wood shavings.
- Black liquor, which is a by-product of wood cooking.
- Residual forest biomass market to complement the Company's biomass needs.

The power plants operate on a self-consumption basis, supplying one of the paper machines, and selling only the production surplus to the national grid. Furthermore, The Navigator Company in partnership with the BIOREF Collaborative Laboratory and the NOVA

University of Lisbon are involved in the research process to produce bioplastics from eucalyptus residual biomass. More specific information about the company can be found in Table 3.8.

Table 3.9 - Demographic Information of The Navigator Company, S. A. Retrieved from (Racius, 2022b).

The Navigator Company, S. A
Activity: Wholesale of cellulose pulp and paper and its derivatives and related products and materials used directly and indirectly in their production.
Legal status: Private Limited Company
About the company: The Navigator Company has its head office in Setúbal. Its share capital is € 500 000 000.00. Its main activity is the wholesale of intermediate goods. The company has been known in the past as PORTUCEL INDUSTRIAL - EMPRESA PRODUTORA DE CELULOSE, S. A. and, more recently, as PORTUCEL, S. A
Core CAE: 46762 - Wholesale of other intermediate goods
Secondary CAE: 46900 - Non-specialized wholesale trade 46750 - Chemical products

Casal & Carreira - Biomassa, S. A (Table 3.9) is a small company located in the Leiria district, which only utilizes forestry, agricultural, and agro-industrial residues to produce their products. This company's business comprises of three sectors: extractive, transformation, and electricity production.

It has a wood-fraction transformation unit, where the woody residues are defibrated, dried and separated by grain size. Then, the residues are transformed into ECO pallets, pellets and injection flour, among others. The injection flour is used to produce electricity in a thermoelectric power plant, which also produces thermal energy that is used in a biorefinery (extractive unit) to produce add-value products, such as pharmaceutical, cosmetic, and animal nutrition.

Table 3.10 - Demographic Information of Casal & Carreira - Biomassa, S. A Retrieved from (Racius, 2022a)

Casal & Carreira - Biomassa, S. A
Main activity: Production of energy chips, wood flour for energy purposes, and wood pellets.
Legal status: Private Limited Company
About the company: Casal & Carreira is 15 years old, having been established on 03/08/2007. Its head office is in Porto de Mós. The capital share is € 5 700 000,00. It develops its main activity in the field of wood sawing.
Core CAE: 16101 - Wood sawing
Secondary CAE: 38322 - Non-metallic waste recovery 33110 - Metal products (except machinery and equipment) - repair and maintenance 20530 - Essential Oils

3.4.2 SC's Information, Material and Financial Flows

3.4.2.1 Information Flow

All the information exchanged, between Logger Y and the SC entities, is registered on the Logger Y's platform. Logger Y has three main suppliers: forest landowners, the state and CMFF. While CMFF contacts Logger Y for forestry residues collection, forest landowners and the state contact him for wood exploitation.

The information flow between the forest landowners and Logger Y is conducted in three ways: word-of-mouth, phone, and e-mail. If the contact is done by word-of-mouth or phone, there is the probability of losing information; thus, Logger Y incentives e-mail, so the request is done in writing. Thus, the forest landowners contacts Logger Y for an evaluation of their land, and Logger Y contacts back the forest landowner with its proposition.

As for the information flow between the state (ICNF) and Logger Y, the two entities only establish contact when Logger Y wins a public auction on the ICNF platform. Then, a contract is made and ICNF workers are allocated to supervise the work done by Logger Y.

Regarding CMFF, the contact is made by an app developed by both entities. It consists of a map where CMFF pins the location of the forest residues to be collected by Logger Y. There is not direct contact between the entities.

Finally, the information flows between Logger Y and its customers are made according to the contracts established between which one. Altri Florestal, S. A, for example, sends an e-mail every week with the supply information needed. Figure 3.13 illustrates the information flows performed in the SC of Case Study 2.

