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Cienfuegos, Bernardo

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Analysis and optimization of sustainable transport processes of biomass for power plants

Analyse und Optimierung nachhaltiger Transportprozesse für Biomasse zur Nutzung in Kraftwerken

Zur Erlangung des akademischen Grades Doktor-Ingenieur (Dr.-Ing.)
genehmigte Dissertation von Dipl.-Ing. Bernardo Cienfuegos Alegría aus Viña del Mar, Chile
Tag der Einreichung: 30. April 2019, Tag der Prüfung: 12. Juli 2019
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1. Gutachten: Prof. Dr. rer. nat. Liselotte Schebek, Technische Universität Darmstadt
2. Gutachten: Prof. Dr.-Ing. Andreas Eichhorn, Technische Universität Darmstadt

TECHNISCHE UNIVERSITÄT DARMSTADT

Fachbereich Bau- und Umweltingenieur-wissenschaften
FG Stoffstrommanagement und Ressourcenwirtschaft

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Dedicado a mis abuelos y a mis hijos. Los dos extremos de mi motivación.

Abstract

This work addresses the transport planning of raw material supply chains for biomass power plants. It considers the need of generating sustainable solutions by analyzing relevant sustainability frameworks. It proposes a novel approach which consists of an architecture to tailor a proposed base model, and to process the relevant data needed to generate sustainable solutions.

The special characteristics of the biomass transport problem and power plant requirements are captured in a formal problem definition in the form of a data model.
The architecture consists of five combined models (called modules). Each module contributes with methods from different disciplines to enrich the solutions with distinct perspectives. The considered modules include elements from the social, weather, geographic information systems (GIS), life cycle impact assessment (LCIA), and mathematical optimization disciplines. An integrated solution is generated combining the results of all the modules.
Important implementation elements for specific potential users are discussed to support a system prototype.
A case study in Chile is used to gain related primary information of a real supply chain, test the architecture, and provide results about the performance, and allows a deeper discussion.
The architecture generates optimized transport plans that make impacts *visible* in the considered sustainability dimensions and give the decision makers a better understanding of the effects of the considered solutions.

Keywords: biomass, transport, sustainable, power plants, electricity generation, optimization, raw materials, supply chain, social, LCA, LCIA, impacts.

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Glossary

abstract class is a class that provides partial implemented functionality to a class. The missing functionality needs to be implemented with a normal class that extends this abstract class.

API An application programming interface (API) is an interface for communication between different computer programs, intended to simplify connectivity between them.

association in the Unified Modeling Language (UML) an association is part of an object class that represents relationships among different objects.

attribute in the Unified Modeling Language (UML) an attribute is part of an object class that represents concrete data contained within the object.

biofuel are largely traded energy carriers. In most commercialized cases, there are two major types of biofuels: primary (unprocessed) biofuels and secondary (processed) biofuels. Primary biofuels are those where the organic material is used essentially in its natural form (as harvested). Such fuels are directly combusted usually to supply cooking, space heating, or electricity production needs, although there are also small and large scale industrial applications for steam raising and other processes requiring low-to-medium temperature process heat. Secondary biofuels in the form of solids (e. g. charcoal), liquids (e. g. alcohol, vegetable oil), or gases (e. g. biogas as a mixture of methane and carbon dioxide), can be used for a wider range of applications, with higher efficiency rates on average, including transport and high-temperature industrial processes (adapted from [FAO12]).

biomass material of biological origin, excluding material embedded in geological formations and transformed to fossil[1].

bulk density mass of a portion of a solid fuel divided by the volume of the container which is filled by that portion under specific conditions[2].

class diagram in the Unified Modeling Language (UML) is a type of static structure diagram that describes the structure of a system by showing the system's classes, its attributes, operations (or methods), and the relationships among objects[3].

Data class in the Unified Modeling Language (UML) is a structure class that represents data in form of attributes and relationships.

decision variables The variables in mathematical optimization are a set of quantities that need to be determined in order to solve the problem. They represent the decisions to be made.

dioxin dioxins and dioxin-like compounds are a group of chemical compounds that are persistent environmental pollutants. Some of them are highly toxic, but the toxicity among them varies 30,000-fold. They are grouped together, because their mechanism of action is the same. They are mostly minor by-products of burning or various industrial processes (polychlorinated dibenzo-p-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF) are formed mostly as side products in burning processes)[4].

energy crops are plants grown to be used for fuel production (such as bioethanol) or combusted to generate electricity or heat.

ENSO El Niño-Southern Oscillation is a coupled climate phenomenon which involve changes in the ocean and the atmosphere (both). It consists of an irregularly periodic variation in winds and sea surface temperatures over the Pacific Ocean. It has three states: El Niño, a warming of the ocean surface; La Niña: a cooling of the ocean surface; and Neutral: neither El Niño or La Niña where sea surface temperatures are generally close to average.

[1] Source: "ERP Technology Review: Bio-energy Technologies", 2011

[2] Source: "Bioenergy – a sustainable and reliable energy source", International Energy Agency Bioenergy, Paris, France, 2009

[3] Source: based on Wikipedia, `https://en.wikipedia.org/wiki/Class_diagram`

[4] Source: based on Wikipedia, `https://en.wikipedia.org/wiki/Dioxins_and_dioxin-like_compounds`

primary forest fuels (PFF) woodfuel produced where the raw material has not previously had another use. Forest fuel is produced directly from forest wood by a mechanical process. PFF are solid biofuels, also referred as energy wood (adapted from [FAO12]).

georeferenced data refers to data that is associated with locations in physical space. For example: points of interest, roads, places, bridges, tunnels, and buildings, among others.

GHG Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide(CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine and bromine containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF_6), hydrofluorocarbons ($HFCs$) and perfluorocarbons ($PFCs$)[5].

inventory turnover ratio is a dimensionless number that represents the number of times the average inventory is replaced during a given time period.

internal rate of return method of calculating the rate of return which is the profit of an investment over a period of time, proportional to the original investment. The term internal refers to the fact that it does not involve external factors (e.g. inflation or the cost of capital).

mathematical optimization is a quantitative method to discover the best solution (or solutions) with regard to some criteria (objective) from a set of feasible solutions.

MILP a type of optimization problem where the constraints and the objective function are linear. The decision variables are scalars, either integer or continuous variables.

NCV net calorific value. Is the energy amount per unit of mass or volume released on complete combustion.

NER Net energy ratio. The total energy demand of all processes and materials related to the biofuel energy content. In other words, the ratio between the total energy demand of all processes to produce a fuel, and the energy provided by the use of it. NET < 1 is preferable.

normalization to adjust the values measured on different scales to a common one.

net present value is determined by calculating the costs and benefits for each period of an investment. After the cash flow for each period is calculated, the present value (PV) of each one is achieved by discounting its future value at a periodic rate of return. NPV is the sum of all the discounted future cash flows.

Open Street Map is a collaborative project that creates and maintains a free editable map of the world. Website: https://www.openstreetmap.org.

Open Source Routing Machine Modern C++ routing engine for shortest paths in road networks. Website: http://project-osrm.org.

particulate matter (PM) mixture of solid particles and liquid droplets found in the air. Some particles, such as dust, dirt, soot, or smoke are large or dark enough to be seen with the naked eye. Others are so small they can only be detected using an electron microscope[6].

primary data data collected directly from sources.

second generation biomass are biomass types that cannot be directly used as a human food source, and therefore do not enter the food v/s fuel dilemma. They consist of lignocellulosic biomass like forest or agricultural residues.

[5] Source: IPCC AR4 SYR Appendix Glossary, `http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_appendix.pdf` (last visited January, 2014)

[6] Source: Environmental Protection Agency (EPA), `https://www.epa.gov/pm-pollution/particulate-matter-pm-basics` (last visited November, 2019)

SI the *International System of Units* is the modern form of the metric system and is the world's most widely used system of measurement, used in both commerce and science. It comprises a coherent system of units of measurement built on seven base units. It defines twenty-two named units and includes many more unnamed coherent derived units. The system also establishes a set of twenty prefixes to the unit names and unit symbols that may be used when specifying multiples and fractions of the units.[7].

SIC the *Sistema Interconectado Central* was the main electric system in Chile spanning from the *Atacama* Region in the north to the *Los Lagos* Region in the south. SIC transmitted 68.5% of the national generation and served 93% of Chile's population.

System Dynamics is an approach to understand the behaviour of systems over time using stocks and flows, internal feedback loops and time delays.

[7] Source:"International System of Units", Wikipedia, https://en.wikipedia.org/wiki/International_System_of_Units

Acronyms

AHP Analytical hierarchy process.

BSC Biomass Supply Chain.

BTL Biomass to liquid.

CLP Chilean Pesos.

dLCA dynamic Life Cycle Assessment.

DSS Decision Support System.

ECMWF European Centre for Medium-Range Weather Forecasts.

GIS Geographic information system.

GUI Graphical user interface.

HTML Hypertext Markup Language.

ICoS Integrative Concept of Sustainability.

LCA Life Cycle Assessment.

LCI Environmental Life Cycle Inventory.

LCIA Environmental Life Cycle Inventory Assessment.

OO Object Oriented.

OR Operation Research.

toe Tonne of oil equivalent.

UML Unified Modeling Language.

WSM Weighted sum method.

1 Introduction

This chapter includes the motivation for the work, presents the research problem in this context, states the research questions, gives insights about the novelty of the proposed approach, and gives an overview of the document structure.

1.1 Motivation

1.1.1 Context

Climate change, the world growing energy consumption, the interest on energy supply security and the limited amount of available fossil fuels are key factors for governments to encourage changes to the current energy mix. The interest in increasing the role of renewable energy sources is being considered in many countries [LNB99, MCL+02, KMM12]. As shown in figure 1.1 (left) the world energy consumption continues an increasing trend. Fossil fuels play an important role in satisfying this demand as shown in figure 1.1 for the world regions. Fossil fuel depletion is also a future challenge, where even IPCC considered scenarios could be improbable, because of too optimistic expectations in fossil fuel production. [HT13].

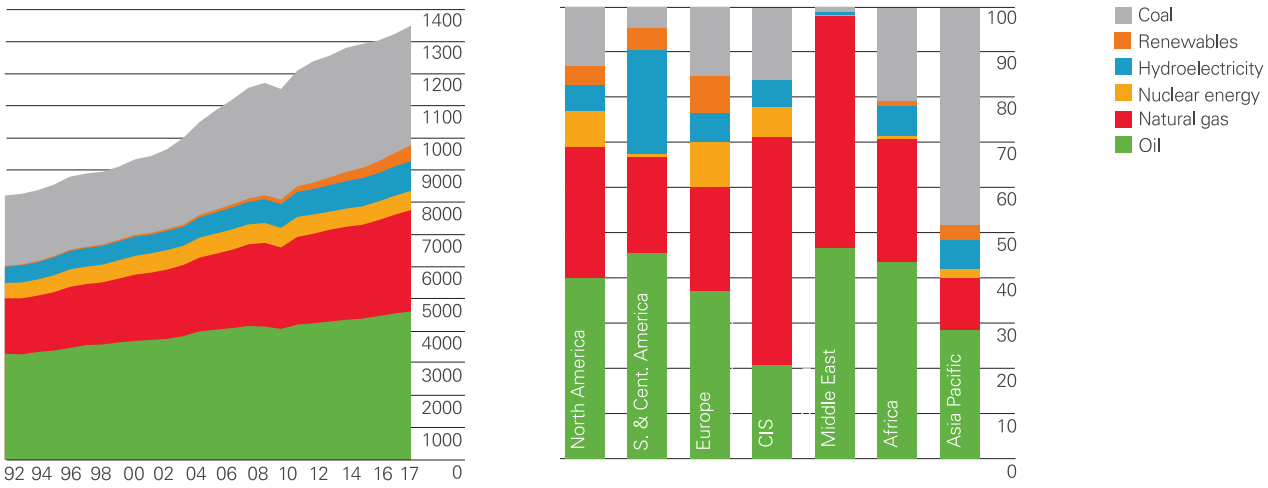

Figure 1.1.: Primary energy world consumption [Million toe] (left) and primary energy regional consumption by fuel 2017 [percentage] (right), Source: [BP18].

Anthropogenic greenhouse gas (GHG) emissions related to the production and use of fossil fuels has been held responsible for the fast climate change observed the last 50 years [KT03], first observed by [Arr96]. Political measures to control these impacts have lead to an increased interest in renewable energies, as they incorporate the potential to become a sustainable fuel for energy generation.
Biomass (in particular forest biomass) has a long world history as an effective energy source. Before the 20th century it was one of the main raw materials for energy generation, but was eventually replaced by fossil fuels in most parts of the world.
Theoretically, the biomass to energy conversion process can be close to a carbon neutral process, if a long term horizon is considered [ZPB12]. The CO_2 released, for example, during a combustion phase of biomass, was earlier captured by photosynthesis. In practice, this is not true for every case as stated by [Joh09], but the use of waste biomass like forest residues can reach this status when compared to fossil fuels as mentioned by [ZPB12]. The use of a fuel with these characteristics has a potential to reduce new GHG emissions, that are related to climate change. This effect targets specific political goals like the Copenhagen Accord and the Kyoto Protocol, and is used as a political argument nowadays to increase the interest in projects that can benefit from it.
If managed correctly, waste biomass is an efficient renewable energy source, which can help hedge against the depletion of fossil fuels reserves. In contrast to other common renewable energies like solar and wind technologies, biomass can be

used as a natural energy storage. In its natural form, it can be stored as a raw material for a themochemical conversion process and used as demand requires. This feature provides biomass the advantage to potentially improve the energy supply security, as this flexibility can be used to balance the electricity grid.
Biomass consisting of forest residues has the potential to increase the available work for people living outside big city areas, because of the usually rural geographic location of the harvest sites. Agricultural residues are burned in the fields in some countries like China [CZWZ08], India, Thailand, the Philippines [GBMG09] and Chile. Biomass based power plants may allow this energy to be used for energy generation (electricity in particular) and diminish the dangers inherent to fires on agriculture fields and the uncontrolled emissions.
Despite the advantages, four main challenges must be faced to manage the added complexity of biomass energy generation: *a*) the selection of distributed biomass locations and harvesting time frames, *b*) the variable biomass properties like humidity and heat power, *c*) a sustainable resource management, and *d*) low energy density.
These challenges are closely related to the biomass supply chain management.

1.1.2 Renewable energies and the role of biomass

Renewable energies are a good candidate to help diminish GHG and as a long term sustainable solution. The debate over the best renewable energy technology to replace the current fossil fuel technologies currently has no single best answer, and depends on each region of the world.A mix of several different energy technologies results in higher energy security level [AMK15]. Every local region has different available raw materials, energy demands, transport accessibility, economic situations, market maturity, environmental issues and social interests. These elements make it impossible to provide a *one size fits all* solution to satisfy every possible combination of these variables. These differences are visible in the regional energy mixes from figure 1.1 (right).
Biomass is defined as biological material from living or recently living organisms. It consist of animals and animal residues, plants and vegetation, forestry and agricultural waste, organic municipal waste, and some specific industrial wastes. First generation biofuels[1] consisting mainly of energy crops have been criticized as they directly influence food prices and availability for the direct and indirect land use change, with the related environmental emissions [OEC08]. Second generation biomass fuels provide advantages against these drawbacks, as they consist of waste biomass that cannot be used as a direct replacement for food. The third generation consist of algae based biomass.
From a second generation biomass fuels point of view, the products/services that demand more of this type of biomass are: electricity, heat, fuels for transportation, and biochemicals. This *waste-to-energy* concept offers environmental advantages for cleaner electricity production and better waste disposal. It has big potential as a method towards a circular industrial economy [PDH$^+$15].

Currently, the two renewable technologies (not including hydro) that have the bigger share on electricity generation are wind power and solar photovoltaic [REN18] (44,2% and 32,4% respectively in 2017 [Glo18]). Both are production ready technologies and are associated with good social acceptance. Both share a critical disadvantage: the electricity generation has a very close correlation with the resource availability. In other words: wind turbines generate only while the wind flows and photovoltaic cells cannot generate electricity in a dark night. As cities electricity-demand profiles cannot be adjusted to the generation profiles which vary constantly (see figure 1.2), there is a need of other technologies that are able to generate electricity on-demand to balance the system. Biomass based generation has the potential to have this feature (as fossil fuels have).
Biomass based power plants are also an interesting strategic alternative for several regions, as reserves are spread over the world and more common than fossil fuels. They can also be created for specific objectives such as industry requirements or urban planning, where the residues of industry operations could be used as a raw materials for energy production.
Another aspect is that the current thermochemical conversion technologies and implementations that use biomass are also well developed in comparison to other renewable energies, like geothermic and tides technologies. This maturity suggest reliability and lower costs. Existing electricity grids with several coexistent technologies could benefit from an earlier implementation for the *ready to market* technologies.

Because of these advantages, this work will focus on the electricity use of second generation biomass fuels.

1.1.3 Energy from biomass and sustainability development

Sustainability is a complex concept. There are several frameworks that try to address the problematic with different approaches. A common one is the *three columns* approach which considers economic, environmental and social dimensions. To address sustainability using this framework, a model needs to include a set of indicators that are able to describe the relevant aspects of these three dimensions to a high extent. The social indicators are usually the most challenging to

[1] fuel produced directly or indirectly from biomass.

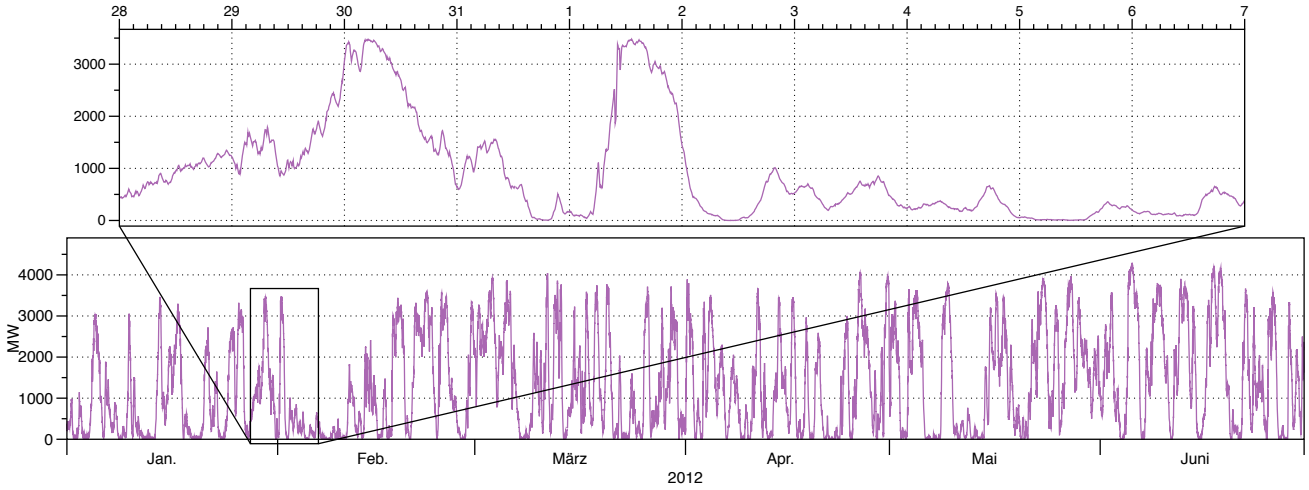

Figure 1.2.: Electricity generation of 41 wind parks with a total of 4711 MW installed capacity.

include and many studies tend to settle with a small amount of indicators for the social dimension, giving a biased sense of sustainability, for example as reviewed by [CS14]. Another approach that addresses the sustainability analysis under a base of *justice* is the *Integrative Concept of Sustainability (ICoS)* [GK06]. This approach incorporates a set of objectives and rules that guide the analysis and the choice of a complete indicators set. Its intended use is on a global sustainability assessment, but with some considerations it could also be adapted for smaller systems.

None of these approaches fits without adapting the considered problem, and an novel option inspired by sustainability frameworks is developed in this work.

1.1.4 Problem definition: the biomass transport

Biomass is a low density fuel with seasonal availability and quality variations. Also for high biomass demand facilities like big power plants, different harvest sources for the demand are usually needed. This can be a difficult problem to solve, as the choice of several types of biomass types, from different locations, with different qualities, and different economic, environmental and social implications is needed.

The cost of logistics operations is one of the main barriers for increased biomass utilization for energy production [IKV$^+$10]. From the overall cost of the biomass delivered in plant, transport costs are expected for some situations to be between 20% and 50% [ABH$^+$98] [HST95], which endorses costs savings potential.

The quality of biomass as a fuel is first influenced by the cultivation, and second by the storage conditions and duration. During storage, rain can increase the humidity and several chemical processes to take place for different types of biomass which changes their characteristics over time.

The optimal planing of the supply chain transport that combines all these elements is not trivial. From a user point of view, every member of the biomass supply chain (e.g.: biomass producers, transport companies, power plants) and other stakeholders can benefit from a system that combine their interests in an integrated way.

The optimal implementation of renewable energies in a complex market is not a simple task. For the case of biomass based power plants, a tool that supports the decision making for the supply chain members can be a clear advantage for increasing the system efficiency.

1.2 Research questions

In the context of the described motivation, the work objectives can be summarized in these three research questions:

1. What are the *key elements* for the planning of a regional sustainable biomass supply chain for power plants?
2. Is there a better approach to address *sustainability considerations* for the biomass supply chain?
3. Can these considerations be combined in a model to *optimize* a regional power plant supply chain?

1.3 Document structure

Chapter 2 starts with a methodological background, and main sustainability frameworks are presented in the context of this work. It continues with a review of the state of the art of the biomass supply problem for power plants. Important research gaps are identified. The relation of the research gaps and this work are presented.

Chapter 3 presents a concrete problem description for this work, and specific details about the biomass supply chain. Two main user perspectives are presented in terms of potential interests for a Decision Support System (DSS) based on the proposed model. This is followed by a formal problem structure in terms of a data model and a model architecture. The general model structure is shown. The considerations for the dimensions integration are described. It relates the addressed sustainability frameworks to the problem and it gives the detailed theoretical explanation of the proposed model architecture that connects the several submodels (modules) and their related methods of implementation.

Chapter 4 continues with a description of the considered users of the DSS, their specific objectives and the benefits that this tool provides to their workflow. A model description from a user and technology perspective is detailed and benefits are discussed.

Chapter 5 presents and analyzes the results for a case study in Chile. The context, a system description, a model formulation based on the proposed methodology, data sets, results and sensitivity analyses are included.

Chapter 6 finishes with a discussions of the main work contributions, outlook of interesting future research, and end conclusions.

2 Biomass supply chain for power plants

This chapter starts describing the methodological background for the biomass to energy model proposed in this work. Relevant sustainability frameworks are presented and linked with biomass supply chain considerations. Afterword a complete literature review of current research related to the topic is presented. The relevant research gaps are also identified and the strategy to address them is introduced. All this information is used to identify the concrete problem elements that are considered in the model described in chapter 3.

2.1 Methodological background

2.1.1 About the used terminology

In this work the terminology used is based on the *Unified Bioenergy Terminology* by [FAO12], which aims to unify and organize terminology and definitions of woodfuels and other biofuels. The most relevant terms are defined in the glossary and throughout the chapter.

2.1.2 Basics about biomass and energy

Biomass is a natural way to store solar energy. There are several processes to transform it to other types of fuels or energy. Examples of producing other solids are carbonization and aerobic decomposition to produce coal and compost. Options for liquids are pyrolysis, compression/extraction and alcoholic fermentation to produce oils and ethanol. For gases there are gasification and anaerobic digestion to produce biogas. To transform the biomass or the derived fuels to other types of energy like electricity, heat and movement, a combustion stage is required[1].
Relevant biomass quality indicators are listed below:

- **Heating value**: is the amount of heat released during the complete combustion of a specified amount of a substance. It is measured in units of energy per unit of mass.
- **Gross calorific value**[2]: the total heat energy produced in a combustion reaction.
- **Net calorific value (NCV)**[3]: the useful heat energy produced in a combustion reaction, discarding the needed for internal processes like water evaporation, as the energy required to vaporize the water is not released as heat.
- **Humidity**: it represents the water share absorbed by a solid, or mixed in a gas.
- **Density**: it is the mass per unit of volume. It is a relevant consideration for transport. The useful variation *weight-density* corresponds to the weight per unit of volume.

The power plants considered in this research use a thermochemical process to directly burn the biomass. The main reason for this decision is to analyze the benefits of this option, as it will most likely improve the net energy ratio (NER) of the system, as every added biomass conversion process (like a process to increase the energy density before the transportation) requires energy to be performed. It also requires a low amount of production processes (e.g. no conversion to a higher density fuel), which results in a cheaper supply chain infrastructure. This suits emerging economies as well as developed ones.

2.1.2.1 Energy and efficiency

The *capacity to do work* is a simple definition of energy. Energy can be transformed into other forms in multiple ways. For example, wood can be burned in a campfire to transform the chemical energy into light and heat. Energy efficiency

[1] Compost is an exception, where heat is released without combustion.
[2] Another term is *higher heating value*.
[3] Another term is *lower heating value*.

can be defined with the help of the first rule of thermodynamics: the conservation of energy. The total energy of a closed system remains constant. It can be transformed from one form to another, but cannot be created or destroyed.

$$\text{Energy transformed from the system} = \text{Energy used for work} - \text{Energy wasted} \tag{2.1}$$

From an efficiency perspective, we can define a systems energy efficiency as:

$$\text{Energy efficiency} = \frac{\text{Energy used for work}}{\text{Energy input}} \tag{2.2}$$

This result offers a way to keep track of energy quantities that flow in a system.

2.1.2.2 Energy v/s power

The common misuse of energy and power in the open media when talking about energy generation is worth clarifying. Power is a rate: energy per unit of time.

$$\text{Power} = \frac{\text{Energy}}{\text{Time}} \tag{2.3}$$

The unit of power in the International System of Units (SI) is joules per second, which is equivalent to 1 watt ($1\,\mathrm{J/s} = 1\,\mathrm{W}$). If we look at it in terms of work, energy measures the total quantity of work done, but it does not say how fast this work is completed. From a power plant point of view, it makes no sense to say "this plant's power generation power is 10 megawatts per year", as this value neither represents energy nor power. A correct way would be to say "10 megawatt-hours per year" (power) and since there are 8.766 hours in a year (average), we can convert the unit to megawatts (MW) by dividing by this number and get the result of equation 2.4.

$$\frac{10\,\mathrm{MWh/year}}{8766\,\mathrm{h/year}} = 1.14\,\mathrm{kW} \tag{2.4}$$

Energy is the total amount of work done, and power is how fast it is done. An example of a unit for power is watts (W) and for energy it is watt-hours (W h).

2.1.3 Mathematical optimization

The biomass transport problem is one with an immense amount of possible solutions. Mathematical optimization is an analytical method to search for the *best* solution inside a space of feasible alternatives. It maximizes or minimizes an objective function relative to a set of restrictions. It has the potential to find better results than just comparing a set of alternatives, as this approach can only find the best one, among the ones considered. The search space considered in mathematical optimization can be infinite (e.g. for problems that consider continuous decision variables.) The objective function allows comparisons of the different alternatives for deciding which might be *better* relative to another.
Mathematical optimization has several subfields, categorized by the properties of the model equations. Relevant to this work are:

- **Linear programming** (LP) the field where the objective function and the constraints are specified using only linear equalities and inequalities. This is a type of convex programming[4].
- **Integer programming** (IP) the field where some or all variables are constrained to integer values. This set of problems is not convex and is usually more difficult to solve than linear programming.
- **Integer linear programming** (ILP), where the objective function and the constraints (other than the integer constraints) are linear. If not all decision variables are constrained to be integers, the problem is known as a **mixed-integer programming** (MILP).

The basic formulation is included in equations 2.5.

$$\begin{array}{rrcll} \max\limits_{Z} & Z & = & c^T x & \text{(objective function)} \\ \text{s.t.} & Ax & \leq & b & \text{(linear constraints)} \\ & x & \geq & 0 & \text{(bound constraints)} \\ & \text{And some x} & \in & \mathbb{Z} & \text{(integrality constraints)} \end{array} \tag{2.5}$$

Where c is a row vector with N elements, x is a column vector with N elements, b is a column vector with M elements (M is the total number of constraints), and A is an M by N matrix.

[4] In Convex programming the objective function is convex (for a minimization objective) or concave (for a maximization objective) and the constraints set are convex.

As the resolution of IP is clearly more difficult than LP (IP is NP-Complete[5]), LP or MILP models are preferred for computational efficiency and to reach useful solution times with current computational power.

For example, the model in equations 2.6 represents a maximization problem with two decision variables.

$$\begin{array}{lrcl} \max\limits_{Z} & Z & = & x+y \\ \text{s.t.} & -2x+2y & \geq & 1 \\ & -8x+10y & \leq & 13 \\ & x,y & \geq & 0 \\ & \text{x , y} & \in & \mathbb{Z} \end{array} \tag{2.6}$$

Two optimum solutions are shown in figure 2.1. An orange marker for the MILP problem solution ((x, y) = (1, 2) with objective value equal to 3), and a blue marker for the associated LP problem, also called *relaxation* ((x, y) = (4, 4,5) with objective value equal to 9,5). Both objective function values are shown with green lines to identify them above the feasible region.

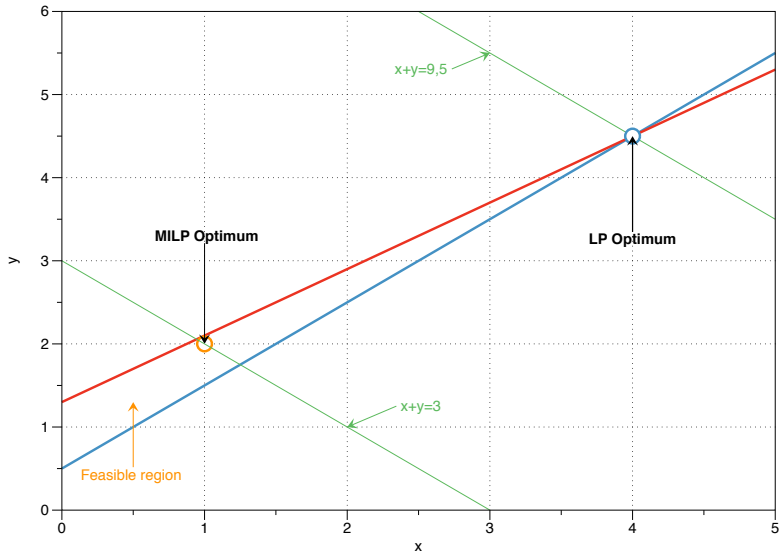

Figure 2.1.: Example LP and MILP solutions.

It is interesting to notice that the integer solution cannot be directly obtained by rounding the linear solution, and it requires more computational power to be calculated.

2.1.4 Life Cycle Inventory Assessment

Life Cycle Assessment (LCA) is a method for calculating the lifetime environmental impact of a product or service. LCA is specified in the International Organization for Standardization (ISO) 14040 series of standards. The four main parts according to [ISO06a] are:

- **Goal and Scope definition**: specifying the objectives, system boundaries, intended use and audience of study results, data requirements, and limitations.
- **Inventory analysis**, Life Cycle Inventory (LCI): collect and aggregate input and output data to quantify materials, energy, and waste associated with the life cycle.
- **Impact assessment**, Life Cycle Impact Assessment (LCIA): understand and evaluate significance of the potential environmental impacts for a product system throughout the life cycle inventory of that product. The LCIA phase shall include selection of impact categories, category indicators and characterization models. Also classification (assignment of LCI results to the selected impact categories) and characterization (calculation of category indicators results).

[5] NP problems have no known way of finding a solution quickly, although it is possible to verify a known answer in polynomial time. Currently, all known algorithms for NP-complete problems require time that is superpolynomial, and it is unknown if there are faster algorithms.

- **Interpretation**: conclusions of results related to the project objectives, results summary, identification of significant impacts, and recommended options to reduce negative effects.

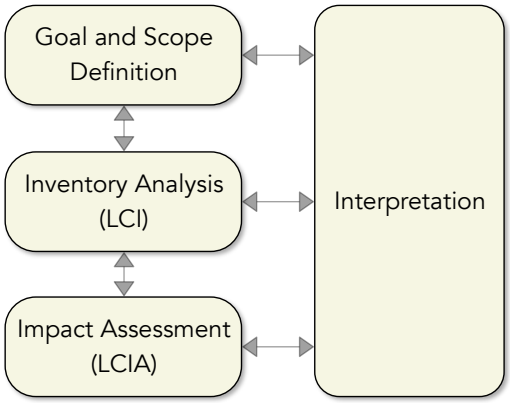

Figure 2.2.: LCA main phases

As [ISO06a] declares, "there are cases where the goal of an LCA can be satisfied by performing an inventory analysis and an interpretation only. This is usually referred to as an LCI study". This is closer to the purpose of the use of the LCA methods for this work. LCI studies comprise three phases:

- Goal and scope definition
- Inventory analysis
- Interpretation

The Environmental Life Cycle Inventory (LCI) describes the mass and energy inflows and outflows of the processes (e.g. transport of biomass, the energy conversion process, etc.) in a given system, and how they are related. This is the data collection portion of LCA. This analysis may involve several unit processes in a supply chain and can be very complex, as well as tracking hundreds of elements.
Still, the LCI provides a huge amount of data, which can require a long analysis to understand the potential impact. This is where the LCIA plays a key role: it provides a way to interpret the effects using impact categories that are able to encapsulate the huge amount of data into aggregated values, by the means of science based characterization models. The steps to conduct an LCIA are:

1. Selection of impact categories.
2. Classification of LCI results to the defined impact categories.
3. Characterization of the emissions and resources into the impacts using a model.
4. Normalization to adjust the characterized impacts to a reference to allow comparison between each factor.
5. Group impact categories into sets.
6. Weighting the impact categories allows having a single indicator, but with strong assumptions about which is more relevant.

The related ISO standards only require the first three elements, leaving the last three optional.
There are two approaches to describe the impact of the LCI emitted elements in the environment: midpoint (problem oriented) and endpoint (damage oriented) indicators. Examples of midpoints indicators are climate change and human toxicity. Examples of endpoints indicators are human health and ecosystem quality.
And important remark is that the relation between the LCI data and the impact category values is linear.
There are several methods to calculate the different impacts like ReCiPe, CML, ILCD, etc.
For this work, the aggregated LCI results of the LCIA midpoint or endpoint indicators are used in the model (ReCiPe 2016 was chosen, more about this in section 3.10). Following the discussion about the benefits and sacrifices of midpoint and endpoint indicators from [BHP00], it is hard to recommend a single answer for every case. For example, for specific

communication of results like global warming potential, the midpoint indicator may be preferred. On the other hand, endpoint indicators like *damage to human health* or *resource scarcity* are more appealing to decision makers that lack of a strong background in environmental science.
For this reason, a case by case approach should be used to decide about whether to use midpoint, endpoint, or even both types of indicators simultaneously.

2.1.5 Unified Modeling Language

The Unified Modeling Language (UML) is a general-purpose, developmental, modeling language in the field of software engineering, which is intended to provide a standard way of visualizing the design of a system [BRJ05].
It is an approved ISO standard published in [ISO05] and is updated to the current revision in [ISO12].
For a good understanding of how a system works by means of a model description, it needs to be modeled at least under a static/structural and dynamic/behavioral perspective. UML provides with a standard set of diagrams for both perspectives. The ones used in this work are the *class diagram* (static perspective), the *activity diagram* (dynamic perspective) and the *use case diagram* (user perspective). The criteria for choosing these instead of others is their similarity to commonly used diagrams in the non-software-specific publications. They look familiar and still provide the precision of an accepted standard.
Another advantage of using these diagrams is that they are known to experts (no need of special explanations about the arrow types specific meaning), as well as the available software to model them. These tools have the advantage of simplifying the validation of diagrams to help find modeling errors, unlike the use of a drawing software (which cannot validate any structure or relation).

2.1.5.1 Class diagram

Class diagrams are useful in showing the building blocks of a system (called classes, hence the name). They allow for describing attributes, operations of each system element, and the relationships between them.
A Class is a representation of a system object. Figure 2.3 shows an example with *name* (top part), *data* which is a set of attributes (middle part), and *logic* which is a set of operations (bottom part).

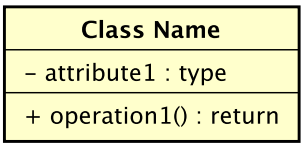

Figure 2.3.: A basic class example.

A Class encapsulates all relevant data of a particular object in a simple visual way.
The Class diagram is a visual representation of several classes and their relationships. The most important relationship types are: association, aggregation and composition.

- **Association** (or directed association) is a simple relationship between two classes. An arrow shows which class knows about the other. For example: a class representing the energy demand relates to a specific period, by a directed association as seen in figure 2.4.
- **Aggregation** is a part-of relationship between a class that represents a whole, and another that represents a part. For example: a biomass harvest site (whole class) has data about biomass characteristics (part class) that can be represented this way as shown in figure 2.4. They can be understood as a *shared association*.
- **Composition** is also a part-of relationship (like an aggregation), but they involve a lifecycle dependency between the two. If the class that represents the whole cease to exist (deleted), the class that represents the part is deleted as well. An example: a power plant technology has specific energy conversion ratios, which make little sense without the power plant existence, as shown in figure 2.4. They can be understood as an *exclusive association*.

Relationships can include a cardinality, which shows the range of number of instances every relationship has. For example a cardinality 1..*, represents that a minimum of one, and a maximum of infinite instances must be related to the other, e.g. a harvest site can have at least one, and a maximum of several (theoretically infinite) biomass types to offer (also shown in figure 2.4).

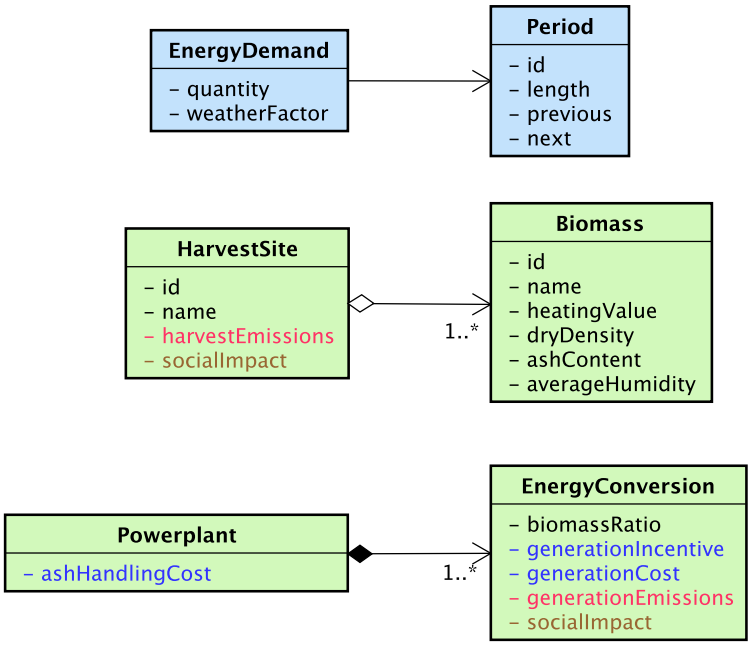

Figure 2.4.: Example of class associations: directed association (top), aggregation (middle) and composition (bottom).

2.1.5.2 Activity diagram

Activity diagrams show the behavioral aspect of a given system (or subsystem). They are very similar to common flow diagrams.
The main symbols are:

- **Start**: represents the process of initiation.
- **Activity**: represents one activity done by the modeled process.
- **Connector**: shows the directional flow.
- **Fork/Joint**: splits and combines parallel activities.
- **Decision**: represents a choice that branches in at least two parts.
- **End**: represents the last step of the process.

All symbols and an example of a process flow is shown in figure 2.5.

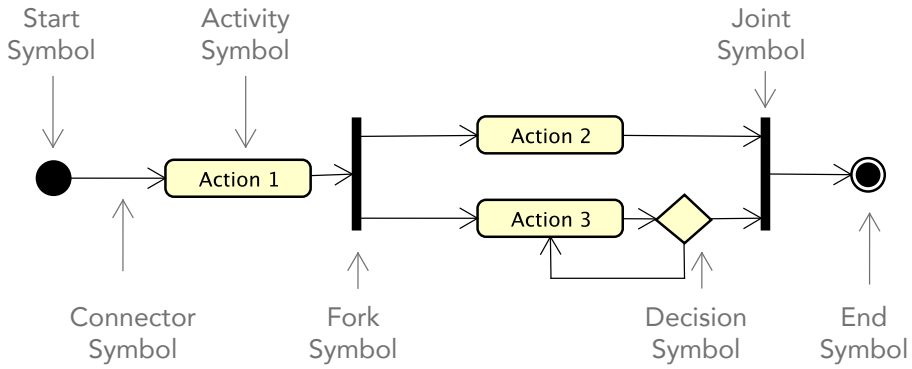

Figure 2.5.: Activity diagram: symbols and an example of a process flow.

2.1.5.3 Use case diagram

The use case diagrams in UML are used to summarize the interactions of the users (also known as actors) and the system. They can have several uses, and the specific one used in this work is to *specify the requirements of a system*, from a user perspective. For this objective, a selection of the simple elements of the notation are used.

- **Actors**: a person, organization or external entity that interacts with the system.
- **Use case**: describes the goal of a specific actor-system interaction, as an action.
- **Associations**: the most simple one relates actors with use cases.
- **System boundaries**: indicates the scope of the system. Elements outside the box represent functionality not included in the system.

An example of a use case diagram with the fundamental elements can be seen in figure 2.5.

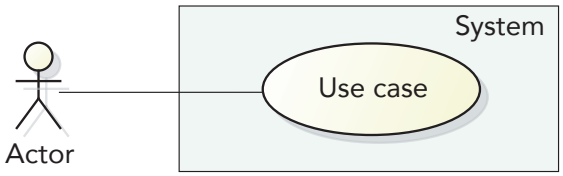

Figure 2.6.: Use case diagram: example with fundamental elements.

2.2 Sustainable development and biomass

[GK06] defines "a sustainable process has the requirement to satisfy the present needs, but without endangering the possibility of satisfying them in the future"[6]. The *sustainability of a system* can be defined as its ability to continue all his defined behavior theoretically indefinitely.
Sustainable development builds on these definitions and adds the content from the *human development goals* to the system. This is a complex and heavily discussed topic. There is no unique definition for this concept and a detailed discussion about the different definitions for sustainable development was made by [HMO05].
It also requires an holistic approach that increases the complexity of every addressed problem that considers this concept. There is also no unique method to measure, nor basis to specify, a common scientific approach relying on a set of aspects, dimensions or indicators being taken into account to be able to guarantee that a specific path leads to a sustainable future.
The basic motivations for sustainable development are the evident from environmental problems and the global social imbalance with inhumane extremes for some groups: access to clean water, sanitation, food, electricity, education or very low incomes are some examples. The inspiration to address sustainable development comes from concepts like *future responsibility* and *justice*. But how to account for these elements, or the effect of decisions related to these concepts is not trivial.
Sustainability is not a new concept and has been debated since at least the 18th century, when, for example, Germany had a high dependency on timber, even as its availability began to diminish. At that time, the German forestry guideline stated: "Do not harvest more timber than will grow back in a certain area and time period.".
The modern debate about sustainability has lead to some key milestones:

- In the book "The limits to grow" [MoRA72] a report for the Group of Rome, global sustainability scenarios were presented. Five global subsystems were included: population, food production, industrial production, pollution, and consumption of non-renewable natural resources. The debate between population growth and resource scarcity was very relevant.