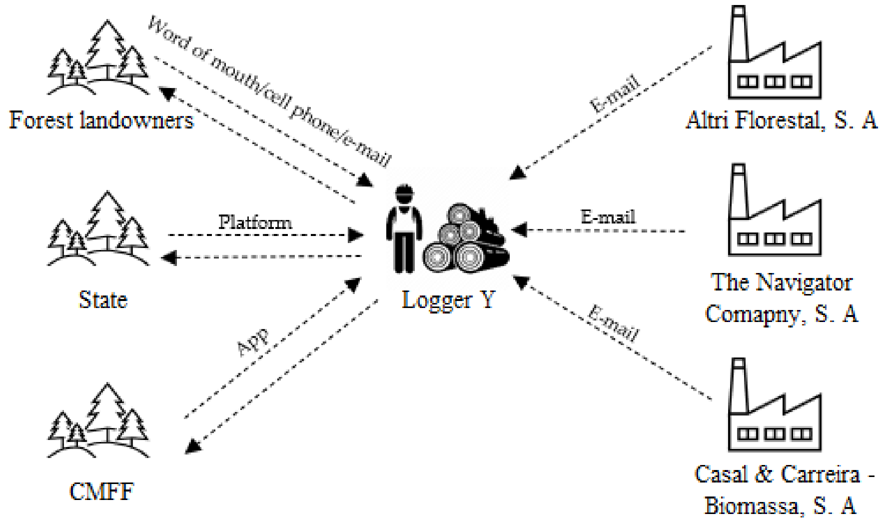


Figure 3.13 - Information Flow of Case Study 2

3.4.2.2 Material Flow

The material flow begins on the forest land, where logs and forest residues are obtained by a harvester and then separated and piled by a forwarder. On-site, these residues can be baled, chipped, or collected in bulk if the number of residues is less than 93 m^3. Thus, according to the type of residue, they are loaded onto the appropriate truck and forwarded to one of the following destinations:

- **Customer's facility** when the truck is fully loaded.
- **Logger Y's open-air parks** when, for example, the quantity of forest residues is not enough to fully load the truck.

Logger Y has two open-air parks: one in Monte Redondo (Leiria district) and another in Soure (Coimbra district). These parks are used to store residues in bulk until there is enough quantity to bale or chip.

Afterwards, the residues are delivered to the customers. It is important to note that the residues from CMFF are delivered to The Navigator Company - Figueira da Foz Industrial Complex or Altri Florestal (Celbi) since these companies are located in the same municipal where the residues are collected. Figure 3.14 illustrates all of SC's material flow.

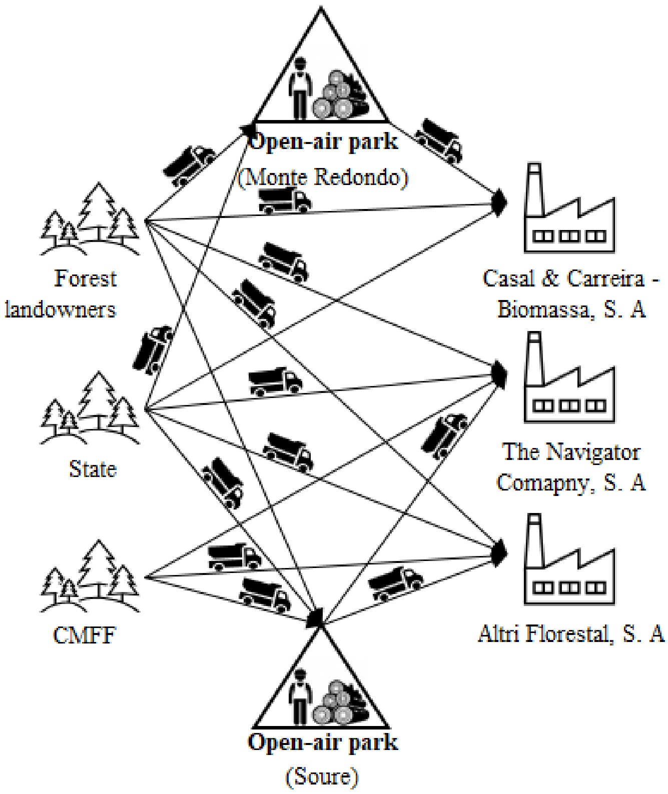


Figure 3.14 - Material Flow of Case Study 2

3.4.2.3 Financial Flow

Regarding the residual forestry biomass SC, Logger Y does not pay the supplier for the forestry residues as mentioned before. Therefore, there is no financial flow between these entities, as Logger Y only pays for the woodland.