- In the United Nations Conference on the Human Environment held in Stockholm in 1972 the group agreed upon a declaration concerning the environment and development. The second and third principles (from a total of 26) are: "2. Natural resources must be safeguarded. 3. The Earth's capacity to produce renewable resources must be maintained.".

[6] Definition based on [GK06, p.11].

- "The World Conservation Strategy" [fCoNI80] in 1980 used the term "sustainable development" for the first time.
- The Brundtland report [oEW87] from 1987 focuses on the political agenda, discussing the environment and development as a single issue. It has an ethical basis on justice between and within generations and human *needs*, instead of *wants*. "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."
- The United Nations conference held in Rio de Janeiro in 1992 *The United Nations Conference on Environment and Development* (UNCED), also known as *Earth Summit*. Among other results, three main documents were produced related to sustainable development: *Rio Declaration on Environment and Development* consisted of 27 principles to guide countries in future sustainable development, signed by over 170 countries[7]; *Agenda 21*, a voluntarily (non legally binding) action plan for sustainable development [8]; and *Forest Principles*[9] which makes recommendations for sustainable development forestry[10].
- Several works followed up the *Earth Summit 1992* in Rio de Janeiro like the *United Nations Millennium Declaration* in New York in 2000, which reaffirms the support for the Agenda 21 principles[11]; the *World Summit on Sustainable Development* (WSSD)[12] in Johannesburg, South Africa in 2002; the *Earth Summit 2012*[13] in Rio de Janeiro in 2012; and the *2030 Agenda for Sustainable Development*[UN15][14] in New York in 2015, which replaces the *United Nations Millennium Declaration* from 2000 with 17 new sustainable development goals for the next 15 years[15].

The following text will discuss three interesting approaches to address sustainability: the common literature approach called the "three pillars of sustainability", insights from the United Nations 2030 Agenda for Sustainable Development, and the "Integrative concept of Sustainability (ICoS)".

2.2.1 The three pillars of sustainability

To address system sustainability, a practical and common approach is to divide the problem into sub-problems grouped in dimensions. Each dimension considers a set of relevant indicators (variables) that are used to model the system. For every dimension type, the literature usually suggest a common set of methods, that tend to be strongly coupled with the specific dimension area of interest and objectives. The most common dimensions set in the literature that focuses on a sustainable approach is a set of three dimensions (see figure 2.7):

- Environmental dimension: addresses the availability of resources (land-use, renewable and non-renewable resources, etc.) and impacts to the environment (GHG emissions, particulate matter (PM), etc.) and ecosystems.
- Economic dimension: considers the financial aspects, from an industrial point of view that focuses on economic production and utility maximization.
- Social dimension: the aspects of social systems (a country, a group of workers, etc.) that require functioning at a defined level of social well being.

For every dimension, a set of indicators is chosen and are measured for the different alternatives to be evaluated. The complete evaluation is then conducted by combining the results of every dimension using any form of multi criteria analysis like the Weighted sum method (WSM), Analytical hierarchy process (AHP), or others as reviewed by [PR04].
The main problems identified to this approach are:

1. Not all models consider indicators for every dimension.
2. The relationships of different indicators of different dimensions are usually not considered.
3. It is easy to pick an incomplete set of indicators for one dimension, as the names are very general.

[7] Full text available at: `http://www.un.org/documents/ga/conf151/aconf15126-1annex1.htm`. Last accessed: January 2016
[8] Full text available at: `http://www.unep.org/Documents.Multilingual/Default.asp?documentid=52`. Last accessed: January 2016
[9] The official name of the *Forest Principles* is "Non-Legally Binding Authoritative Statement of Principles for a Global Consensus on the Management, Conservation and Sustainable Development of All Types of Forests"
[10] Full text available at: `http://www.un.org/documents/ga/conf151/aconf15126-3annex3.htm`. Last accessed: January 2016
[11] Full text available at: `http://www.un.org/millennium/declaration/ares552e.pdf`. Last accessed: January 2016
[12] Also know as *Earth Summit 2002*.
[13] Official name: *United Nations Conference on Sustainable Development* (UNCSD), also known as Rio 2012, Rio+20.
[14] Full text available at: `http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1`. Last accessed: March 2019.
[15] More information available at `http://www.undp.org/content/undp/en/home/mdgoverview/post-2015-development-agenda.html`. Last accessed: January 2016.

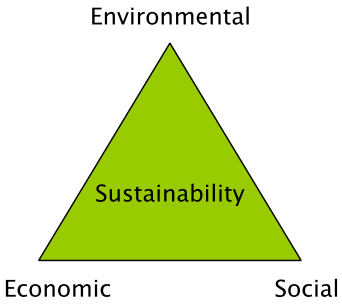

Figure 2.7.: Sustainability as a three dimensional problem.

Some works in the literature claim sustainability analysis for a problem using this approach, while sometimes just considering a single indicator for one of the dimensions. This problem is usually seen in the social dimension, which tends to be the most complicated to acquire quantitative data.
The integration of the dimensions is not guaranteed by this approach, but it has the advantage of being easy to understand and widely used, as will be presented in section 2.3.
For these reasons, two more concepts are discussed before the formal description of the used approach in section 3.6.

2.2.2 United Nations: 2030 Agenda for Sustainable Development

"2030 Agenda for Sustainable Development" is the current resolution adopted by the General Assembly of the United Nations. This report covers a broader range of problems in comparison with previous versions, and applies to all countries (not only developing ones, as other approaches do). [UN15] presents five areas of critical importance from which a series of 17 goals with a total of 169 targets are presented. The five areas are: *a*) People, *b*) Planet, *c*) Prosperity, *d*) Peace, and *e*) Partnership.
The 17 goals name summaries are: *a*) Poverty, *b*) Hunger, *c*) Health, *d*) Education, *e*) Gender, *f*) Water, *g*) Energy, *h*) Growth and Employment, *i*) Infrastructure, *j*) Inequality, *k*) Human Settlements, *l*) Consumption and Production, *m*) Climate Change, *n*) Oceans, *o*) Terrestrial Ecosystems, *p*) Peace and Inclusion, and *q*) Means of Implementation.
There is a declared commitment to review the progress at 4 levels: sub-national, national, regional (as: multi national) and global. The intended progress review at a sub-national level, suggests the importance of regional (as: local) impacts from concrete initiatives.
This set of goals provides a general overview of key elements to consider, but it appears disconnected, as there is no explicit sustainability framework alongside to explain relationships and potential synergies.
[LB15] attempts to integrate the goals as a network of targets, as shown in figure 2.8[16].
In comparison to the *three pillars*, this approach is radically different, as it does not categorize types of objectives, but a specific set of goals. This decision lowers the value of the approach in the long term, as what is important today, may not be in the future. It is a good source of elements that can be considered in the analysis. Also the relations between them as identified by [LB15] can be used to explore model relationships, for the case of variables existing in related to goals.

2.2.3 The Integrative concept of Sustainability (ICoS)

The Integrative concept of Sustainability (ICoS) is developed and described in books like "Nachhaltige Entwicklung integrativ betrachtet" [KBJ+01], "Nachhaltigkeit" [GK12], and "Theories of Sustainable Development" [ER14]. The *integrative concept* is based on three general goals of sustainable development:

1. Securing human existence
2. Maintaining society's productive potential
3. Preserving society's options for development and action

[16] The last goal *Means of implementation* is left out of the analysis to focus on the links between thematic areas, and restrictions of the used methodology.

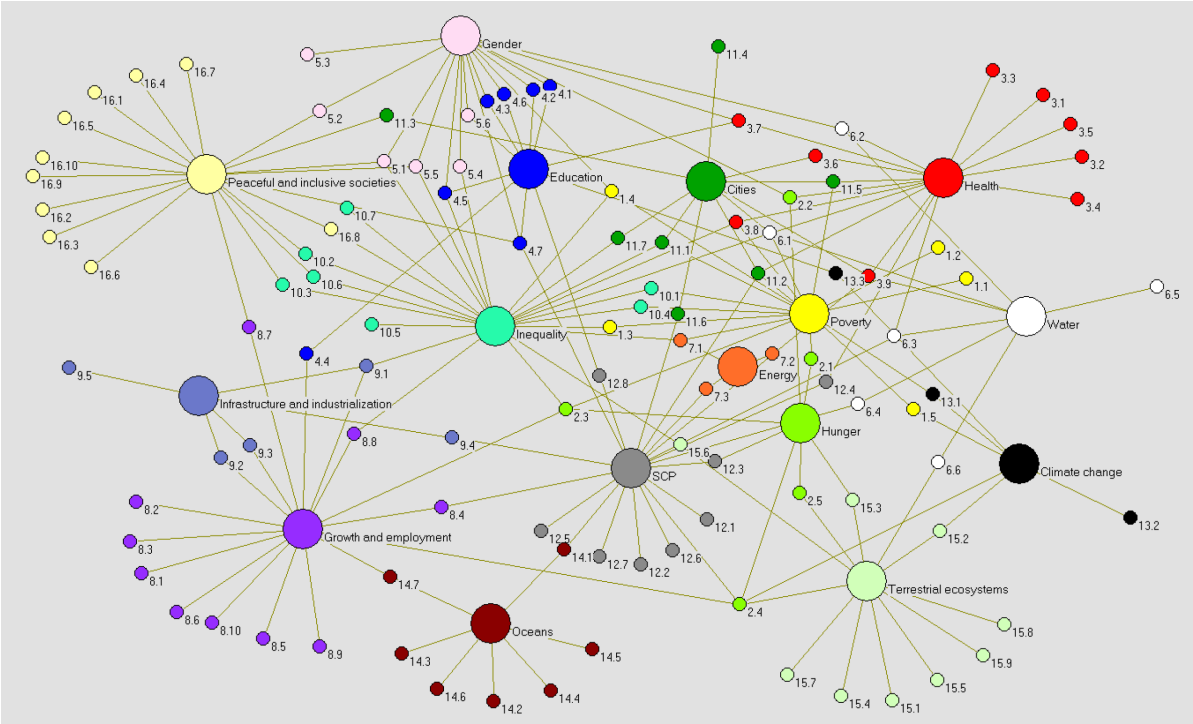

Figure 2.8.: The Sustainable Development Goals as a network of targets [LB15].

These general goals lead to a list of sustainable rules that are measured using indicators sets. For these indicators, target values are defined. Table 2.1 gives an overview of the goals and rules.
The underlying idea comes from the principle of a planetary trust from [Wei84]: "We hold the natural and cultural heritage of our planet in trust for future generations. As trustees we have a fiduciary obligation to conserve this heritage for future generations. Our fiduciary obligation consists of two duties: to conserve options by conserving the diversity of the natural and cultural resource base; and to conserve the quality of the trust's corpus by leaving the planet in no worse condition than we received it."
This approach does also generate a set of categories, similar to the "three pillars of sustainability" model, but the categories are chosen in relation to general sustainability goals. In comparison to the "2030 Agenda for Sustainable Development", this approach is time-independent, as it is not inspired by the current world conditions, but a general sustainability concept.
These advantages are interesting for the current work, as they include the benefits of the integration of elements, and the universality of an agnostic solution to current problems, which may or may not exist in the future.

2.2.4 Sustainability and the biomass supply chain

The analysis of the biomass supply chain under the presented sustainability frameworks can turn the problem into a very complex one. A supply chain interacts naturally with many elements, as it exchanges goods from one point to another by traveling through several locations, and also transfers information about demand, time-frames, etc. These interactions are hard to keep isolated from the system boundaries, as they will naturally appear.
From a modeling standpoint, a complete system needs to expand the boundaries to include as many other entities that relate to the supply chain, as needed. From a data acquisition standpoint, a large problem is hard to manage. A huge amount of qualitative data, which is probably very hard to obtain, needs to be considered and its effects well understood. For these reasons the creation of a general model from the type *one size fits all* that considers all relevant aspects of sustainability for every case makes little sense, as computational power and data availability is limited.
From a user standpoint, an extremely complex model that considers too many elements is hard to understand, therefore also harder to trust.
A more reasonable solution approach could first gain specific knowledge about the specific supply chain system and identify relevant elements under the criteria of the involved community (system specific). If a general no-system-specific model is considered, model flexibility is critical to adapt to the case specific implementation (e.g. by custom design elements).

Table 2.1.: Integrative concept of Sustainability (ICoS) : the sustainability rules.

General sustainability goals		
Securing human existence	Maintaining society's productive potential	Preserving society's options for development and action
Substantial rules		
Protection of human health	Sustainable use of renewable resources	Equal access of all people to information, education and occupation
Ensuring the satisfaction of basic needs (nutrition, housing, medical care, etc.)	Sustainable use of non-renewable resources	Participation in societal decision-making processes
Autonomous subsistence based on income from own work	Sustainable use of the environment as a sink for waste and emissions	Conservation of cultural heritage and cultural diversity
Just distribution of opportunities for using natural resources	Avoiding technical risks with potentially catastrophic impacts	Conservation of the cultural function of nature
Reduction of extreme income or wealth inequalities	Sustainable development of man-made, human and knowledge capital	Conservation of "social resources"

For this work, the developed model considers a combination of these approaches, with the objective of capturing the advantages of them for the current solution.

1. From the "three pillars of sustainability" model, the category names are used. This is because there are common words in the sustainability literature, understood by a broad audience, and which allow a comparison with other approaches based on the common approach.

2. The "2030 Agenda for Sustainable Development" provides a source of indicators ideas and the relationships between them. It will be used to categorize the chosen indicators with the intention of analyzing the relationships with other categories. This allows the search for other possible indicators that could improve the model considered for the problem.

3. From the "Integrative concept of Sustainability" the categories and integration between variables are relevant. The presented goals and rules will be used in the social analysis to expand and relate it with the techno-economic and financial considerations (see section 3.7).

In section 3.6 a methodology is proposed that is able to help recognize the key custom elements, along with a model flexible enough to provide the means to incorporate them.

2.3 Biomass supply chain literature review

2.3.1 Introduction

The optimization of a biomass supply chain is not a new concept in the literature. There are several studies that analyse and suggest methods for the high amount of configurations and scopes a biomass supply chains can have. The following review of literature confirms that there is a need for multi-criteria optimization models that consider multi-biomass sources and that are able to be used in a DSS. To approach this challenge effectively, this review starts with the key elements of the most relevant review papers associated with the logistics of the biomass supply chain. The second part focuses on specific research works which provide a deeper understanding of the specific problem and methods. The last part highlights the main research gaps this work aims to solve and summarizes the key problem elements and relationships identified in the literature.

2.3.2 Review of relevant publications

There are hundredths of papers related to biomass, transport and supply chain. To get a good insight of the relevant literature, two strategies were used. First, a selection of relevant review papers was analyzed in order to get overviews provided by different authors (section 2.3.2.1). The results are general conclusions and a selection of specific publications to be reviewed with more depth. Second, searches using keywords sets was conducted, in order to identify relevant papers to the specific problem (section 2.3.2.2). This second strategy allowed deeper analysis of specific relevant publications and includes the newest ones, not available in the analyzed reviews.

2.3.2.1 Relevant review papers

[IKV+10] provides an overview of the biomass energy production technologies in the context of waste biomass to energy supply chain analysis. A typical bioenergy supply chain is composed of five stages: harvesting and collection, pretreatment (optional), storage, transport and energy conversion. They conclude that "the vast majority of the studies in the field of biomass to energy production examine the system from a purely technological or ecological point of view, there is a subset of the literature body that addresses the relevant and highly critical supply chain management issues". And in this subset they also identify that most of the literature is about biomass potential and strategic decisions. The review concludes that tactical and operational decisions are a research area that has not been investigated thoroughly.
In the technologies diagram from the paper included in figure 2.9, the technology addressed in this work correspond to the thermochemical direct-combustion.

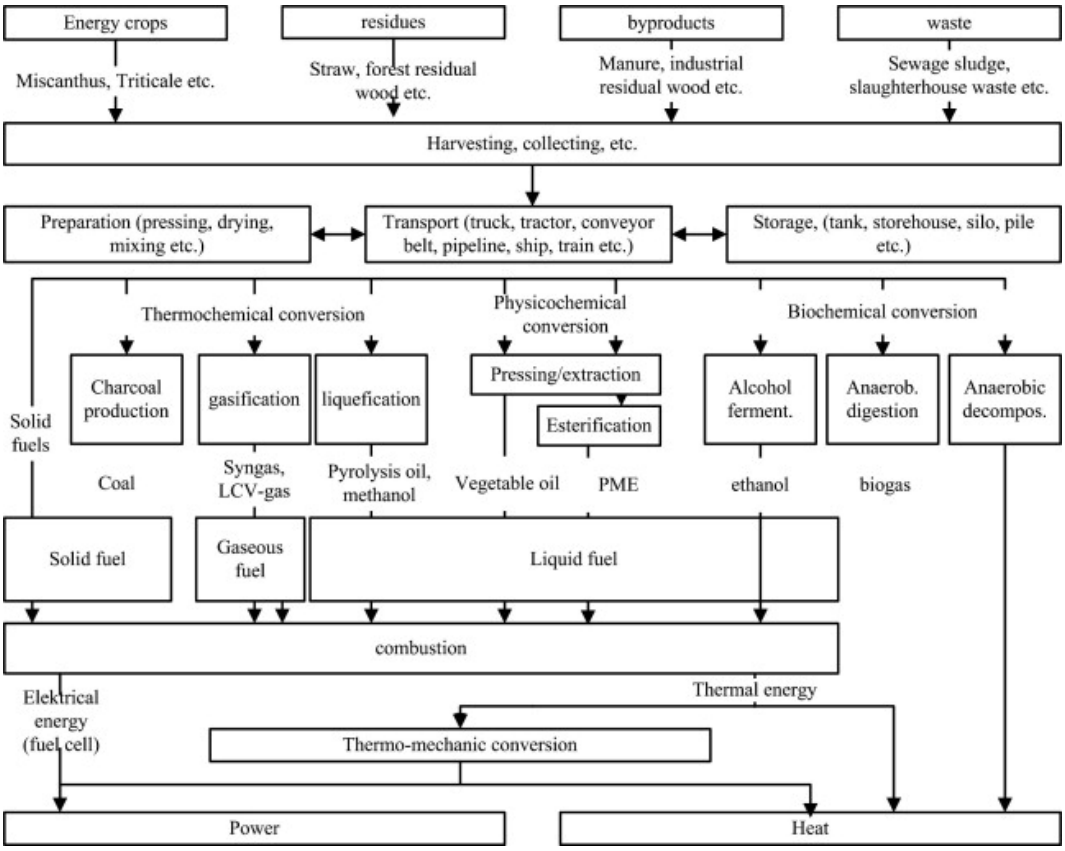

Figure 2.9.: Overview of renewable energy production from organic substrates [IKV+10].

[AZ12] provides an overview about uncertainties and sustainability concepts related to the biofuel supply chain found in the literature. Although it includes additional elements like biorefineries which are not addressed in this work, both supply chains share common elements.
Decision making in the supply chain can be categorized into strategic, tactical, and operational decisions. Strategic long term decisions need revision every five or more years, and usually involve some kind of major investment in things like: technologies, network configurations, long term contracts and sustainability considerations. Tactical "medium term decisions usually span between six months and one year. They take into account logistical needs, distribution

parties or network and inventory planning levels. Usually tactical decisions are made to provide cost benefit due to the constraints of the strategic decisions.". They include decisions about the biomass harvest sites, transportation and logistical contracts, inventory, planning and scheduling processes. Finally, operational decisions tend to be short term (like production scheduling) and aim to fulfill the tactical goals.

The presented uncertainties include details about the biomass supply, transportation and logistics, production and operations, demand and price, and others.

For biomass supply, the raw material yield, type, quality, transportation lead time, congestion and financial uncertainties are mentioned.

Uncertainties in transportation and logistics include the inability to deliver in a timely and cost efficient manner. At this point, fleet scheduling, demand and inventory, transportation costs, coordination, delivery constraints, storage costs, and transportation lane availability, are critical.

Production and operational uncertainties enable the production of the planned products. Raw material acquisition times, production yields, machine failure, lead time constraints, and inventory decisions are good examples where these uncertainties play a role.

Demand and price uncertainties refer to variations in the quantity and timing of demand, and the price changes of products, respectively. For this point, tax subsidies, regional policies, and the price of substitutes are very relevant.

Regarding modeling sustainability issues in the supply chain, "there is little literature that models the sustainability issues in the biofuel supply chain". Some works that address it are presented where examples include analytical models like Mixed Integer Linear Programing (MILP).

[CS14] review focuses on forest biomass supply chains and modeling approaches for optimization. It supports the importance of biomass as a fossil fuel replacement for uses like biofuels and bioproducts. However, the work makes clear that there are several challenges to address for a successful intensified use such as collection from scattered locations, transport costs, low energy density, and quality, among others. The article makes clear that the supply chain design plays a critical role in the biomass to fuel/product conversion process. The authors present a set of three dimensions to consider in the design of the supply chain and classify 54 assessment papers.

The first dimension is the technical and economic considerations. The efficiency and scale of the conversion technology is the first relevant aspect. High efficiency lowers the operating costs but increase the capital requirements. Economies of scale are important to justify the costs of conversion technologies, but the available biomass in the supply chain restricts the options. Forest biomass relevant parameters are mainly availability and quality, defined as the energy content, moisture content, particle size and contaminant components. The article describes the second dimension as the environmental considerations, where the main concerns are carbon balance, greenhouse gas emissions, particulate matter, and the health of the forest ecosystem. Understanding the environmental impacts of different supply chain choices allows the maximization of the benefits to the environment. The last dimension corresponds to the social considerations. The article argues that most of the relevant effects like community systems, politics, health impacts, well being, personal and property rights, and fears and aspirations are difficult to quantify with consistency. Therefore, they are usually not considered. Commonly considered aspects are number of jobs and income creation.

93% of the works reviewed by Cambero consider a single optimization factor, either economic or environmental. Only four studies consider the three presented dimensions. The most common methods are production costs and internal rate of return (IRR) for the techno-economic studies, and LCA for the environmental impacts. As for the social dimension the article states that the methods to evaluate them in the forest biomass supply chain need to be developed, as the current ones can compare solutions, but not recommend optimal ones.

As for the optimization of the solution, mathematical programming was the most used tool. 28 of the studies did consider a single economic objective function, 4 bi-objective and 3 tri-objective. As for the options considered, only 6 considered tactical decisions like biomass logistics, planning and scheduling. The article concludes that "There is a need for decision support tools that quantify and optimize the economic, environmental and social aspects of the forest biomass supply chain simultaneously".

[ALP16] also reviews the recent research on biomass supply chain optimization. The considered supply chain is similar to [CS14] for this work relevant system: harvest, transport, storage, pre-processing and conversion. It also considers the same challenges and adds the argument that the improvement of the supply chain can result in cost reductions to increase competitiveness.

The publication classifies the objective functions into four types: *minimization of total costs*, *maximization of profits*, *maximization of net present value (NPV)* and *multi-objective*, with *minimization of total costs* being the most common one. In this analysis, the work of [YW12] is described as a good example of multi-objective optimization.

The review classifies levels of decision making as *strategic* (long term, e.g. conversion plants locations), *tactical* (medium term, e.g. order size) and *operational* (short term, e.g. vehicle scheduling). From the tactical perspective, the work of [GRL04], [DAS07], [ZLYC11] (closely related to [ZY11]) and [SS16] are relevant for this research.

Atashbar also classifies solution methods into five groups: Mathematical programming, Heuristics, Multi-Criteria Decision Analysis (MCDA), Geographic Information Systems (GIS), and Simulation. The article concludes that most publications use mathematical programming, but multi-criteria and heuristics are rare.

The work of [ZLYC11], [KGGM$^+$12] and [FM13] are presented as good examples of a specific group of models, which are more general and sophisticated than earlier publications.

The article discussion gives a critical look on several aspects. Too few articles optimize the complete supply chain. Many only support one type of biomass, and most only consider road transport. In addition, the collection of data from multiple locations is a major problem, and there are concerns about the computational running times of current solvers, which may require major simplifications for real world use.

The conclusions of the article reveal some important gaps. Mainly that most studies focus on the strategic levels, which suggests a gap in the tactical and operational ones. Multi-objective and multi-biomass models are considered by only a small amount of authors.

[GPM16] is another relevant review, especially for the 146 papers considered. It focuses on strategic decisions, as it considers supply chain network design. Still, there are some relevant insights for the current work. Multi-objective and multi-period (which is closely related to tactical decisions) approaches are rare. The article states the dynamics of the biomass supply chain, which supports the need of tactical decision models that can complement the strategic results.

[SIJK13] reviews published works with the objective of analyzing the modeling techniques used in the biomass supply chain. The article reviews a total of 32 references. Again, most works did focus on strategic decisions. Tactical and operational decisions were about the flow of materials, inventory management, and fleet management. Three articles addressed GHG emissions in the models and one [YW11] included social considerations in terms of accrued jobs. As the author states: "Most of the models reviewed had a network structure with biomass supply sites, collection sites and processing sites being the most common types of entities considered. The most widely used modeling technique for Biomass Supply Chain (BSC) was the mixed integer linear programming model. The purpose of the majority of the models was cost minimization and the next most popular performance measure was revenue maximization." The suggested future works are models handling large-scale problems, uncertainty, and sustainability issues. Other relevant suggested challenges include incorporating economic, environmental and social measures into the models, as well as addressing computational complexities.

[WR14] reviews articles specifically about primary forest fuels (PFF) supply chains. Due to spatial distribution, low mass density, low energy density and low bulk density, the transportation of primary forest fuel is crucial for economic efficiency as well as for reduced CO_2 emissions. A principal finding is the assumption of perfect coordination and cooperation among all the supply chain actors. This is a major issue, as it could sabotage a good solution, due to an unrealistic implementation. [RGH10] calculates non cooperative procurement would lead to 20% higher costs and to a 34% higher total transport distance. Another finding is the exclusion of long distance transport modes (e.g. rail and ship), but the reason can be a strategic one, in order to diminish the ecological impacts of long distant transportation of low density fuels. A third conclusion is the inappropriate planning horizons of the models, but this critic focuses on the strategic decisions where a 10 years horizon in suggested. A fourth finding is the lack of consideration for supply delays. Fifth is the focus on a single cost parameter for finding solutions, which can produce sub optimal real solutions, as supply security or biomass quality is not considered. Lastly, a discussion about the limits of modeling the bioenergy sector is included. The exclusion of political influence, environmental concerns of private consumers, information asymmetry and local conditions, among others make the modelled energy systems not able to represent the real system in its full extent. The conclusion is based on the work of [RR00] which mentions: "A conflict between simplicity and realism is, however, to be expected. Energy models tend to lose credibility if they are too complex". Under this consideration, a model that does not represent the complete reality is expected. One with reasonable complexity is necessary to achieve stakeholders acceptance.

[ZALP18] presents results of recent studies of the biomass supply chain, including tactical models. 102 papers were included in the review. They identify that most of the studies are single objective ones, usually with an objective of either minimization of total cost, maximization of total profit, or maximization of net present value. Environmental and social objectives are usually considered only in multi-objective models, which are not the common ones in the literature. They state that most researchers writing about the biomass supply chain usually have an affiliation to agriculture or chemical engineering departments. For tactical models, many papers limit themselves to small case studies to avoid large running times to solve the model. Experts in biomass are helpful, but more specialists in operations research could bring knowledge from industrial logistics, and multi-disciplinary teams are proposed. Model granularity is also an issue, as to solve big instances, many authors divide the territory, which could lead to a "lack of realism". They conclude that more research in the topic is still needed.

2.3.2.2 Relevant specific papers

In this subsection specific works are reviewed, either by references in the review papers, or by direct search findings using the Google Scholar[17] search engine. The keywords used were different combinations of the words: *biomass, transport, optimization, supply chain, sustainable, regional, energy, electricity, life cycle analysis, biofuel, forest, tactical*, and synonyms.

[YW12] considers a Biomass to liquid (BTL) supply chain, from harvesting sites, to biofuel demand zones. It uses a multicriteria MILP model to optimize the total annualized cost and greenhouse gas emissions. It concludes that improving conversion technologies are key for commercializing biomass-derived liquid fuels. This conclusion supports the use of biomass for electricity (with the current commercial available technologies) for energy production in power plants, as the environmental impacts are in general lower, because of the simplified process chain (less steps that require energy and produce waste).

[GRL04] also uses an MILP model and focuses on forest residues in harvest areas, or byproducts from sawmills with a tactical perspective. The biomass flows consider a harvest site (or a harbour for imports) origin, a terminal for storage, and the heating plants as consumers. The objective is to minimize total cost. The system of the problem is similar to the one addressed in this work. The import consideration were interesting, but they are included only in the discussion, not in the model.

[DAS07] also implements an MILP model with the objective of minimizing total costs. The considered system considers two stages: a *farm site process* where cultivation, harvest, and first storage occur, and a *plant site process* where second storage and combustion takes place. Both storage locations included drying and chipping options. The publication considers high land use costs (33% of total energy costs of the supply chain), which result in an estimated 10% costs associated with transport. The high land use cost is supported by the idea of considering opportunity cost of land which has economic and environmental impacts on minimizing land use "acting as a soft constraint within an effective multi-objective analysis", according to the authors. A heuristic was used for the solution with good results in comparison to an optimal method (6.8% difference from the base case), but with the remark that a more complex system would probably increase the gap between the two. Also, potential technical issues from high moisture biomass combustion are identified, but not strictly managed in the model to force a specific humidity range.

[ZLYC11] considers a model specific for a single feedstock (switchgrass) for ethanol production in biorefineries. The model formulation is an MILP model for a one year horizon. The system considers the transport of switchgrass and residues using trucks and trains. To address unexpected biomass supply interruptions, a safety stock level is imposed for each biorefinery storage. Residue recirculating constraints ensure they get a use as fertilizers in the switchgrass production fields. The model has the advantage of considering the details of the chosen feedstock, but the challenge to choose the optimal mixture from the wide range of biomass types is left open in the discussion.

[ZY11], which is related to the switchgrass system presented in [ZLYC11] considers multiple feedstock by adding two agricultural residues (corn stalk and wheat straw), with the same 1 year horizon as the previous work. With these new feedstocks, seasonality of switchgrass can be alleviated, as there is the assumption that stalk and straw can be purchased throughout the year. But the lower unit price of them ($35/dry ton against $50/dry ton) do change the solution substantially, even with the increased transport costs, unless specific restrictions for mandatory use of the switchgrass are included. A motivation for switchgrass production costs reduction is mentioned.

[KGGM$^+$12] works on models for the sugar cane industry supply chain for sugar and ethanol production in Argentina. It considers strategic decisions for determining number, location and capacities of the sugar cane facilities. It uses deterministic, stochastic, and multi-objective models for the solutions. There is a focus on the resolution of the models and strategies are discussed. For example, the strategic decisions of the deterministic model involve several integer and binary variables. A rolling horizon[18] approach is implemented with success. The presented solutions result in a centralized network. The environmental implications are considered, but although they result in decentralized networks, they conclude that the centralized solution balances the benefits for the considered perspective [MKGG11].

[FM13] includes another more-complex-than-usual approach to solve the suggested models by using decomposition methods. The experience is useful for this work from a resolution method perspective, but the problem differs from the one addressed in this work.

[BLEP09] considers the optimization of the supply chain (in general) and combines it directly with LCA. Although the focus is on strategic decisions, the combination with the LCA methods is valuable. By following the common LCA

[17] https://scholar.google.com/

[18] The rolling horizon technique decomposes the original problem into a number of smaller sub-problems that are solved sequentially. The sub-problems relax the integer variables for the future of the considered division for an approximation, and fix the results of the previous sub-problems. That way the number of integer and binary variables is effectively reduced, with the need to resolve more smaller problems.

practice of considering linear direct environmental impacts with respect to the functional unit, the work incorporates LCI parameters directly into the model. Every transportation activity adds to the midpoint indicators. Damage categories are calculated in the model using the values of midpoint indicators. The work also models CO_2 emissions trading by adding a variable to buy rights to emit, and another for rights to sell.

[YPY16] does also combines LCA and optimization into what they call the Life Cycle Optimization Framework (LCO) to compare alternatives from economic and ecologic perspectives. The selected case study shares similar elements with the one from this work, but the proposed hybrid LCO approach requires more data in comparison to traditional LCO.

[YTGS11] propose an optimization model, that combines LCA methods for a cellulosic biomass supply chain for biofuel. This publication shares key elements with the current work. The system boundaries are similar in a way that can be made compatible, it considers a multi objective sustainable approach with economic, ecologic and social dimensions, and the model method is an MILP model. It also combines with LCA methods. The social impacts considered are reduced to accrued local jobs, which, however, are quantifiable.

[BPP18] focuses on tactical planning for the biomass supply chain with the objective of cost optimization. Using an MILP model, it offers a network structure and a model developed to feed a biorefinery with several crop types over a one year horizon. To reduce optimization times, a *macro-task* concept was used to simplify the first network nodes. It aggregates states and tasks related to harvesting, but it must be done manually. This concept could be adapted to this work in case optimization times are too high, specially if related to too many integer variables.

[ASG18] proposes a model that integrates strategic and tactical decisions for the forest biomass supply chain, from an economic (financial) perspective. Important findings are that some solutions that are obtained by using strategic models, are not feasible at a tactical level: it was not feasible to meet either the biomass demand or the generation capacities during some specific months. This further confirms the value of tactical models to improve the results of strategic models.

2.3.3 Main conclusions of the literature review

- There is a big biomass supply chain literature available, but it addresses mainly the strategic decisions. More research on the tactical and operational decisions is needed.
- To address the sustainability of the system in the model is a critical advantage for the long term solutions and not a common approach. Methods need to be developed to address it in a reliable way.
- Multi-objective optimization is a useful approach to include more than one decision dimension, but it is not common in the literature.
- Multi-biomass is a common situation in real world problems, but it is not usually considered.
- Computational running times are important to be considered, especially for tactic and operational models, which need to evaluate solutions in shorter term cycles.
- For electricity generation, a biofuel supply chain can be shortened to include from harvesting to a biomass to energy conversion stage. Usually models extend the system to include the biofuels transport to the demand areas. This consideration allows the simplification of some model aspects to decrease computational solution times.
- Models that can be implemented in the form of decision support systems are needed.

Specific gaps (as quotes from the literature) that this study contributes to overcome are:

- [ALP16] “The review shows that the majority of studies focus on the strategic levels. However, few studies have been done on the operational levels of biomass supply chains. There are also a considerable number of studies using mathematical programming, but the papers which employ multi-criteria decision analysis and heuristics methods are still rare. [...] Most of biomass supply chain models are based on single type of biomass and very few authors deal with multi-biomass and different parts of biomass.”
- [CS14] “There is a need for decision support tools that quantify and optimize the economic, environmental and social aspects of the forest biomass supply chain simultaneously. This might involve the use of tools, such as life cycle assessment, multi-objective optimization and the development of other tools to quantify sustainability impacts.”

- [DMCRVO14] “The major part of the mathematical programming models refer to a network structure [...] The social objective is measured by the number of local jobs. This approach seems simplistic since social sustainability also covers the integration of human rights, labourer’s rights and corporate governance [...] Finally, the paper shows that the presented models are usually developed for specific cases addressing a specific part of the supply chain considering specific operations at one certain hierarchical decision level. Also, most papers target the optimisation problem from the bioenergy producer’s point of view [...]”

- [IKV+10] “[...] our analysis has demonstrated that strategic decisions for waste biomass supply chains have attracted more the interest in the research community than tactical and operational decisions. Specifically, tactical decisions and mainly aggregate production planning emerges as a challenging research area that has not been investigated thoroughly thus far.”

2.3.3.1 Relevant supply chain elements and relationships

This subsection has the objective to summarize relevant elements from the supply chain and their relationships.
From a biomass-to-energy point of view, the identification of the elements that are relevant for biomass based electricity generation is the first stage to properly address them.
Every electricity generation technology available has an impact on the environment and society, and biomass based ones are no exception. In a regional context, they increase the demand for biomass in the area, which is good for the local economy and can translate into new work opportunities. As the price increases, because of this demand, it opens the possibility for recycling or using waste biomass from other processes. From another point of view, the biomass needs to be transported and the power plant must be operational, which involves some negative effects in the population nearby, like biomass waste on the roads, and noise. Meanwhile, the world market situation and the current power plant park, electricity demand, and resources availability determine the electricity prices, which results in a social period with a specific acceptance level.
Figure 2.10 gives a visual summary of the general relationships of key elements related to biomass electricity generation, using a System Dynamics cause-effect diagram.

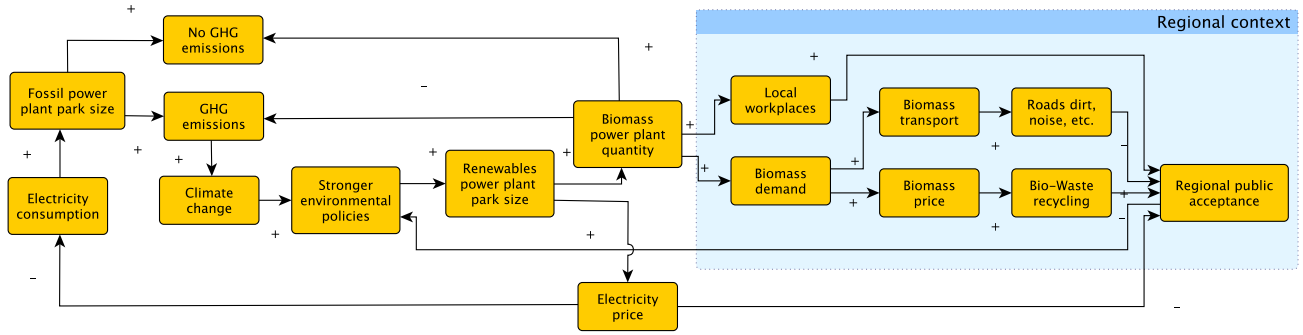

Figure 2.10.: System dynamics cause-effect diagram about selected general relationships between relevant variables that influence biomass power plants electricity generation.

This diagram is useful to provide a general overview of related impacts. It proved also useful to share with some actors of the supply chain for the model tasks described in section 3.7.

2.4 Steps to address the selected gaps

The objective of this work is to analyze and build a model to optimize the biomass supply chain for power plants under the perspective of a sustainable solution. This research offers the following contributions that relate directly to the study research questions:

1. A structured problem definition for the biomass supply chain.

2. A method to do a sustainability analysis for the biomass supply chain, and a concrete approach to implement it.

3. A model that combines sustainable considerations for the supply chain and generates optimized solutions.

2.4.1 Biomass supply chain data model

There are many descriptions in the literature about the existing biomass to energy supply chains. Some apply to second generation *biomass to electricity* production. This work goes a step further by building a UML structure data model to include the relationships between the data. This model provides with a deeper understanding about the data connections inside the problem, and it provides a base to check the completeness and validity of acquired data. It also works as a starting point for possible expansions of specific scenarios. From an implementation perspective of the solution, it serves as a database to integrate the different calculations. For this works implementation case, all modules use it to read and record data on a common platform.

2.4.2 Biomass supply chain sustainability and system objectives

Relevant approximations for sustainability assessment are analyzed and combined to include in the model. The financial approach has been seen in other models in the literature as directly included in the objective function of the optimization equations of the model. The environmental considerations are included with a flexible methodology that allow the model to adapt to different scenarios. The model makes use of common LCA software to calculate specific parameters that are later input to the optimization module. As for the social aspects, they are not given as a strict set of equations to apply to all cases, but as a method to to help identify and include the relevant ones. This aspect is novel and relevant, as the social elements among stakeholders in specific supply chains can vary a lot between countries and specific realities. This can also take many shapes like coefficients in an optimization function, additional optimization objective equations, new parameters, new constraints to limit values, etc.

2.4.3 Integrated optimization model

The third element is the concrete optimization model. It delegates the tasks into specific modules that serve a specific purpose and require different knowledge backgrounds. They provide the model with a feature set to grow in different areas, as modules can become more complex in an independent way, as long as they honor the data that relates them. Complex improvements can still be included and made available to the other modules by changes in the data model, that can prepare the scene for the other modules to improve and evolve with them. From an implementation perspective, it allows the growth and customization of it to advance in a modular way that avoids the problems of a big monolithic tool. This flexibility is paramount for prototyping in real world conditions, as a *fail fast, fail cheap* approach is common nowadays to implement platforms that survive in time [GN13], by incorporating relevant stakeholders in early phases.

3 Model for optimization of a sustainable supply chain

This chapter describes the model developed in this work. It starts with the definition of the problem and its main elements. The second section describes potential users for a system based on the proposed model. Afterward, a formal structured data model for the problem is presented. The next sections give an overview of the model architecture and the relationships between the conforming modules and data. Sustainability considerations for the model are addressed as well. The advantages of the proposed approach, theoretical considerations about how the different sub-models relate and their implications are discussed.

3.1 The biomass to energy supply chain

A generalization of the the supply chain for a biomass to energy system is needed as a base for the solution model. This allows a detailed problem description that should be compatible with the scenarios seen in the published literature and available use cases, and it should be able to describe all the data requirements and assumptions.
As presented in the literature review, there are several models that address the biomass supply chain.
The synthesis by [IKVT10] includes a representation of a (waste) biomass supply chain, which summarizes the main steps as *collection*, *storage*, *transportation* and *energy conversion*. Additional optional steps are *pre-treatment* and additional storage and transportation processes.
The supply chain configuration considered by [SS13] shares a tactical perspective with this work. The included schematic for a wood biomass supply chain considers several *suppliers* which consolidate the wood residues in a common *storage facility*, which then feeds a *production* stage that produces electricity and ash.
For this work, the biomass supply chain to feed power plants consists of the processes shown in figure 3.1. They will be used as basic system elements.

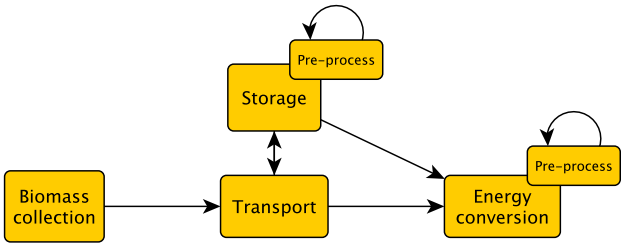

Figure 3.1.: Basic processes of a biomass supply chain for power plants.

The biomass is collected on the production sites (Biomass collection process) and transported (Transport process) either directly to feed the power plant (Energy conversion process), or for storage in inventories at available locations (Storage process). If the storage location is at the power plant location, it can directly feed it. If not, another transport to either a second storage location or to the power plant is needed. A pre-process stage (Pre-process) could also occur either at the storage facilities or just before the energy conversion. They can either actively change the biomass characteristics (e.g. chipping) or do it passively (e.g. dry storage for several months).

Biomass collection: second generation raw materials can be forest residues, agriculture residues, wood-industry biomass waste (for example from sawmills) or some specific industrial waste. Examples are: wood chips, bark, sawdust, or also partial burned or contaminated trees, which cannot be used for cellulose or furniture production. Biomass with high water content like animal residues and organic municipal waste is more suitable for biogas production and not suitable for efficient thermochemical combustion. This process should consider:

- Geographical distribution, availability, and seasonality of different biomass sources.
- Biomass energy density (calorific value).
- Biomass chemical composition, which could impose restrictions in the combustion stage.
- Biomass moisture content and humidity absorption related to weather conditions.
- Country policies, government incentives, and other fuel prices.
- Sustainability concerns in the biomass productions sites.

- The effect on demand by other energy production systems.
- Weather effects that could limit harvest plans.

Transport: biomass needs to be transported from the harvest areas to the power plants, or storage facilities. The lower forest biomass density in comparison to fossil fuels requires the transportation of large volumes. This translates into a usually complex logistic system with high costs, where small improvements, can turn into important costs reductions. From a regional perspective, local suppliers should be able to satisfy most of the power plant's raw material demands. This allows for the determination of a profitable delivery radius around the power plants. This process should consider:

- Available transport options.
- Volume, shape special transport requirements and other restrictions for every biomass type.
- Routes and its characteristics (for example: traveling speed, closeness to towns) for every transport medium.
- Handling time and costs by loading and unloading.

Storage: has an influence on the biomass effective burn power. Different types of biomass react differently to specific storage conditions: some improve their burn quality after some resting time, others could self ignite when stored in a pile for long periods. For every type involved, specific considerations should be taken into account. Some general considerations include:

- Volume, shape, and special storage requirements for every biomass type.
- Biomass storage degradation and environmental emissions.
- Self ignition danger for specific biomass types.

Pre-process: for optimal combustion, a specific particle size is required. Also, there are restrictions in the plant design regarding the humidity content that the fuel can have before it enters the boiler. A pre-process can take place near the power plant or storage locations to give the biomass the given needed characteristics.

Energy conversion: small size power plants have lower efficiency in comparison to large ones. Still, the local biomass availability restricts the maximum plant size, which usually has a maximum size of around 25[MW], with an efficiency between 20% and 40% electric. The generation process also translates the energy demand for the plant into raw materials requirements. "The power plant consumes biomass which is transferred by conveyors to a boiler where it is burned to generate heat for steam production. The steam is then transferred into a turbine, where the thermal energy is converted to electrical power. The exhaust steam is converted to water by a condenser and used in the system again. The water is reused for almost seven cycles and then it is discharged to the sewer network. Other equipment pieces might include a high voltage step up transformer, a solid fuel handling system, an ash removal/handling system and other steam cycle auxiliary pieces of equipment, multiple cyclones and an electrostatic precipitator"[SS13].

Direct combustion plants will be considered. "Combustion is defined as a series of chemical reactions resulting carbon and hydrogen deoxidization. Biomass elements, moisture content, and air are critical components of wood combustion. The products of these reactions include CO, hydrocarbons HC, oxides of nitrogen, sulfur and inorganic species such as the alkali chlorides, sulfates, carbonates and silicates. When wood is combusted, a mass loss process takes place which is related to the combustion temperature. This can be depicted in a plot, called the burning profile. The first pick in the burning profile is related to the release of moisture content and small amount of other absorbed gases. Then, as the temperature increases to 175–225º, other volatiles start to be released and ignite. Then, the rate of mass loss increases drastically up to temperatures between 325º and 425º, when the mass loss process starts to decrease. This decline will continue and finally the weight will be almost constant. These temperatures are different for different types of biomass"[SS13].

Beside gas emissions, solid waste (ash) is constantly produced as a combustion sub-product. Depending on the source the biomass characteristics, it can be used as soil improver, fertilizer, as an additive for asphalt roads, etc. Some also ends in landfills. "Wood ash properties are related to several factors such as: species of tree or shrub, part of the tree or shrub (bark, wood, and leaves), type of waste (wood, pulp, or paper residue), combination with other fuel sources, type and quality of soil, weather conditions and combustion process. Forest biomass ash generally contains calcium (Ca) and potassium (K). Two kinds of ash are generated in the production process: one is resulted from soil and rock contamination (called bottom ash) and the other one is resulted from the minerals in the foliage or wood (called fly ash). Ash disposal is a challenge for most of the power plants and has economic, environ- mental and social costs for the power plant. High ash content biomass is less desirable to be used as fuel. For example, sawdust has lower ash content than bark and logging residues"[SS13].

3.2 The user perspective

Two stakeholders have been identified as potential users to use the system: *a*) power plant managers; *b*) local governments or the interested community. Hypothetical requirements of both actors are presented, based on the inputs provided by the meetings described on section 5.2.1.1.

3.2.1 User case: power plant managers

The main interest of power plant managers is a regular transport plan optimization that can help the daily operation and planning. As a tactical problem, the optimization times to achieve a solution must be kept short (a *few seconds*, rather than a *few minutes*). This is needed, because tactical decisions usually require several adjustments, which forces the user to recalculate optimal solutions several times.
The main use case requirements can be seen in figure 3.2.

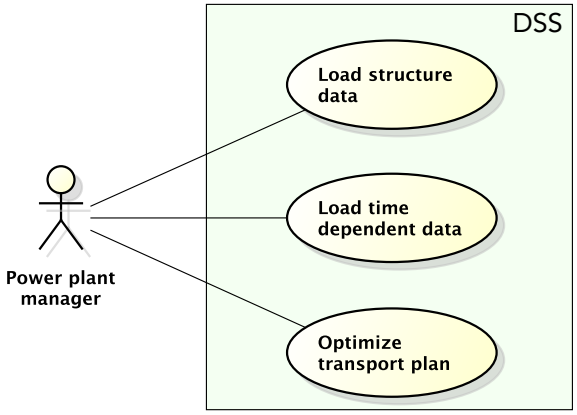

Figure 3.2.: Use case diagram: power plant manager.

In general terms, the planner needs to be able to do three main tasks with the software:

1. Be able to load structural data for the problem: this includes biomass and power plant locations, transport options and biomass compatibility, biomass characteristics and parameters relevant to the power plant, among others static data. This group of data tends to remain constant.
2. Be able to load time dependent data, like biomass availability for specific periods, specific transport restrictions, update weather forecasts, electricity demand, and other dynamic data.
3. Be able to optimize the defined problem and generate reports to evaluate the proposed solutions and support the decision making process.

The generated logistic plan should include a *a*) medium/long term plan for a general overview about the inventory levels and long term contracts (one year), and a *b*) short term plan to decide about the specific transport schedule (1-3 months).

3.2.2 User case: Government/Community

An important goal for a regional government is to improve cooperation and coordination of action of the different stakeholders, promoting cooperation between regional partners. This is not easy to achieve, as stakeholders usually to search for their particular interests. This turns into an uncoordinated competition for resources among regional stakeholders, which can result in inefficient solutions when looking at the problem from a regional perspective. A tool that can provide a common data base, solutions options, and impact evaluations of regional solutions could help reach this complex and valuable goal.
In comparison to the first user case, this approach can generate regional optimal solutions and their impacts data, and not only company-specific local optimums.
The model can support scenario analysis through simulation by providing ways to evaluate supply chain decisions. For example, impacts of biomass availability changes, impacts of a new power plant location in a specific area, changes in the biomass flows for a specific biomass type, or investment in new trucks technology, among many other possible scenarios. This user case can include tactical and strategic decisions as well. Although strategic decisions beside biomass storage locations are not directly included in the model, to reduce its complexity and keep the optimization times as low as

possible, there are at least two approaches to deal with strategic decisions if needed: The first one is to include them in the model decisions variables (in the module described in section 3.11). With this change, the model can optimize, for example, the location for new elements of the supply chain, at the cost of more optimization time. The are many models in the literature that propose options to include strategic decisions in this model, as most models dealing with supply chain of biomass do focus on them (see section 2.3). The second approach is to use this model to evaluate possible solution alternatives. This approach does not require including the strategic variables in the model, but add/change the infrastructure (e.g. new power plant location) where they are most likely to be built, and simulate the scenario solutions. This allows for keeping the optimization times low, and provides a more controlled way to try and evaluate strategic changes. The downside is the loss of optimized locations, but usually the infrastructure location is a very complex problem with many political and social elements that tend to escape the model system boundaries of a (currently) solvable model.
These use case requirements can be seen in figure 3.3.

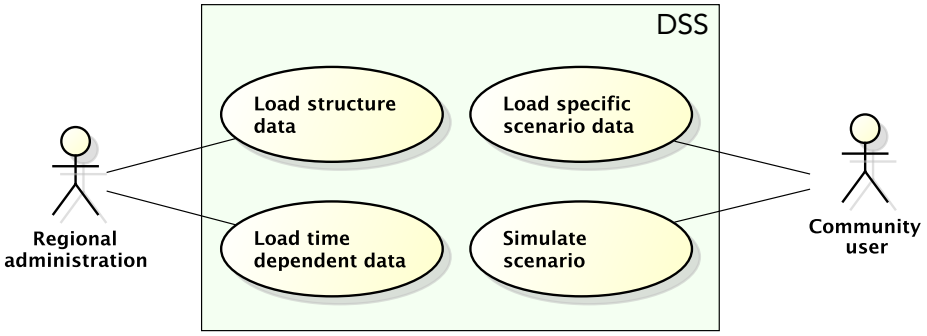

Figure 3.3.: Use case diagram: regional administration.

In general terms, this scenario usually includes two potentially different actors. The first, usually administrated by a regional authority, has two general tasks:

1. Prepare the problem structure with the relevant contextual data. This includes data related to the current situation, like existing power plants, biomass characteristics and current transport options.
2. Some time dependent information can be included as well, such as main biomass availability locations, weather forecasts, etc.

The second actor complements this data with some specific objectives:

1. Add specific information about a scenario to be evaluated. Possible scenarios could include new power plants, new biomass sources, new transport options, or the elimination of some existing facilities or services.
2. Triggers an optimization and evaluates the results.

3.3 Formal problem structure

The information presented in the previous section is used to identify the relevant elements to define a formal problem to assess. In summary, the problem is to generate sustainable biomass transport plans that consider the available biomass in a specific region. It must be compatible with concrete energy conversion technologies and schedule the transport to the power plants and inventories. The on-location biomass should allow for creating a mix with specific characteristics to the power plant in order to be able to generate the demanded electricity at optimal working conditions. The problem considers the existence of multiple harvest site locations, multiple storage points (with specified feasible locations), multiple transport modes and routes, multiple biomass types and biomass characteristics, biomass quality changes from storage, capacity restrictions for relevant resources, energy demand targets (electricity for the case study), and weather considerations. It includes the calculation of best routes based on road features and available road data.
The system boundaries are the biomass harvest locations on the input side, and the electricity generation process on the output side.
A graphical static data structure was constructed to visualize the details of the considered elements of the supply chain plan, which allows the visualization of the required data and relationships. This data model is used to define and analyze data requirements of the processes related to the problem.

The data is modelled using Object Oriented (OO) techniques with UML class diagrams[1] which are suited for a precise and concrete description with a graphical overview to show data relationships. Class diagrams are built using data classes that contains *attributes*, and *associations* that represent the relationships between the classes.
This approach provides a rich model where all data is linked together. It is a robust data model structure in terms of good generalization for different related supply chains, as the model is compatible with various data sets, and not just the one considered in the case study in chapter 5. It allows the testing of the completeness and validness of a data set, to avoid incomplete or inconsistent data instances, which can be easily discovered. This ensures quality in the data acquisition and manipulation.
All the data considered in this problem can be assigned to four disjoint sets:

1. Time independent data: includes data of the problem structure that is independent of time. This data usually does not change often. Examples are travel routes, power plants technical specifications, biomass harvest locations, transport options, etc.

2. Time dependent data: this information is the kind that regularly needs to be feed into the system, as it changes continuously. Examples are biomass inventory levels, biomass availability, weather conditions, etc.

3. Solution data: this category includes all data generated by the model as part of the problem solution (endogenous variables). It is the detailed transport plan for a specific defined horizon.

4. Assessment data: consists of data related to economic costs, environmental emissions, and social impacts that are used for the model to quantify the several impacts of the solution.

The separation of time dependent and independent data is useful for a tactical model, as it allows for clear identification of which data sets require a regular input of fresh information.
All the elements of the graphical model are shown together in figure 3.4. The green elements correspond to time independent data, the blue ones to time dependent data, the orange boxes to solution data, and the colored elements inside the boxes to assessment data.
The complete detail of the problem structure is described in appendix D.

This data model should be considered as a base model, as different use cases may require additional (specific) parameters to be added. This data model provides a useful structure to add them in an organized manner, and that allows the model to scale appropriately. It also provides a common data base for the different model elements to communicate between each other.

[1] The latest UML model specification is available at the Object Management Group Website at: https://www.omg.org/spec/UML/

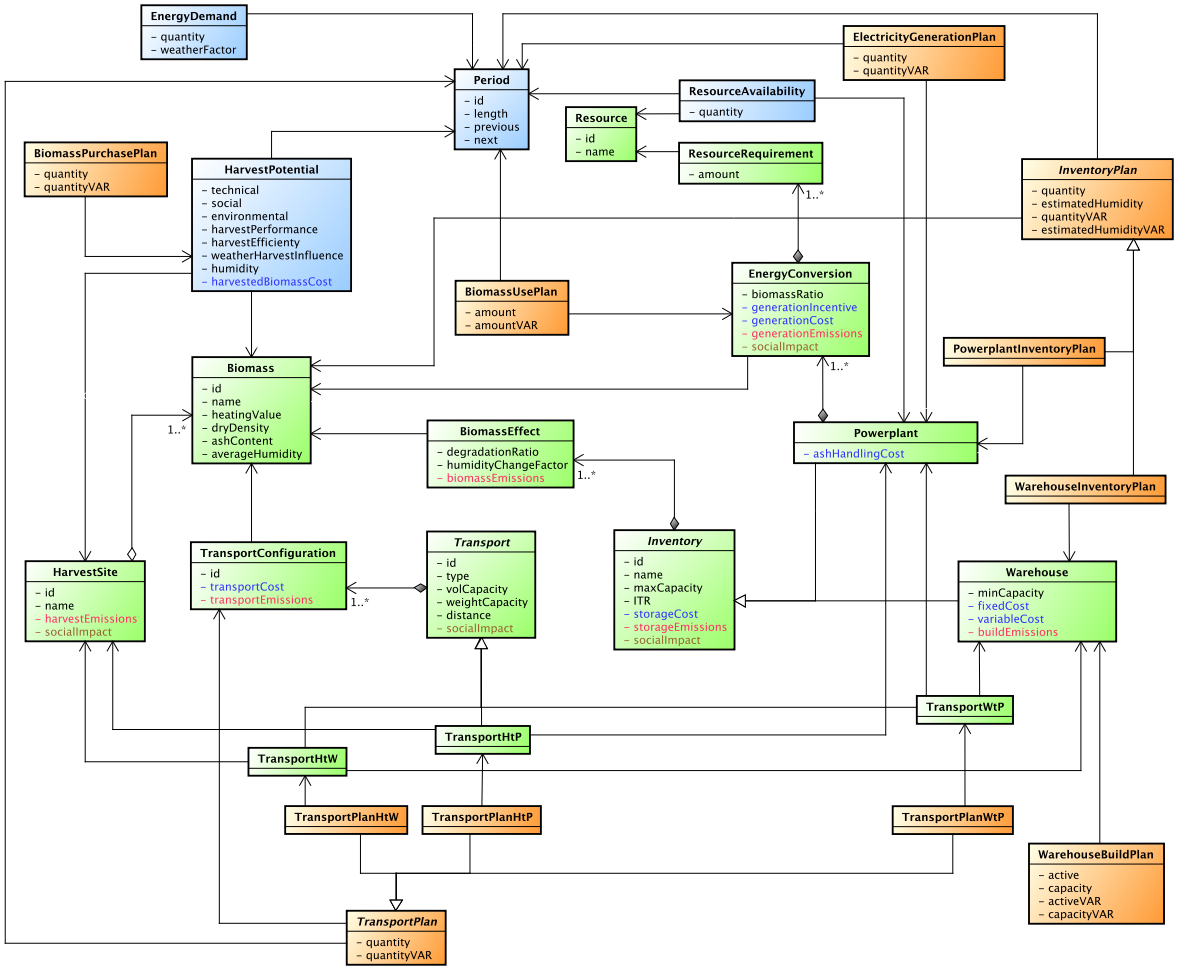

Figure 3.4.: Summary diagram of the data model relationships (UML Class diagram). *Details available in appendix D.*

3.4 Model architecture

The purpose of the architecture is to specify the structure of the solution process for the biomass supply chain.
The proposed model architecture takes a set of *best practices* from the currently available literature (see section 2.3.2) associated with the problem specification (see section 3.3).
The architecture consist of five submodels (referred as *modules*) that are built to work together in an integrated way, as well as a data model as a *common language* for them to communicate seamlessly. A general overview of the modules is shown in figure 3.5.
The modules are built to cooperate to generate a common solution.

1. The **social module** is used to gather qualitative data. This is the type of data is hard to directly incorporate in a mathematical model (because the lack of a fully accepted translation into numbers). This makes the integration a particular challenge.

2. The **Geographic information system (GIS) module** is used to manage the georeferenced relevant data. This data includes the location of the power plants, the location of the biomass sources, the routes that are available for transport, the transport options, potential locations for storage, and the available biomass characteristics.

3. The **weather module** considers weather influences, which is divided in two groups of data. The first is a short term forecast that can influence the possibility to collect biomass from a specific area or temporarily block some available routes. The second is a long term forecast, which provides a general weather trend that influences the yield for specific biomass types, and influences the electricity grid demand. It can also be used to block some routes for longer periods (like routes that cannot be used during the complete winter).

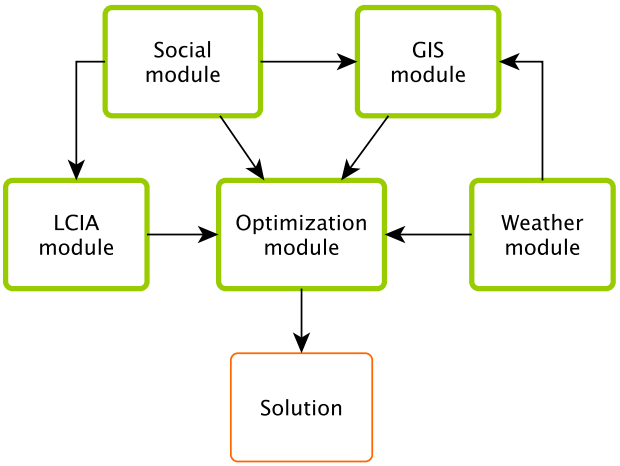

Figure 3.5.: Model architecture: static dimension.

4. The **Environmental Life Cycle Inventory Assessment (LCIA) module** is the source of all environmental parameters to calculate the environmental impacts of the possible solutions.

5. The **optimization module** is a modules integrator and solution generation model. It uses the outputs of the other modules to generate solutions optimized for the model objectives and the defined parameters.

From a stakeholders perspective, this architecture allows the specification of:

- Relevant social implications associated with specific stakeholder interests.
- Geographic-referenced biomass sources, their characteristics, and biomass type availabilities.
- Geographic-referenced power plants and their demand.
- Available transportation options and their restrictions.
- Emissions related to relevant processes.

An overview of the architecture dynamic can be summarized like this: the *social module* activities identify relevant social concerns and influence the GIS data. The weather data is gathered and translated in the *weather module* to the system standard units, which then influences the GIS parameters. The GIS data is updated and the optimized routes are precalculated in the *GIS module*. In parallel, the environmental impact coefficients are calculated in the *LCIA module*, based on the specified problem structure. All the outputs of these activities transform into inputs for the optimization model, which is the final stage that generates the solution through the *optimization module*.
The flow chart in figure 3.6 provides a graphical overview of the process dynamic.

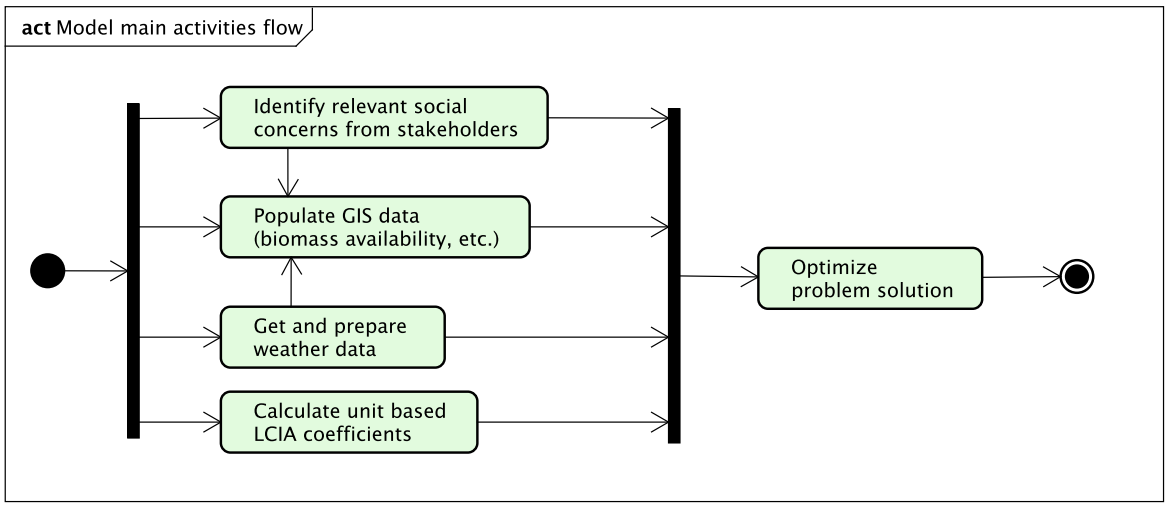

Figure 3.6.: Model main activities flow

3.5 Considerations for using mathematical optimization as model integrator module

The decision of choosing the best suited decision model for a given problem is not trivial. The multi dimensional decision making methods paradox first mentioned by [TM89] suggests that using different methods to select between a set of models to find a solution for a given problem results in a different model selection for the different methods used. This result makes even the selection of the *best* method a non trivial task.

To choose the right approach for the described problem, the available data and the model output requirements need to be taken into account. Mathematical optimization was chosen, as it is a mature method with many successful related use cases (see section 2.3). Relevant advantages are *a*) a focus on optimum solutions and not being limited to comparing limited alternatives (optimization); *b*) flexibility for a specific problem definition (problem customization); *c*) consideration of big amounts of data (mature solvers available); *d*) reasonable resolution times that can be controlled by adding or removing model complexity (solution customization).

Mathematical optimization also allows a critical feature of this model: the consideration of multiple optimization objectives. Objectives can be considered together by e.g. blending them, prioritizing them, moving them to constraints, etc. This work is compatible with those approaches and suggests a specific one based on a variation of priorities of the objective functions and constraints modifications. The technical details about the used approach are described in section 3.11.3.1.

3.6 Model approach to address sustainability

As presented in section 2.2, the consideration of more elements to address the sustainability of the system do always increase the problem complexity. After theoretical considerations it is not hard to come to the conclusion that the only way to fully address sustainability for any given problem is to consider all the elements of the planet (or even the universe), as they all relate in some way, therefore playing a role on the sustainability of the whole. To decrease the high complexity related to sustainability considerations, sustainability frameworks (or models) are proposed to help choose the most relevant elements for a given problem. The proposed model to address sustainability is based on the frameworks proposed on section 2.2: *The Integrative Concept of Sustainability (ICoS)*, *The three pillars of sustainability* and the *United Nations: 2030 Agenda for Sustainable Development*.

The first framework (ICoS) is a more complex approach of related sustainability elements that is used as a base to lead the analysis of the relevant problem elements. The elements of this model are interpreted with a focus on regional impacts. These should be community-relevant concerns that need to be considered for a solution acceptance. The second one (three pillars) provides specific categories that are easy to understand and communicate, and they assist the identification of the relevant indicators. The third one (2030 Agenda) provides a guideline of current world relevant objectives to consider and prioritize.

The specific implementation is available in the modules descriptions in the following sections.

3.6.1 The integrative concept for the supply chain

The integrative concept includes a structure of objectives and rules that are used to find indicators to measure the effects on sustainability of the possible solutions. For every one of them, indicators have been selected and are described in this section.

1. Securing human existence
   - 1.1. Protecting human health
     - Work dangerous situations : this indicator counts the number of possible dangerous situations in which people may be involved. Specific examples are the dangers of field fires to burn waste straw, loading trucks at high altitude, manually having to install covers for the truck cargo, etc.
     - Human toxic emissions : the thermochemical process of burning biomass could emit dangerous emissions that may need to be considered. For example, dioxin and PM. Transport trucks and specific harvest equipment emissions may also need to be considered.
     - Noise : short high volume noise and constant low volume noise emitted by the considered infrastructure.
   - 1.2. Ensuring basic needs are met
     - Security of the biomass supply : the lack of a secure supply of biomass for power plants can translate in inefficiencies by the generation or even interruption in extreme situations.
   - 1.3. Securing one's livelihood
     - Workplaces : the direct and indirect regional workplaces related to the supply chain can translate to more stability to the persons involved[2].
     - Salaries : a reasonable salary is as important as a workplace, as it can be used as an economical way to measure the quality of a workplace.
   - 1.4. Offering equal opportunities of using the environment for everybody

     None considered.
   - 1.5. Reducing excessive income or wealth inequalities

     None considered, but for the scope of this problem related is point 1.3.
2. Maintaining society's ability to manufacture products or provide services
   - 2.1. Using renewable material and energy resources sustainably
     - Use of renewable fuels : for the transport process the use of renewable fuels like bio-diesel or some electric alternatives that could benefit the electricity matrix (e.g. electric train).
     - Use of water : the second most used resource for the power plants operation.
   - 2.2. Using non-renewable material and energy resources sustainably
     - Excess use of non renewable fuels : the requirement of fossil fuels or materials for the transport process or the building of new related infrastructure.
   - 2.3. Using the environment without damaging its absorption capacity of harmful emissions
     - Waste disposal : the amount and treatment of ash of power plants and waste related to the different biomass options and the transport process.
     - Emissions from the transport process : e.g. GHG and particulate matter (among others listed in section 3.10).
     - Emissions from the energy conversion process : e.g. GHG and particulate matter (among others listed in section 3.10).
   - 2.4. Avoiding unacceptable technical risks

     None considered, as for example, power plant technology selection is considered a strategic decision.
   - 2.5. Developing property as well as skills and knowledge sustainably

     None considered.
3. Preserving options for development and action

[2] Although the number of workplaces indicator is controversial. One can maximize the number of jobs, but do those jobs offer good salaries and working conditions?.

3.1. Providing equal opportunities of education, employment, public office, and information

Recruiting methods : the transparency of the job opportunities offered in the system.
Information strategies : ways from the public to be informed of the way the transport is being managed.

3.2. Ability to take part in social decision-making processes

Public participation : the instruments for the public to be involved in the decision making. Specially relevant for the government/community user case presented in section 3.2.2.

Supply chain structure : the level of involvement a specific structure provides. For example: transport with trucks usually involves several drivers and many trucks that can include some kind of information to the public, as they travel using public roads. Trains on the other side could require a lower amount of working people and less public involvement.

3.3. Preserving cultural heritage and cultural diversity

None considered.

3.4. Conserving nature and landscape as cultural assets

Not use of waste/residual biomass : if first generation biomass (like energy crops) are used in the solution, the nature biodiversity and landscape could be negatively influenced.

3.5. Maintaining social cohesion

None considered.

3.6.2 Sustainability and system objectives

The problem described in section 3.3 and its defined objectives requires a model architecture capable of considering and integrating the different problem objectives. The *three pillars of sustainability* framework is used to build three concrete objectives categories:

- The economic (financial) objective: includes all indicators that can be measured in monetary units. It focuses on minimizing total costs.
- The environmental objectives: groups all variables that relate to environmental emissions and uses emission units like, e.g. carbon-dioxide-equivalent (more examples in section 3.10). The objective is to minimize a negative effect of chosen impact categories.
- The social objectives (descriptors): groups quantitative and qualitative indicators that do not apply to the other two groups. These objectives aim to describe and in some instance limit the effects of the proposed solution.

These categories provide a simple classification that is commonly used, and therefore easy to understand. It also provides a way to simplify comparisons between this model and others from the literature, which share the same common categories.
The three objective categories require specific data for the calculations. They may address the same problem, but the different perspectives require data from different sources and aggregation. Although the model modules aim to produce a close interconnection between the listed categories, if the responsibilities for the objective categories had to be assigned, it would be like the following list:

- Social indicators module for the social objectives.
- LCIA module for the environmental objectives.
- Mathematical optimization module for the economic objectives (and final integration of the other modules).

The list is provided for better understanding of the modules role in relation to the models objective.

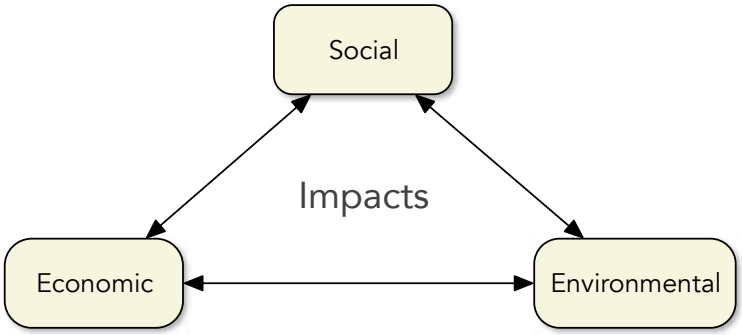

Figure 3.7.: Interaction between the problem groups of objectives.

3.6.3 Multiple objectives

The selection of these modules to address the specified objectives results in challenges to integrate them, as the chosen methods do not necessarily blend seamlessly together. Figure 3.7 shows a simple view of the interactions between the groups that are considered in the proposed model, although more details are available by looking at the modules' architecture (section 3.4) and the modules' interaction in the following sections.

The LCIA and the social indicators models provide a structure to evaluate the specific dimensions and the mathematical optimization model incorporates these structures to generate an integrated solution. With this approach, the social and environmental modules can provide restrictions and objectives to the mathematical model, and directly influence the optimization. For example, they could limit the minimum amount of needed workplaces, the maximum amount of permitted CO_2 emissions, the trucks traffic rate in specific routes, etc. On the other hand, the optimization model requires infrastructure and resources for the proposed solutions. Those are evaluated using the dimension specific methods to avoid over simplifications, which results in measurable indicators for every dimension.

To give a general overview, table 3.1 includes each method objectives and some proposed indicators.

Table 3.1.: Objective and indicator examples for every method.

Method	Objective	Indicator examples
LCIA	Calculate environmental impact categories	Emissions related to GHG, human toxicity, PM, etc.
Social indicators by sustainability frameworks	Evaluate social impacts	Number of work places, route traffic congestion, workers income, working conditions, etc.
Mathematical optimization	Calculate financial costs and optimize the integrated solution	Direct costs, opportunity costs, investments, and other quantifiable monetary expenses.

3.7 Social Module

The social module focuses on qualitative information. This type of data does not blend directly with quantitative data, therefore it requires a special approach. The module requires the following tasks to be completed:

1. Identify the relevant concerns among all the pertinent regional stakeholders related to the supply chain.
2. Search for relations between these concerns and the models' solution parameters.
3. Add indicators for the optimization model that allow the quantification of solution elements that have a corresponding relevant social impact.
4. Interpret the indicator values in the solution context.

This work specifies the following steps to finish these tasks:

1) The first task is accomplished by doing stakeholder interviews. Specific questionnaires with a focus on the specific region should made for the identification of the relevant elements.
Two models can lead the interview and discussion. The first is the set of sustainability models discussed in section 3.6. The second is the diagram 2.3.3.1 that also proved to be useful is some cases to help focus the conversation. Its important to keep the questions open, as this is an *explorative phase*. The questions should allow the stakeholders to talk freely about their concerns, provide the chance for a direct discussion of their issues, and add new topics. It's good to interview community representatives and directives, along with stakeholders in the supply chain, in order to discover indirect effects to the community. It should end with a summary report to be made available to all participants. It is also recommended to avoid keeping a list of participants to protect their anonymity, as may help some feel like they can talk freely about specific concerns.

2) The second objective puts the social concerns alongside with the supply chain model. Here, an active search for possible indicators to relate them should be done. The data model presented in figure 3.4 and other modules parameters are a starting point to find these relationships, but new elements that can be later included in the model should be considered as well. If there were quantifiable limits identified in the first task, they can be added as numeric goals/limits too. For example, noise issues could be related with the frequency of trucks driving through a specific route. The impact on local workplaces can also be monitored by counting the total direct and indirect men/women working hours.

3) The third goal is to modify the model in order to implement the indicators in the optimization module and gather the sources of the additional information (if needed) for successful implementation. This can be achieved by adding an extra parameter in an objective function, an additional variable to sum the effects, or additional constraints to limit specific variables.

4) The last task is relevant after the model solution, in order to provide correct guidance to interpret the indicators. This task is specially important, as some customization to the original intentions could have been made to make it compatible with the implemented model, and without proper explanations it could lead to misinterpretation of solution impacts. It is also interesting to discuss the indicators interpretation with the pertinent stakeholders to make sure they will be useful for them and can be understood.

A complete example is included in section 5.2.1.

3.8 Weather Module

The weather module is used to capture weather conditions data that can influence the solution, therefore making it available to the other modules. This information is used for two specific goals:

1. Transport network modifications for the expected weather conditions: not all transport routes are available at all times, because of weather conditions. For example, heavy rains can occasionally block some routes, making the access impossible for types of trucks or other vehicles.

2. Adjust the electricity demand: in regions with a strong hydro-generation presence, a year with high precipitation can limit the need of electricity generation with other technologies (like biomass), decreasing the yearly demand.

3.8.1 Transport network modifications

The input data for this task are short to medium term weather forecasts. The route modification output of this module task can be a:

- Modification of specific routes that are not available for a specific amount of time, which results in a modification of the routing data in the GIS module (see section 3.9), like temporarily making a road unavailable, or changing a road feature (like maximum speed).

- Restriction of the transport modes that can travel through a specific route, which influences the Optimization Module (see section 3.11).

For this effect, *short term forecasts* are obtained from weather forecast services. For example, services based on data from the European Centre for Medium-Range Weather Forecasts (ECMWF), like Meteored[3], or other sources like Open-Weather[4], World Weather Online[5], etc.

[3] https://www.meteored.cl
[4] https://openweathermap.org
[5] https://www.worldweatheronline.com

3.8.2 Electricity demand adjustments

The input data needed are medium to long term weather forecasts. This influence is not applicable in all world regions, but its relevant for zones where big weather phenomena influences can change the energy mix (e.g. the amount and frequency of rain). For example: a rainy winter can provide a region with higher water reserves for hydro power plants. This can lead to a lower need in other power plant requirements, like biomass based ones, therefore lowering the expected demand.
After the analysis of the available data for the planing horizon periods, the parameters WD_t from equation 3.22 in the optimization module should be calculated (see section 3.11). If there is not available information, all parameters must be set to 1, as shown in equation 3.1.

$$WD_t = 1 \quad \forall\ t \in T \tag{3.1}$$

Long term forecasts are used for this effect, which are less reliable in comparison to short term ones. Specific regional characteristics provide useful forecast of this kind. For example, on the Pacific coast of north and south America, the El Niño-Southern Oscillation (ENSO) cycle describes the fluctuations in temperature between the ocean and atmosphere. The cold phase of ENSO is called *La Niña* and the warm phase *El Niño*. There has been research about the impacts on rains, for example by [CSRAE15]. According to the NOAA[6] "these deviations from normal surface temperatures can have large-scale impacts not only on ocean processes, but also on global weather and climate. El Niño and La Niña episodes typically last nine to 12 months, but some prolonged events may last for years. While their frequency can be quite irregular, El Niño and La Niña events occur on average every two to seven years. Typically, El Niño occurs more frequently than La Niña."
This phenomenon allows a long term forecast that may allow weather predictions with a certain degree of confidence, such as if rains will be more (or less) frequent than average. With this information, electricity grid demand can be adjusted, if a higher availability of electricity related to hydro power plants is available.
Figure 3.8[7] shows the Multivariate ENSO Index (MEI) which summarizes 6 variables: sea-level pressure (P), zonal (U) and meridional (V) components of the surface wind, sea surface temperature (S), surface air temperature (A), and total cloudiness fraction of the sky (C). A complete description by [Wol93] (shares same variable names). More information is included in appendix K.

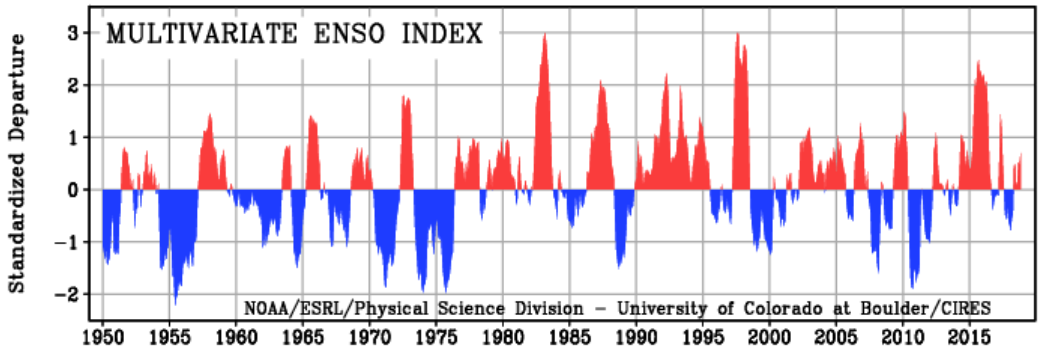

Figure 3.8.: Multivariate ENSO Index (1950-2018)

3.9 GIS Module

The GIS module is used to gather, process, and make available the georeferenced data for the other modules. It collects the specific locations of all biomass sources, the power plants, and the available transport routes and restrictions. This information is used to calculate transport distances and travel times of the transport vehicles.
This module tasks can be divided in two groups: *georeferenced data management* and *routes optimization*.
A complete example is available in section 5.2.3.

[6] National Ocean Service of the National Oceanic and Atmospheric Administration of the U.S Department of Commerce, USA. https://oceanservice.noaa.gov/facts/ninonina.html
[7] Source: https://www.esrl.noaa.gov/psd/enso/mei/

3.9.1 Georeferenced data management

This is a very data intensive module task, as most of the problem data has relevant geographic locations. It manages time independent data (like the supply chain structure: e.g. power plant locations), and time dependent data (like the biomass availability at the harvest locations). The details of the specific data can be seen in appendix D.
The model provides an interface to enter and consolidate all the information about available biomass, locations, amounts, quality, etc. It provides standard units and aggregates the information needed for other modules. It also promotes the reuse of data (like biomass features) to avoid duplicates that can help keep the model simple, without compromising better solutions and avoiding possible mistakes, as the same data is only stored in one place. An example of this feature is the option to enter the information about one type of biomass for a specific location, and then there is no need to enter it again for another location, as it can be selected from the already entered available alternatives.

3.9.2 Routes optimization

Every transport combination has a specific optimized route to transit. This module task has the objective of finding those routes and translating this information according to the other modules needs.
The approach chosen is the use of open available street data sources. The two main options are the community OpenStreetMap project[8], and the closed source Google Maps[9]. Both provide an updated roads service. From a use perspective, OpenStreetMap provides the additional option to edit every detail of the map (as the source is available) and even add custom roads that can be used for a specific implementation. It allows the inclusion of special road *features*, that can give the streets special characteristics like: maximum speed, probability of being closed because of heavy rains, a noise factor, a traffic factor etc.
The Google service has an advantage in terms of the embedded routing algorithms. It has online traffic information, and the service is very easy to use. An OpenStreetMap compatible implementation called OSRM[10] (check appendix J) provides a similar service, but it is more limited in comparison.
From a theoretical standpoint, both options are suitable. For this work, prototypes for both options were created, but at the end, OpenStreetMap was chosen. More details on chapter 4.
The output of this module is the transport specific data for every route combination for the optimization module. The model chooses faster instead of shorter routes. It makes more sense to choose a 6 kilometer trunk road at 70[km/h], in comparison to a (shorter) 5 kilometer unclassified road at 40[km/h].
The technical details of the implementation are described in section 4.3 and appendix J.

3.10 LCIA Module

To consider precise environmental effects of the possible solutions for the environmental objectives, a module based on LCIA results (part of LCA) has been chosen. The life cycle approach provides a detailed view of the environmental effects in the system from cradle to grave. The model is specified by standard ISO norms [ISO06a], [ISO06b] [11].The amount of data needed for an environmental life cycle evaluation is large, as the upstream and downstream parts of the supply chain usually include many processes with several parameters. Specific databases suitable to work with LCA software are available[12] and allow a faster implementation, as they include many common processes. These elements make this module data intensive.
The module objective is to aggregate the supply chain processes data, to do a *first stage* of the LCIA calculations, and leave the *second stage* of the calculations to the optimization module.
The LCIA module is built upon base elements of the supply chain of the transport problem. Every stage of the transport chain can be modeled (harvest sites, storage locations, power plant inventories and all the possible transport modes between locations) and therefore provide data for environmental impacts. As mentioned, the first part of the LCIA calculations are made in this module. All calculations are made for one base unit of a chosen input/output parameter (e.g. kg, km, etc.), which translates as a variable coefficient in the optimization module. These coefficients must comply with a specific set of impact categories. For this work, the LCIA methods ReCiPe 2016 Midpoint (H) and ReCiPe 2016 Endpoint (H) from [HSE+16] were used. This close coupling of the design allows the last part of the calculation to be made by the optimization module, which brings the processes together.
In terms of the optimization model, the following parameters need to be calculated:

[8] Official Website: https://www.openstreetmap.org/
[9] Official Website: https://maps.google.com/
[10] Official Website:http://project-osrm.org
[11] LCA procedures are part of the ISO 14000 environmental management standards: ISO 14040:2006 and 14044:2006.
[12] For example: ecoinvent: www.ecoinvent.ch , GaBi: www.gabi-software.com , BioEnergieDat: www.bioenergiedat.de

1. $EBHV_{e,b,h}$: emissions for the acquisition of a unit of biomass b, at the harvest site h, for the impact category e, [impact category unit], e.g. CO_2-eq, etc. (linked to equation 3.33)

2. $ETBU_{e,b,m}$: emissions for the transport of a unit of biomass b, using the transport mode m, for the impact category e, [impact category unit], e.g. kg PM2.5-eq, etc. (linked to equation 3.34)

3. $ESBU_{e,b}$: emissions for the storage of a unit of biomass b, for the impact category e, [impact category unit], e.g. CO_2-eq, etc. (linked to equation 3.35)

4. $EPCV_{e,b,p}$: emissions for the biomass to energy conversion process of a unit of biomass b, at the power plant p, for the impact category e, [impact category unit], e.g. species.yr, etc. (linked to equation 3.36)

The process for the calculation of the parameters if as follows:

1. Every element that produces measurable emissions to the environment can be modeled with the LCA software: harvest sites, storage locations, transport modes, power plants, etc.
2. If the process exists in an LCA database (like *ecoinvent*[13]), it can be taken from there, but it is advised to examine the supply chain related to the unit process of interest, as some elements may need to be removed if they are not considered in the proposed system. If the process does not exist in a database, it can be build with a mix of primary data and database information.
3. The target amount of the process must be set according to the base unit used later in the optimization stage.
4. Then midpoint and endpoint results for the base input/output must be calculated and exported to be used by the optimization module.