Nevertheless, the residues are sold to the customers Altri Florestal, The Navigator Company and Casal & Carreira - Biomassa. The financial flow between Logger Y and the customers occur according to the celebrated contract. For example, Altri Florestal pays the Logger Y every two weeks.

Figure 3.15 allows the visualization of the SC's financial flow of Case Study 2.

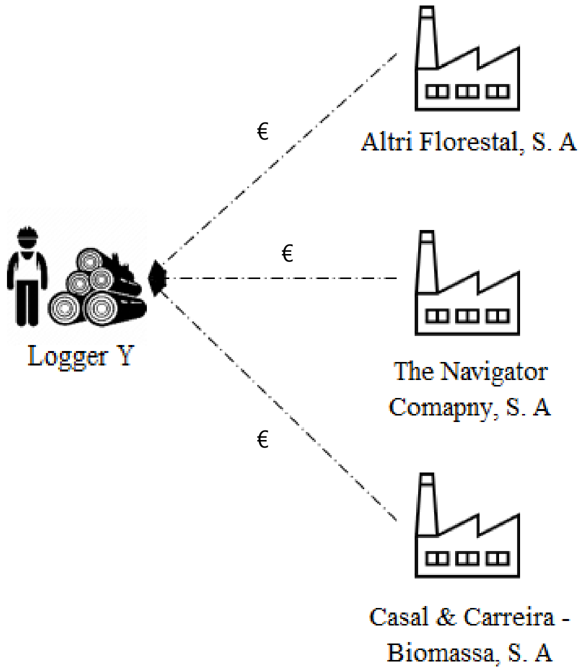


Figure 3.15 - Financial Flow of Case Study 2

3.4.3 SC Characterization of Case Study 2

The SC of Case Study 2 consists of a valorization process of forest residues. When the customer is a forest landowner, Logger Y evaluates the woodland using the *GPS Fields Area Measure* App to map the land and through a generic conversion of one hectare corresponds to 180 m^3 of wood, Logger Y presents the purchase price to the forest landowner. The mentioned App is synchronized with the Logger Y's platform, allowing to know:

- Which forest lands remain to be evaluated
- The forest lands that have been subject to an evaluation and are waiting to be exploited

- Which forest lands started to being exploited
- When the exploitation work is finished

Regarding state forest lands, as they are allocated to companies through public auctions, Logger Y sets a purchasing price as other companies and the best tender is usually the chosen one. Therefore, there is more competition not only because it is a public auction but also because the land is larger than that of the forest landowners, making it a more attractive business opportunity.

The Municipal Hall of Figueira da Foz (CMFF) is a specific supplier since Logger Y does not obtain forest residues through the exploitation of forest lands. CMFF inspects the municipal's land to ensure it is in compliance with the legislation presented in subsubsection 3.1.1. If it identifies forest residue piles, CMFF contacts the forest landowner, giving them ten workdays to remove the residues. After the given period of time, if the pile is still there and consists of more than $3m^3$, CMFF pins it in the App created by both entities (CMFF and Logger Y), Logger Y can collect and sell them to its customers.

The first operation in forest exploitation is the cutting of the trees with a harvester to obtain the wood logs separated from the branches and pecks. Then, the forwarder gathers the logs and stacks them on the roadside, doing the same for the branches and pecks.

In order to transport the residues efficiently, they are transformed into chips or baled, using a chipper and a brash baler. If the residues are stumps and coarse roots, they are directly loaded onto a truck. Afterward, the residues are transported directly to the Logger Y's customers or if the residual biomass is not enough to load a truck, it is carried out to an open park until there is enough biomass to chip or bale.

The following Table 3.12 shows the Logger Y's estimated cost of each SC operation.