This work used the software implementation openLCA[14]. The main advantage of openLCA is the available source code, which provides ways to check how the software calculates results. This advantage allows scientific works to be transparent about how calculations are made inside a system, eliminating the need to trust a *black box*.

For example: by using *openLCA* and the database *ecoinvent* it is possible to model a product system for the *transport, freight, lorry >32 metric ton, EURO5*, for 1 [ton] of a biomass type, a distance of 1 [km]. With the same software, the calculation of midpoints and endpoints parameters can be done, and the results can be exported to use as parameters in the optimization module.

As said, the results of this module are the values for the midpoint and endpoint indicators for every relevant element of the system, in terms of LCIA impact categories, for a defined base unit. The most relevant ReCiPe 2016 midpoint categories chosen for this work are:

- Fine particulate matter formation
- Freshwater ecotoxicity
- Freshwater eutrophication
- Global warming
- Human carcinogenic toxicity
- Human non-carcinogenic toxicity
- Ozone formation, Human health
- Ozone formation, Terrestrial ecosystems
- Terrestrial acidification
- Terrestrial ecotoxicity

Results that are closer to the safeguard subjects are calculated through endpoint LCIA methods. Relevant endpoint impact categories for this problem are:

- Damage to human health
- Damage to ecosystems

This work has a tactical decisions spectrum, so it would make sense to consider categories that are closely influenced by those decisions. Still, as environmental impacts do add up over time, a more general approach is chosen, where all problem-relevant categories are considered to assess long term effects too.
Figure 3.9 shows the causal relationship between the environmental intervention and the potential impacts on ReCiPe 2016.
A theoretical relationship between the structure of a combined model of the LCIA unit processes and the optimization model is discussed in appendix E.

[13] ecoinvent: www.ecoinvent.ch

[14] openLCA is a Life Cycle Assessment (LCA) and Footprint software created by GreenDelta. The software and its source code are freely available. More information at http://openlca.org

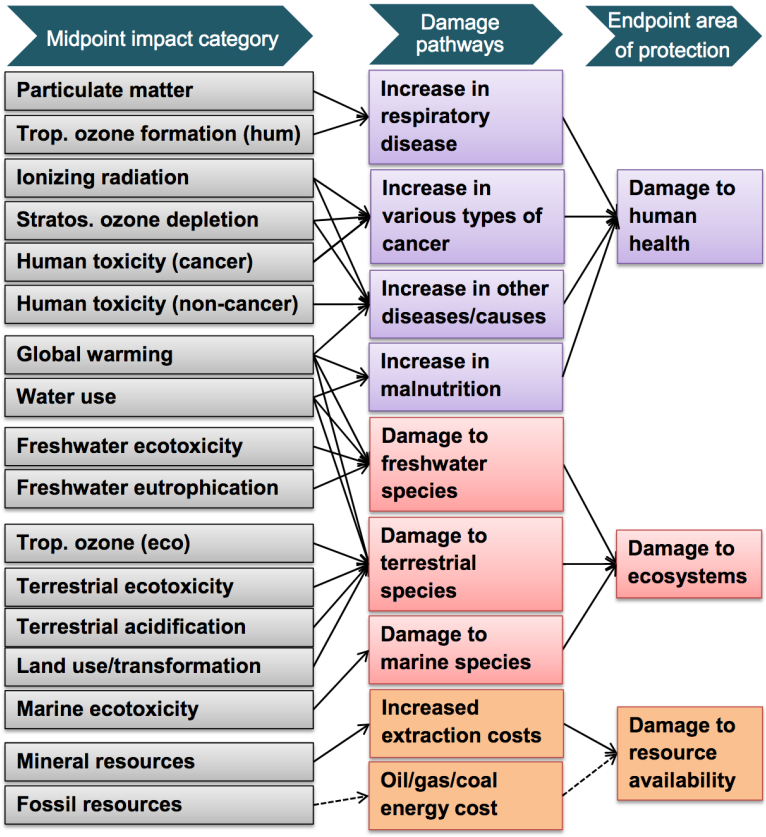

Figure 3.9.: ReCiPe2016 causal relationship between the environmental intervention and the potential impacts. [HSE+16]

3.11 Optimization Module

For the economic (financial) indicators and the modules integration, a mathematical optimization model was chosen. This approach has two main advantages: *a*) the optimization approach focuses on the optimal solution rather than evaluate identified alternatives; *b*) the models flexibility allows an *ad hoc* model to address specific problem requirements and complexities.
Mathematical optimization considers one or many optimization objectives, and a (usually) infinite set of *feasible solutions* called the solution space. The optimization method explores the solution space to find the *best* solution (or solutions). Those solutions are defined as the ones that maximize (or minimize) the specific objective (or objectives), which is defined by an objective function. This is a clear advantage against alternative evaluation, where a finite number of known alternatives are compared. Some good unknown alternatives could be overseen and not included in the analysis. This optimization module is modeled for the specific base supply chain problem formalized in section 3.3. But optimization problems like this provide the flexibility to add/modify/remove equations to customize the model for the specific needs of a real use case. This open approach provides an advantage against competitive commercial products, with general modeling alternatives for the supply chain. They may provide competitive solution options for general supply chain problems, but for useful implementations, the need to address specific details of the *real world* problem is critical.
This module uses an MILP model to generate solutions. MILP models include a linear objective function and a linear set of constraints. The decision variables can be either integer or continuous variables. It is a multiobjective optimization problem, as the formulation considers more than one objective function.
As there are publications that use MILP models to address similar problems, one with good features and a similar approach was chosen as a starting point. This MILP model is based on the one published by [YTGS11]. The original model considers ethanol production in bio-refineries. The original model was modified in order to transform it to requirements of the specified problem (direct combustion for power plants). Some equations were removed, modified, and added, in order to comply with this work problem's requirements, creating a new model formulation.

Naming conventions: parameters have names in uppercase (e.g. *PBTL*) and variables (integer and continuous) in lowercase (e.g. *harv*). Indices are written in lowercase as well. The corresponding cardinality of an index is written with the same letter in uppercase.
All sets, parameters and variables are defined together in appendix A.

3.11.1 Sets

B : set of biomass types, indexed by the letter b.
H : set of harvesting/collection sites, indexed by the letter h.
S : set of storage facilities, indexed with the letter s.
P : set of power plants, indexed with the letter p.
M : set of transport alternatives (modes), indexed with the letter m.
R : set of resources besides biomass needed for the conversion process, indexed with the letter r.
T : set of time periods, indexed with the letter t.
I : set of by-products that can be generated for different types of biomass, indexed with the letter i.
E : set of the considered impact categories related to the environmental emissions, indexed by the letter e.

3.11.2 Constraints

These set of constraints describe the solution space of the problem.

Harvest biomass potential: the maximum amount of biomass b harvested from site h in time period t is limited by the effective harvest potential *ehp*, which is determined in equations (3.2).

$$harv_{h,b,t} \leq ehp_{h,b,t} \quad \forall_{h\in H, b\in B, t\in T} \tag{3.2}$$

This restriction allows the model to consider, for example, seasonality and harvesting windows. The maximum available amount is calculated considering a sustainability approach that is the result of the minimum value between the technical biomass harvest potential *PBTL*, the environmental harvest potential *PBEL*, and the social harvest potential *PBSL* at the site h, for the biomass type b, at the time period t. This selection is made by the model using equations (3.3).

$$ehp_{h,b,t} = \min\left\{PBEL_{h,b,t}, PBTL_{h,b,t}, PBSL_{h,b,t}\right\} \quad \forall_{h\in H, b\in B, t\in T} \tag{3.3}$$

Limits to harvest rate: every harvest site has a maximum rate at which the biomass can be collected. Equations (3.4) limits the possibility of the collected biomass for every harvest site from exceeding the the available amount in a specific time period. *HRate* is the biomass harvesting rate at the site h, for the biomass type b, at the time period t. W is the weather factor that influences the harvest rate at the site h, for the period t, and D represents the available time (effective duration) of the period.

$$\sum_{b} \frac{harv_{h,b,t}}{HRate_{h,b,t} \cdot W_{h,t}} \leq D_t \quad \forall_{h\in H, t\in T} \tag{3.4}$$

Mass balance at harvest sites: the biomass type b harvested at site h at period t must be equal to the biomass transported out of the site. *EFFH* represents the percentage of effective collected biomass b in the operation at harvest site h for every time period. *shiphs* and *shiphp* are the amounts of transported biomass from harvest sites to storage s, and from harvest sites to power plants p, respectively. m represents the transportation mode for these variables.

$$EFFH_{h,b,t} \cdot harv_{h,b,t} = \sum_{s}\sum_{m} shiphs_{m,b,t,h,s} + \sum_{p}\sum_{m} shiphp_{m,b,t,h,p} \quad \forall_{h\in H, b\in B, t\in T} \tag{3.5}$$

As equations (3.5) show, biomass storage at harvesting sites is not included in the model, as it is directly transported away either to storage facilities or power plants.

Mass balance at storage facilities: for equations (3.6) the biomass type b transported to a storage facility from site h at period t must be equal to the biomass transported out of the facility, plus the inventory level difference. *invs* is the storage inventory level for biomass b at location s at period t. *BDEGS* represents the percentage of degraded biomass on storage, per time period. *shiphs* are the amounts of transported biomass from to storage location s to power plant p.

$$\sum_{h}\sum_{m} shiphs_{m,b,t,h,s} + \left(1 - BDEGS_{b,t}\right) \cdot invs_{b,s,t-1} = \sum_{p}\sum_{m} shipsp_{m,b,t,s,p} + invs_{b,s,t} \quad \forall_{s\in S, b\in B, t\in T} \tag{3.6}$$

$$invs_{b,s,0} = INVS0_{b,s} \quad \forall_{b\in B, s\in S}$$

The initial inventory (for period 0) is set by the parameter *INVS0*.

Limits to the storage facilities implemented capacity: the model can suggest storage locations to be implemented, considering a lower and upper capacity limit. In equations (3.7), *bs* is an integer variable that states if a storage facility should be implemented at location s. *capinvs* is the capacity of the suggested storage at location s. *LSL* and *USL* are the lower and upper storage capacity limits for the location s, respectively.

$$LSL_s \cdot bs_s \leq capinvs_s \leq USL_s \cdot bs_s \quad \forall_{s \in S} \tag{3.7}$$

Storage location volume capacity: every storage can store different types of biomass simultaneously. This constraint keeps the maximum storage volume capacity from being exceeded. *BH* is the humidity content of biomass type b, for time period t. *BD* is the density of biomass type b.

$$\sum_b \frac{invs_{b,s,t}}{\left(1 - BH_{b,t}\right) \cdot BD_b} \leq capinvs_s \quad \forall_{s \in S, t \in T} \tag{3.8}$$

$$\sum_b \frac{invp_{b,p,t}}{\left(1 - BH_{b,t}\right) \cdot BD_b} \leq CAPINVP_p \quad \forall_{p \in P, t \in T} \tag{3.9}$$

Safety stock inventory for power plants: to avoid interruption in operation, because of external factors, a safety stock inventory is forced in the system. *SS* is system safety stock for time period t.

$$\sum_p \sum_b CONV_b \cdot invp_{b,p,t} + \sum_s \sum_b CONV_b \cdot invs_{b,s,t} \geq SS_t \quad \forall_{t \in T} \tag{3.10}$$

Biomass throughput at storage locations: under the assumption that a storage facility has regular movement of inventory, the capacity to handle the movements is twice the average inventory level. The volume of this inventory, divided by the inventory turnover ratio, equals the location throughput. *ITR* is the inventory turnover ratio, which is the number of times the inventory is replaced per time period.

$$2 \cdot \sum_b \sum_p \sum_m \frac{shipsp_{m,b,t,s,p}}{\left(1 - BH_{b,t}\right) \cdot BD_b \cdot ITR_s} \leq capinvs_s \quad \forall_{s \in S, t \in T} \tag{3.11}$$

Transport weight and volume limits: for all transport, volume and weight limits must be considered. These first set of four constraints make sure that the if a storage facility is constructed, those limits are respected. Therefore, no transports would be made to a non existing facility.

$$\sum_b \frac{shiphs_{m,b,t,h,s}}{\left(1 - BH_{b,t}\right) \cdot BD_b} \leq SHIPMAXVOLHS_{h,s,m,t} \cdot bs_s \quad \forall_{h \in H, s \in S, m \in M, t \in T} \tag{3.12}$$

$$\sum_b \frac{shiphs_{m,b,t,h,s}}{1 - BH_{b,t}} \leq SHIPMAXWEIHS_{h,s,m,t} \cdot bs_s \quad \forall_{h \in H, s \in S, m \in M, t \in T} \tag{3.13}$$

$$\sum_b \frac{shipsp_{m,b,t,s,p}}{\left(1 - BH_{b,t}\right) \cdot BD_b} \leq SHIPMAXVOLSP_{s,p,m,t} \cdot bs_s \quad \forall_{s \in S, p \in P, m \in M, t \in T} \tag{3.14}$$

$$\sum_b \frac{shipsp_{m,b,t,s,p}}{1 - BH_{b,t}} \leq SHIPMAXWEISP_{s,p,m,t} \cdot bs_s \quad \forall_{s \in S, p \in P, m \in M, t \in T} \tag{3.15}$$

The last set of two transport restrictions limit the weight and volume of transported biomass from harvest sites directly to power plants, for every transport option m.

$$\sum_{b} \frac{shiphp_{m,b,t,h,p}}{\left(1-BH_{b,t}\right)\cdot BD_{b}} \leq SHIPMAXVOLHP_{h,p,m,t} \qquad \forall_{h\in H,p\in P,m\in M,t\in T} \tag{3.16}$$

$$\sum_{b} \frac{shiphp_{m,b,t,h,p}}{1-BH_{b,t}} \leq SHIPMAXWEIHP_{h,p,m,t} \qquad \forall_{h\in H,p\in P,m\in M,t\in T} \tag{3.17}$$

Mass balance at power plants: the biomass balance at power plant p at period t is guaranteed by constraint (3.18). *usedbp* is the used biomass b at the power plant p at period t. *invp* represents the inventory level of the power plant p at the time period t.

$$\sum_{h}\sum_{m} shiphp_{m,b,t,h,p} + \sum_{s}\sum_{m} shipsp_{m,b,t,s,p} + \left(1-BDEGS_{b,t}\right)\cdot invp_{b,p,t-1} = usedbp_{b,p,t} + invp_{b,p,t} \quad \forall_{b\in B,p\in P,t\in T} \tag{3.18}$$

$$invp_{b,p,0} = INVP0_{b,p} \qquad \forall_{b\in B,p\in P}$$

The initial inventory (for period 0) is set by the parameter *INVP0*.

Energy conversion capacity at power plants: the conversion of biomass to energy capacity is modeled by equation (3.19). *CAPBP* is the maximum volume capacity to process biomass in power plant p. *MPCAPBP* is the percentage of this capacity that needs to at least be processed for the plant p, and *DY* is the sum of all effective production periods of the year.

$$MPCAPBP_{p}\cdot\frac{CAPBP_{p}}{DY}\cdot D_{t} \leq \sum_{b} usedbp_{b,p,t} \leq \frac{CAPBP_{p}}{DY}\cdot D_{t} \qquad \forall_{p\in P,t\in T} \tag{3.19}$$

Energy conversion balance at power plants: the conversion from biomass to energy is modeled by equation (3.20). *en* is the total electricity generated at power plant p in the period t. *CONV* is the conversion ratio of biomass b to energy.

$$en_{p,t} = \sum_{b} CONV_{b}\cdot usedbp_{b,p,t} \qquad \forall_{p\in P,t\in T} \tag{3.20}$$

Limits to other resources use at power plants: the conversion process may have other limiting resources to be considered. *RESREQ* is the amount of resource r needed to convert one unit of biomass b into electricity at the power plant p. *RESMAX* is the capacity limit to use resource r at the power plant p, at period t.

$$\sum_{b} RESREQ_{b,p,r}\cdot usedbp_{b,p,t} \leq RESMAX_{p,r,t} \qquad \forall_{p\in P,r\in R,t\in T} \tag{3.21}$$

Energy demand satisfaction: the energy demand *DEM* for the time period t, must be at least the sum of the generation of all considered power plants. *WD* is a parameter that changes the total demand as a result of the influence of other generation technologies. For example, a rainy year can increase the amount of hydro energy available in the grid, that can lower the generation requirements for the considered power plants.

$$\frac{\sum_{p} en_{p,t}}{WD_{t}} \geq DEM_{t} \quad \forall_{t\in T} \tag{3.22}$$

3.11.3 Objective functions

The objective functions purpose is to provide a mathematical way to compare different options of the solution space. This allows determining if *one solution is better, worse, or equal to another*, in terms of the aspects the objective function considers. As stated in the previous chapters, solutions for sustainable problems require more than one problem dimension to be considered simultaneously. With this in mind, to keep one mathematical dimension (unit) for the objective function, more than one objective function is needed.

3.11.3.1 Multi criteria mathematical considerations

There are techniques to solve optimization models with multiple objective functions. The common approach is to blend the objective functions together into one, providing a weight for each of them. For example, if a model has two objective functions $x + y$ and $3y + z$, with weights of 1 and 2, a blended objective would be $1 * (x + y) + 2 * (3y + z)$ (usually both equations are first normalized too, in order to make the changes comparable due to relative numerical values from the considered units.).
Another option is to assign priorities to each objective and optimize in priority order. With this approach, the best solution for every current objective is found, but without decreasing the solution quality of objectives with higher priority.
A third option is to remove them as objective functions and convert them into model constraints to force something to happen, or give an upper or lower limit to some decision variable.

For the economic and environmental objective functions, this work uses the priority approach, with a modification that allows the decrease of the higher priority objective quality to a given amount specified either by a relative or absolute amount. This is achieved by fixing some variables to their optimal solution value of the higher priority objective, and adding a parameter to limit the maximum degradation.

For the social objectives, those are either moved as constraints to the model and calculated along side to give a numeric picture of the considered social impacts, or calculated as another objective function. In this case, the social objective functions have no weight for the optimization, but the values are still calculated. This allows the stakeholders to see the impact of the solutions in the considered social categories, without the obligation for stakeholders to settle on whether the increase of the value of one is *better* or *worse*[15]. This lack of influence in the model solution is recommended for the general case, but if stakeholders are able to come to an agreement, they can of course be considered to influence the model's solution.

3.11.3.2 Economic objective function

This function objective is to minimize the total annualized cost *c_tap* of the transport plan. This cost is calculated using equation (3.23). The first term *c_it* represents the annualized storage facilities implementation costs, whether the next forth represent operational costs. The last two terms represent the credits gained for selling by-products and incentives (if they exist) for renewable energy generation. Every term will be defined in this section.

$$\min \; c_tap = c_it + c_ba + c_bt + c_bs + c_pp - c_bp - c_re \tag{3.23}$$

Infrastructure total cost function (c_it): this cost includes the fixed costs of the installations and the variable costs of the operation on an annual basis. The installation cost *c_if* consist of the cost involved in the decision to implement storage facilities. The fixed cost of a storage facility and the variable one that correlates to the maximum capacity of the implemented facility, are represented by parameters *C_FS* and *C_VS*, respectively. The costs of the power plants' infrastructure is not considered by the model, as the model does not determine their existence, therefore it is a constant value.

$$c_if_s = C_FS \cdot bs_s + C_VS \cdot capinvs_s \qquad \forall_{s \in S} \tag{3.24}$$

The annualized value of the fixed cost for all the installations *c_it* is described in equation (3.25), where *DR* represents the discount rate, and *PY* the years of the project lifetime to be considered. The second factor of the equation represents the installations total costs for the project life time. The first factor converts this value into an equivalent annualized value for every year, useful as the total yearly cost.

$$c_it = \frac{DR \cdot (1 + DR)^{PY}}{(1 + DR)^{PY} - 1} \cdot \sum_s cif_s \tag{3.25}$$

[15] As discussed earlier: are more jobs better or worse? Under one perspective more is *better*, as more jobs help decrease unemployment. However, according to the perspective, if those jobs have bad salaries and working conditions, fewer jobs may be preferable. This is a complex debate.

Biomass acquisition function (c_ba): the cost of biomass acquisitions (harvest and purchase) is calculated on equation (3.26) with the parameter *CPBH*, which is the harvest and acquisition cost of the biomass type b at the harvest site h, at the period t.

$$c_ba = \sum_{b}\sum_{h}\sum_{t} CPBH_{b,h,t} \cdot harv_{b,h,t} \tag{3.26}$$

Biomass transport cost function (c_bt): this component includes the fixed and variable cost related to the biomass transport cost. In equation (3.27), *TFCM* is the transport fixed cost, and *TVCM* is the related variable cost of using medium m for every unit of transported biomass b. The parameter *DHS* represents the distance between the harvest site i and the storage site j, *DHP* the distance between the harvest site h and the power plant p, and *DSP* the distance between the storage site s and the power plant p.

$$\begin{aligned} c_bt = &\sum_{b}\sum_{h}\sum_{s}\sum_{m}\sum_{t}\left(TFCM_{b,m} + TVCM_{b,m} \cdot DHS_{h,s,m,t}\right) \cdot shiphs_{m,b,t,h,s} + \\ &\sum_{b}\sum_{h}\sum_{p}\sum_{m}\sum_{t}\left(TFCM_{b,m} + TVCM_{b,m} \cdot DHP_{h,p,m,t}\right) \cdot shiphp_{m,b,t,h,p} + \\ &\sum_{b}\sum_{s}\sum_{p}\sum_{m}\sum_{t}\left(TFCM_{b,m} + TVCM_{b,m} \cdot DSP_{s,p,m,t}\right) \cdot shipsp_{m,b,t,s,p} \end{aligned} \tag{3.27}$$

Biomass storage cost function (c_bs): the biomass inventory cost in storage facilities and in power plants is addressed with equation (3.28).

$$c_bs = \sum_{b}\sum_{s}\sum_{t} CIUS_{b,s} \cdot invs_{b,s,t} + \sum_{b}\sum_{p}\sum_{t} CIUP_{b,p} \cdot invp_{b,p,t} \tag{3.28}$$

Power plant operational cost function (c_pp): equation (3.29) sums the variable costs associated with the use of the different types of available biomass. *CBCV* is the variable cost of converting biomass b at power plant p.

$$c_pp = \sum_{b}\sum_{p}\sum_{t} CBCV_{b,p} \cdot usedbp_{b,p,t} \tag{3.29}$$

Power plant credit for bi-products (c_bp): credits for every by product generated for the conversion of every type of biomass are considered in equation (3.30). *CBP* is the number of credits for the by-product i created by the process related to biomass b.

$$c_bp = \sum_{p}\sum_{b}\sum_{i}\sum_{t} CBP_{i,b} \cdot usedbp_{b,p,t} \tag{3.30}$$

Power plant credit for renewable energy (c_re): if there are any incentives for the amount of renewable energy generated in the power plants, they can be included in equation (3.31). The parameter *CRE* represents the amount of credits, which can vary in every period.

$$c_re = \sum_{t}\sum_{p} CRE_{p,t} \cdot en_{p,t} \tag{3.31}$$

3.11.3.3 Environmental objective functions

The environmental objective is to minimize negative environmental impacts that result from the decisions of the considered transport plan. By using an LCIA approach to measure the impacts, it is easier to notice that it is impossible to consider all possible impacts under one mathematical function, unless compromises are made. It is not possible to sum CO_2-equivalent GHG emissions with PM values, as they measure the impacts with different units. As a unit dimension problem, it could be solved by using an arbitrary conversion factor, but that requires consensus among all stakeholders to avoid low acceptance among some of them. To keep the calculations transparent, for every impact category of environmental emissions, a specific objective function is considered. Not every existing impact categories is interesting for every real world scenario. For many, it may be very hard or expensive to measure/collect the needed data. Nevertheless, the architecture is designed to be flexible enough to consider all the needed points (see figure 3.9 for examples), whether the case has access to the required data, and find them relevant to their decision making process.

As addressed in section 3.11.3.1, a priority based approach for the objective functions is used. This requires to choosing priority values for every selected impact category. It is a reasonably conservative approach to choose the same priority to all categories. For real world cases, stakeholders involvement should help find agreement about priorities.
For a non expert stakeholders group, endpoint categories are recommended, as concluded by [BHP00].

The emissions for every impact category follow the same structure. This structure will be described in detail in the next equations where it is repeated for every impact category e from the set E.

OF: total annualized emissions for an impact category (e_tap_e): these objective functions sum the considered impact category e emissions for the transport plan and are presented in equations (3.32). e_tap is the total annualized emissions for the category e.

$$\min\ e_tap_e = e_bh_e + e_bt_e + e_bs_e + e_pp_e \qquad \forall_{e \in E} \tag{3.32}$$

Emissions from biomass acquisition (e_bh_e): the emissions associated with the harvest and acquisition of biomass are considered in equation (3.33). *EBHV* are the impact category e emissions related to the acquisition of biomass b at the harvest site h.

$$e_bh_e = \sum_b \sum_h \sum_t EBHV_{e,b,h} \cdot harv_{b,h,t} \qquad \forall_{e \in E} \tag{3.33}$$

Emissions from biomass transport (e_bt_e): the emissions for the use of the available transport mediums is considered in equation (3.34). *ETBU* are the impact category e emissions for the transport of a unit of biomass b using transport option m.

$$\begin{aligned} e_bt_e = & \sum_b \sum_h \sum_s \sum_m \sum_t ETBU_{e,b,m} \cdot DHS_{h,s,m} \cdot shiphs_{m,b,t,h,s} + \\ & \sum_b \sum_h \sum_p \sum_m \sum_t ETBU_{e,b,m} \cdot DHP_{h,p,m} \cdot shiphp_{m,b,t,h,p} + \\ & \sum_b \sum_s \sum_p \sum_m \sum_t ETBU_{e,b,m} \cdot DSP_{s,p,m} \cdot shipsp_{m,b,t,s,p} \qquad \forall_{e \in E} \end{aligned} \tag{3.34}$$

Emissions from biomass storage (e_bs_e): storage emissions of biomass in storage locations and power plants are calculated using equation (3.35). *ESBU* are the emissions for a unit of biomass b storage, for one period, for the e impact category.

$$e_bs_e = \sum_b \sum_s \sum_t ESBU_{e,b} \cdot invs_{b,s,t} + \sum_b \sum_p \sum_t ESBU_{e,b} \cdot invp_{b,p,t} \qquad \forall_{e \in E} \tag{3.35}$$

Emissions from power plant processes (e_pp_e): equation (3.36) includes the emissions related to the biomass to energy conversion processes. The parameter *EPVC* consist of the emissions produced by the processes of the biomass b to the energy conversion process at the power plant p.

$$e_pp_e = \sum_b \sum_p \sum_t EPCV_{e,b,p} \cdot usedbp_{b,p,t} \qquad \forall_{e \in E} \tag{3.36}$$

The parameter values to calculate these emissions are an output of the LCIA module (see section 3.10).

3.11.3.4 Social objectives functions

Optimization functions for social variables are no trivial task.
Data collection for social variables can lead to loss of information do to the translation to a mathematical environment. When using widely used scales like the ones described by [Ste46] to quantify qualitative data, this type of data is usually assigned to nominal or ordinal ones, which restrict the available mathematical tools that can be used[16].

Beside the quantification of the data, there is also the comparison issue that mathematical optimization requires.
Mathematical optimization relies on a numerical way to tell if one solution is better than another, by comparing numerical values.
For a useful optimization, the mathematical model needs to be able to distinguish whether a given objective function value is *better* or *worse* than another. For social variables, it is hard to tell with complete confidence for all involved stakeholders. A variable value increase may be positive from a social point of view for one group, but the same change may be negative for another. Such situations makes them very hard to compare from a mathematical optimization point of view.
For example, the quantification of *number of new available works* is a common considered social parameter. It is commonly assumed that an increase in this number always results in a positive outcome for the solution under this dimension. But under a closer inspection, not all job salaries and conditions are equal. Therefore, a bigger number could result in more underpaid jobs, which could result in a *lower* social condition. And these types of judgements can grow complex fast. Even the answer to the question: *what is a good payment for a specific job?* is not always straight forward for every stakeholder to answer, as the discussion could even end in a national critique about equality.
This opens the discussion about whether there is indeed a way to mathematically compare two solutions that consider qualitative data, and even if it is a reasonable idea to include them as an optimization objective.
It is also not viable to use a decision method to choose the best decision method, as a paradox is always reached, which makes any attempt to use this path to be of limited success [TM89].

For this reason, as commented in section 3.11.3.1, the mathematical optimization module does calculate a numerical impact for qualitative variables, but it does not maximize of minimize it, providing a way to understand the effects that will appear for a given solution. This allows decision makers to consider them as useful information in the final solution to be implemented (after the analysis of the results of the model), in order to complement the expert judgement from a social point of view. Of course, if there are stakeholders agreements about the maximization or minimization of one variable, that can be included, but extreme caution is recommended.

The optimization model calculates social indicators, derived from the social concerns of the specific stakeholders, but it does not implement them as objective criteria in the optimization. If a goal or restriction was quantifiable in the third step of the social module analysis (see section 3.7), it will be added as an equation to the constraints group of the model. For the case that stakeholders agree about the importance of some quantifiable social impact categories, they can be implemented as regular objective functions and influence the model, as commented in section 3.11.3.1.

This approach is novel, as it doesn't proposes optimization, but instead creating awareness about relevant social impacts, of the different possible solutions. The chance to add constraints to the model also allows for trying different social scenarios (like forcing the solution to have a specific range of human working hours, or limit the traffic in a specific perimeter), which makes this an interesting approach for providing more information to decision makers.

[16] From a statistical point of view, nominal scales only allow the use of the *mode* to calculate the central tendency, where for ordinal scales the *mode* and the *median* are the only options. The *average* value makes no sense for these type of scales.

4 Implementation concept for a regional supply chain optimization

This chapter describes the proposed software architecture for a concrete implementation of the model described in chapter 3. The architecture integrates different technologies to acquire data to a common data model and provides a framework for the modules to generate the results using a client-server approach.

4.1 Introduction

It is not always possible to implement and use the *perfect* model for a given problem in a real life context. Data must be gathered and processed, calculations must be made, and results must be interpreted usually within short time limits. Common challenges are: data that cannot be gathered fast enough, several data formats that need to be made compatible, and time limits for model calculations lower than a couple of minutes (or seconds), among others.

Computer software can be defined as *a model implementation, suitable for a specific type of users*. From a mathematical model perspective, a software needs to implement all the mathematical calculations that a given model considers, in an efficient way that makes the software useful for the user. Data management is another important task of software. It considers the way to acquire the data using either automatic programmed procedures, or by using ad-hoc input methods for the user and the structure to store them.
Software also allows the input of data and its validation in a standard way, usually considering the user access to it. Data output should also be in a format that the target user can understand and use to support her/his decisions.

The software architecture is the design of the different parts and relationships that provide the software the expected functionality and features.
Based on the model presented on chapter 3, the model architecture on figure 3.5 is further developed. Two new layers are presented based on this model, in order to describe the modules from a user and a technological perspective. The first one gives an idea about the user interaction, and the second one of the technologies chosen for a concrete implementation of the architecture.

4.2 The user perspective layer

The *user perspective* aims to describe the model in term of the user requirements and expectations. Figure 4.1 displays graphically a one to one relationship between the model modules and the interaction with the user.

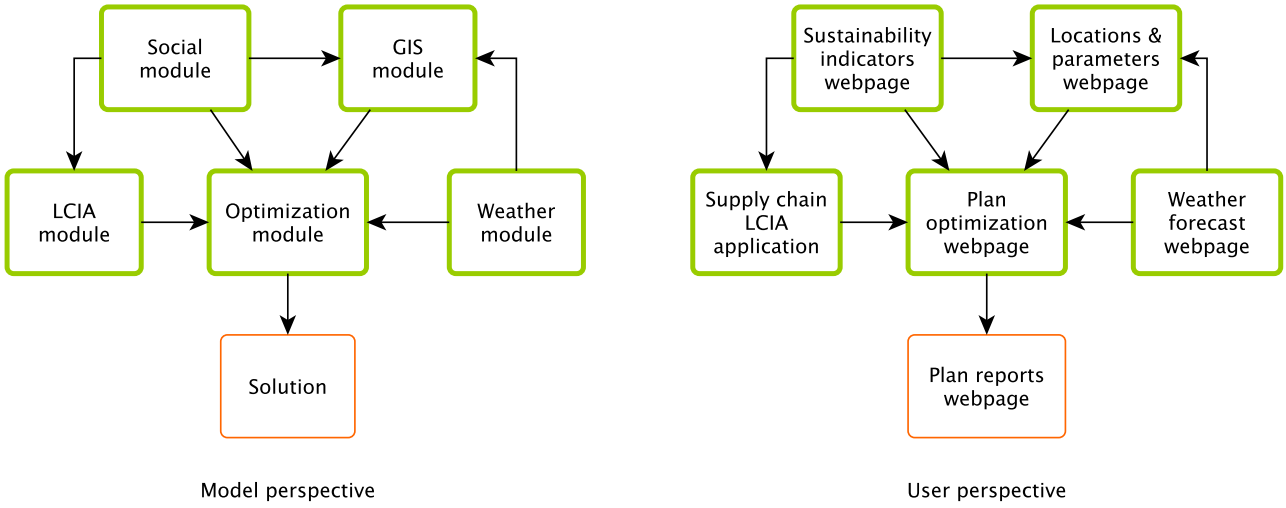

Figure 4.1.: Software architecture layers side by side: the model and the user perspectives.

Every actor relevant to the system has a specific list of requirements, expects results delivered in a specified format in a reasonable time frame, and interacts with the system using an ad-hoc user interface.

Most of the interactive elements of the user interface are web based ones, as they provide several advantages in terms of simplifying the interface with the use of common tools like web browsers and smartphones. The client-server approach also allows centralizing the mathematical calculations with specific hardware (servers), lowering the user computer requirements (clients) and simplifying system updates (as everything resides just on the servers).
To design the proper user interface for the users, they need to be identified, and their requirements and expectations need to be modeled.

4.2.1 User interface: Sustainability indicators web page

Relates to the social module (see section 3.7).
The sustainability indicators user interface has a complex work, since the ways of the possible solutions and integrations of this module can vary a lot from implementation to implementation, as they depend on specific stakeholder interests. For this reason, this user interface *web page* acts as a summary of the results of the tasks done in relationship to the social module. This interface allows entering social concerns to the system administration, but the model needs expert intervention to add them, as there is no automatic system for either: judging qualitative ideas as relevant to the solution or an easy system to implement every possible variation. The incorporation of these concerns is done *behind the scenes* by the team that executes the needed tasks, usually at the first steps of the system implementation. For example, the page could declare the quantification of *new jobs* by the model, but also that the model does not try to maximize this value. This modification to the model would have been done during the first implementation stages of these module tasks.
Other information relates to the interpretation of the solution data. For example, the page could declare that the output *amount of straw that would have been burned in open fires* only refers to the savings of the used straw by the considered system, and does not consider other region initiatives to reduce it.
In summary, this user interface communicates the relevant social considerations of the concrete implementation to the end user.

4.2.2 User interface: Weather forecast web page

Relates to the weather module (see section 3.8).
This user interface provides a way to update the short term (e.g. next 14 days) and the long term weather forecasts for the season.The required data can be either added manually to this web page, or be imported from an available web service. Examples of such services that include an application programming interface (API) to allow an automatic data update are: OpenWeatherMap[1], Weatherbit[2], Weather2020[3], World Weather Online[4], or Meteored[5].

The effects of the weather forecasts possibilities should be categorized.
For every defined weather forecast category, specific GIS data should be made available to the model. For example for the effect on routes can be that for the category 'heavy rain' a specific GIS roads file should exclude unavailable routes for that condition. An example for the effect on demand is that for *dry seasons*, the power plants demand will be the full plants capacity, but for *rainy seasons*, it should be lower for specific months of the year. The route changes must be made using GIS software like QGIS[6].
These weather category effects allow a quick choice (either manual or automatic) for changes related to the expected weather conditions. This approach requires an initial setup to generate all available routes and related features configurations for the defined conditions, and for the effects of the long term forecasts on the electricity demands.
After the setup is done, the optimization module can automate the selection, based on the available forecast information.

4.2.3 User interface: Locations & parameters web page

Relates to the GIS module (see section 3.9).
The location information is managed by the Locations & parameters web page. This front end offers a graphical user interface to add the listed data relevant for the power plant planner. The location of the biomass sources and power plants is made graphically using a map. At the same time, the characteristics of these two types of elements can be added and updated. Information about other elements and resources are added using tables. A Graphical user interface (GUI) example for this interaction can be seen in appendix I.

1 https://openweathermap.org/api
2 https://www.weatherbit.io
3 http://api.weather2020.com
4 https://www.worldweatheronline.com/developer/api
5 https://www.meteored.cl/api
6 https://qgis.org/en/site/

The main actors need to be able to input the following data:

1. for each biomass type, create and edit the location and characteristics of the biomass sources
2. specify the location and characteristics of power plants
3. indicate the available transport options and the compatibility with the available biomass types
4. the energy demand that the power plants should generate for specific periods
5. availability of other resources needed for the operation

The advantage of this approach is that it allows every biomass producer the option to *add and modify* the biomass availability and characteristics of their business. This simplifies the update of the data, as the people interested in selling it can made their offer available, and the ones with medium to long term contracts can update the specific availability dates. This is useful, as biological raw materials may need changes in availability dates and quantities, as they depend on biological systems, not machines.

4.2.4 User interface: Supply chain emissions application

Relates to the LCIA module (see section 3.10).
The supply chain emissions application is used to load the emissions information for the different processes of the supply chain. Because of the potential big amount of information from the LCIA, the use of a LCA software was chosen (e.g. openLCA). This approach allows the use of mature and familiar software, and direct use of third party databases, like ecoinvent. Local data can also be included with these software interfaces, and the calculations for midpoint and endpoint indicators is also easy to do, as well as export in a common file format (like a spreadsheet, or a text file with comma separated values (CSV). The specific (exported) impact assessment results are then used to update the systems database, by either direct access to the database or by using a web interface.
This approach allows current LCA experts to easily generate usable data for the model, as they can use their regular LCA software to process and update the modules data.

4.2.5 User interface: Plan optimization web page

Relates to the optimization module (see section 3.11).
This user interface allows the parametrization of the optimization (a complete list of parameters is included in appendix A), and to start the generation of a solution. It integrates the information provided by the other modules and provides a solution to the user. The solution relevant data is presented here. An example of this data is available in the case study in chapter 5.2.3. The shape of this interface also needs to be customized for the specific users, as their knowledge level about the problem can vary. Advanced users may feel comfortable interpreting the values of the model *slack variables*, but others may prefer to just look at a more simple solution overview.
The generation of solution reports resides also in this interface, thus providing a way to output the solution data in a document (or a series of documents) that can be directly used by the different stakeholders. The reports should be custom made for the concrete users, as the best way to support their decisions is to create documents as similar as possible to the ones they used before the system implementation.

4.3 The technology perspective layer

This section explains more detail about the technologies used for the software implementation of the model.
Specific technologies support the modules functionality. In summary, the interaction between users is made using a website, with specific web pages for every module. The website allows the users to input required data and parameters, and it gives the results as web page summaries or detailed reports. Technical configurations for GIS and LCIA data are made using specific software. A relational database contains the system data model described in section 3.3, which allows data exchange between the modules.
Figure 4.2 gives a graphical overview of the used technologies and the interaction between the system modules.

4.3.1 Technology: Sustainability indicators web page

This page is used as a visualization of the result of the tasks of the social module. It also explains correct ways to interpret the social parameters from the solution reports. All modules rely on the use of NGINX[7] web server software to

[7] https://www.nginx.com/

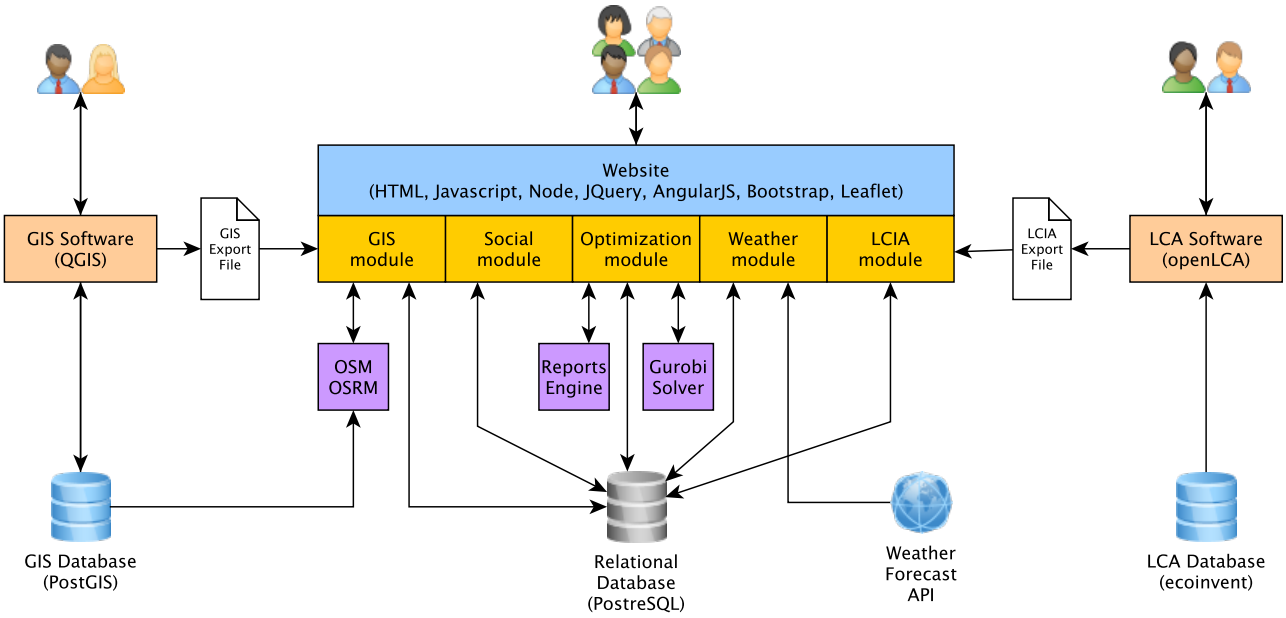

Figure 4.2.: The relationships between the modules and the technologies used for the implementation.

serve Hypertext Markup Language (HTML) pages (Apache[8] is another good alternative too). The dynamic functionality is provided with Javascript and Node[9] libraries like JQuery[10] and Bootstrap[11].

4.3.2 Technology: Weather forecast

The weather forecast web page is based on HTML and Javascript for the visualization and data input. The dynamic functionality is provided with Javascript and Node like for the *Locations & parameters* description on section 4.3.3. The internal database updates are made using php[12] server code, which needs to connect to the weather forecasts APIs like: Meteored[13], OpenWeatherMap[14], Weatherbit[15], Weather2020[16], or World Weather Online[17].

4.3.3 Technology: Locations & parameters

The core of the data served by this module is divided on a GIS database provided by PostGIS[18], as well as a relational database with the no-location-referenced data, using a PostgreSQL[19] database. The dynamic functionality is provided with Javascript and Node, with the addition of AngularJS[20] and Leaflet[21]. The combination of these libraries allow the interaction with the Open Street Map (OSM) tile server, which provides the interactive map images. To calculate and show the optimized routes between two locations, a routing service based on Open Source Routing Machine (OSRM)[22] is used.

8 https://httpd.apache.org
9 https://nodejs.org
10 https://jquery.com
11 http://www.getbootstrap.com
12 https://secure.php.net/
13 https://www.meteored.cl/api
14 https://openweathermap.org/api
15 https://www.weatherbit.io
16 http://api.weather2020.com
17 https://www.worldweatheronline.com/developer/api
18 http://postgis.net
19 http://www.postgresql.org
20 https://angularjs.org
21 http://leafletjs.com
22 http://project-osrm.org

The installation details of the OSM tile server and the OSRM routing service is included in appendix J.

4.3.4 Technology: Supply chain emissions application

The emissions input application uses openLCA[23] as a graphical front end. openLCA is an open source Java based LCA software that is gaining popularity, as its features allows it to calculate full LCIA (needed for this work), and it is compatible with common databases like ecoinvent version 2 and 3. It also allows for modifying the processes and including primary data by updating coefficients with local values. The specific data is exported from the LCA software and uploaded through a web page form that adds the updated data to the relational database using php server code. The impact output is delivered through the optimization module which performs the last step of the LCIA impact calculations (see section 3.10).

4.3.5 Technology: Plan optimization web page

The plan optimization web pages use the same web server, complemented with a Java web service application to prepare the data and initiate the optimization. This application loads the data from all the other input modules, integrates them into a concrete problem with specific defined optimization parameters, and starts the solution generation. This process includes the generation of a concrete mathematical optimization model, which must be created for a specific solver language like Gurobi[24] or CPlex[25]. For the proposed implementation, the solver Gurobi was installed in the server that was invoked by the web service to solve the model instances. The solver results are then mapped by the web application to the system's internal database. This result is the source data needed for the *reports engine*. The reports need to be custom designed for the specific users, and engines like BIRT[26] can help this customization.

4.4 Proposed regional implementation

Either the *power plant manager* or the *government/community* actors are considered users.

The power plant specific approach is a simpler one, as it involves a smaller problem (with less variables), and it can be used inside a company controlled environment. Investments and objectives can be done and decide with flexibility and provide measurable benefits for the company, as the solution is modeled according company interests.

The community approach is a novel one. There are platforms that provide shared information to an industry in order to increase the general competitiveness of it in relation to other markets, but they don't usually incorporate a *regional optimized solution* for the group to evaluate and discuss. Even more rare would be the inclusion of sustainability considerations. It is a big challenge to implement such a solution, but one particular advantage encourages it. There is usually very low motivation to optimize operations besides the costs functions, specially in developing countries. The proposed way to present the solution, as an integrated regional one, can increase the community awareness about the benefits to the region of a coordinated solution against the individual personal interests. For example, the regional optimized solution (with this system known to everybody) can show the relevance of one power plant to buy biomass from one specific harvest site. But if the power plant decides to buy biomass from another location, the harvest site owner could refuse to sell biomass to the power plant, as they would have a way to check if the transaction is *a good one* for the region, or not.

An alternative to this approach is the option for the stakeholders to decide to choose a reasonable *good choice* for them, for example, after group negotiations. An automated system like this can still provide with benefits such as consolidation of the data related to the problem, validation of errors in calculations, and the chance to use it as a communication tool. And this is beside the option to provide with optimized scenarios (probably the most important feature). It could also reach a broader audience, as an automated system can communicate the data and solutions in the moment they are generated using common Internet tools, and even allow the community user interaction (like tools for easily browsing the solution that allow users to add comments, or the option to edit data like biomass availability, etc.).

This is a very complex concept to implement in reality, but it could turn into an interesting outlook for this work if business culture changes from an individual to a regional emphasis. More in section 6.2.

[23] http://www.openlca.org
[24] http://www.gurobi.com
[25] https://www.ibm.com/analytics/cplex-optimizer
[26] Business Intelligence and Reporting Tools. https://www.eclipse.org/birt/

A DSS implemented like this could provide with:

- Transparency: everybody can know the choices each actors should make in order to have a regional optimum solution. This gives pressure to the actors to follow the plan, as is going to be clear to the buyer/seller of e.g. biomass if someone does not follow it. Not following the solution may improve the personal solution in some way, but at the expense of a worse solution for the region (hence the optimality of it).
- Impact assessment: the effects of not following the recommendation of optimal solution can be calculated and show in terms of all the considered impacts (economic, ecologic and social dimensions). This allows flexibility to consider simulation scenarios and provides a tool for industry unions to improve the group, with sustainability in focus.

5 Case study

In this section, a summary of an implementation of the proposed model in a case study is presented. First the objective, relevance and general context is described. Then the proposed methodology is followed for the case study and the specific model is generated. Next the data set elements are commented. Finally the optimization results give insight about the benefits of multidimensional optimization for this case study.

5.1 Case study description: biomass power plant in Chile

5.1.1 Objectives for the case study

A case study about a biomass electricity generation in the Araucanía region in Chile is presented. This case provides an empirical way to detail the functionality of the proposed model, and gives good insights about benefits in a real world situation.

The main advantages of including a case study in this research are two: first, the possibility of interacting with the details of a real problem, asking direct questions to relevant stakeholders, and getting expert advice about assumptions. Second, the case study allows for testing the system with real life considerations and the opportunity to check how the solution fits the problem.

The selected case study is relevant for the model for the following reasons:

- The power plants of the case study can generate more than 20MW electric of pure biomass power each. Therefore they require an important amount of biomass transportation.
- There are several types of available biomass types in the surrounding territory.
- There is high uncertainty in the biomass availability. This uncertainty translates into high levels of safety stocks at the plant, and the potential need to update the transport plan frequently.
- Long term weather conditions related to ENSO affect the region. This allow the potential inclusion of this factor in the long term electricity demand forecasts.
- There is interest from the company that owns the power plants from the case study to use a system that can provide the functionality this model considers. They are interested in the economic objective in the short term, and eventually wish to include environmental and social impacts into their decision criteria.

The proposed model supports tactical decisions, and should run in a regular basis to update the data to the current conditions, availability, and other time dependent parameters (summary in figure 3.4).

5.1.2 Chilean energy context

Chile is a 4300 km long and narrow[1] country with a population estimated on 18 millions inhabitants[2]. To supply electricity to the entire population, four independent electricity systems coexisted (before 2017).

1. *Norte-Grande* Interconnected System: (SING *Sistema Interconectado del Norte Grande*) serves the three northernmost regions of Chile (I, II (north and center area) and XV).

2. Central Interconnected System: (SIC, *Sistema Interconectado Central*) serves the 10 central regions of the country (from II (south area) to X plus XIV and RM).

3. *Aysén* System: (SEA, *Sistema Eléctrico Aysén*) serves the XI Region.

4. *Magallanes* System: (SEM, *Sistema Eléctrico Magallanes*) serves the most southerly XII Region.

The regional locations are shown in figure 5.1[3]. Physical restrictions, like long distances and geographic elements, as well as geographic demand distribution makes the integration of the four systems difficult.

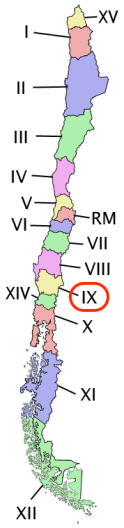

Figure 5.1.: Regions of Chile.

The table on figure 5.2 shows a summary of the capacities and the generation mix for every one of the energy systems. Biomass share was 3% of the installed capacity of the SIC in 2015.
Effective generation by source can be seen in the figure 5.3. Biomass share was 5% of the effective generation of the SIC in June 2015.
The case study selected is located in the *Región de la Araucanía* IX region, which is served by the SIC. The complete SIC infrastructure can be seen as a figure in appendix B.
This scenario did change by the end of 2017, when the two most important systems were connected (SING and SIC) with a 600[km], 2 x 500[kV] transmission line.

The Araucanía Region is one of the poorest regions in Chile with an unemployment rate of 13%[4]. Before 2010, it had around 35000 inhabitants without big electricity generation projects. The region imports almost all of its electricity requirements. It is a biomass rich area, with 7777 companies related to agriculture, hunting, and forestry[5].
This scenario was favorable for the building of a biomass based thermo-electrical power plant in the center of the region, near the city of Lautaro in January 2010. The operation started in august 2011.
A map of the region can be seen in appendix C, figure C.1.

5.1.3 Specific supply chain description

The specific power plants to be analyzed are the ones owned by Comasa S.A. Both plants are located together in the center of the Araucanía region, near the city of Lautaro[6]. Both use 100% biomass fuel to generate exclusively electricity and are directly connected to the SIC distribution lines. Comasa 1 has a capacity to generate 26 MW-electric and started its operation in August 2011, and can be feed with many types of forest biomass. Comasa 2 has a capacity of 22MW-electric and began its operation in April 2014. This power plant is exclusively designed to burn straw.
The raw material processed is mostly straw, sawdust, wood chips, grain husk, bark, and discarded wood. All are bought from more than 200 suppliers before being transported to the power plants inventory, just meters away from the power plants. The transport is made either directly by the biomass suppliers or by a third party transport company. This decision depends on the agreed purchase contract, as they can either negotiate an *in plant* or *pickup* price.
The case study biomass supply chain is very similar to the general processes described in figure 3.1. The main difference is that the case study only includes inventories of biomass close to the power plants, which eliminates the flows to and from the storage locations to the transport process, as all the biomass from storage is delivered to the energy conversion process directly.

1 At the widest point east to west its 350 km long.
2 Source: Resultados Definitivos CENSO 2017. National Statistics Institute (INE): http://www.censo2017.cl
3 The name order is not consecutive, because some regions were added years after the first regions were defined.
4 Source: Encuesta de Caracterización Socioeconómica Nacional (CASEN) 2009, Ministerio de Desarrollo Social, Chile.
5 Source: Servicio de Impuestos Internos (SII) 2010, Chile.
6 Address: Ruta 5 sur, kilómetro 645; camino a Colonia, kilómetro 1

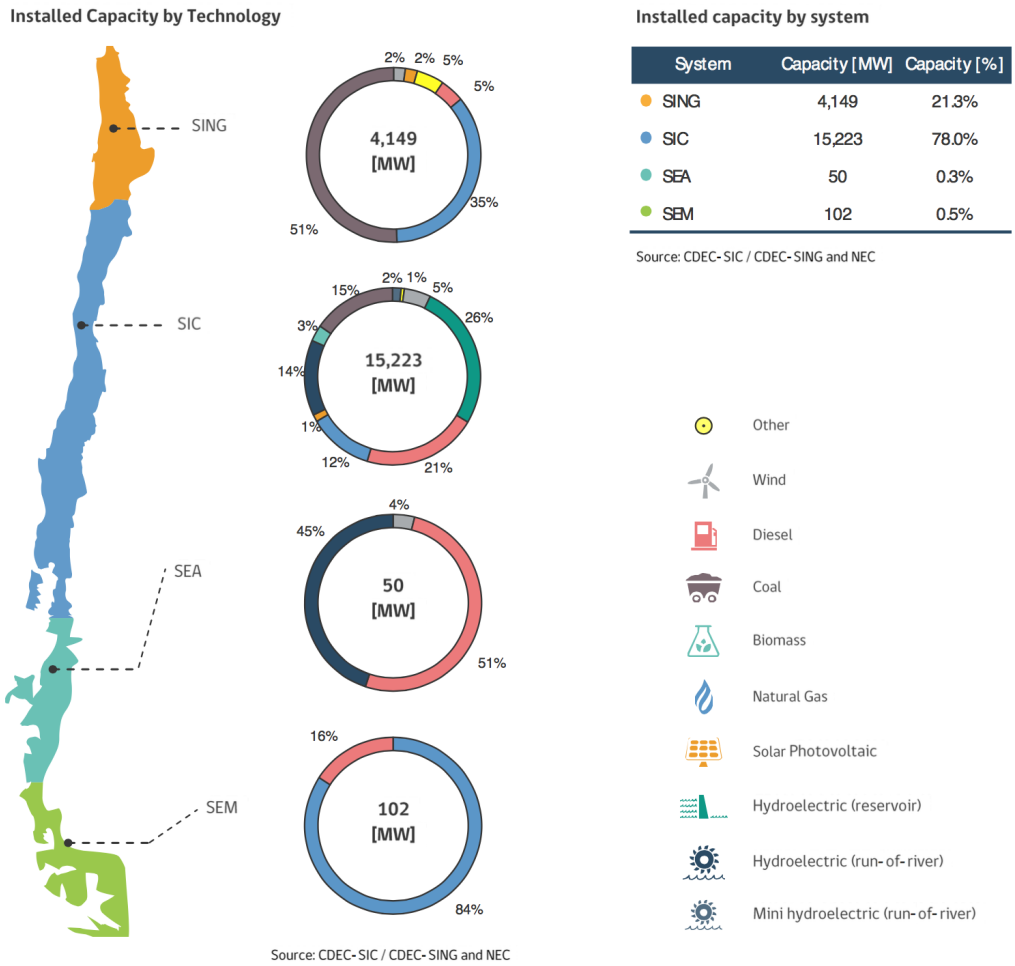

Figure 5.2.: Installed electric generation capacity for SIC and SING (CNE, 2015).

Figure 5.4 shows a simple schematic of the general power plant elements, and figure 5.5 shows a diagram of the main flows. Photos of the real facilities are included in appendix F.
Direct firing burns the biomass fuel with excess air inside an incinerator to generate heat. The main products of the process are heat, which is used to generate electricity, air emissions (like carbon dioxide and many others), and ash. A coupled boiler transfers the generated heat to a water stream to generate vapor. This vapor is used to feed a steam turbine connected to a generator to produce electricity. The electricity then feeds the grid through a transformer.

5.1.4 Biomass characteristics

The power plants from the case study use only second generation biomass, mainly forest and agriculture residues for the energy conversion process. This avoids the *biomass for food or fuel* dilemma. The power plant *Comasa 1* is designed to work with a mix of forest and agriculture biomass, with a humidity between 35% and 47%. The second power plant, *Comasa 2*, burns exclusively straw and husk with a humidity between 15% and 18%. Husk is mainly used to reach the required humidity levels of the mix for power plant 1, but it lowers the density of it. This makes the right mix of biomass types and amounts a relevant issue in order to reach and maintain optimal technical operational conditions.
Table 5.1 gives a general overview of the observed biomass characteristics of the different available options in the region that supply both plants. This information is calculated as the average of measured values of the biomass characteristics at the arrival to the plant storage on the transport trucks.
The biomass deterioration rate was estimated to be around 0,125%/week, similar to [YTGS11].
The biomass market for the raw materials used in the plant is currently in an early stage of development. About ten years ago, local sawmills had to pay a service to remove and dispose the sawdust. Now they are able to sell it and make profit from it, but there are doubts about committing to long term contracts, as there continues to be uncertainty about biomass prices in the future. This situation gives the market a high level of uncertainty about availability and prices, which turns into higher safety stocks inventory levels.

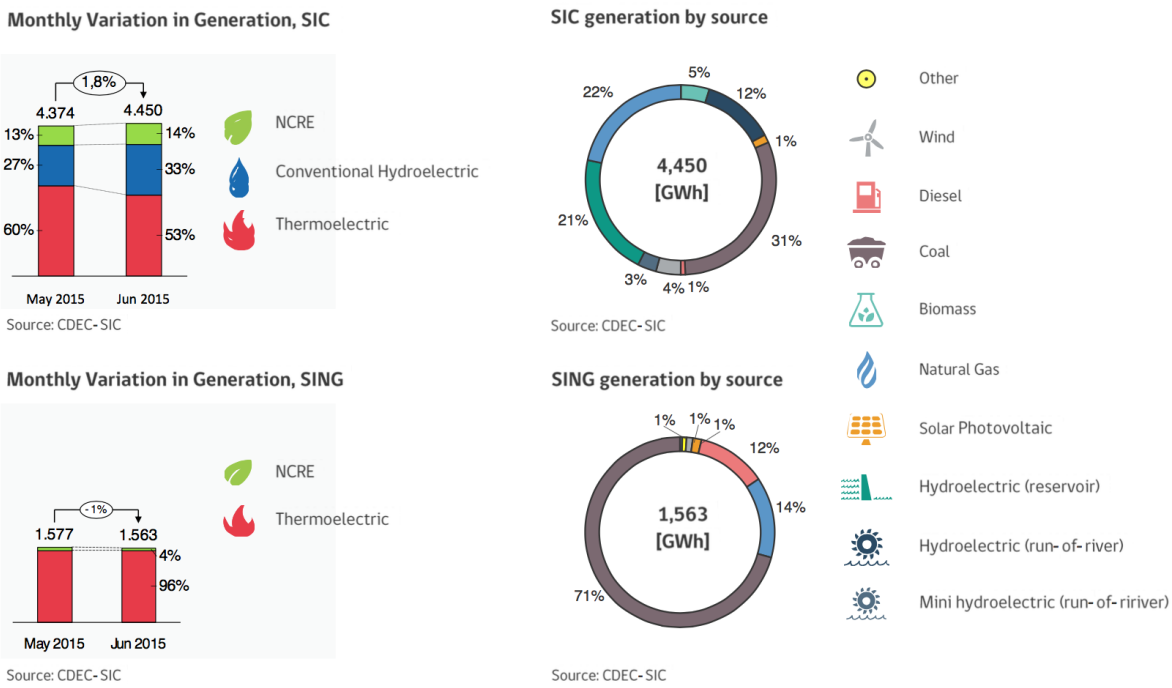

Figure 5.3.: Electric generation for SIC and SING (CNE, 2015).

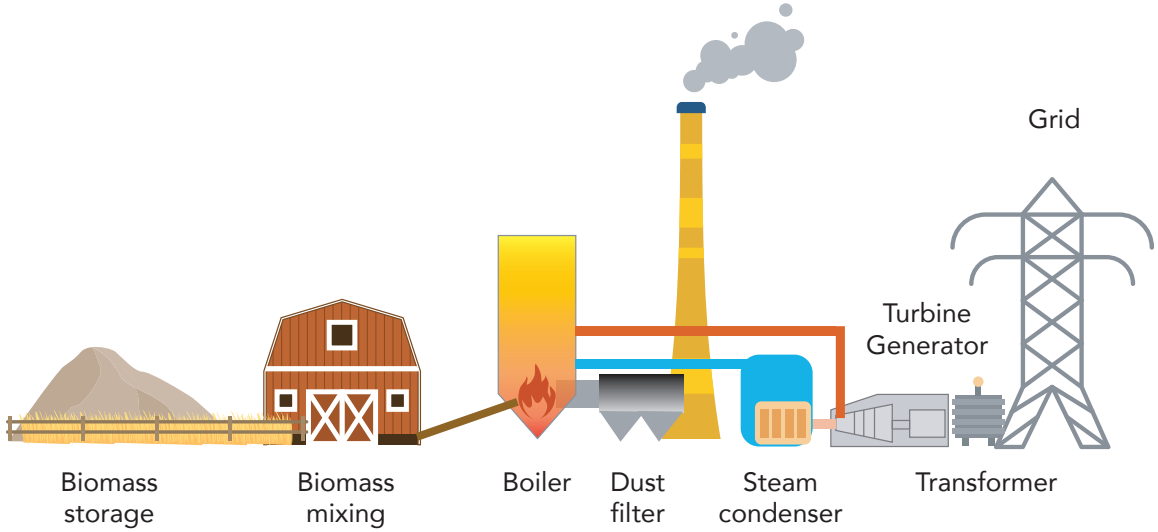

Figure 5.4.: Case study power plant basic elements. Flows from left to right.

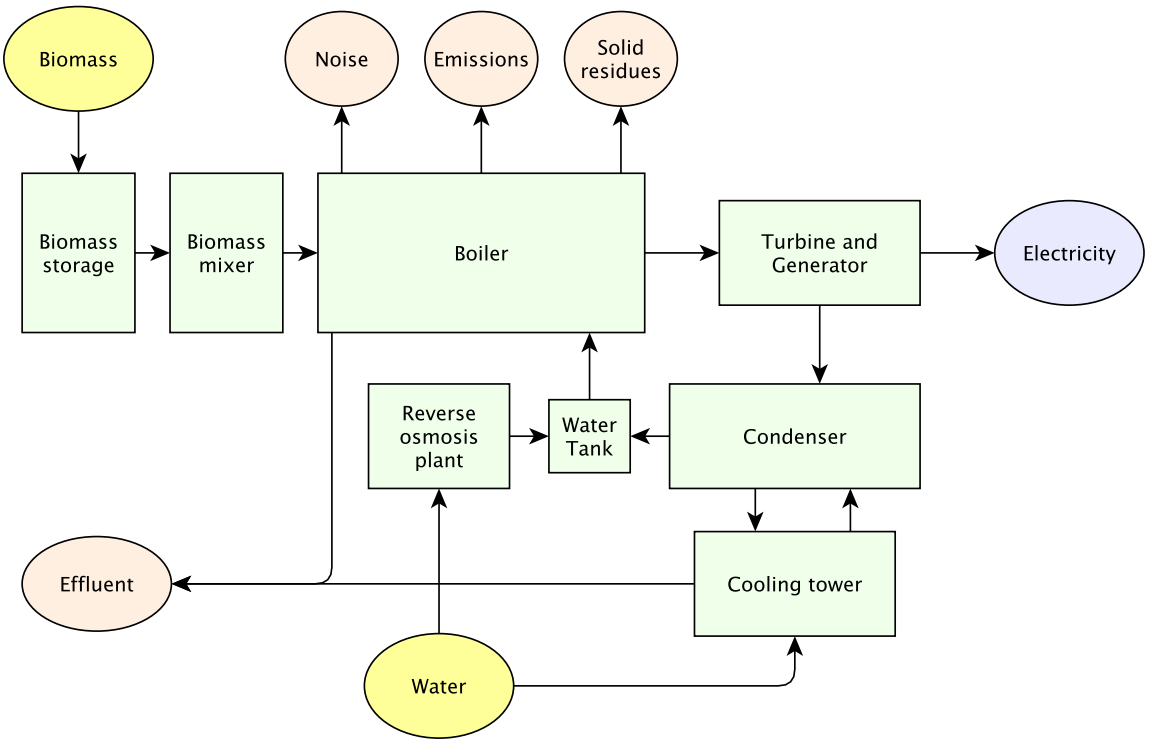

Figure 5.5.: Case study power plant main elements and flows between them.

Table 5.1.: Biomass characteristics for the case study.

Index	Biomass original name	Biomass name translation	Gross calorific value [kcal/kg]	Net calorific value [kcal/kg]	Humidity [%]	Density [kg/m3]
1	Aserrín	Sawdust	4600	1696	0,5564	349
2	Astilla	Splinter	4600	1949	0,5080	315
3	Corteza Pino	Pine bark	4600	1856	0,5257	376
4	Desecho de madera	Wastewood	4600	2662	0,3713	323
5	Viruta	Shaving	4600	3872	0,1395	140
6	Corteza eucaliptus	Eucalyptus bark	4600	2451	0,4117	210
7	Lampazo	Burdock	4600	2679	0,3681	274
8	Leña pino	Pine firewood	4600	2810	0,3430	287
9	Cascarilla	Husk	4100	3595	0,1071	238
10	Fardos	Straw bale	4600	3479	0,1127	166
11	Leña de Álamo	Poplar firewood	4600	1910	0,5154	287
12	Leña nativo	Native firewood	4600	3113	0,2849	341
13	Pinchip	Woodchips	4600	2065	0,4857	313
14	Otras	Others	4600	1809	0,5347	466

5.2 Case study model

To create the model for the case study, the tasks for every module described on chapter 3 need to be completed. The results of these steps are described in the following subsections from 5.2.1 to 5.2.5.

5.2.1 Case study: social module

For the social module, four tasks need to be completed (as described in section 3.7): 1) identify concerns, 2) search for relationships, 3) indicators for the mathematical model, and 4) correct results interpretation.

5.2.1.1 Identify relevant concern among stakeholders

The objective of this task is to explore the current relevant aspects of the electricity generation with biomass, among the stakeholders in the Araucanía region in Chile. This analysis aims to identify relevant social elements to be considered for this particular case. These elements may be based on the current case study, but they can still deliver a general insight about potential important matters for other cases.
The methodology used to obtain the information was a set of 10 moderated focus groups. There was intentionally no register made of the specific participants that attended the meetings, as their anonymity aimed to promote a free discussion. Additionally, 30 personal interviews were conducted in the downtown area of the city of Temuco to complement the answers. The study was done during may 2015 in Lautaro (the closes town near the power plants) and Temuco (the biggest city nearby).
The 10 focus groups included representatives from these stakeholders:

- Government representatives on energy and environment topics from the Araucanía region.
- Workers of electricity generation plants in the region. Different working levels were interviewed in different focus groups.
- Representatives of biomass transport companies.
- Local university investigators.
- Representatives of local citizens groups.

The specific meetings were:

1. Power plant: general management.
2. Power plant: operational workers (2 meetings).
3. Truck transport representatives: medium/big companies (with more than 10 trucks).
4. Truck transport representatives: small companies (with maximum of 3 trucks).
5. Biomass production: management (2 meetings).
6. Community groups, like *Amigos de la biblioteca de Lautaro*, with participation of several social leaders (2 meetings)
7. Government: Regional Environmental Department, *Seremi Medio Ambiente*.

The focus groups had an explorative objective and were moderated using open questions. The list of questions that the moderator used were:

- What is your opinion about electricity generation in the Araucanía region?
- What is your opinion about the use of biomass for electricity generation?
- Do you know the difference between a biomass and a coal thermoelectric power plant?
- Do you have other electricity generation preferences?
- What are your thoughts about the trade off industry growth versus respect for the environment?
- How do you evaluate the regional contamination level?
- Do you recognize different types of contamination and possible impacts?
- What have been the experience with the nearby biomass thermoelectric power plant?

Not all questions were needed in all meetings, but they were useful to guide the discussion to the topics of interest. The same questions were used for the personal interviews.

A summary of the results was categorized in positive observations, negative observations, no-consensus observations, and recommendations. A copy of the original document sent to the participants with a summary of the conclusions is included in appendix G (in Spanish).

Positive observations

- Economic: generation of direct and indirect local workplaces.
- Economic: potential to take advantage of wasted agricultural resources, especially straw.
- Environmental: reduction of burning straw in open fields with the associated environmental problems (mainly fine dust) and dangers of open fires. The possibility for power plants to use this waste as raw material prevents these hazards and increases the resources efficiency by giving a value to waste.
- Social: certain level of regional independence from electricity imports because of the local generation. Natural catastrophes like earthquakes are common in Chile and they can cause electrical distribution problems.

Negative observations

- Social: straw leftovers on streets and highways because of the increased amount of trucks transporting it through specific locations, and of the difficulty of perfectly installing protection covers to avoid leaks.
- Environmental: concerns about possible fire accidents in big biomass storage locations.

No-consensus observations

- Environmental: there was not consensus if biomass based power plants do considerably increase the local pollution.
- Social: for the particular case of the power plant *Comasa*: there exist complaints about noise perceived during the night in a town nearby that are associated to the plant. It does not seem to be about whether it is the plant or another source.

Recommendations

- Include public participation from the first planning stages of new power plant projects.
- Deliver public information about the emissions produced by power plants.
- Inform local groups about the environmental benefits of electricity generation in a power plant using renewable fuels like biomass, compared with fossil fuels like coal.
- Locate power plants outside of valleys that could trap the emissions.
- Evaluate projects of district heating coupled with electricity generation, because of the important concern about the environmental pollution associated with burning wood for heating (specially fine dust).

The summary of the results of this task is:

1. There was a better understanding of the role of the different groups of actors.
2. It started new discussions about the sustainability interests of the groups, and provided them with general information about the biomass power plants and this work's objectives.
3. The identification of the aligned, not-aligned and non-consensus objectives.
4. The collection of recommendations from the groups that belong and relate to the supply chain.

These results also improved the information about biomass energy production among stakeholders:

1. Better information to the groups about the project and the possibility of participating at some level in the development.
2. Gain acceptance about the electricity production with biomass technology in the groups, with the intention of providing real world data to validate the results in the future.
3. Discussion about model optimization objectives and their alignment with groups specific problems for the specific case study.

5.2.1.2 Relationships with solution elements

Among all identified concerns, there were some relationships with the model. These are discussed in this subsection.

- Available workplaces: there was an interest in quantifying the impact on direct and indirect jobs that the power plants have in the region. This could be partially implemented in the model with the assignation of human hours to specific processes, like truck transport, power plant operators and administration, additional harvest site operations, etc.

- Amount of burned straw: the total amount of burned straw is relevant to the region, as there are reported dangers of burning straw in open fields for uncontrolled fires. There is also an environmental impact difference when burning it in better burning conditions, such as inside a power plant with emissions monitoring.

- Straw waste on the streets: possibility of limiting straw carrying trucks from specific routes to minimize waste on city streets. Some measures have been taken, like covers for the trucks while carrying straw, but not all have been successfully implemented, nor have they provided good enough results.

- Biomass power plant emissions: the overall emissions of the power plants could be compared with other power plants to improve the understanding of the real impacts of the technology.

- Noise: as the reported noise was not related to trucks, but to the operation of the power plants itself, it is hard to include them in the model, as the only possible to suggestion is to restrict operations at night, which is not feasible. There were some noise measurements made in the plant surroundings during the night, to try to detect the specific source. Those test measured almost imperceptible power plant noise levels, which resulted in the counter argument that the noise source could be another source. It is still something to continue to monitor, as there is no consensus about it, and it is important for general acceptance.

- Project improvements: for future strategic decisions, community participation was highly suggested. For the tactical nature of the model, it cannot directly support this participation with concrete tools. Still, the awareness among stakeholders about this interest can open discussion spaces about new ideas that will be evaluated for implementation in the future in an early stage.

5.2.1.3 Modifications to the optimization model

To implement the identified indicators in the model, new social objective functions were added. These functions have a different influence in the model, in comparison to the other ones. They do not shape the solution (they have a zero weight parameter), but do allow for quantifying the related results to be presented as part of the solution.
Included in the model:

- Associated regional workplaces: jobs created during infrastructure construction phases of power plants are not included, as the scope of the model is not strategic. Equation (5.1) shows the modification to the model. The new parameters definitions are included in appendix A.

$$
\begin{aligned}
s_arw = & \sum_{b}\sum_{h}\sum_{t} CPBH_{b,h,t} \cdot harv_{b,h,t} \cdot JBA_b + \\
& \sum_{b}\sum_{h}\sum_{s}\sum_{m}\sum_{t} \left(TFCM_{b,m} + TVCM_{b,m} \cdot DHS_{h,s,m}\right) \cdot shiphs_{b,h,s,m,t} \cdot JBT_b + \\
& \sum_{b}\sum_{h}\sum_{p}\sum_{m}\sum_{t} \left(TFCM_{b,m} + TVCM_{b,m} \cdot DHP_{h,p,m}\right) \cdot shiphp_{b,h,p,m,t} \cdot JBT_b + \\
& \sum_{b}\sum_{s}\sum_{p}\sum_{m}\sum_{t} \left(TFCM_{b,m} + TVCM_{b,m} \cdot DSP_{s,p,m}\right) \cdot shipsp_{b,s,p,m,t} \cdot JBT_b + \\
& \sum_{b}\left(\sum_{s}\sum_{t} CIUS_{b,s} \cdot invs_{b,s,t} + \sum_{p}\sum_{t} CIUP_{b,p} \cdot invp_{b,p,t}\right) \cdot JBS_b + \\
& \sum_{h}\sum_{b}\sum_{p}\sum_{t} CBP_{h,b} \cdot usedbp_{b,p,t} \cdot JBP_h + \\
& \sum_{p}\sum_{b}\sum_{t} CBCV_{b,p} \cdot usedbp_{b,p,t} \cdot JPP_p + \\
& c_it \cdot JIT
\end{aligned}
\tag{5.1}
$$

This linear relationship used in other studies like [YTGS11] is considered reasonable, as the solution cost usually has a direct relationship with work-to-be-done by someone. The implication is that the number of workplaces has a direct relationship with the solution cost.

- Amount of used straw: all the biomass type in this category can be reported for the solutions. The modification to the model is the inclusion of equation (5.2).

$$s_tfwb = \sum_{b}^{FWB} \sum_{p} \sum_{t} usedbp_{b,p,t} \quad \forall\ b\ = straw \tag{5.2}$$

  The decision variable *s_tfwb* corresponds to the total amount of straw biomass used.

- Straw waste on the streets: the implementation is made by modifying the GIS module routes data, by rerouting the straw transport modes to avoid the identified problematic streets. This resulted in an increase in the length of the routes. This was accomplished by removing the selected routes from the GIS street data model for all weather conditions.

- Biomass power plant emissions are calculated using model equation 3.36. Still, a general discussion about the benefits of this technology in comparison to others with some stakeholders was important. This clarification and discussion about the different electricity production technologies was easier to communicate to and be understood by the general public, in comparison to the technical environmental impacts data. The impact data is still calculated, but the benefits will probably be more useful in the future.

Not included in the model:

- Noise: the noise levels were not associated with tactical or operational plant decisions, so they were not included in the model. The only practical way would be to turn the plant off during the night, which is not feasible from a technological perspective, as the plant would never reach optimal working conditions. Still, recommendations about further noise measurements with the participation of the community were made.

- Improvements that require high investment: also not included, for the strategic nature of them. Community participation in early stages for future projects was communicated to the relevant stakeholders.

5.2.1.4 Interpretation notes

- Available workplaces: the workplaces are an aggregated estimation of the human hours to achieve the goals. The real needed job vacancies depend on local working conditions, contract options, etc., which need to be considered too. The measure of the number of jobs should be complemented with information about working conditions and salaries for a proper estimation of the local benefits.

- Amount of used straw: the comparison of the environmental impact differences do not include the lower risk involved on open burning of the residues, which could be estimated from the solution results.

- Straw waste on the streets: although several streets options have been removed from the model solution, there is no guarantee that the drivers will comply and may continue to drive the shorter routes to reach their target locations faster. Some kind of compliance related incentive to the related companies is suggested.

5.2.2 Case study: weather module

For the weather module, two tasks should be completed:. 1) transport network modifications, and 2) electricity demand adjustments. For details please see section 3.8.

The first task has the objective of adjusting the transport network for the expected weather conditions. This allows the model to adapt to the available roads related to the effects of the influence of the weather. For the use case, some road restrictions were used to modify the route data of the GIS module. For example, some routes at specific forest areas were removed for the winter weeks, where the bad road conditions make them impassable for big and medium size trucks. Also some roads near houses at the town of Lautaro were removed to avoid straw waste coming from trucks on the streets, as a result of the tasks of the social module. The GIS data modification was made later in the tasks of the GIS module.

The second task should find the weather parameters to adjust the electricity demand. They correspond to the variable WD_t from equation 3.22 in the optimization module. One for every period should be found.
It was hard to estimate an exact number for a correct estimation on the effects. [CSRAE15] reports predict probabilities for rain given cool and warm phases of ENSO. It is out of the scope of this work to propose definitive values to change the electricity demand, but it is suggested to consider a mix of observed rain effects from the literature and historical data specific for the region. The pattern promotes cool->dry and warm->wet associations with ENSO, but excluding the winter season, where no strong association was found. Also, historical data could play a role by searching for a correlation between the ENSO phenomena and the hydro plants electricity production and water reserves. For the this case study, no change on the electricity demand was incorporated, but the model allows the option to include it in the future after further research about the correlation with the grid electricity demand from Chile is made. Numerical data to consider for the correlation is included in appendix K.1.

5.2.3 Case study: GIS module

The information provided by this module provides a good overview and helps to understand details of the system (e.g. average distances, maximum and minimum road speeds, type of available biomass, among many others). For that reason it is recommended to do the task of this module in parallel to the social module (see section 5.2.1).
As detailed in section 3.9, this module requires the completion of two tasks: 1) GIS data management, and 2) route optimization.

5.2.3.1 Main GIS data

GIS data management tasks can be divided in getting structural data (time independent) and tactical/operational data (time dependent).

For the structural data, general inventory data and restrictions (e.g.: locations, maximum capacities), power plant parameters (e.g.: biomass to energy ratios), resource requirements (e.g.: water), available biomass types in the region (e.g. identify names), transport modes regional offers (e.g. transport companies, truck models), and the list of potential harvest locations (e.g.: locations and potential biomass availability).
For the case study, the power plant near the town of Lautaro was considered. A big biomass storage area near the plant is the main biomass storage location. There are more than one hundred possible biomass harvest locations, with several types of biomass. Among the identified resources (beside biomass) that could restrict the process, water was identified as a potential candidate. But under the current conditions, it was not considered restrictive to the power plant management, and therefore was not included in the model. The transport modes are only trucks from different transport companies. Some are owned by the harvest locations. They do little to no biomass processing at the storage location. Right before the biomass enters the transport conveyors to the burning process, the biomass is mixed in a special facility, where the raw materials are loaded in a way to reach the density and humidity conditions required by the power plant. Here, the optimal working humidity and density of the mix should be obtained.
There was little interest from stakeholders to evaluate the use of a secondary major biomass storage location in the region, as they estimate an unnecessary cost related to the unload/reload of trucks. For this reason no potential storage location was included in the case study.

For the time dependent data, different sources were needed. For the specific harvest locations, there were two options to obtain it.
The first option was to build a regional biomass availability forecast. A set of historic data from the plant operation logs was used to determine the expected regional biomass offer and complement it with new information from possible new sources. The second option was to allow biomass harvest locations to directly update their biomass offer information into the system, by using a specific web page. The page allows them to set the biomass location in a map and edit relevant information like the biomass type, and the expected availability for the weeks in the future. There is no limit to how much information each location can add, but the model will only consider data between the current date and the optimization time horizon.
There is currently no special open market platform to buy and sell biomass in this region, but some existing platforms were used, where potential offers could be found.
The main biomass location areas in the region are shown in figure 5.6. The distance between the providers' harvest sites and the power plant's location varies mostly between 1 km and 250 km, with some rare shipments reaching a distances of up to 773 km.
The current biomass inventory levels at the power plant location were obtained directly from the power plant operation data.

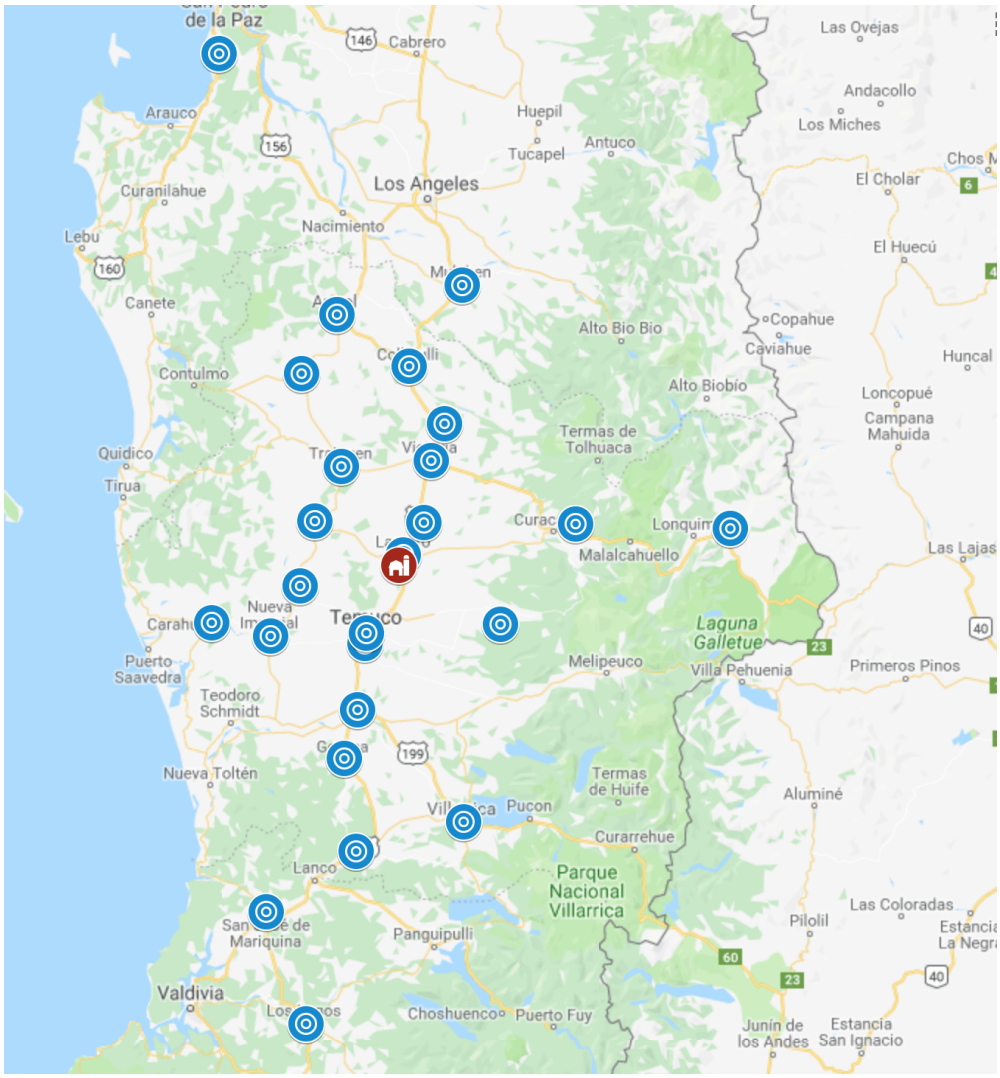

Figure 5.6.: Biomass main source location areas in the Araucanía region.

5.2.3.2 Routes data

For the routes, a detailed street map is needed. For this case study, the data from OpenStreetMap was chosen. The OpenStreetMap database is huge, and as the model focuses on the regional problem, the specific map from the region is enough to consider. The map from Chile was downloaded from Geofabrik[7], and the specific Araucanía Region and surrounding routes were loaded in the route server database. For specific technical details see appendix J.1.
The modifications to the available routes proposed from the results of the social and weather modules were completed in this task. The map modifications were made using the QGIS software directly to the local GIS database.

With this information, for every harvest location, storage, and power plant combination, the optimized routes were calculated to be made available to the optimization module. It is important to mention that this route optimization must be made for every period, as a different transport network could be available because of the social and weather modules influences. In practice, it is reasonable to check precisely where those route modifications exist, to reuse the optimization data for all periods with similar transport networks, thus lowering the amount of needed calculations.

5.2.4 Case study: LCIA module

As mentioned, the first part of the LCIA calculations are made in this module (more details on section 3.10). Before, some fundamental elements were made explicit:

[7] Website: www.geofabrik.de

- Goal: this specific task should allow the identification of unit-based emissions that correspond to the system supply chain. The results are going to be the input of an optimization model.

- Scope: it is not intended to do a full LCA of the complete system, but to generate the specific information needed to be able to compare different solutions under an environmental impacts perspective.

- Impact categories: the selected impact categories for the system were two endpoints: *damage to human health* and *damage to the ecosystem* (ReCiPe LCIA model). This decision was made with the argument that the target audience is not made of experts in environmental science, which could lead to wrong interpretations of midpoint indicators. Still, midpoint categories were calculated as well to be able to understand more details about the environmental emissions related to this study.

With these considerations, the calculations of the needed coefficients were made using LCA software and an LCA database. One set of the following parameters were selected for every chosen impact category.