Table 3.11 - Logger Y's estimated cost of each SC Operation

Operation	Estimated Cost (€/ton)
Harvesting and Collection	10
Baling/Chipping	10 - 12
Transportation (<50 Km)	7

Therefore, having as reference the truck capacity of 90 m^3, which corresponds between 20 and 30 tons of residual biomass, the total estimated cost of the forest residues valorization process is about 540 to 870€ per load, if the transport consists of less than 50 km.

Finally, the SC was mapped in Figure 3.16 using the symbology suggested in chapter 2.6.3 to better comprehend the relationships between the elements in Case Study 2.

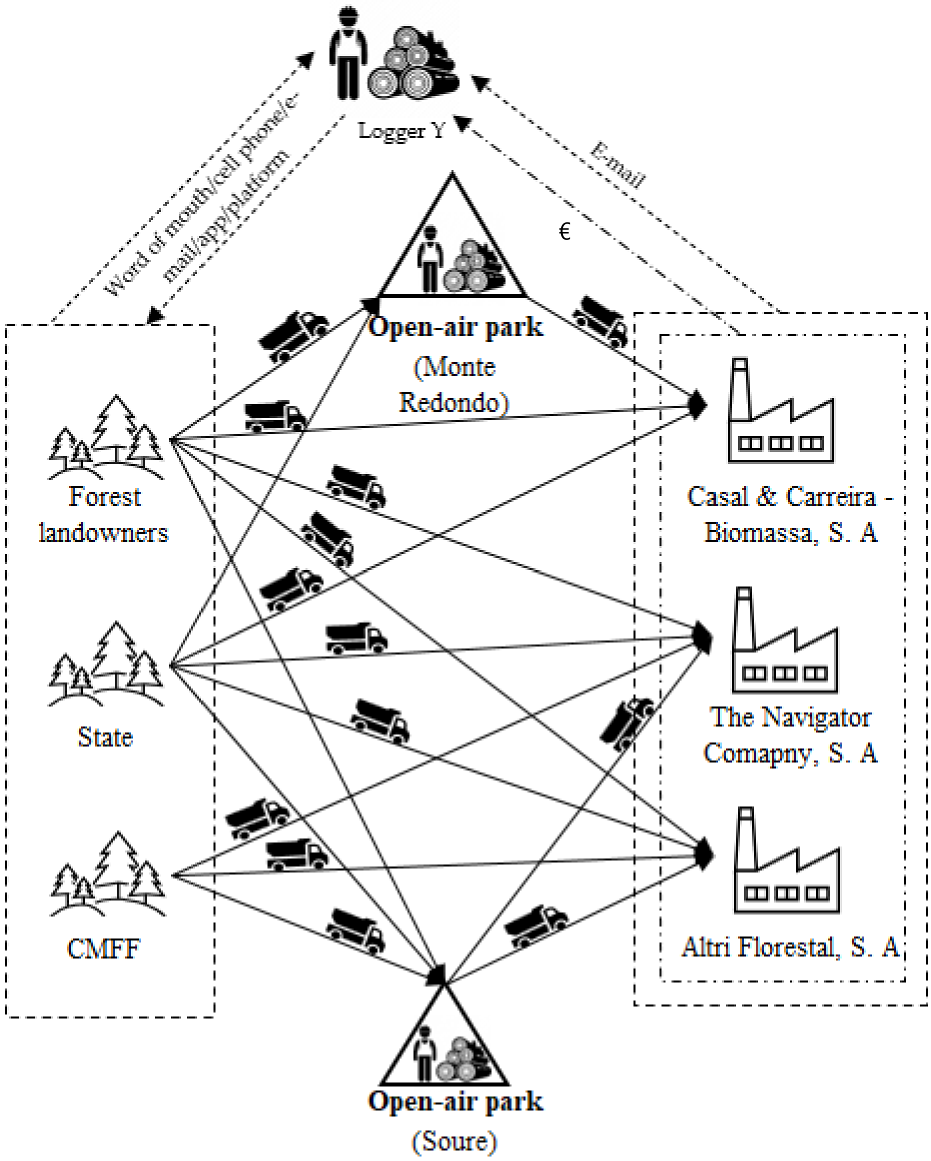


Figure 3.16 -Mapping of the Residual Forestry SC of Case Study 2

3.5 Cross-Case Analysis

A cross-case analysis entails a thorough examination of similarities and differences between multiple cases to provide empirical generalizations (Terziovski & Hermel, 2011). Thus, this section will present a comparison of the residual forestry biomass valorization options of both case studies, their operations, and the material, information, and financial flows.