1. $ETBU_{e,b,m}$: emissions for the transport of a unit of biomass b, using the transport mode m, for the impact category e. (Refer to equation (3.34))

2. $EPCV_{e,b,p}$: emissions for the biomass to energy conversion process of a unit of biomass b, at the power plant p, for the impact category e. (Refer to equation (3.36))

Emissions data for the acquisition of biomass was not available, and the emissions related to the storage was estimated to be of lower significance, in comparison with the others categories.

For emissions data, published literature and the ecoinvent 3.3[8] database were used to calculate two sets of parameters: 1) transport emissions, and 2) biomass combustion emissions.
The emissions data was made available as parameters to the model to calculate ReCiPe 2016 Midpoint (H) and ReCiPe 2016 Endpoint (H) from [HSE+16], as mentioned in section 3.10.

For **transport emissions**, the data of the reference process: *market for transport, freight, lorry 16-32 metric ton, EUROX | APOS, U*, for EURO3, EURO4, EURO5 and EURO6 truck alternatives was used. The reference process location was *Rest-of-World*. The data was adjusted for a distance of 1 km. This data is used to calculate emissions from different transport options. They are the parameters *ETBU* for model equations (3.34).

For **biomass combustion**, the used reference process was *heat and power co-generation, wood chips, 6667 kW | electricity, high voltage | APOS, U* with Chile as the reference location. As there were no other available processes for other types of biomass, they were estimated using information from emission factors for specific biomass types: [Age09] for Pine bark and Pine firewood, [GYV19] for Eucalyptus bark, [IRA+14] for Husk, and [SSS+07] for straw.
The parameters of all considered types of biomass were extrapolated with the base of the mentioned wood chips data available in the database and emission factor information found in the literature. A simple way to understand the logic behind the extrapolation is that better combustion (from better pore factor, lower lignin proportion in relation to cellulose, or different ignition temperatures) impacts the emissions by e.g. decreasing fine particulate matter formation and increasing CO_2 and NOx. For the water consumption, a proportion with the specific net calorific values was used, as those values are directly correlated. Although these estimations do not consider the complete life cycle assessment specifics for every particular typo of biomass, they do provide data with the correct bias to the model. This allowed the model to differentiate biomass type emissions associated to combustion.The calculated parameters for midpoints and endpoints impact categories for all considered biomass types are included in appendix H. They correspond to parameters *EPCV* for model equations (3.36).

5.2.5 Case study: optimization module

The optimization model described on section 3.11 was implemented for the case study. Some modifications to the model were needed in order to be able to adapt to the local situation.

As the power plant is compatible with several types of biomass, the correct mix of them is critical to stay within the limits of the power plant design conditions. Two variables needed to be monitored: humidity and density.

[8] https://www.ecoinvent.org

For the **humidity** ranges, two more equations were added. Equation (5.3) limits the minimum required humidity, with parameter *MinBH* as the minimum humidity content compatible with the power plant design, and equation (5.4) limits the maximum required humidity, with parameter *MaxBH* as the maximum humidity content compatible.

$$\sum_b usedbp_{b,p,t} \cdot MinBH_p \leq \sum_b usedbp_{b,p,t} \cdot BH_{b,t} \quad \forall t \in T, p \in P \tag{5.3}$$

$$\sum_b usedbp_{b,p,t} \cdot BH_{b,t} \leq \sum_b usedbp_{b,p,t} \cdot MaxBH_p \quad \forall t \in T, p \in P \tag{5.4}$$

In terms of humidity, the power plant has been designed for working conditions between 35% and 47%, as mentioned in section 5.1.4. These parameters relate to equations (5.3) and (5.4).

The biomass also has a minimum **density** for the biomass mix that can be processed. The model needs to adjust the biomass mix to always reach the minimum density *MinD* for proper operation. Equation (5.5) is used to guarantee such a mix for every period.

$$\sum_b BD_b \cdot usedbp_{b,p,t} \geq \sum_b MinD_p \cdot usedbp_{b,p,t} \quad \forall t \in T, p \in P \tag{5.5}$$

As for the density mix to be fed to the power plant, it must have a density of at least 218 [kg/m2]. This parameter relates to equation (5.5).

Another type of constraints are biomass type restrictions to specific power plants. The first power plant can burn all the supplied feedstock. The second power plant only burns straw. For this restriction, equation 5.6 was added.

$$usedbp_{b,p,t} = 0 \quad \forall p = 2 \ \wedge \ b \neq straw \tag{5.6}$$

Additionally some slack variables were included in the model for better report of errors, in case the problem has no feasible solution (especially for biomass humidity, biomass density, and biomass availability).

5.3 Case study data set specifics

Disclaimer: the model was tested with data from year 2012, which was made partially available for this research. Data about biomass availability, biomass types, biomass characteristics, routes, and some data to compare against the real performance was obtained. Specific data for the power plants transport plan was not made available for this research. Hypothetical close-to-reality data was used instead.

5.3.1 Biomass availability

Figure 5.7 shows the volume of biomass shipped from the nearly 200 suppliers of the problem in 2012. 20% of the providers delivered around 80% of the obtained biomass. From a model perspective, this allows focusing on a smaller providers set for the model and reducing the data set with almost no impact on the solution. This does not mean ignoring them in the real operation. They can still be included with the simple buy-all criteria, as the amounts are small. In the case that they increase their share, they can join the considered providers group. If there are no concerns about the size of the data set, they can be included in the model too. This argument assumes that none of these biomass providers have a poor economic, environmental, or social impacts on the regular operations in comparison to the average, which is a real observation among stakeholders.
For the case study, the most relevant 51 providers were considered, which concentrate more than 95% of the delivered biomass to the power plants.

The available offer for the model was built using the **harvest sites** that were available during 2012 and multiplied by a number generated with a uniform probability distribution function[9] (with parameters $a = 1,2$ and $b = 1,4$) to increase the offer. This is reasonable under the assumption that the company did not buy all the available biomass, which corresponds to the information gathered on the interviews with the plant management.

The **distance** between the considered harvest sites and the power plants location is between 2 km and 350 km, with an average distance of around 70 km. The costs were estimated using the results from [AR06]. They conclude that the transportation cost is significant in the agricultural sector, specially for small farmers. The study estimated a cost of US$ 2,01 per kilometer for land freight transportation for the agricultural industry in the Maule Region in Chile.

[9] The uniform distribution (continuous) is defined by parameters a and b, which are its minimum and maximum values; U(a,b).

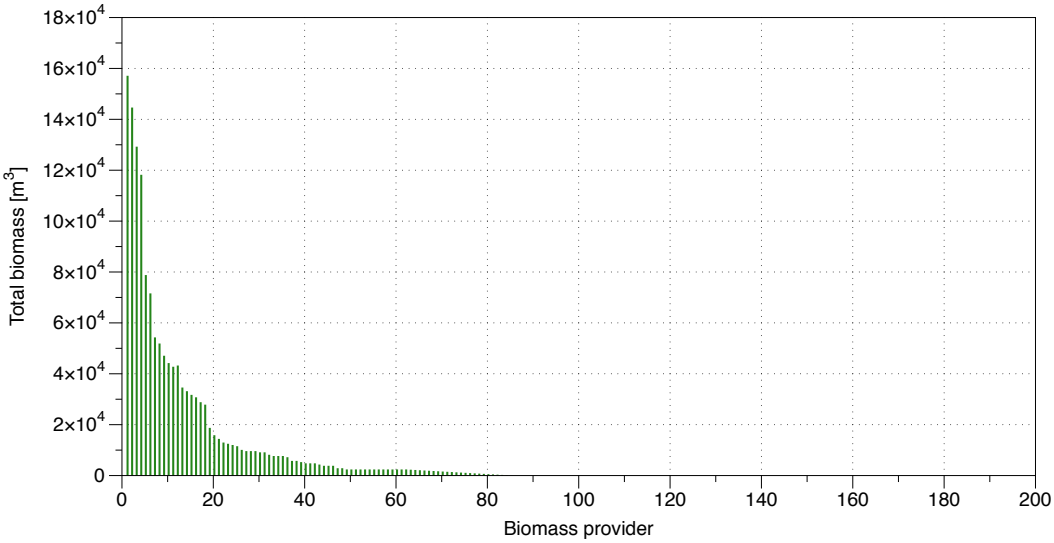

Figure 5.7.: Biomass providers, ordered by amount shipped.

5.3.2 Biomass storage

The available biomass types and their characteristics are shown in table 5.1 in section 5.1.4. All biomass types from the real problem were considered. The biomass **storage** location at the power plants had initial inventory levels for the biomass types summarized in table 5.2.

Table 5.2.: Biomass initial inventory for the case study.

Index	Biomass	Initial inventory of biomass in 2012 [kg]
1	Sawdust	47.002.335
2	Splinter	42.423.311
3	Pine bark	7.797.921
4	Wastewood	49.015
5	Shaving	0
6	Eucalyptus bark	225.120
7	Burdock	18.656.195
8	Pine firewood	7.033.942
9	Husk	1.894.480
10	Straw bale	11.819.034
11	Poplar firewood	227.701
12	Native firewood	1.061.396
13	Woodchips	0
14	Others	2.815.668

The high inventory levels produced by the uncertainty of the biomass availability and prices had two bad consequences: 1) the opportunity cost of the large inventories, and 2) the dangers of the high levels of flammable raw materials.

This is specially important, as the plant has experienced two major fires (February 2013 and February 2019[10]) in the storage location near the plant that had huge costs in the three considered sustainability dimensions. This produces direct rejection of the technology. A lower safety stock policy is included in the model to help address the issue. The optimizations were made considering 4 weeks of safety stock. Because of the biomass seasonal availability, it is not expected that the model will be able to keep those safety stocks levels during all periods, as a feasible solution may require higher amounts.

[10] Sources: http://www.revistaei.cl/2019/02/19/incendio-afecta-la-empresa-comasa-la-region-la-araucania/ and https://www.latercera.com/nacional/noticia/incendio-afecta-la-empresa-comasa-la-region-la-araucania/534234/

5.3.3 Electricity demand

For the case study there are two power plants installed close to each other in the same location. *Comasa 2* only consumes straw and was not considered in the case study, in favor for the more complex scenario of *Comasa 1*. This power plant that can be fed with several types of biomass because of its design conditions. It is a challenge in terms of the needed calorific energy and the specific mix conditions for the biomass types and proportions to be fed.

The electricity demand for the power plant was based on the generation profile from 2012, which corresponds to around 17MWh of electricity for a normal time period. The plant needs maintenance every 6 weeks, which lowers the generation to 12 MWh for that particular period. The minimum operating condition for the plant is 8 MWh.

5.4 Optimization results

5.4.1 Multiobjective optimization result and validation

5.4.1.1 Economic: cost comparisons, validation and solution description

The model comparison with the real scenario was made from a general perspective, because of the limitations of the available data. A key performance indicator is the comparison of the total biomass acquisition costs. Table 5.3 gives a summary of the comparison and shows the 17,6% savings by prefering the optimized solution from the proposed model.

Table 5.3.: Summary of costs comparison

Item	Cost [Chilean Pesos (CLP)$]
Total real cost of acquisition of biomass in 2012	3.123.525.411
Total optimized cost of acquisition of biomass in 2012	2.573.853.154
Total savings	549.672.257
Savings percentage	17,6%

This result is similar in terms of biomass acquisition amounts per week, weekly inventory levels, inventory mix to reach humidity and density constraints, and electricity generation that considers the planned fluctuations from the maintenance program. It was also seen as *reasonable* given the normal operation of the plant.
The main reasons for the difference are the model analytical buying decisions, but also the more aggressive inventory levels. For the model, the inventory levels are determined by the safety stock policy, and not complex assumptions made by the decision makers, which may be influenced by market uncertainty.

About the biomass types acquisitions, the model did buy a mix similar to the documented real one. The total lower amount is because the model looks for optimizations on the inventories to reduce the total cost. For most biomass types, the acquisition amounts were similar. The differences were mainly on poplar firewood, the *others* group of biomass, wood chips, sawdust and splinter. To a lower extend, straw bales, pine firewood, native firewood pine bark and waste wood. A graphical representation is included in figure 5.8.

Figure 5.9 allows for comparing the total for every time period (week). For the real case, as there is uncertainty in the future availability and prices of the biomass, the decision maker gathers more raw materials in comparison to the model. The model keeps the inventory levels lower (considering the safety stock constraint, and the initial inventory amounts) to save costs. The model delays the acquisition of some biomass types to the last (dried) months. The biomass types, ordered by acquisition amount, stays the same for both scenarios.

Six periods evenly spaced were selected to analyse the chosen biomass mix that should be processed. Figure 5.10 shows the mixes for the selected time periods. There are differences in the results, as the model searches meticulously for optimizations. For example, the model prefers to delay the use of Husk to periods with more humidity. The model prefers to not use it at all during the first analyzed period. It prefers other biomass types, especially burdock, which is available and dry during the warm season. In period 21, there is a different available biomass mix, and the humidity at harvest locations increases, which forces the model to change the mix. The model introduces the use of Husk at this point to balance humidity. At period 31, the model continues the use of the available Husk to lower the humidity levels of the mix.
This flexibility in the mix relation is not seen in the real case, but is still compatible with the power plant's working conditions. The real mix stays more or less homogeneous during the year, considering the biomass seasonal availability.

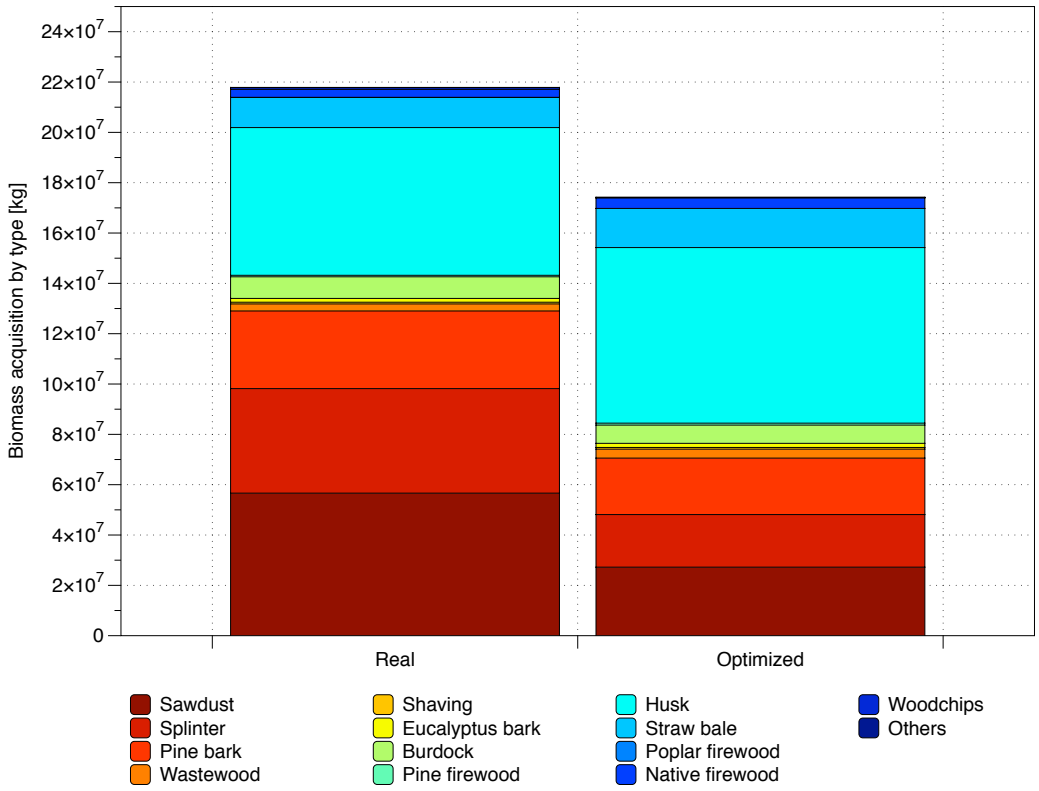

Figure 5.8.: Biomass acquisitions by type, real and optimized total amounts.

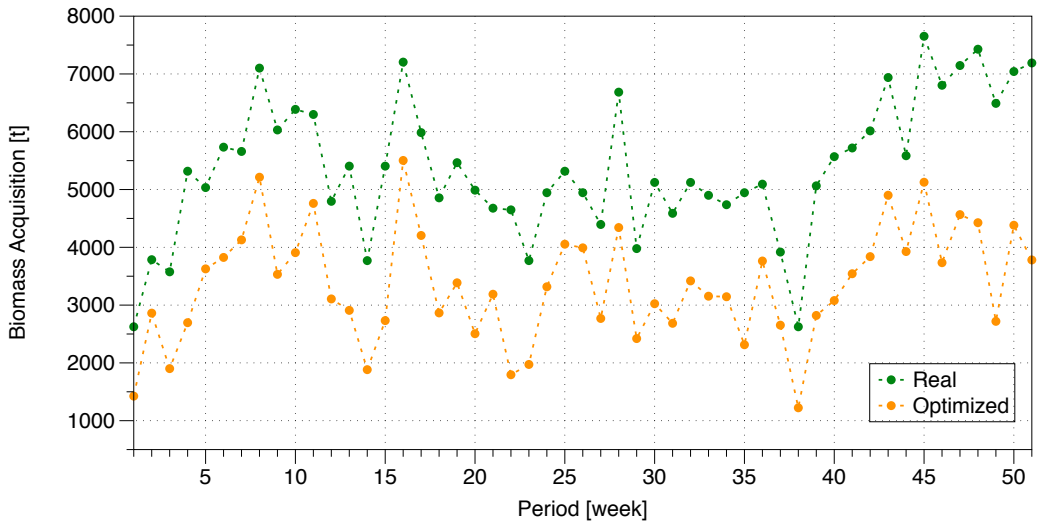

Figure 5.9.: Biomass acquisitions, real and optimized amounts.

This is reasonable, because the decision makers know the mixes that have given them good operational results, and keep reasonable ranges similar to them.

It is important to declare that the model uses the restrictions criteria to suggest the biomass types mix. This mix will most likely need some adjustment in the real operation, as there may be other unmentioned guidelines about the power plant's operation and biomass specific conditions. Considering the known information, the proposed solution is compatible with the operation conditions, as the needed decision rules are included in the model.

A selection of 5 biomass type examples in figure 5.11 show the transported quantities for the optimal solution.

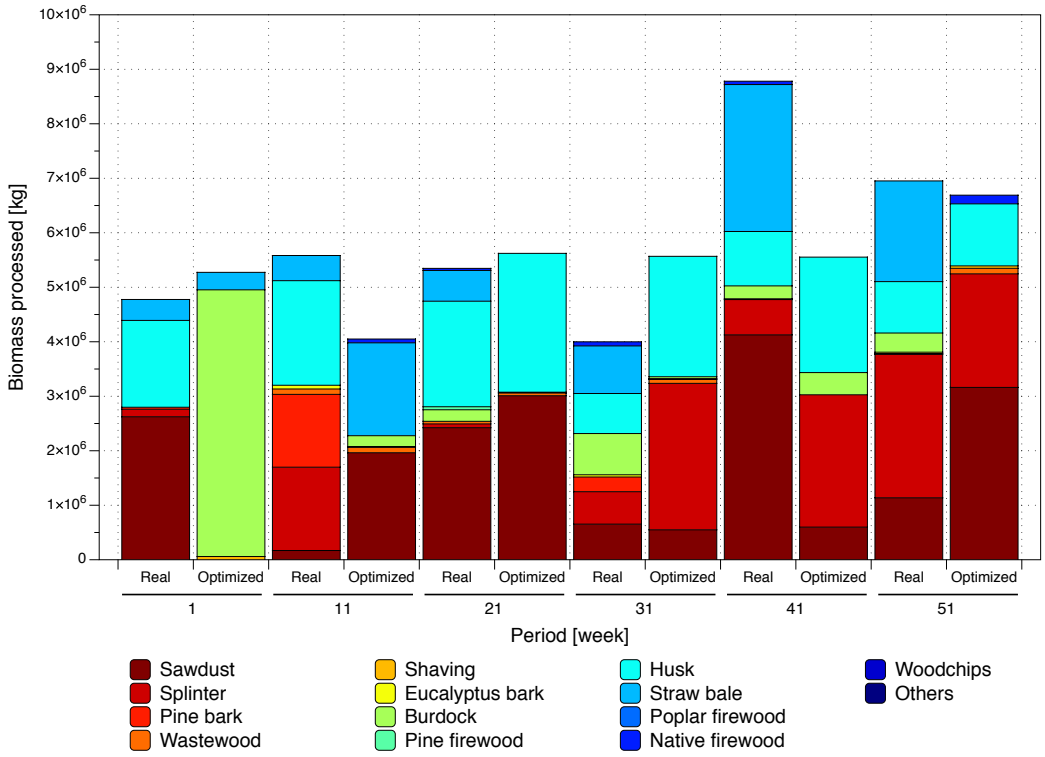

Figure 5.10.: Biomass processed in power plants, real and optimized amounts.

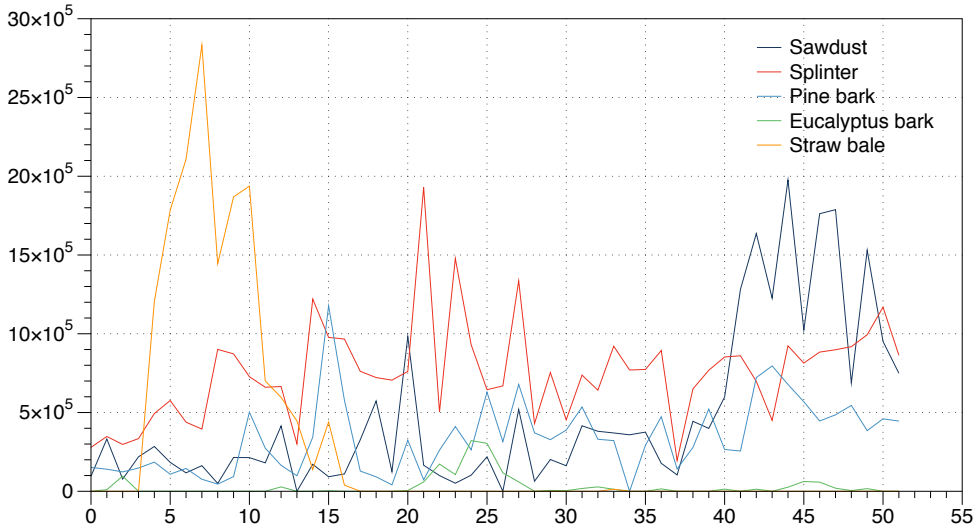

Figure 5.11.: Biomass transport, optimized amounts.

5.4.1.2 Environmental: impact categories values

The model includes several objective functions for the environmental dimension: one for every ReCiPe 2016 midpoint and endpoint indicators. The model uses the two selected endpoint impact categories as active objective functions, but still calculates the information for all midpoint variables as well. The selection is made in favor of endpoint impact categories as a result of considerations about the target audience and remarks in section 2.1.4.

Table 5.4 shows the results for the selected endpoint impact categories.

The results for every midpoint impact category are in table 5.5.

All the values correspond to the operation of the complete considered time horizon of 52 weeks.

Table 5.4.: Endpoint impact category values for the multiobjective solution.

	Multicriteria
Total cost (CLP)	3.275.896.823
Human health (DALY)	98,5464
Ecosystems (species.yr)	0,110747798
Straw amount (kg)	26.694.744
Route restrictions	Included

Table 5.5.: Midpoint impact category values for the multiobjective solution.

ReCiPe 2016 Midpoint (H)	Value	Reference unit
Fine particulate matter formation	127.659,484	kg PM2,5 eq
Fossil resource scarcity	470.222,755	kg oil eq
Freshwater ecotoxicity	436.039,035	kg 1,4-DCB
Freshwater eutrophication	1.104,615	kg P eq
Global warming	3.681.317,247	kg CO2 eq
Human carcinogenic toxicity	390.456,656	kg 1,4-DCB
Human non-carcinogenic toxicity	57.159.023,054	kg 1,4-DCB
Ionizing radiation	48.536,680	kBq Co-60 eq
Land use	60.905,296	m2a crop eq
Marine ecotoxicity	684.829,025	kg 1,4-DCB
Marine eutrophication	39,791	kg N eq
Mineral resource scarcity	26.352,994	kg Cu eq
Ozone formation, Human health	477.932,016	kg NOx eq
Ozone formation, Terrestrial ecosystems	479.382,145	kg NOx eq
Stratospheric ozone depletion	79,407	kg CFC11 eq
Terrestrial acidification	162.016,334	kg SO2 eq
Terrestrial ecotoxicity	213.410.994,134	kg 1,4-DCB
Water consumption	12.011,918	m3

5.4.1.3 Social: influence in the results

The social dimension objective functions were not included in the optimization because of the complexity of determining whether they improve or worsen the situation (already discussed in section 3.11.3.1 and 5.2.1.3). Still, the procedure described in section 5.2.1 has an impact on the solution.

In terms of the available **regional workplaces**, the model is able to calculate the amount based on parameters proportional to the solution cost categories. There was no data available to estimate the parameters, but as the relationship is linear to the solution cost, conclusions can be taken from those values.

The total amount of **used straw** is calculated by the model. For the optimized solution are 26.694.744 [kg], which would not need to be burned in open fields, avoiding the discussed dangers. This value would dramatically increase if *Comasa 2* is considered, as it is exclusively designed to burn straw.

For the topic of **straw waste on the streets**, the GIS data was changed to avoid routes that travel through the identified problematic streets. In general terms, it produced an average route length increase of around 5%. By this change in the data set, this concern was fully addressed.

5.4.2 Multiobjective against single objective optimization: results comparison

The multidimensional optimization is compared against three other optimization criteria:

1. Minimization of total solution cost.
2. Minimization of total impact on human health.
3. Minimization of total impact on ecosystems.

Minimization of total solution cost shares the same cost objective function, but changes the weight value of all the environmental ones to zero. The environmental and social variables are still calculated in order to be able to show the results. Lower total cost of the solution is expected.
Minimization of total impact on human health considers the related specific objective function. The cost, ecosystems, and social variables are still calculated for comparison. Lower human health impact is expected.
Minimization of total impact on ecosystems shares the ecosystem impact objective function similar to the other two strategies. Cost, human health, and social variables are still calculated and a lower impact on the ecosystems is expected.

This comparison will allow for determining the advantages of the multidimensional proposed method in section 3.11.3.1 against more common approaches that optimize along one dimension of interest (usually total cost). Table 5.6 gives a summary of the results in terms of the objective functions values.

Table 5.6.: Multicriteria optimization: comparison against different O.F. prioritization

	Priority			
	Multicriteria	Economic	Human health	Ecosystems
Total cost (CLP)	3.275.896.823	-0,09%	8,36%	8,94%
Human health (DALY)	98,5464	4,81%	-1,07%	5,48%
Ecosystems (species.yr)	0,110747798	1,29%	0,60%	-9,98%
Workforce (% from optimal)	Base value	-0,09%	8,36%	8,94%
Straw amount (kg)	27.220.556	0,00%	-0,20%	-6,27%
Route restrictions	Included	Included	Included	Included

Figure 5.12 shows a graphical comparison where the changes between every optimization prioritization are shown alongside with three overlapped diagrams.

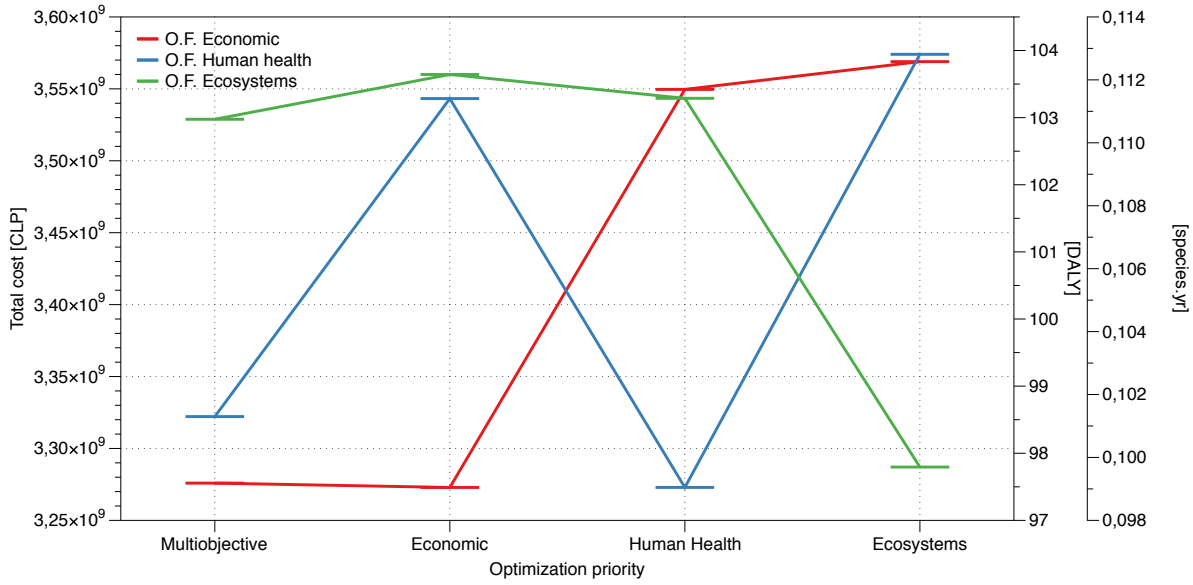

Figure 5.12.: Comparison of objective functions values between different optimization prioritization strategies.

There is a visible benefit of considering the multicriteria solution with the proposed approach, as it creates cost comparable solutions (which is very relevant to the real world implementation) that improve both the environmental impact categories and do consider the included social elements (the latter not shown in the comparison for reasons stated in section 5.4.1.3).

5.4.3 Sensitivity analysis: transport distance

For a transport problem optimization, the distance between the supply chain elements is a fundamental parameter. To analyze the effect of increasing the biomass harvest locations radius coverage, a sensitivity analysis that considers

variations of this parameter is presented. This is especially relevant of the current available biomass sources changed over time with the need to increase the operational radius distance.
The scenarios considered for the analysis are generated with factors that multiply the distances between the harvest locations and the power plant location. This approach allows for keeping the relative distances proportional.
The factors considered are 1/2, 2, 5 and 10 in order to complement with data from smaller and bigger radiuses. It is arguable that the factors selected for the analysis are big in comparison to regular scenarios, but the effect of biomass availability issues can affect large areas, which may force the operational radius to increase by an important factor.
Table 5.7 show a summary of the analysis results.

Table 5.7.: Sensitivity analysis: harvest location distance variation.

Distance factor	1/2	1	2	5	10
Total cost (CLP)	2.880.436.724	3.275.896.823	3.885.434.787	5.601.291.329	8.448.377.567
Transport cost (CLP)	444.093.239	723.522.534	1.155.638.072	2.850.038.331	5.692.372.890
Transport cost of total (%)	15%	22%	30%	51%	67%
Human health (DALY)	97,63034	98,54636	100,49935	104,23384	110,31343
Ecosystems (species.yr)	0,10822	0,11075	0,11508	0,12357	0,13760
Workforce (% from optimal)	-12%	0%	19%	71%	158%
Straw amount (kg)	26.694.744	27.220.556	27.219.545	27.192.665	27.192.252
Route restrictions	Included	Included	Included	Included	Included

The higher transport distances can dramatically increase the proportion of the transport costs in relation to the total costs. Emissions are strongly related to the biomass burning selection rather than the transport, but there is a measurable effect as the distance increase.

5.4.4 Sensitivity analysis: transport cost

Another relevant parameter for the transport plan is the cost of the transport modes. Truck fuel price increments in particular are a latent risk, especially for countries that have to import almost all of their fossil fuels, like Chile.
For this analysis, a factor is applied to the variable cost of transportation as a multiplication.
Small 10% variations (up and down) are optimized first, and then later this is increased until the costs are doubled (factor 2).
Table 5.8 shows a summary of the analysis results.

Table 5.8.: Sensitivity analysis: transport cost variation.

Transport cost factor	0,9	1	1,1	1,5	2
Total cost (CLP)	3.203.889.918	3.275.896.823	3.342.999.385	3.594.836.212	3.885.398.630
Transport cost (CLP)	667.195.077	723.522.534	749.672.571	900.249.192	1.157.441.232
Transport cost of total (%)	21%	22%	22%	25%	30%
Human health (DALY)	98,46175	98,54636	98,79080	99,04202	99,27087
Ecosystems (species.yr)	0,11050	0,11075	0,11137	0,11188	0,11226
Workforce (% from optimal)	-2%	0%	2%	10%	19%
Straw amount (kg)	27.220.878	27.220.556	27.220.139	27.219.545	27.219.545
Route restrictions	Included	Included	Included	Included	Included

The total cost shows an increase in the cost of transportation for all transport modes. For the 10% variations, the total cost changes stay near the 2%, but for the 5% variations, they reach almost 10%, and almost 19% when the cost doubles. There are no big differences in terms of emissions, since the model makes some adjustments in the mix in favor of closer biomass locations, as they become more attractive. Still, changes remain below 0,8% for damage to human health and 1,4% for damage to ecosystem endpoint indicators.
The social effects need some closer examination. The assumption of the direct correlation between the costs and the workforce would probably not apply for this price increment if it is derived by a fuel price increase. On the other side, if the price relates to better working conditions, either by a wage increase or shorter workdays, then it would. The specific cause must be identified before a correct statement can be made. The burned star amount remains (almost) constant for all options, with changes below 1%.

5.4.5 Sensitivity analysis: biomass availability

Regional biomass availability is critical. The transportation of low energy density raw materials over very long distances usually is not cost effective enough to justify intercontinental cargo, which makes regional availability paramount. The use of several biomass types lowers this risk. This analysis focuses on variations on the availability of the biomass in the considered region.
A factor is applied as a multiplication for every combination of biomass and harvest location for every time period.
The used factors are in 25% steps around the considered offer, plus an additional one that doubles the offer for a mayor variation case. It is important to realize that biomass availability factors below 0,7 do limit the biomass availability enough to keep the model from finding feasible solutions.
Table 5.9 show a summary of the analysis results.

Table 5.9.: Sensitivity analysis: biomass availability variation.

Biomass availability factor	0,75	1	1,25	1,5	2
Total cost (CLP)	3.915.123.804	3.275.896.823	2.965.222.012	2.852.713.899	2.700.083.007
Acquisition cost (CLP)	2.754.093.814	2.552.374.289	2.445.184.395	2.398.837.702	2.306.175.926
Acquisition cost of total (%)	70%	78%	82%	84%	85%
Human health (DALY)	102,72354	98,54636	98,50579	98,33006	97,40813
Ecosystems (species.yr)	0,11945	0,11075	0,10856	0,10785	0,10682
Workforce (% from optimal)	20%	0%	-9%	-13%	-18%
Straw amount (kg)	23.358.003	27.220.556	29.989.075	29.264.812	20.184.411
Route restrictions	Included	Included	Included	Included	Included

Figure 5.13 show the biomass mix acquisition changes from the different biomass availability variations.

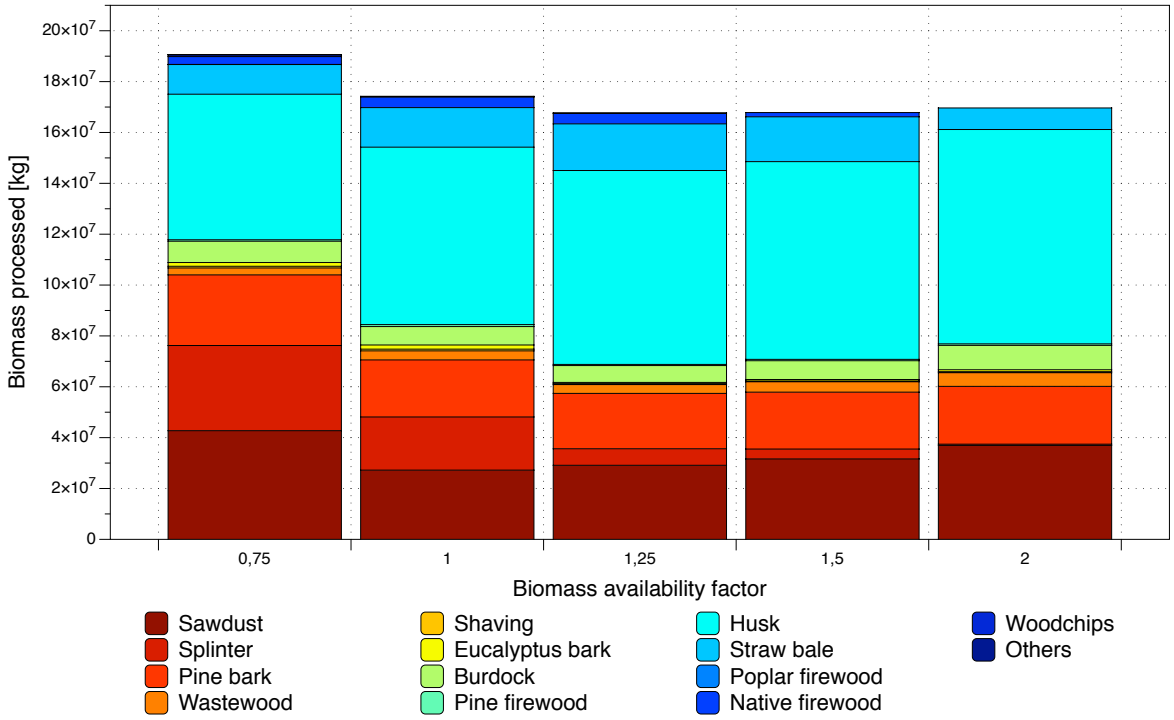

Figure 5.13.: Sensitivity analysis: biomass availability variation, impact on the biomass mix acquisition.

An increase in the biomass availability allows for a lowering of the total cost, as closer harvest locations can supply the power plants. Biomass mix changes are also a new option, as for every biomass type which the model consumed 100% in the base solution, there is more availability. A decrease in the demand availability by 25% increases the total cost by a big margin, as the solution space gets smaller close to the limit where the only solution is to simply buy all available

biomass in the region, regardless of the distance and cost. Still, there is a limit to the buy-all strategy, as the humidity and density operational restrictions force the model to balance the biomass mix to the power plant.
For a larger available biomass offer the model is able to lower the emissions to improve the solution in that dimension, for the two analyzed indicators.
As for the social considerations, the lower cost may reduce the workforce. The burned straw increases as there is more available, but it reaches a point where there is enough husk available to start to replace it to balance the mix.

5.4.6 Sensitivity analysis: net calorific value

The net calorific value is closely related to the quality and the amount of humidity of the available biomass. Humidity changes produced by weather related changes, or quality differences from variations in the process makes this possible.
A factor that multiplies the conversion parameters for all biomass types is applied to the data set.
Small decreases are applied in an incremental pace from 2% until 20% is reached.
Table 5.10 show a summary of the analysis results.

Table 5.10.: Sensitivity analysis: net calorific value variation.

Net calorific value factor	1	0,98	0,95	0,9	0,8
Total cost (CLP)	3.275.896.823	3.440.712.564	3.708.625.567	4.218.231.504	5.755.744.026
Acquisition cost (CLP)	2.552.374.289	2.667.552.866	2.823.857.691	3.159.287.001	3.916.958.492
Acquisition cost of total (%)	78%	78%	76%	75%	68%
Human health (DALY)	98,5464	100,7497	104,1508	111,0616	129,7137
Ecosystems (species.yr)	0,1107	0,1131	0,1164	0,1246	0,1497
Workforce (% from optimal)	0%	5%	13%	29%	76%
Straw amount (kg)	27.220.556	27.226.155	27.235.868	27.251.374	27.280.489
Route restrictions	Included	Included	Included	Included	Included

Figure 5.14 show the biomass mix acquisition changes from the different biomass net calorific value variations.

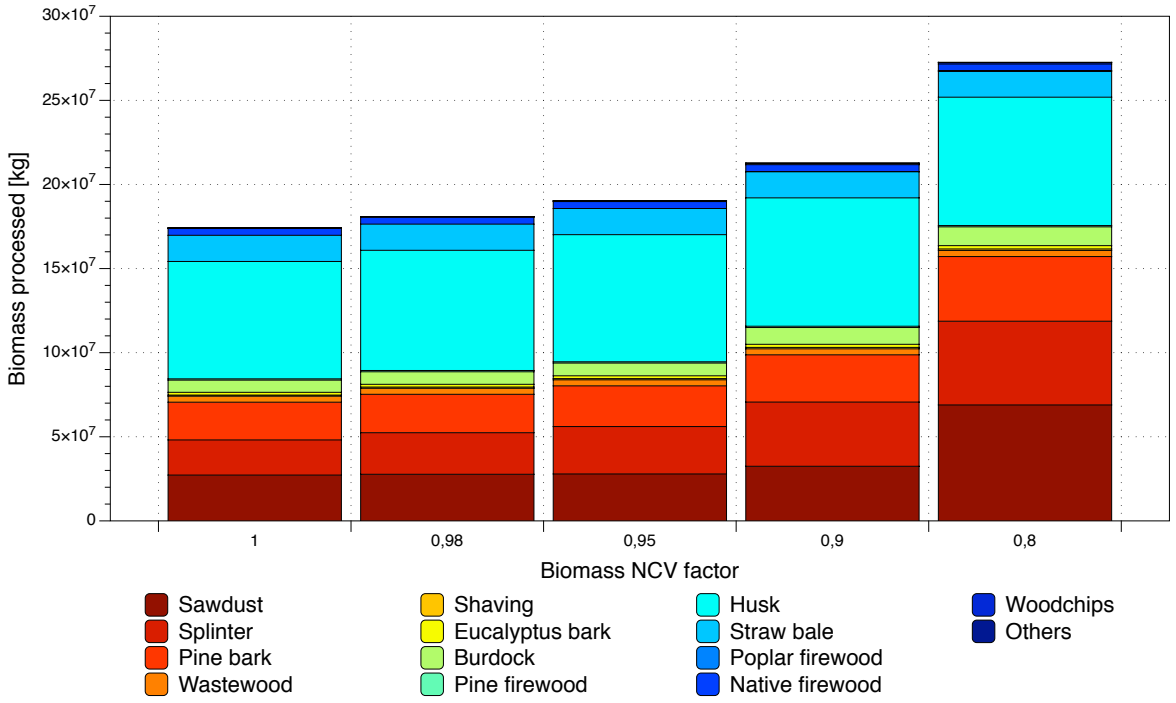

Figure 5.14.: Sensitivity analysis: net calorific value variation, impact on the biomass mix acquisition.

There is a very clear cost increase with the change. A lower NCV results in a bigger quantity of raw materials to be fed to the system to reach the energy production targets for every period. A 5% total cost increase for the 2% factor, 13% for the 5% disminution, and a worrying 75% increase for the 20% lower NCV are observed.

The environmental impacts are also clearly increased for every case. More biomass needs to be burned, which generates more emissions in all impact categories. Even for the apparently small decrease of 2%, the emissions also increase around 2%, and for the extreme 20% decrease, the danger to human health category increases by 31%, as the danger to ecosystems reaches a 35% increase.
The solutions require more biomass to be harvested and transported to the plant, which leads to an increase in the needed workforce to deliver the needed raw materials. The biomass mix remains more or less constant, as shown in figure 5.14, which leads to a proportional increase in the burned straw.

5.4.7 Sensitivity analysis summary

From the conducted sensitivity analysis for the case study, the biomass harvest location distance and the cost of transport show a direct relationship, as shown in figures 5.15 and 5.16. As the distances increments, or the transport costs increases, the total cost grows accordingly, without limit.
For the biomass availability, the cost starts to decrease, as more biomass is accessible for the model to choose from. But the cost improvement rate starts to decrease, as the model is closer to being able to choose an optimal mix. It will eventually reach a point where no more improvements are possible. This behaviour is shown in figure 5.17.
As for the NCV changes, which are closely related to the biomass quality, the cost changes fast for small percentage changes, as seen in figure 5.18. This shows the importance of a consistent biomass quality for planning, and the potential benefits of biomass options with higher NCV that are compatible with the considered power plant's working conditions.

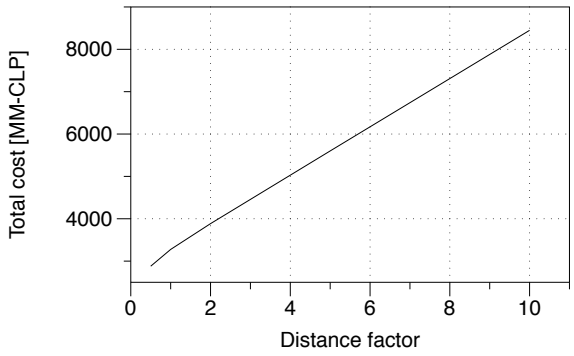

Figure 5.15.: Relationship between total cost and biomass harvest sites distance.

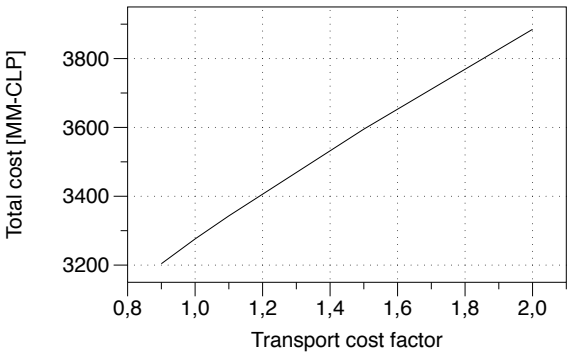

Figure 5.16.: Relationship between total cost and transport cost.

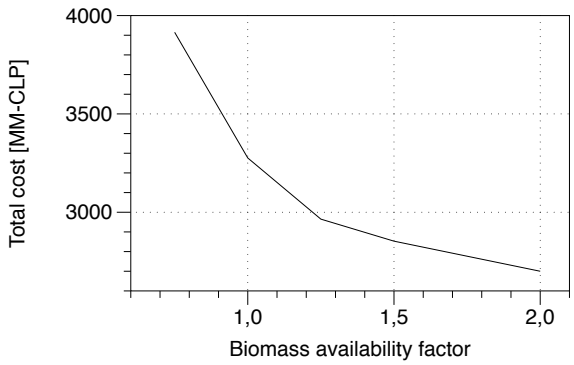

Figure 5.17.: Relationship between total cost and biomass availability.

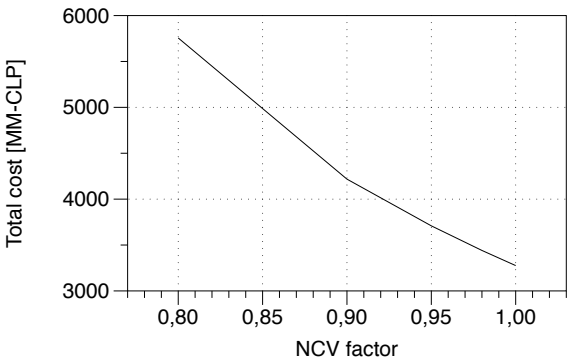

Figure 5.18.: Relationship between total cost and biomass NCV.

6 Discussion and conclusions

This chapter wraps up the presented research with a discussion about the principal contributions. It includes an outlook section with research gaps for future research and finishes with work conclusions.

6.1 Discussion

This work provides a general model to optimize the tactical biomass transport problem for power plants, with a focus on regional supply chains, in a sustainable way. It presents a model structure and a step by step method based on modules to adjust and complement it for the needs of specific local realities.

This section discusses the results implications of the addressed research questions, which are:

1. What are the *key elements* for a regional sustainable biomass supply chain planning for power plants?
2. Is there a better approach to address *sustainability considerations* for the biomass supply chain?
3. Can these considerations be combined in a model to *optimize* a regional power plant supply chain?

6.1.1 Biomass supply chain data model

Question 1: What are the key elements *for a regional sustainable biomass supply chain planning for power plants?*

The work starts by presenting a concrete model to define the biomass supply chain for power plants. The model is built on the basis of the UML language, which allows it to be very specific in terms of the included elements, data, and their relationships.

In the literature, the problem is usually described in terms of flow diagrams and data tables. The relationship between the elements must be understood by means of the specific solution model, and the needed calculation (e.g. an mathematical optimization model). This provides a way for understanding the underlying considered data model, but it does not ease comparisons between different publications. There is no set of standard diagrams used to define the details of the considered problem among the reviewed literature. For this work, UML was chosen to model the considered data, as is it a common language among data scientists.

There are other advantages of this approach, as these kind of models provide an easy way to implement data quality and validity assurance. UML provides paths to direct programing language implementations and data base automatic implementation. This can ease generation of the needed data source in a more robust format than spreadsheets. Spreadsheets provide great flexibility, but they cannot handle large amounts of data, and usually lack of any validation provided by database fields (by e.g. the use of data types) or relationships (by e.g. the use of foreign keys). Researchers can benefit from these data management tools and get the benefits of data error avoidance and inconsistencies for research experiments, which can improve research quality.

From a technical point of view, it is also a very good way to validate and have a base structure for the model data. For this particular work, the implementation of this type of data model served as a communication protocol (like a data translator) between the different tools used in the modules proposed like GIS, LCA, and mathematical optimization.

The evident drawback of this approach is the longer time to define the model. It needs to comply with the strict language specifications and all relationships must be found and specified. UML is a language used often in computer science, but is not necessarily part of others disciplines' curriculum.

The model is able to identify the key elements of the supply chain for the addressed problem. Those element are also found in the addressed case study.
From a supply chain stakeholder point of view, a biomass supply chain data model can serve as a communication tool that can ease the data collection stage from the needed actors. The graphical arrangement to show the needed data to them allows easy identification of data relationships that can speed up the understanding of the specific types of data needed. And if the persons providing the data have a background in data science, they will very likely understand (and have used) the UML standard already, and therefore be able to understand the requirements faster.

Multidisciplinary groups could find this tool as a welcome addition to improve communication in a structured way.

6.1.2 Biomass supply chain sustainability and system objectives

Question 2: Is there a better approach to address sustainability considerations *for the biomass supply chain?*

Sustainability is a complex topic. It aims to connect many elements that were usually not studied together and force interdisciplinary work to assess it as best as possible. The sustainability frameworks analyzed have a clear strategic context. This may suggest that they may not be compatible with models that focus on tactical decisions, but that does not need to be the case. Although big impacts require strategic decisions to be done, small but constant improvements can be obtained at a tactical level. And those changes may be easier to implement than strategic ones. When sustainability is seen as a three pillar problem of economic, environmental, and social dimensions, the first one is usually very well addressed in the literature, while the environmental and social pillars less so [CS14].
As stated by [DMCRVO14], the social objective is usually measured by the number of local jobs [YTGS11], land use changes [CVKK12], and traffic impacts (addressed as potential traffic annoyance [SBDM$^+$14]). For example, the accrued jobs approach is used, as jobs are one of the social elements that can be quantified and therefore included in a mathematical model. Land use changes are a good quantifiable option too, but they have an almost exclusive strategic scope. As for traffic impact, noise had been identified as one of the most important transport annoyances [Pat11], but should be consider with caution because of its subjectivity.

This work shows that although these options may indeed be good starting points, there are more elements than can be considered, and which do not always require a quantification. Also, not every system may require those elements to be considered, and a method to find a custom solution may be preferred.
For this work, the process starts before the mathematical model in a stage of identifying stakeholders' concerns and discussing them between the relevant actors. This was done within the context of the case study, which delivered to the participants a summary of common positive, negative, non-consensus observations, and a set of collected recommendations. This stage created awareness of others' concerns that did not appear in most models in the literature (like concerns about not using a specific biomass (straw), as a proportion would otherwise end up being burned in open fields), and also prepared the groundwork for better communication and the model elements that were assessed.
There are also drawbacks related to this method, as the stakeholders' involvement requires a lot of coordination, interest in participating, discussions on common myths, and past experiences with potential prejudices.
Also, the expectation from a model can grow fast, surpassing the possibilities of a solvable model. It was also a good opportunity to discuss the boundaries of current technology and teach about correct result interpretation.

The case study resulted in jobs quantification, straw burned quantification (as a way to lower the danger of open burning them in the fields), and restrictions on specific routes to avoid traffic and dirt problems in specific sectors.
These elements were identified by following the tasks of the proposed sustainability module. It is a method and a source of ideas that do help find relationships between the identified elements.The method based on these frameworks allow the results of the analysis to be converted into a useful input for the other parts of the model.

6.1.3 Integrated optimization model

Question 3: Can these considerations be combined in a model to optimize *a regional power plant supply chain?*

The objective of generating a model that can solve the problem in a sustainable way is no easy one. There are some attempts in the literature, but they are still uncommon [CS14]. The economic (costs) mono objective is still the most common one [ALP16]. This also shows significant interest in research that considers solution costs (as cost minimization, or profit maximization), and this work considers them too.

Multiobjective mathematical optimization is a tool to combine different optimization objectives. The objective functions used in this work prioritize the minimization of costs, as emphasized in the literature and business practices, while still integrating the other objectives (environmental and social), with the option to decrease the quality of the cost objective in a controlled way.

The results of this case study show that the solution of the multidimensional approach can compete with the classic cost optimization, and that is also able to generate measurable improvements when other dimensions are considered, compared to only using cost optimization. It provides a good way to negotiate with stakeholders about *slightly* more expensive solutions that can lead to big improvements related to other dimensions.

From the case study policy and business context, there is currently little incentive to optimize anything else beside the total cost. But as policies evolve, CO_2 prices increase, community environmental awareness gets stronger, and more strict environmental regulations are put into action, the need to consider multidimensional solutions will be unavoidable.
This works provides a base model and a method to customize it to the specific scenario in a novel approach that is not found in the literature with this emphasis.

6.2 Outlook

Especially for emerging economies, a proper use of resources is paramount to the success of renewable energy initiatives. A key problem of biomass to energy generation is the transport low energy-density raw materials. This problem must be understood along sustainable related criteria to implement solutions that include something other than pure financial interests. All proposed solutions at this point of time should incorporate sustainable considerations that include the usually more complex environmental and social elements in a reasonable way. A new approach for the integration of mathematical optimization with social objectives was made in this work. The concept of having a custom made model, that is dynamic, adaptive, can improve over time, and that follows a specific method, is one that could enhance communication and understanding among stakeholders. This approach could be tested in more scenarios, and the specific ideas found in the different situations could feed into a regional concerns data base to inspire future applications.
To include the implementation concept in the model creation increases the probability of a successful real result. A prototype allows the stakeholders to see how the model inside a system can provide value to the organization and the industry.

The work presented a proof-of-concept and functional prototype. Still, a larger scale platform is needed as a second step to test the feasibility of a system like the one proposed to improve the market collaboration, transparency, and competitiveness of a regional biomass marketplace.
This work suggests a new hypothesis to test in future work: *Information transparency about the economic, ecologic, and social impacts of given industry decisions can change the usual company-local-cost-optimization to more sustainable regional community solutions*, as commented in section 4.4. This collaboration and transparency in search for a regional optimum will imply a cost increase for some stakeholders, compared to their optimal personal solutions. But a better understanding about the positive implications to the region, can be be supported by this model, as it provides with specific impact results to compare the available options. The proposed model could be used as a simulation tool to generate optimized decision alternatives that a given region can promote and that stakeholders can evaluate and compare under transparent criteria.

Another interesting point of research is to implement this model in other industries that require a heavy use of biomass. Biorefineries could gain similar benefits after some model customization for their specific needs.

6.3 Conclusions

Communities can benefit from green electricity production from regional power plants. If a community gets involved in a regional project, there are many benefits to be expected for education, acceptance, collaboration, and innovation. The first step for successful community involvement is integrating sustainability criteria into the solutions. Sustainability must be understood and addressed with the inherent complexity it involves. There is probably no direct shortcut to reach it, and it is probably an unreachable goal, where every iteration towards a better solution, improves it. In this sense, communication among stakeholders and common vocabulary are needed elements for a good understanding.

This work proposes a model to generate optimized solutions for the biomass supply chain for electricity generation. The model includes a way to incorporate community requirements into it, and is able to generate solutions that report sustainability indicators. If implemented for a regional biomass marketplace in a transparent way, every stakeholder could evaluate the same information about the impacts of the solutions, the benefits, and the problems they create. This could make stakeholders' negotiations easier, help explain the effect of specific decisions, and in the long term, help create or support a regional sustainable development concept that relies on transparent data and information about the consequences of specific decisions.

Green electricity sources add more complexity to the grid. They are usually generated when the environmental energy is available, which can lead to an energy surplus on sunny or windy days, but to a lack of it on calm and cloudy days. The solution about the best electricity mix generation is currently not about using one perfect technology, but to have a combination of several green technologies that help grid balance and supply security. With this in mind, biomass can play an important role as natural energy storage for supporting grid balance. The importance of grouping power plants' raw materials to the local products industry gives it the advantage of helping by using waste biomass and helping reach a circular economy concept. For example, waste forest biomass produces environmental impacts when left forgotten in the woods. For this reason, a better use of it can provide benefits from an economic point of view, manage the emissions related to them in controlled environments (like power plants), and generate social benefits, such as avoiding open fires to burn waste biomass. As the supply chain plays a big role on low density fuels like biomass, the optimized sustainable transport solutions like the ones generated by models like the one presented in this work can effectively help the implementation of biomass energy technologies in more locations around the world.

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A Appendix: Mathematical optimization model definitions

Sets

B = the set of biomass types, indexed by the letter b.
E = the set of the considered impact categories related to the environmental emissions, indexed by the letter e.
H = the set of harvesting/collection sites, indexed by the letter h.
I = the set of by-products that can be generated for different types of biomass, indexed with the letter i.
M = the set of transport options (modes), indexed by the letter m.
P = the set of power plants, indexed with the letter p.
R = the set of resources besides biomass needed for the conversion process, indexed with the letter r.
S = the set of storage facility locations, indexed with the letter s.
T = the set of time periods, indexed with the letter t.

Parameters

BD_b = density (weight) of dry biomass type b, [weight/volume], kg/m^3
$BH_{b,t}$ = humidity content of dry biomass type b at time period t, dimensionless, expressed as a decimal
$BDEGS_{b,t}$ = percentage of degraded biomass b on storage, at period t, dimensionless, expressed as a decimal
$CAPBP_p$ = maximum volume capacity to process biomass in power plant p, [volume/time], $m^3/year$
$CAPINVP_p$ = maximum volume capacity of storage at the power plant p, [volume], m^3
$CONV_b$ = conversion ratio of biomass b to electricity, [energy/mass], kwh/kg
D_t = available time (effective duration) of the period, [time], day.
DEM_t = energy demand for the time period t, [energy/time], kwh/day
$EFFH_{h,b,t}$ = percentage of effective collected biomass b in the operation at harvest site h, at period t, dimensionless, expressed as a decimal
$HRate_{h,b,t}$ = biomass harvesting rate at the site h, for the biomass type b, at the time period t, [weight/time], kg/day
$INVS0_{b,s}$ = initial inventory (period 0), for biomass b, at storage location s, [weight], kg
$INVP0_{b,p}$ = initial inventory (period 0), for biomass b, at power plant p, [weight], kg
ITR_s = inventory turnover ratio, which is the number of times the inventory is replaced, per period, dimensionless, expressed as a decimal
LSL_s = lower storage capacity limits for the location s, [volume], m^3
$MPCAPBP_p$ = least percentage of capacity that needs to be processed for at plant p, dimensionless, expressed as a decimal
$PBEL_{h,b,t}$ = environmental harvest potential at the site h, for the biomass type b, at time period t, [weight], kg
$PBSL_{h,b,t}$ = social harvest potential at the site h, for the biomass type b, at time period t, [weight], kg
$PBTL_{h,b,t}$ = technical biomass harvest potential at the site h, for biomass b, at time period t, [weight], kg
$RESMAX_{p,r,t}$ = capacity limit to use resource r at the power plant p, at period t, [unit], $units$
$RESREQ_{b,p,r}$ = amount of resource r needed to convert one unit of biomass b into electricity at the power plant p, [unit/mass], $units/kg$
SS_t = system safety stock for time period t, [energy], kwh
$SHIPMAXWEIHS_{m,t,h,p}$ = maximum weight to transport by mode m, at time period t, from site h, to storage s, [weight], kg
$SHIPMAXWEISP_{m,t,h,p}$ = maximum weight to transport by mode m, at time period t, from storage s, to power plant p, [weight], kg
$SHIPMAXWEIHP_{m,t,h,p}$ = maximum weight to transport by mode m, at time period t, from site h, to power plant p, [weight], kg
$SHIPMAXVOLHS_{m,t,h,s}$ = maximum volume to transport by mode m, at time period t, from site h, to storage s, [volume], m^3
$SHIPMAXVOLSP_{m,t,s,p}$ = maximum volume to transport by mode m, at time period t, from storage s, to power plant p, [volume], m^3
$SHIPMAXVOLHP_{m,t,h,p}$ = maximum volume to transport by mode m, at time period t, from site h, to power plant p, [volume], m^3
USL_s = upper storage capacity limits for the location s, [volume], m^3
$W_{h,t}$ = weather factor that influences the harvest rate at the site h, for the period t, dimensionless, expressed as a decimal
WD_t = changes of the total demand by the influence of weather, dimensionless, expressed as a decimal

Parameters: cost related

$CPBH_{b,h,t}$ = cost of harvest and acquisition of a unit of biomass b, at the harvest site h, at period t, [monetary unit / weight], \$/kg
$CIUS_{b,s,t}$ = cost of storage of a unit of biomass b, at the storage location s, at time period t [monetary units/weight], \$/kg
$CIUP_{b,s,t}$ = cost of storage of a unit of biomass b, at the power plant p, at time period t [monetary units/weight], \$/kg
$CBCV_{b,p}$ = variable cost of converting a unit of biomass b, at the power plant p [monetary units/weight], \$/kg
$CBP_{i,b}$ = credit of converting a unit of biomass b to the by-product i [monetary units/weight], \$/kg
$CRE_{p,t}$ = credit for producing an amount of renewable energy [monetary units/energy], \$/kwh
$TFCM_{b,m}$ = fixed cost of transporting a unit of biomass b, using transport mode m, one period, [monetary unit], \$
$TVCM_{b,m}$ = variable cost of transporting a unit of biomass b, a distance of 1 [km], using the transport mode m, [monetary unit/weight], \$/kg

Parameters: emissions related

$EBHV_{e,b,h}$ = emissions for the acquisition of a unit of biomass b, at the harvest site h, for the impact category e, [impact category unit], CO_2 – eq, etc.
$ETBU_{e,b,m}$ = emissions for the transport of a unit of biomass b, using the transport mode m, for the impact category e, [impact category unit], CO_2 – eq, etc.
$ESBU_{e,b}$ = emissions for the storage of a unit of biomass b, for the impact category e, [impact category unit], CO_2 – eq, etc.
$EPCV_{e,b,p}$ = emissions for the biomass to energy conversion process of a unit of biomass b, at the power plant p, for the impact category e, [impact category unit], CO_2 – eq, etc.

Parameters: case study related

$BH_{b,t}$ = average humidity content of the biomass b, at the time period t, expressed as a decimal
$MinBH_p$ = minimum humidity content compatible with the power plant p desired operation, expressed as a decimal
$MaxBH_p$ = maximum humidity content compatible with the power plant p desired operation, expressed as a decimal
$CPBH_{b,i,t}$ = cost of purchase and harvest of biomass b, at harvest site i, at time period t, [monetary units], \$
JBA_b = direct jobs related to biomass b unit acquisition cost, [jobs per year/monetary units], *jobs*/\$
JBT_b = direct jobs related to biomass b unit transport cost, [jobs per year/monetary units], *jobs*/\$
JBS_b = direct jobs related to biomass b unit storage cost, [jobs per year/monetary units], *jobs*/\$
JBP_b = direct jobs related to a unit of all bi-products costs for biomass b, [jobs per year/monetary units], *jobs*/\$
JPP_b = direct jobs related to biomass b unit conversion cost at power plants, [jobs per year/monetary units], *jobs*/\$
JIT = direct jobs related to the cost to implement a storage location, [jobs per year/monetary units], *jobs*/\$
$DHS_{h,s,m,t}$ = distance between harvest and storage, for transport mode m, at time period t, [length], *km*
$DHP_{h,p,m,t}$ = distance between harvest and power plant, for transport mode m, at time period t, [length], *km*
$DSP_{s,p,m,t}$ = distance between storage and power plant, for transport mode m, at time period t, [length], *km*
$CUIS_{b,s}$ = inventory cost of one unit of biomass b, at at storage location s, [monetary units/weight], \$/kg
$CUIP_{b,p}$ = inventory cost of one unit of biomass b, at at power plant p, [monetary units/weight], \$/kg
$TFCM_{b,m}$ = transport fixed cost (period length scope) of using medium m for every unit of transported biomass b [monetary units/weight], \$/kg
$TVCM_{b,m}$ = variable cost of using medium m for every unit of transported biomass b [monetary units/weight], \$/kg

Variables: integer

bs_s = integer variable that states if a storage facility should be implemented at location s, dimensionless, value 0 or 1.

Variables: continuous

$capinvs_s$ = capacity of the suggested storage at location s, [volume], m^3
$ehp_{h,b,t}$ = effective harvest potential at the site h, for the biomass type b, at the time period t, [weight], kg
$en_{p,t}$ = total electricity generated at power plant p in the period t, [energy], kwh
$harv_{h,b,t}$ = amount of biomass b harvested at site h in the period t, [weight], kg
$invp_{b,p,t}$ = inventory level of the power plant p at the time period t, [weight], kg
$invs_{b,s,t}$ = storage inventory level for biomass b at location s at period t, [weight], kg
$shiphp_{m,b,t,h,p}$ = amount of transported biomass b from harvest sites h to power plants p using transportation mode m, [weight], kg
$shiphs_{m,b,t,h,s}$ = amount of transported biomass b from harvest sites h to storage s using transportation mode m, [weight], kg
$shipsp_{m,b,t,s,p}$ = amount of transported biomass b from storage s to power plants p using transportation mode m, [weight], kg
$usedbp_{b,p,t}$ = used biomass b at the power plant p at period t, [weight], kg
DY = sum of all effective production periods of the year, [time], $days$

Variables: continuous; cost related

c_tap = total annualized cost of the transport plan, [monetary units], $
c_if_s = cost to implement a storage facility at location s, [monetary units], $
c_it = total (storage) infrastructure cost, [monetary units], $
c_ba = total biomass acquisition cost, [monetary units], $
c_bt = total biomass transport cost, [monetary units], $
c_bs = total biomass storage cost, [monetary units], $
c_pp = total power plants operational cost, [monetary units], $
c_bp = total by-product credits, [monetary units], $
c_re = total renewable energy credits, [monetary units], $

Variables: continuous; environmental related

e_tap_e = total annualized emissions of the transport plan per impact category e, [impact category unit], CO_2-eq, etc.
e_bh_e = emissions from biomass acquisition per impact category e, [impact category unit], CO_2-eq, etc.
e_bt_e = emissions from biomass transport per impact category e, [impact category unit], CO_2-eq, etc.
e_bs_e = emissions from biomass storage per impact category e, [impact category unit], CO_2-eq, etc.
e_pp_e = emissions from power plants operation per impact category e, [impact category unit], CO_2-eq, etc.

Variables: continuous; social related

s_arw = associated regional workplaces, [jobs per year], *jobs*
s_fwb = total amount of forest waste biomass used, [weight], kg

B Appendix: SIC

Figure B.1.: SIC, electric infrastructure (CDEC-SIC, 2015).

C Appendix: Maps of Araucanía Region, Chile

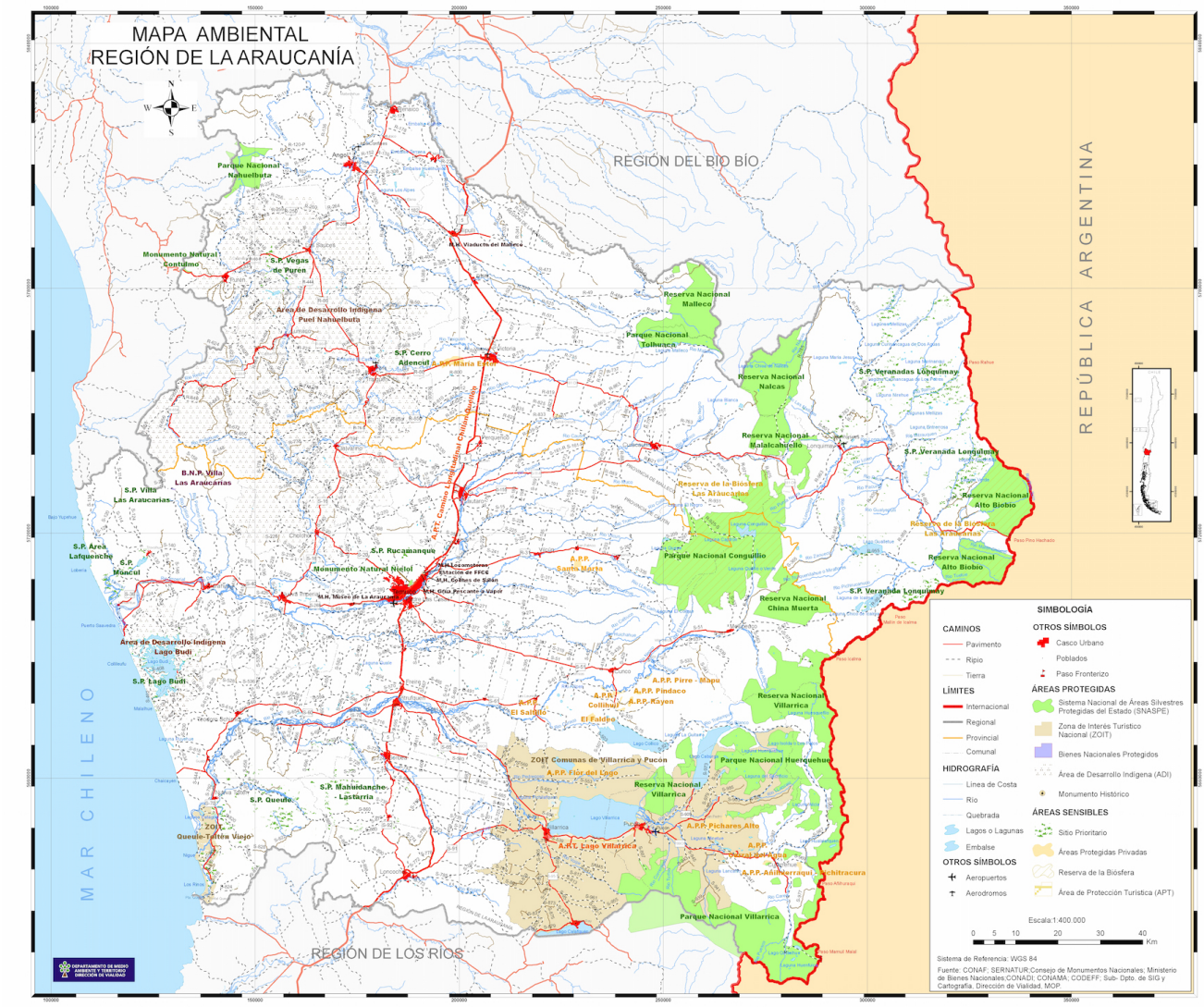


Figure C.1.: Araucanía Region, Chile. Source: Mapas Ambientales, Ministerio de Obras Públicas, Gobierno de Chile, 2009

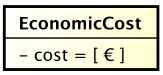
D Appendix: Supply chain problem structure: a graphical model

The problem description is described following the order of these sets. Every data class and main relationships are presented. At the end of this section, a diagram with the complete data model containing all data classes and relationships is included for a general overview. The first three sets include all the required data for the model. The forth one (Solution data) contains only data generated by the model. Data value dimensions are presented as unit examples next to the data name. A special case is used for costs, environmental, and social attributes, which are color coded, and the units are commented on the section D.1.

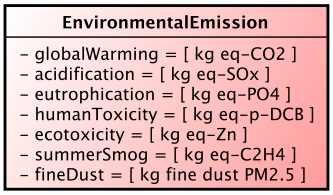
D.1 Assessment data

Assessment data is a special type of data which is used to rate and compare different solutions, which closely relate to the three named sustainability dimensions and are described in the next paragraphs.

Economic cost: it is used to quantify all finance data. Every aspect of the problem that incurs a cost, an investment, receive incentives, or other type of money related operation relates to this data type.



Environmental emission: this element encapsulates relevant data to measure environmental impacts. It considers emissions that are standard LCIA impact categories. The specific categories to include must be based on the results of the social and LCIA modules of the proposed model. This example includes global warming, acidification, eutrophication, human toxicity, ecotoxicity, summer smog, and fine dust.



Social impact: it encapsulates relevant social indicators. They should be based after the social module tasks. Here are some examples included for the impact categories *worker*, *consumer*, *local community*, *society* and *value chain actors* (inspired by [BNVNV+11]). This selection was made to focus the needed data on the specific transport planning problem. The subcategories considered in every category are listed below.

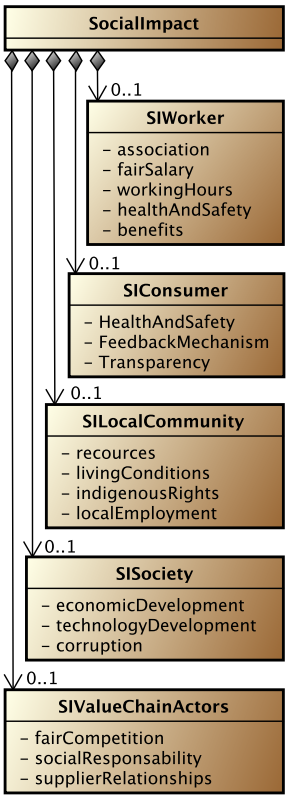
SIWorker: Freedom of association and collective bargaining, Fair salary, Working hours, Health and safety, Social benefits/social security. [1]

SIConsumer: Health and safety, Feedback mechanism, Transparency.[2]

SILocalComunity: Access to material resources, Safe and healthy living conditions, Respect of indigenous rights, Local employment.[3]

SISociety: Contribution to economic development, Technology development, Corruption.[4]

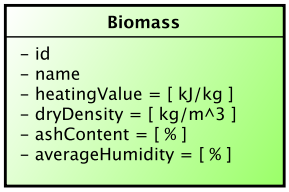
SIValueChainActors: Fair competition, Promoting social responsibility, Supplier relationships.[5]



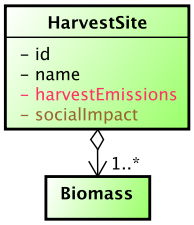
[1] Subcategories not included: Child labor, Forced labor, Equal opportunities/discrimination.
[2] Subcategories not included: End of life responsibility, Consumer privacy.
[3] Subcategories not included: Access to immaterial resources, Community engagement, Delocalization and migration, Cultural heritage, Secure living conditions.
[4] Subcategories not included: Public commitments to sustainability issues, Prevention and mitigation of armed conflicts.
[5] Subcategory not included: Respect of intellectual property rights.

D.2 Time independent data

Biomass: several types of biomass raw materials can be considered. Examples are woodchip, husk, and bark. The compatible types are restricted by the technologies of the considered power plants on the system. They are defined in terms of a unique identifier, name, heating value (kJ/kg), dry density (kg/m^3), and expected average ash content (%).

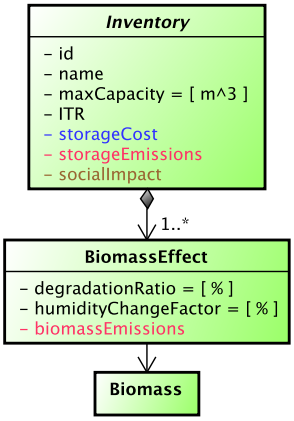


Harvest site: these are the places where the biomass is produced or collected. The time independent data about harvest sites include a unique identifier, name, and a set of one or more types of biomass that it produces[6].



Inventory: the abstract description of inventory is to describe characteristics of all the considered elements that are able to store biomass for longer than one period. For the data model, the inventory is an abstract class that shares every element that is allowed to store biomass for longer than a time period. It includes a unique identifier, a name, a maximum storage capacity, a set of biomass effect descriptions, and the maximum inventory turnover ratio (ITR) policy[7].

Biomass effect: describes every type of biomass that can be stored in the inventory object and the effect that the storage has on the biomass every time period. It includes a humidity change factor and a degradation ratio which represents mass reduction. Both are accounted per time period.

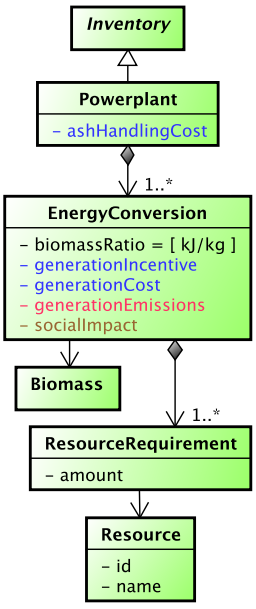


Power plant: they are responsible for the biomass to energy conversion. They inherit the properties of the inventory abstract class and add specific characteristics related to power plants. They include a list of energy conversion parameters, for every type of compatible biomass.

Energy conversion: describes the parameters for the conversion process for every compatible biomass type for the related power plant. They consist of the mass-to-energy conversion ratio and assessment data.

Resource requirement: every energy conversion description includes a list of resources (besides biomass) needed for the conversion. A recipe of resources can be made by considering the list of all this elements.

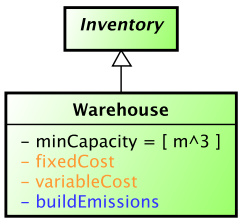
Resource: it refers to resources beside biomass that are needed for the operation of the power plant. For example: water, a special group of people, etc. They are identified by a name.



[6] Other time dependent data like 'specific periods a biomass type is available', is described later in the 'Harvest potential' data class.

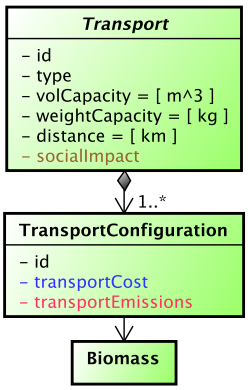
[7] The inventory turnover ratio represents the maximum number of times the inventory can be completely replaced, in each time period.

Warehouse: they can be used to aggregate biomass from many harvest sites for a more efficient transport or to pre-process the biomass before the shipping to the power plant. They inherit the properties of the inventory abstract class and add specific characteristics related to warehouses, like minimum wanted stored capacity and assessment parameters.



Transport: they describe all the available transport options for every route. They are described in terms of a unique identifier, a transport type (like *truck* or *train*), weight and volume capacities, and the route distance. A list of compatible biomass is included as transport configurations options.

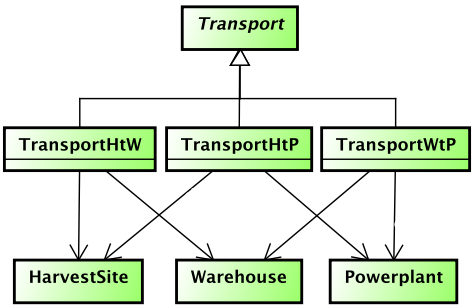
Transport configurations: they provide specific assessment data for every type of compatible biomass.



TransportHtW: *harvest site* to *warehouse* transport specifies the specific origin and destination of the transport description.

TransportHtP: *harvest site* to *power plant* transport specifies the specific origin and destination of the transport description.

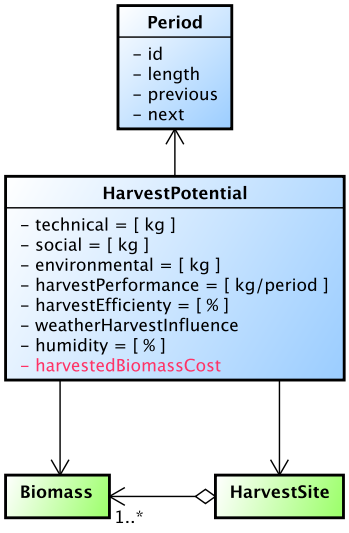
TransportWtP: *warehouse* to *power plant* transport specifies the specific origin and destination of the transport description.



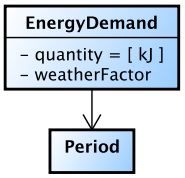
D.3 Time dependent data

Period: period represents the length of the time interval shared for every time dependent data.

Harvest potential: complements the basic information for harvest sites. It includes the economic, environmental, and social harvest availability for every period and every biomass type. It also includes a limit on how much biomass can be harvested (performance) in a given time period for every biomass type.

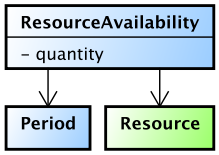


Energy demand: the demand for electricity is for every time period and needs to be satisfied by all the power plants in the system. A weather factor allows some overall predictions to be considered[8].



[8] The weather factor could also be used to simulate weather scenarios.

Resource availability: the availability of resources at every time period is also considered. It is a common limit for all power plants.



For a general overview of all the data required for the model, figure D.1 shows all the data classes and associations together.

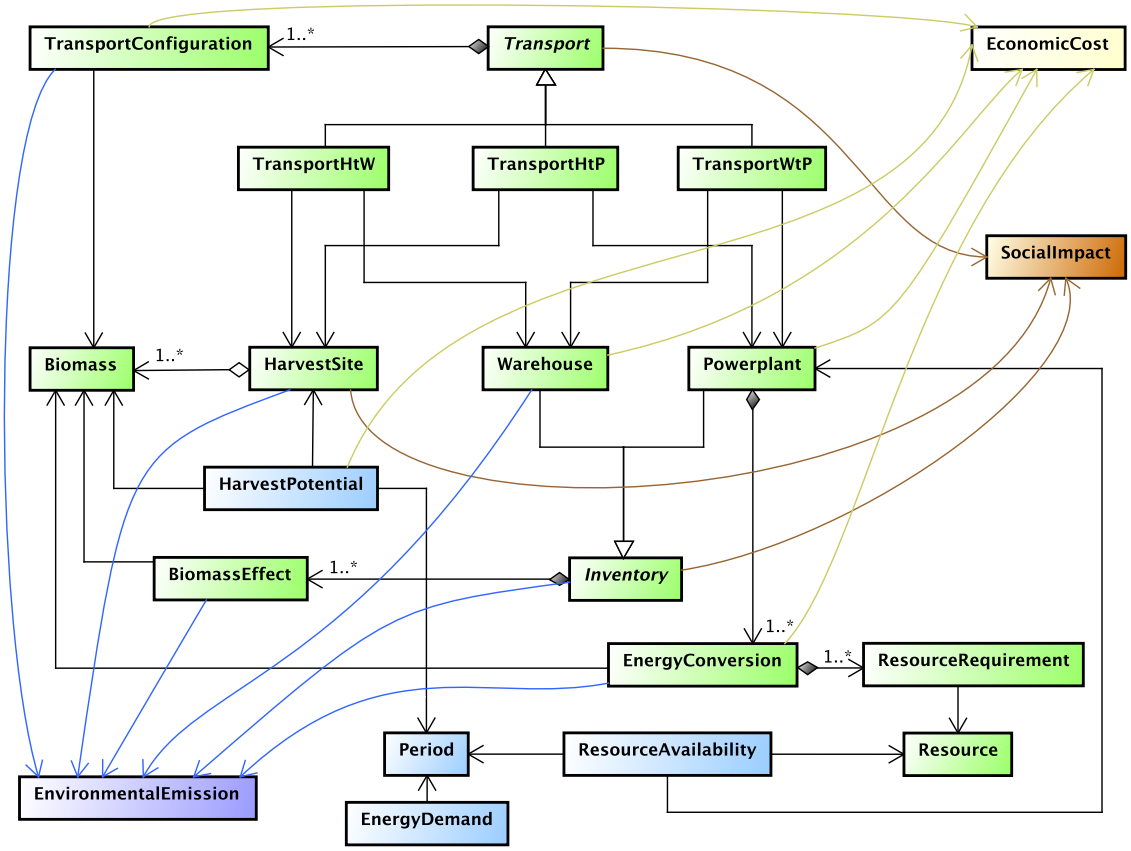
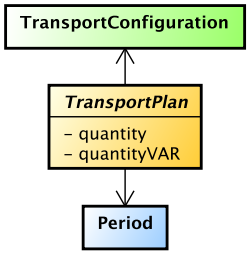


Figure D.1.: All source data classes (UML Class diagram).

D.4 Solution data

The solution data consist of a set of elements that correspond to the output of a single solution of the model.

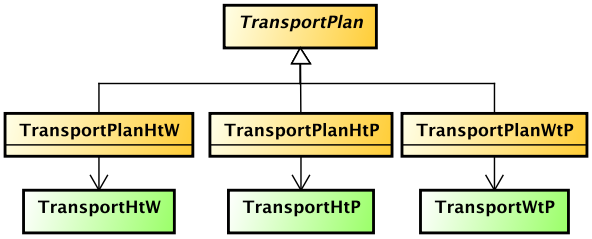
Transport plan: the transport plan corresponds to the main expected tactical result. It consist of exact quantities to be transported for every *transport configuration* and for every time period. For the data model, the inventory is an abstract class that shares every element that specifies transport from one specific point to another.



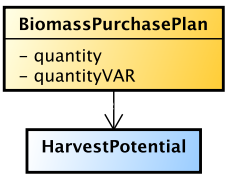
Transport plan HtW: is a concrete *transport plan* data class that specifies the transport between *harvest sites* and *warehouses*.

Transport plan HtP: is a concrete *transport plan* data class that specifies the transport between *harvest sites* and *power plants*.

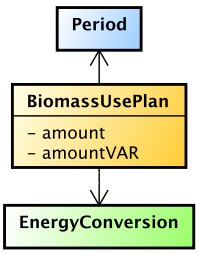
Transport plan WtP: is a concrete *transport plan* data class that specifies the transport between *warehouses* and *power plants*.



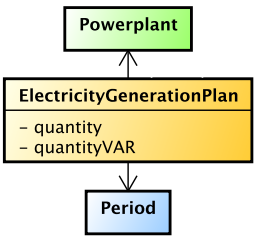
Biomass purchase plan: consists of the amount of biomass to purchase for every *harvest site*, for every *biomass* type and for every *period*.



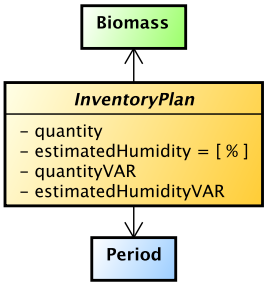
Biomass use plan: specifies the amount of biomass that will be assigned for every *energy conversion* process at every *power plant*.



Electricity generation plan: consists of the expected energy output for every power plant, for every time period.