Both case studies exploit residual forestry biomass to produce electricity. Nevertheless, Case Study 2 also valorizes it through the production of ECO pallets, pellets, injection flour, and add-value products, such as pharmaceutical, cosmetic, and animal nutrition, among others. It is important to note that among the Case Study 2 customers, only Casal & Carreira - Biomassa, S. A is producing these products, besides electricity. Although the findings presented in Table 2.4 in section 2.5 are further, the case studies' valorization options are according to it. The loggers interviewed did not identify other alternatives for valorization, perhaps because the companies to which they deliver the residual biomass do not exist in the geographical areas where they operate or do not exist in Portugal.

The case studies' operations are similar since both consists of a residual forestry biomass SC. The main differences are the number of suppliers, open-air parks and customers, and the equipment each logger owns. Case Study 2 presents a superior number of entities and open-air parks due to its greater geographical dispersion when compared to Case Study 1. Furthermore, Logger X has to rent the chipper or the bash baler to pretreat the residual biomass, while Logger Y has all the equipment needed and gets to rent it to other loggers. Table 3.11 highlights the similarities and differences of the upstream operations of the case studies.

Table 3.12 - Similarities and Differences between Case Study 1 and Case Study 2

Operations	Similarities	Differences
Harvesting and Collection	Both loggers have the necessary resources to perform the exploitation of the wood.	The geographic dispersion of Case Study 2 is greater than Case Study 1. Therefore, Logger Y has more resources (equipment and human) to perform the exploitation of forest lands than Logger X.
Pretreatment	Both pretreat the residual biomass by chipping or baling it.	Logger X does not have the equipment necessary to chip or bale. Therefore, it has to rent it from third parties. Logger Y has all the equipment necessary.
Storage	When the residual biomass is not enough to fully load a truck, it is collected in bulk and transported to an open-air park.	Logger X has on open-air park located in Figueira da Foz. Logger Y has two open-air parks, one in Soure and the other in Monte Redondo.
Transportation	The transportation is mainly done directly to the customer.	The transportation cost for Logger X is relatively low since its only customer is located in the same municipal of the majority of its suppliers. Logger Y has a higher transportation cost due to its suppliers' geographic dispersion (all municipals of Portugal).

The information flow between Logger Y and the other SC entities is considered more efficient than that of Case Study 1 due to the existence of a platform where all the information on each supplier and customer is recorded. Furthermore, Logger Y advises suppliers to communicate by e-mail instead of by phone. Since there is a probability of losing information over the phone, Logger Y may have to contact the suppliers again if that happens, which makes the process less efficient. As for the information flow of Case Study 1, Logger X records the information on a physical agenda. This is only possible because the number of entities in the SC is considerably smaller than in Case Study 2, and Logger x only has one type of supplier - forest landowners.

The material flow is very similar in both case studies. The only factor that makes Case study 2's material flow more complex is its geographical dispersion. Otherwise, the theory behind the material flow is the same. Wherever possible, deliver the pretreated residual forestry biomass directly to the customer; otherwise, it is transferred to an open-air park until there is enough residual biomass to fully load a truck. Moreover, both loggers have a contract with each customer specifying the quantity and frequency of delivery of the residual biomass. Therefore, Logger Y has to manage the residual biomass quantity according to what was established in each contract. Logger X only has one customer, which eases the process.

The financial flow is also identical in both case studies. Logger X and Logger Y get paid for the residual biomass by their customers. Nevertheless, it is essential to emphasize that the suppliers do not receive any value for the residual biomass. The forest landowners and the state are only paid for the woodland exploitation; the CMFF cannot profit from the residual biomass since it is not a municipal company.

Finally, based on the information described above regarding the residual forestry biomass valorization options, SC operations, and the material, information, and financial flows of both case studies, it was possible to map their SCs (Figure 3.17). The visualization of the SCs through their mapping allows a better understanding of the points in common, such as the fact that they have Altri Florestal, S. A as a customer, and to understand the differences, mainly the size of each case study. Moreover, the equipment flow is not represented in the SC mapping because, for this study, it was decided to focus on information, material (forestry residues) and monetary flows. Nevertheless, it is important to mention that there is an equipment flow between Logger X and third parties since Logger X does not have a bash baler or a chipper. This third party could be Logger Y since it rents its equipment to other loggers. However, it was not possible to confirm if Logger X and Logger Y have this type of business.

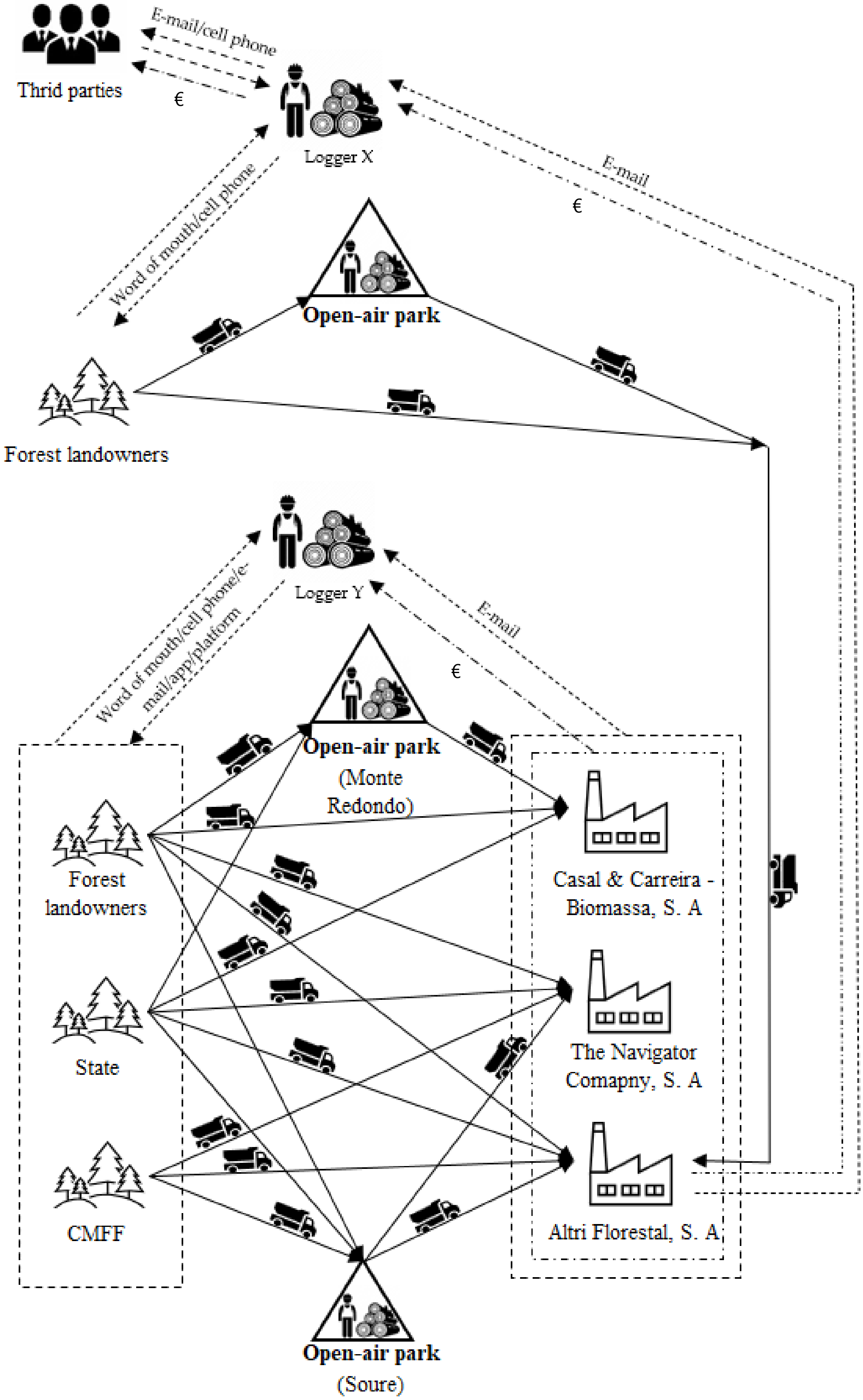


Figure 3.17 - Overall Residual Forestry Biomass SC Mapping

4

CONCLUSIONS

This last section summarizes the work on the SC of residual agroforestry biomass. Additionally, this section offers some recommendations for related future work.

Based on the case studies and the literature review conducted previously, it is possible to understand that the primary type of residual biomass valorization in Portugal is electricity production. Nevertheless, the study has identified one company that is investing in new types of residual biomass valorization: Casal & Carreira - Biomassa, S. A. This company produces, among other products: ECO pallets, pellets, and injection flour, among others. Moreover, it investigates the production of add-value products, such as pharmaceutical, cosmetic, and animal nutrition. Therefore, there is at least one company in Portugal with the initiative to valorize residual biomass for the production of various bioproducts and renewable electricity, which means there is potential for this market to grow. The government's support is fundamental for growing interest in the valorization of residual biomass.

Furthermore, there are no significant differences between case studies regarding the residual biomass valorization operations. However, small-business loggers struggle more to make the SC operations effective and profitable due to the use of high-value equipment.

The information, material and financial flows show some differences caused mainly by the geographical dispersion of each case study. Nevertheless, these flows must be efficient whether it is a small, medium or large company, which is only possible if they are well managed. The information must be well collected and analyzed. For this purpose, some platforms allow this to be done adequately and promptly. For example, Logger Y's platform provides information about each phase of the work, suppliers, and customers, among others. Some apps also help to map forestlands with more precision. The efficiency of the material flow depends on several factors. The distance between the customers and the forest land is one of them. The majority of customers are situated in the central region of Portugal, meaning that when the residual biomass is obtained from southern regions like Algarve, transportation costs rise dramatically. The financial flow represents a dilemma. The forest landowners reach out to loggers to exploit the woodland. Thus, the loggers only pay for the woodland. However, they obtain wood (logs) and residues from the exploitation work, which are afterwards sold to the loggers' customers.

The main contribution of the present dissertation is mapping the residual biomass SC. It enables the visualization of the SC entities, operations, and the information, material, and financial flows. It allows a better and quick comprehension of the SC to identify opportunities and strategies for risk mitigation. Nevertheless, this research is limited to two case studies in Portugal, one of which has a particular geographical distribution. As a result, generalizations about the residual biomass SC are not attainable.

As a suggestion for future research, developing a platform or app with information regarding the value of woodlands and residues is proposed. Currently, loggers purchase only the wood at the price they propose. This happens due to the lack of information by the forest landowners. Therefore, it is urgent to address this misinformation.

Additionally, research on integrating agricultural residues in the SC to produce renewable energy and other bioproducts in Portugal should be conducted, as these residues also have calorific value and are already valorized in other countries.

Finally, creating open-air parks to give residents, particularly small farmers, a place to dispose their residues from lawn mowing, tree pruning and other activities for future valorization would also contribute to risk mitigation of forest fires.

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APPENDIX

This survey is intended to collect data for subsequent analysis within the scope of the project PCIF/GVB/0083/2019 - **Sustainable Model for Supply Chain Management of Residual Agroforestry Biomass Supported on a Web Platform**, which aims to enhance the value of agricultural and forestry residues, while promoting the reduction of fires. Thus, this questionnaire aims to find out the expectations of stakeholders and potential stakeholders on the possible use of a business model powered by this solution, as well as to collect practical ideas that may be useful in implementing the model and some requirements that may shape the final platform.

The information collected will be treated and disclosed in aggregate form and only for scientific research purposes, respecting the privacy rules of the respondents, ensuring the security and confidentiality of the information collected, in strict compliance with the General Data Protection Regulation (RGPD).

Thank you in advance for your collaboration!

☐ I am aware of the conditions and understand the objectives and, as such: I agree to answer the questionnaire

1. What is your function or position in the company where you work? ________________________

2. How many years of experience do you have in the residual biomass valorization sector? ____

3. Are you aware of what usually happens to the residues resulting from the cleaning of forests and agricultural lands (agroforestry residues)?

□Yes

□ No

3.1. If you have answered yes to the previous question, please indicate the main disposal of these residues:

□ Left on-site for decomposition

□ On-site burning

□ Collection and storage for energy recovery (domestic heating in the form of firewood, use in ovens in restaurants, bakeries, or other similar uses)

□ Forwarding for energy valorization (in biomass power plants) or for industrial valorization (production of pellets or charcoal)

□ Other. Which one? ____

Definition of Information, Material and Financial Flows

The supply chain of residual agroforestry biomass comprises several entities, hence the need to understand their relationship. Therefore, information on the flows inherent to the supply chain and its process is relevant to this study.

Information Flow

4. Do residual biomass suppliers need to make an appointment to deliver?

□Yes

□ No

4.1. What is the delivery schedule for the residual biomass? ____________________

5. How is communication with suppliers of residual biomass carried out?

□ E-mail

□ Cell phone

□ Word of mouth

□ Other: ____

5.1 How often the company communicates with the suppliers of residual biomass?

□ Never □ Sometimes □ Often □ Very Often

6. How is the information recorded?

□ Company's platform

□ Excel

□ Form

□ Other? ______________________________

Material Flow

7. What types of residual biomass is received?

□ Forestry residues

□ Agricultural residues

□ Others. Which? ______________________________

8. What is the accepted format of residual biomass?

□ Chipped

□ Baled

□ Residues in bulk

□ Other? ______________________________

9. Who are the suppliers of the residual biomass?

□ Small forest landowners (< 5 hectares)

□ Loggers

□ The company itself

□ Others? ______________________________

9.1. Can any small forestry producer be a supplier of residual biomass? ______________________________

10. Is there seasonality of residual biomass?

□Yes

□ No

10.1. If you have answered affirmatively to the previous question, please indicate in which months there is a significant decrease in the supply of residual biomass.

 January February March April May June
 July August September October November December

11. On what days of the week is the residual biomass received and at what time? ____

12. How much biomass is supplied daily? ______________________________________

13. Do you consider the amount of residual biomass supplied sufficient for the capacity of the cogeneration boiler?

Yes
 No

13.1.Why?____
____

Financial Flow

14. Do you consider the biomass business profitable?

 No A little Reasonable Very

15. On average, what is the monetary value corresponding to 90 m3 (20 - 30 ton) of residual biomass?

 <400 €
 400 € – 700 €
 > 700 €
 Other value? ____

15.1. Does the monetary value differ depending on how the residual biomass is delivered? (e.g. chips, bales, etc.)

Yes
 No
15.1.1. If yes, how? ____

16. When is payment for the residual biomass made?

 At the time of delivery

 Monthly

 Other? ____

Characterization of the valorization process

17. How is the residual biomass received?

____

____

18. How is the quality and quantity assessment of the residual biomass carried out?

 % of inert

 % of moisture

 Cargo weight

 Other? ____

18.1 Description of the process: _______________________________________

____

____

____

19. After receiving the residual biomass, is there a pretreatment process?

Yes

No

19.1. If yes, what is the process and its description? ____________________

____

____

20. Do you store residual biomass?

Yes

 No

20.1. If yes, what type of storage? ___________________________________

21. What equipment is used for the valorization of residual biomass? ______________________

____

21.1. Description of the valorization process: ____

____

____

22. What are the end product(s)?

□Electricity

□ Thermal power

□ Pellets

□ Other?

22.1. What type of technology do you use to manage residual biomass?

____

____

Thank you very much for your participation!

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