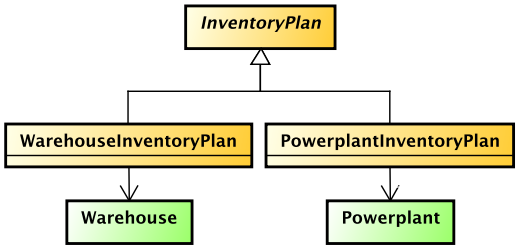


Inventory plan: represents the expected inventory level for every biomass type at every location that is allowed to store biomass for longer than a time period. For the data model, the inventory is an abstract class that share every element that provides biomass storage.

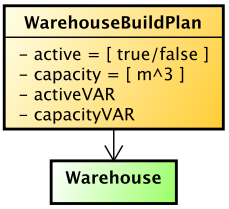


Warehouse inventory plan: contains the expected inventory levels for *warehouses*.

Power plant inventory plan: it contains the expected inventory levels for *power plants*.



Warehouse built plan: contains the data about the strategic decision of the location and size of new warehouses. The *active* parameter is *true* when the warehouse should be built and the *capacity* parameter specifies the optimal size.



E Appendix: Theoretical considerations: optimization and LCA

E.1 Motivation

Operation Research (OR) tools like mathematical optimization offer a structured method to find optimal solutions for complex problems and are widely used to solve economic trade-offs. On the other hand, LCA is one of the preferred approaches for the assessment of environmental impacts for a product. The combination of these two methods to address a problem which considers economic and environmental aspects has a high potential for good results. Both techniques are well accepted, as they are commonly used and the solutions obtained are valued.

E.2 Objective

The proposed raw material supply model brings mathematical optimization and LCIA methods together to provide scientific based advice for decisions makers dealing with the described challenges. This section addresses the theoretical implications of integrating these two model paradigms together and recommendation for achieving the expected results.

E.3 General definitions

- **LCA**: a balanced material flow model with allocation strategies to assess environmental impacts of a product life cycle.
- **Mathematical optimization**: a mathematical model that minimizes or maximizes an objective function value, under a set of mathematical constraints.
- **Biomass**: set of all biomass products to be used as raw materials for the considered supply chain.
- **Harvest site**: biomass production locations. They allow biomass storage.
- **Storage location**: specialized biomass storage warehouses.
- **Power plant**: facilities for the conversion from biomass to energy. They allow biomass storage.
- **Transport configuration**: transport option between two locations: harvest sites, storage locations, or power plants.

E.4 System boundaries

The system boundaries for the raw materials supply problem begin at the harvest sources and end at the conversion process in the power plants. From an LCIA perspective, harvest sources have an external input flow of biomass (raw materials needed for the biomass production), and power plants have an external output flow (energy converted from biomass, the problem functional unit). Warehouses have only biomass flows inside the system boundaries[1].

E.5 Modules tasks division

The addressed transport problem models takes advantage of the LCI model structure and uses a linked mathematical optimization model to define the flow allocations for an optimum solution, defined by a set of objective functions.
The link between LCI and mathematical optimization models requires special consideration for a seamless coupling:

1. A set of all biomass types that are going to be transported needs to be done. They will define the decision variables for the mathematical optimization model that will correspond to the LCI biomass flow values.

2. The problem *structure* is defined by the LCI modeling. Processes and their relations in terms of material flows are defined in a LCI model. Allocation decisions for all biomass flows inside the system boundaries are not relevant at this point, as they will be optimized by the mathematical model.

3. The problem *objective* is defined by the mathematical optimization model. A set of objective functions is defined to measure the value of a solution and be able to compare them. They could be environmental aspects based on LCIA impact categories, economic aspects, etc.

[1] Storage locations with biomass production could be considered as a fourth element. They should consider an external input flow of biomass.

4. The *allocations* are calculated by the mathematical optimization model. This model is also responsible for maintaining the flows balance in the system boundaries. *Capacity* restrictions of processes are considered by the mathematical optimization model.

5. The *dynamic* aspect of the problem is addressed by replicating instances of the LCI model with different flow value variables within one mathematical optimization model, with several periods[2].

E.6 LCI processes and optimization constraints

The mathematical optimization and LCI models link closely with the allocation and biomass flows values. Strictly speaking, for every flow in the LCI model, a corresponding balance constraint should exist in the mathematical optimization model. These constraints also maintain the problem period to period (dynamic) balance. A general formulation should look like equation (E.1).

$$\sum^{A} input_{p,b,t} + inventory_{p,b,t} - \sum^{B} output_{p,b,t} - inventory_{p,b,t+1} = 0 \quad \forall_{p,b,t} \tag{E.1}$$

Where A is the set of all biomass input flows to the process p, B is the set of all biomass output flows of the process p, b represents a specific biomass type, and t a specific time period. Figure E.1 shows a graphical representation of an hypothetical process with input and output biomass flows.

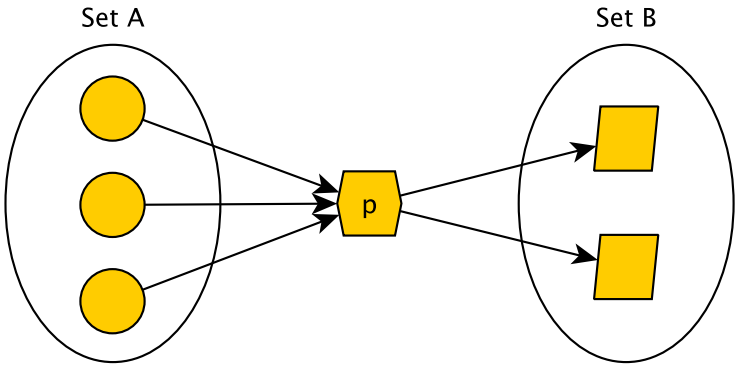


Figure E.1.: Biomass material flow of an abstract example.

E.7 LCI flows and optimization variables

Every biomass flow (transport) defined in the LCI model requires exactly one variable in the mathematical optimization model. After giving the problem some reasonable structure, the maximum number of flows can be calculated. Let us define:

- Processes: four types of supply chain processes are considered:
  - Harvest sites (HS) which have only system external biomass input flows.
  - Power plants (PP) which have only system external biomass output flows.
  - Warehouses (WH) which have only system internal biomass flows.
  - Transport configurations (TC), which have only system internal biomass flows[3]. They represent the transport of biomass from one specific location to another, using a specific mode.
- Levels: they define a hierarchy about how biomass flows through the system. By looking at the biomass flows dependencies in the LCI model, every *process* can be allocated at a specific level.

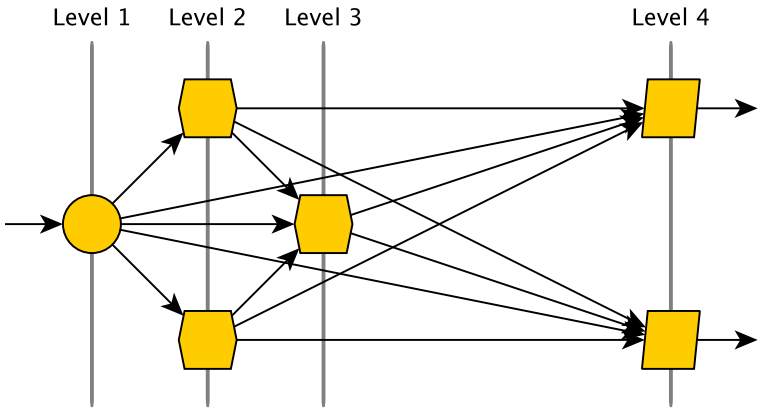


Figure E.2.: Process assigned to levels for biomass flows of an abstract example.

Figure E.2 shows an example where the transport processes are included in the other processes. With this structure, equation (E.2) calculates the maximum number of possible flows in the system.

$$MaxFlows = \sum_{i=1}^{L-1} \left(E_i \cdot \sum_{j=i+1}^{L} E_j \right) + T_{HS} + T_{PP} \tag{E.2}$$

Where L is the number of levels of the problem, E_i are the number of processes in level i, T_{HS} is the total number of harvest sites, and T_{PP} is the total number of power plants.

If the transport options are modeled as processes, the model structure changes. This approach allows the use of several different transport options between two locations. As transport configurations are specific for every location pair, they have the same number of biomass input and output flows[4]. As the only way to transport biomass is by using a transport configuration, all *even* levels are composed exclusively by transport processes. Figure E.3 shows an example.

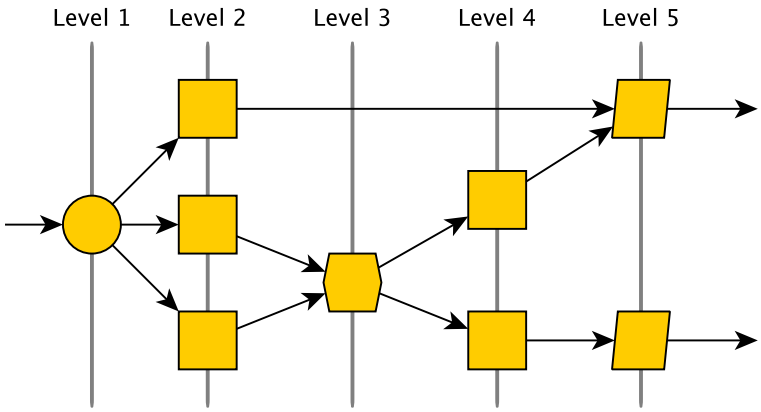


Figure E.3.: Problem structure with explicit transport processes for biomass flows of an abstract example.

[2] Some dynamic Life Cycle Assessment (dLCA) models use the same approach of changing the flows' expected values to include the dynamic aspect. Others consider the dynamic aspect by varying impact categories parameters.

[3] The idea of allowing warehouses and transport configurations to have system external input or output flows can be modeled with the addition of other harvest sites. This allows, for example, the consideration of biomass imports into or exports out of the system boundaries.

[4] Biomass losses during transport are not considered for this example, but can be added easily by modifying the mathematical optimization balance constraints.

Under these assumptions, the maximum number of possible flows is now equal to the total system flows (assuming there are no isolated processes, which would be ignored in an LCI). Equation (E.3) shows how to calculate the number of system flows.

$$MaxFlows = SystemFlows = 2 \cdot \sum_{i=2\ \&\ even}^{L} (E_i) + T_{HS} + T_{PP} = 2 \cdot T_{TC} + T_{HS} + T_{PP} \tag{E.3}$$

The parameter T_{TC} is the total number of transport configurations.
If we extend the results for several types of biomass we can conclude that the total number of flow variables for a linked mathematical optimization model should be equal to the number of LCI biomass system flows, multiplied by the number of biomass types that every flow includes. As harvest sites are always be assigned to the first level, and power plants to the last level, we can calculate the number of variables in the model with equation (E.4).

$$FlowVariables = 2 \cdot \sum_{i=2\ \&\ even}^{L} \sum_{j=1}^{E_i} BT_{ij} + \sum_{k=1}^{E_1} BT_{1k} + \sum_{m=1}^{E_L} BT_{Lm} \tag{E.4}$$

The parameters BT_{ij} correspond to the number of biomass types in the process j at level i.

E.8 LCIA impacts and optimization objective function

An objective function of the mathematical optimization model can assess the environmental impacts of the solution. From an LCIA perspective, this requires the calculation of impact categories using the concrete data provided by the LCI. As the calculation of these impacts requires only linear equations, the calculation is not done in a specific LCA software, but on the mathematical optimization model.To speed up calculations, only the parameters that are influenced by the flows inside the system boundaries should be included, that means only the environmental information that would allow the mathematical optimization model to compare two different solutions is needed. Upstream chains should be simplified in a pre-optimization stage to avoid repeating the same calculations over and over again. This results in using a selection of impact categories within the borders of the system considered in the optimization model. This approach follows the LCIA standard calculation methods, which means that an LCA software should output the same results.

F Appendix: Images of the case study power plant, Araucanía Region, Chile

Figure F.1.: Image of the biomass loading procedure.

Figure F.2.: Image of an example biomass.

Figure F.3.: Image of the biomass mixing facility.

Figure F.4.: Image of the power plant boiler building.

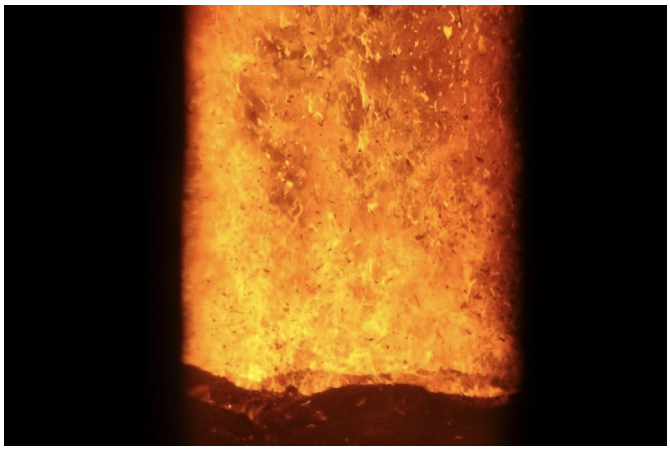


Figure F.5.: Image of the combustion inside the boiler.

Figure F.6.: Image of the electricity generator.

Figure F.7.: Image of the cooling elements.

G Appendix: Focus groups results summary for participants

Estudio social: generación de energía eléctrica en la región de la Araucanía

Resumen ejecutivo

Responsable: Bernardo Cienfuegos, *Karlsruhe Institut of Technology*, Alemania
Contacto: bernardo.cienfuegos@kit.edu | mail@bcienfuegos.net
Fecha documento: Agosto 2015

Objetivo: explorar temas de interés local sobre la generación de energía eléctrica utilizando biomasa en la región de la Araucanía. Este trabajo fue realizado en el contexto del trabajo de doctorado del responsable de este estudio.

Metodología: se realizaron reuniones tipo *focus group*[1] moderadas con los distintos actores. No se guardó registro de los participantes, ni fueron estos asociados con las opiniones, para garantizar un ambiente de libre discusión. El estudio fue realizado durante el mes de mayo 2015.

Participantes: fueron entrevistados un total de 10 grupos representando distintos actores involucrados: encargados gubernamentales de temas de energía y medio ambiente, trabajadores de empresas generadoras de electricidad (diferentes niveles), representantes de empresas transportistas, investigadores de universidades locales, y agrupaciones locales representantes de la población. Se complementaron las observaciones con 30 entrevistas personales realizadas a transeúntes en el centro de la ciudad de Temuco.

Principales elementos positivos observados por todos los grupos
- Económico: generación de empleos para la región, tanto directos como indirectos.
- Económico: potencial aprovechamiento de desechos agrícolas u otros, especialmente la paja.
- Medioambiental: disminución de la quema de paja en campos, con los peligros y la contaminación asociada, dado que los fardos pueden ser utilizados como materia prima.
- Social: cierto nivel de independencia al generar electricidad en la región, con una potencial ventaja en caso de problemas de distribución eléctrica ocasionados por alguna catástrofe.

Principales elementos negativos observados por todos los grupos
- Social: restos de paja encontrados en ciertas calles y carreteras por el aumento del transporte en camiones, dada la dificultad para poder encarparlos perfectamente.
- Medioambiental: preocupación por los potenciales incendios en grandes inventarios de biomasa.

Principales elementos donde no fue observado consenso entre algunos de los grupos
- Medioambiental: no se observó consenso entre los grupos, si plantas de energía basadas en biomasa generan un aumento considerable en la contaminación ambiental de la zona.
- Social: para el caso particular de Comasa, preocupaciones por el potencial ruido que produce la planta en regiones cercanas. No parece haber acuerdo si la planta efectivamente genera ruido molesto perceptible durante la noche en ciertas zonas cercanas, o si proviene de otras fuentes.

Principales sugerencias expresadas por al menos uno de los grupos
- Incluir la participación ciudadana desde la planificación en nuevos proyectos de generación.
- Entregar información pública sobre las emisiones producidas por las plantas de energía.
- Informar sobre las ventajas medioambientales entre las plantas termoeléctricas que utilicen materias primas renovables (como biomasa) y fósiles (como carbón).
- Ubicar las plantas de energía fuera de valles que pudiesen acumular las emisiones.
- Evaluar proyectos de calefacción distrital acoplados con generación de energía eléctrica, dada la preocupación por la contaminación ambiental asociada a la quema de leña para calefacción.

1 https://es.wikipedia.org/wiki/Grupo_focal

H Appendix: LCIA Parameters

Table H.1.: ReCiPe 2016 estimated midpoint and endpoint factors for the considered biomass types

		Sawdust	Splinter	Pine bark	Wastewood	Shaving	Eucalyptus bark	Burdock
Human health								
Global Warming	DALY/kg CO2 eq.	1.215E-08	9.346E-09	6.075E-09	9.346E-09	1.215E-08	6.075E-09	9.814E-09
Stratospheric ozone depletion	DALY/kg CFC11 eq.	1.500E-10	1.500E-10	1.500E-10	1.500E-10	1.500E-10	1.500E-10	1.500E-10
Ionzing Radiation	DALY/kBq Co-60 emitted to air eq.	9.151E-13	9.151E-13	9.151E-13	9.151E-13	9.151E-13	9.151E-13	9.151E-13
Fine particulate matter formation	DALY/kg PM2.5 eq.	2.117E-07	2.647E-07	3.970E-07	2.647E-07	2.117E-07	3.970E-07	2.514E-07
Photochemical ozone formation	DALY/kg NOx eq.	1.741E-09	1.339E-09	9.376E-10	1.339E-09	1.607E-09	9.376E-10	1.406E-09
Toxicity (cancer)	DALY/kg 1,4-DCB emitted to urban air eq.	3.280E-09	4.100E-09	6.150E-09	4.100E-09	3.280E-09	6.150E-09	3.895E-09
Toxicity (non-cancer)	DALY/kg 1,4-DCB emitted to urban air eq.	4.625E-08	4.625E-08	4.625E-08	4.625E-08	4.625E-08	4.625E-08	4.625E-08
Water consumption	Daly/m3 consumed	4.802E-11	5.518E-11	5.256E-11	7.538E-11	1.096E-10	6.941E-11	7.585E-11
Damage to human health	DALY	2.753E-07	3.259E-07	4.566E-07	3.259E-07	2.753E-07	4.566E-07	3.130E-07
Terrestrial ecosystems								
Global Warming	species.yr/kg CO2 eq.	3.666E-11	2.820E-11	1.833E-11	2.820E-11	3.666E-11	1.833E-11	2.961E-11
Photochemical ozone formation	species.yr/kg NOx eq.	2.477E-10	1.905E-10	1.334E-10	1.905E-10	2.286E-10	1.334E-10	2.000E-10
Acidification	species.yr/kg SO2 eq.	1.007E-10	1.258E-10	1.888E-10	1.258E-10	8.809E-11	1.888E-10	1.195E-10
Toxicity	species.yr/kg 1,4-DBC emitted to industrial soil eq.	7.959E-12	7.959E-12	7.959E-12	7.959E-12	7.959E-12	7.959E-12	7.959E-12
Water consumption	species.yr/m3 consumed	2.920E-13	3.355E-13	3.196E-13	4.584E-13	6.667E-13	4.221E-13	4.612E-13
Land use - occupation and transformation	species.yr/(m2 annual crop eq)	7.345E-13	7.345E-13	7.345E-13	7.345E-13	7.345E-13	7.345E-13	7.345E-13
Freshwater ecosystems								
Global Warming	species.yr/kg CO2 eq.	1.002E-15	7.705E-16	5.008E-16	7.705E-16	1.002E-15	5.008E-16	8.090E-16
Eutrophication	species.yr/kg P to freshwater eq.	2.493E-12	2.493E-12	2.493E-12	2.493E-12	2.493E-12	2.493E-12	2.493E-12
Toxicity	species.yr/kg 1,4-DBC emitted to freshwater eq.	7.805E-13	9.756E-13	1.463E-12	9.756E-13	7.805E-13	1.463E-12	9.268E-13
Water consumption	species.yr/m3 consumed	1.307E-17	1.501E-17	1.430E-17	2.051E-17	2.983E-17	1.888E-17	2.064E-17
Marine ecosystems								
Toxicity	species.yr/kg 1,4-DBC emitted to sea water eq.	2.489E-13	2.489E-13	2.489E-13	2.489E-13	2.489E-13	2.489E-13	2.489E-13
Eutrophication	species.yr/kg N to marine water eq.	2.069E-16	2.069E-16	2.069E-16	2.069E-16	2.069E-16	2.069E-16	2.069E-16
Damage to ecosystems	species.yr	3.975E-10	3.573E-10	3.537E-10	3.574E-10	3.662E-10	3.538E-10	3.620E-10

		Pine firewood	Husk	Straw bale	Poplar firewood	Native firewood	Woodchips	Others
Human health								
Global Warming	DALY/kg CO2 eq.	8.412E-09	7.010E-09	7.944E-09	8.879E-09	7.477E-09	9.346E-09	9.346E-09
Stratospheric ozone depletion	DALY/kg CFC11 eq.	1.500E-10	1.500E-10	1.500E-10	1.500E-10	1.500E-10	1.500E-10	1.500E-10
Ionzing Radiation	DALY/kBq Co-60 emitted to air eq.	9.151E-13	9.151E-13	9.151E-13	9.151E-13	9.151E-13	9.151E-13	9.151E-13
Fine particulate matter formation	DALY/kg PM2.5 eq.	2.911E-07	3.705E-07	3.440E-07	2.779E-07	3.176E-07	2.647E-07	2.647E-07
Photochemical ozone formation	DALY/kg NOx eq.	8.249E-09	1.005E-09	1.138E-09	1.272E-09	2.679E-09	1.339E-09	1.339E-09
Toxicity (cancer)	DALY/kg 1,4-DCB emitted to urban air eq.	4.510E-09	5.740E-09	5.330E-09	4.305E-09	4.920E-09	4.100E-09	4.100E-09
Toxicity (non-cancer)	DALY/kg 1,4-DCB emitted to urban air eq.	4.625E-08	4.625E-08	4.625E-08	4.625E-08	4.625E-08	4.625E-08	4.625E-08
Water consumption	DALY/m3 consumed	7.956E-11	1.018E-10	9.851E-11	5.408E-11	8.814E-11	5.847E-11	5.123E-11
Damage to human health	DALY	3.588E-07	4.308E-07	4.050E-07	3.388E-07	3.791E-07	3.259E-07	3.259E-07
Terrestrial ecosystems								
Global Warming	species.yr/kg CO2 eq.	2.538E-11	2.115E-11	2.397E-11	2.679E-11	2.256E-11	2.820E-11	2.820E-11
Photochemical ozone formation	species.yr/kg NOx eq.	1.169E-09	1.429E-10	1.619E-10	1.810E-10	3.810E-10	1.905E-10	1.905E-10
Acidification	species.yr/kg SO2 eq.	9.812E-11	1.249E-10	1.636E-10	1.321E-10	1.510E-10	1.258E-10	1.258E-10
Toxicity	species.yr/kg 1,4-DBC emitted to industrial soil eq.	7.959E-12	8.755E-12	8.755E-12	7.959E-12	7.959E-12	7.959E-12	7.959E-12
Water consumption	species.yr/m3 consumed	4.838E-13	6.189E-13	5.991E-13	3.289E-13	5.360E-13	3.556E-13	3.115E-13
Land use - occupation and transformation	species.yr/(m2 annual crop eq)	7.345E-13	7.345E-13	7.345E-13	7.345E-13	7.345E-13	7.345E-13	7.345E-13
Freshwater ecosystems								
Global Warming	species.yr/kg CO2 eq.	6.934E-16	5.778E-16	6.549E-16	7.319E-16	6.164E-16	7.705E-16	7.705E-16
Eutrophication	species.yr/kg P to freshwater eq.	2.493E-12	2.493E-12	2.493E-12	2.493E-12	2.493E-12	2.493E-12	2.493E-12
Toxicity	species.yr/kg 1,4-DBC emitted to freshwater eq.	1.073E-12	1.366E-12	1.268E-12	1.024E-12	1.171E-12	9.756E-13	9.756E-13
Water consumption	species.yr/m3 consumed	2.165E-17	2.769E-17	2.680E-17	1.471E-17	2.398E-17	1.591E-17	1.394E-17
Marine ecosystems								
Toxicity	species.yr/kg 1,4-DBC emitted to sea water eq.	2.489E-13	2.489E-13	2.489E-13	2.489E-13	2.489E-13	2.489E-13	2.489E-13
Eutrophication	species.yr/kg N to marine water eq.	2.069E-16	2.069E-16	2.069E-16	2.069E-16	2.069E-16	2.069E-16	2.069E-16
Damage to ecosystems	species.yr	1.306E-09	3.031E-10	3.636E-10	3.527E-10	5.677E-10	3.573E-10	3.573E-10

I Appendix: Graphical user interface

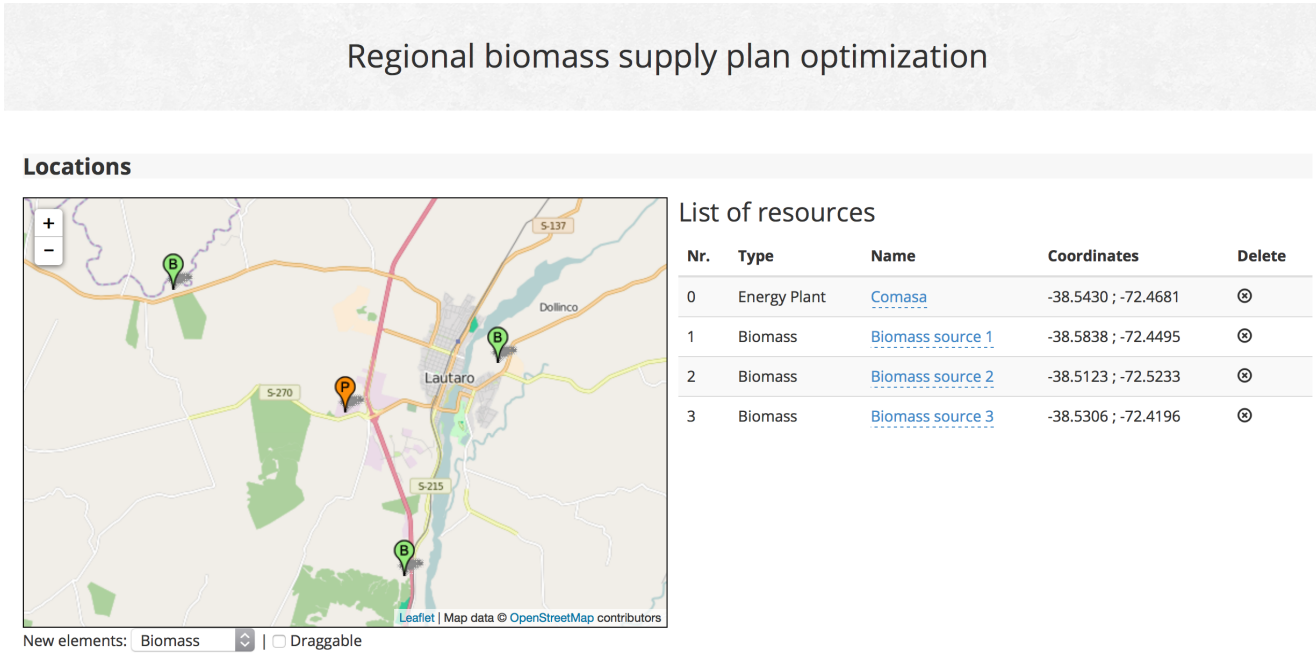


Figure I.1.: Example screenshot of the locations and parameters web page.

J Appendix: Software dependencies

J.1 Open Street Map Tile Server installation

The chosen server operating system is Ubuntu Server 14.04 LTS[1], which is recommended to be installed with *OpenSSH* support for remote *ssh* administration.
There are packages ready for this distribution to be used that can be loaded with the following directive. It is important to update the package manager afterwards:

```
$sudo add-apt-repository ppa:kakrueger/openstreetmap
$sudo apt-get update
```

Then the package *libapache2-mod-tile* should be installed. PostGIS[2] will be installed as a dependency, which is a spatial database extender for the PostreSQL[3] relational database. It is a good idea to add a second user besides *www-data* to be able to import data to the database afterwards.

```
$sudo apt-get install libapache2-mod-tile
```

For the study case, only the map from Chile was important and was downloaded from Geofabrik[4]. This data needs to be imported to the database with *osm2pgsql*. This process will take some time, depending on your server machine. For the best results, read the osm2pgsql included help, or some documentation at the Open Street Map Wiki Page[5].

```
$wget http://download.geofabrik.de/south-america/chile-latest.osm.pbf
$osm2pgsql --slim -C 2000 --number-processes 4 chile-latest.osm.pbf
```

After finished importing, change the timestamp of the planet-import-complete file and restart the rendering daemon.

```
$touch /var/lib/mod_tile/planet-import-complete
$sudo /etc/init.d/renderd restart
```

For a fast tile service, the graphic tiles should be pre-rendered before the service is available for use. This can be done using the program *render_list*. It can render the entire world which is a very processor intensive task that can take several hours or days at high zoom levels, or just specific areas. For the study case, just the Araucanía Region in Chile was rendered at zoom levels from 0 to 17. The needed parameters for that specific area from zoom levels from 12 to 20 are listed below. For lower zoom levels, the complete world can be rendered, as it is a fast operation. For that use the same function without the coordinate parameters x, X, y and Y.

```
render_list -a -n2 -z12 -Z12 -x1209 -X1234 -y2511 -Y2539
render_list -a -n2 -z13 -Z13 -x2418 -X2468 -y5022 -Y5078
render_list -a -n2 -z14 -Z14 -x4836 -X4936 -y10044 -Y10156
render_list -a -n2 -z15 -Z15 -x9672 -X9872 -y20088 -Y20312
render_list -a -n2 -z16 -Z16 -x19344 -X19744 -y40176 -Y40624
render_list -a -n2 -z17 -Z17 -x38688 -X39488 -y80352 -Y81248
render_list -a -n2 -z18 -Z18 -x77376 -X78976 -y160704 -Y162496
render_list -a -n2 -z19 -Z19 -x154752 -X157952 -y321408 -Y324992
render_list -a -n2 -z20 -Z20 -x309504 -X315904 -y642816 -Y649984
```

The instructions are based on information available at switch2osm-org [6].

1 https://insights.ubuntu.com/2014/04/17/whats-new-in-ubuntu-server-14-04-lts
2 http://postgis.net
3 http://www.postgresql.org
4 www.geofabrik.de
5 https://wiki.openstreetmap.org/wiki/Osm2pgsql
6 https://switch2osm.org/serving-tiles/building-a-tile-server-from-packages

J.2 Routing Service installation

Besides the GIS database and tile server for map visualization, a routing web service is needed to be able to find the closes street for a given coordinate, or the shorter path between a two coordinates. A project that has these routing features is the OSRM project[7] [LV11]. It is based on OSM data and the results can be shown in OSM maps with APIs like OpenLayers[8] and Leaflet[9].
OSRM needs to be built from source. To install the needed dependencies, clone the repository and build the package:

```
$sudo apt-get install build-essential git cmake pkg-config libbz2-dev libstxxl-dev libstxxl-doc
libstxxl1 libxml2-dev libzip-dev libboost-all-dev lua5.1 liblua5.1-0-dev libluabind-dev
libluajit-5.1-dev libtbb-dev
$git clone https://github.com/Project-OSRM/osrm-backend.git
$cd osrm-backend
$mkdir build
$cd build
$cmake ..
$sudo make install
```

The most important executable binaries installed are:

- *osrm-extract* pre-processes the OSM data for the routing queries.
- *osrm-prepare* processes the output of *osrm-extract* and computes the routing options for the data, according to a given profile.
- *osrm-routed* the web service daemon, which answers the routing queries.

For the pre-process a configuration file needs to be created with name *.stxxl*.

```
$vi .stxxl
```

A sample configuration is listed next, but all details are available at the *stxxl* homepage[10].

```
disk=/tmp/stxxl,0,syscall unlink
```

To extract the map a *speed profile* needs to be chosen for the wanted optimization. The are default speed profile scripts included in the OSRM in the *profiles* directory. For the study case, the *car.lua* profile was used.

```
$ln -s osrm-backend/profiles/car.lua profile.lua
$ln -s osrm-backend/profiles/lib
$osrm-extract chile-latest.osm.pbf
```

Among several output files, *chile-latest.osrm* is needed to calculate the travel times.

```
$osrm-prepare chile-latest.osrm
```

To start the service just run:

```
$osrm-routed map.osrm
```

To automate the execution of the service during restarts, the tool called *supervisor* was chosen, which is a process control system[11].

```
$sudo apt-get install supervisor
$sudo vi /etc/supervisor/conf.d/osrm.conf
```

Below is a sample configuration file for a user called *osrm-user*:

[7] http://project-osrm.org
[8] http://openlayers.org
[9] http://leafletjs.com
[10] http://stxxl.sourceforge.net/tags/master/install_config.html
[11] http://supervisord.org

```
[program:osrm]
directory=/home/osrm-user/osrm
command=/usr/local/bin/osrm-routed -p 5000 chile-latest.osrm
user=osrm-user
```

You can now restart the service and check the status.

```
$sudo service supervisor restart
$sudo supervisorctl status
```

The result should look like the next example:

```
osrm          RUNNING    pid 1234, uptime 0:12:34
```

The service is now ready to answer queries for the available services. The OSRM API describes the detailed use of the services at the API-Homepage[12]. The queries have this structure:

```
http://{server address}/{service}?{parameter}={value}
```

And the available services are (taken from the documentation on the cited website):

- *viaroute*: shortest path between given coordinates.
- *nearest*: returns the nearest street segment for a given coordinate.
- *locate*: returns coordinate snapped to nearest node.
- *table*: computes distance tables for given coordinates.
- *match*: matches given coordinates to the road network.
- *trip*: compute the shortest round trip between given coordinates.

[12] https://github.com/Project-OSRM/osrm-backend/wiki/Server-api

K Appendix: El Niño-Southern Oscillation

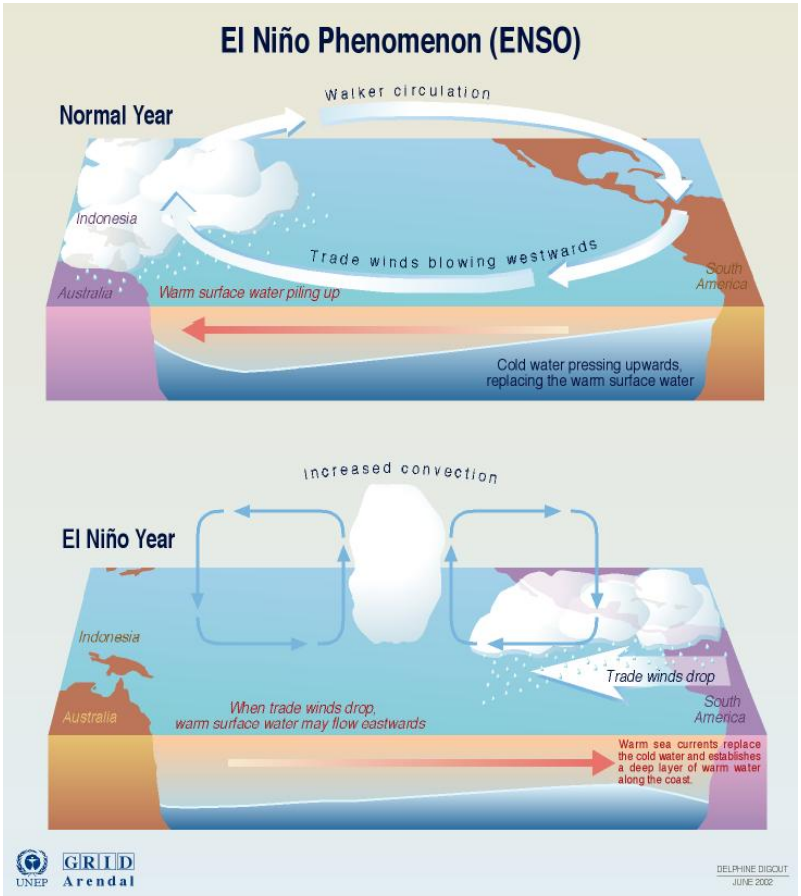
El Niño-Southern Oscillation (ENSO) is the strongest natural fluctuation of climate on an interannual time-scale. Mann & Kump give an effects summary in the book *Dire Predictions: Understanding Climate Change, 2nd Edition (©2015 Pearson Education, Inc.)*:

El Niño

- Descending air and high pressure brings warm, dry weather
- Southeast trade winds reverse or weaken
- Warm water flows eastward, accumulating off South America
- Cold upwelling reduced or absent due to weakened trade winds
- Low pressure and rising warm, moist air associated with heavy rainfall

La Niña

- Low-pressure system, positioned farther west than normal
- Pool of warm water positioned farther west than normal
- Southeast trade winds stronger than usual
- Strong upwelling of cold, deep water
- Seas surface cooler than normal in eastern Pacific



Sources: Climate Prediction Center-NCEP; NOAA.

Figure K.1.: El Niño Phenomenon

K.1 MEI Index - Numerical table

Bimonthly MEI values (in 1/1000 of standard deviations), starting with Dec1949/Jan1950, updated: 7 December 2018. More information on the MEI can be found on the MEI homepage[1]. Missing values are left blank (last table value). An updated table is available at https://www.esrl.noaa.gov/psd/enso/mei/table.html. All values are normalized for each bimonthly season so that the values from 1950 to 1993 have an average of zero and a standard deviation of "1".

YEAR	DECJAN	JANFEB	FEBMAR	MARAPR	APRMAY	MAYJUN	JUNJUL	JULAUG	AUGSEP	SEPOCT	OCTNOV	NOVDEC
1950	-1.03	-1.133	-1.283	-1.071	-1.434	-1.412	-1.269	-1.042	-.631	-.441	-1.151	-1.235
1951	-1.049	-1.152	-1.178	-.511	-.374	.288	.679	.818	.726	.72	.694	.504
1952	.433	.138	.071	.224	-.307	-.756	-.305	-.374	.31	.265	-.351	-.098
1953	.044	.401	.277	.687	.756	.191	.382	.209	.483	.087	.078	.351
1954	-.036	-.027	.154	-.616	-1.465	-1.558	-1.355	-1.456	-1.159	-1.335	-1.124	-1.088
1955	-.74	-.669	-1.117	-1.621	-1.653	-2.247	-1.976	-2.05	-1.829	-1.738	-1.821	-1.846
1956	-1.408	-1.275	-1.371	-1.216	-1.304	-1.523	-1.244	-1.118	-1.35	-1.478	-1.024	-.993
1957	-.915	-.348	.108	.383	.813	.73	.926	1.132	1.117	1.068	1.138	1.268
1958	1.473	1.454	1.313	.991	.673	.812	.7	.421	.171	.203	.476	.691
1959	.553	.81	.502	.202	-.025	-.062	-.112	.111	.092	-.071	-.17	-.247
1960	-.287	-.253	-.082	.007	-.322	-.287	-.318	-.25	-.47	-.358	-.33	-.39
1961	-.15	-.235	-.073	.017	-.302	-.185	-.208	-.3	-.3	-.536	-.433	-.608
1962	-1.065	-.963	-.692	-1.04	-.89	-.87	-.683	-.538	-.56	-.671	-.617	-.482
1963	-.718	-.837	-.675	-.761	-.473	-.144	.404	.59	.734	.805	.837	.765
1964	.878	.481	-.256	-.545	-1.234	-1.15	-1.384	-1.486	-1.309	-1.216	-1.229	-.907
1965	-.536	-.329	-.259	.086	.464	.867	1.367	1.425	1.379	1.202	1.343	1.27
1966	1.307	1.186	.689	.515	-.178	-.193	-.116	.152	-.094	-.05	-.003	-.181
1967	-.462	-.898	-1.05	-1.03	-.448	-.236	-.492	-.391	-.627	-.677	-.424	-.357
1968	-.602	-.727	-.635	-.944	-1.093	-.812	-.503	-.104	.213	.424	.582	.367
1969	.67	.849	.458	.622	.674	.801	.49	.212	.162	.496	.659	.417
1970	.38	.432	.228	.014	-.099	-.636	-1.055	-1.007	-1.251	-1.088	-1.074	-1.203
1971	-1.204	-1.507	-1.79	-1.839	-1.429	-1.42	-1.207	-1.213	-1.467	-1.415	-1.311	-.969
1972	-.575	-.398	-.256	-.166	.423	.966	1.826	1.8	1.522	1.617	1.704	1.787
1973	1.723	1.515	.87	.491	-.099	-.758	-1.056	-1.334	-1.734	-1.66	-1.489	-1.826
1974	-1.912	-1.768	-1.743	-1.62	-1.048	-.694	-.75	-.664	-.628	-1.05	-1.24	-.886
1975	-.522	-.576	-.85	-.927	-.838	-1.148	-1.497	-1.712	-1.876	-1.978	-1.756	-1.732
1976	-1.587	-1.366	-1.213	-1.157	-.483	.276	.633	.654	1.018	.927	.49	.565
1977	.529	.29	.145	.552	.31	.414	.888	.684	.783	.97	.962	.877
1978	.777	.912	.935	.199	-.378	-.605	-.42	-.199	-.391	-.028	.175	.406
1979	.608	.379	.002	.301	.374	.429	.396	.615	.759	.655	.734	1.004
1980	.677	.601	.684	.912	.958	.911	.769	.329	.263	.192	.248	.111
1981	-.25	-.14	.455	.669	.189	-.024	-.026	-.09	.174	.101	-.039	-.126
1982	-.258	-.125	.1	.008	.443	.93	1.612	1.778	1.783	2.001	2.394	2.425
1983	2.677	2.931	3.008	2.812	2.498	2.235	1.793	1.159	.459	.024	-.132	-.17
1984	-.314	-.509	.151	.39	.18	-.049	-.054	-.155	-.12	-.006	-.35	-.585
1985	-.546	-.576	-.696	-.468	-.706	-.166	-.126	-.365	-.535	-.148	-.06	-.279
1986	-.293	-.183	.028	-.107	.353	.279	.401	.765	1.077	.96	.865	1.202
1987	1.249	1.218	1.716	1.855	2.107	1.958	1.878	1.973	1.851	1.617	1.257	1.293
1988	1.115	.716	.495	.389	.193	-.582	-1.109	-1.295	-1.526	-1.328	-1.453	-1.311
1989	-1.103	-1.241	-1.035	-.76	-.393	-.242	-.43	-.494	-.315	-.342	-.073	.131
1990	.243	.573	.951	.46	.652	.511	.147	.127	.366	.273	.383	.362
1991	.319	.323	.399	.449	.741	1.051	1.044	1.008	.739	.99	1.172	1.34
1992	1.747	1.886	1.985	2.247	2.085	1.735	1.045	.559	.488	.624	.569	.664
1993	.692	.99	.987	1.408	1.993	1.616	1.204	1.026	.966	1.045	.822	.595
1994	.352	.193	.159	.465	.58	.803	.904	.762	.893	1.389	1.282	1.251
1995	1.219	.959	.845	.453	.57	.507	.234	-.147	-.445	-.481	-.474	-.537
1996	-.597	-.566	-.236	-.391	-.041	.087	-.173	-.374	-.457	-.359	-.149	-.325
1997	-.48	-.605	-.248	.527	1.132	2.275	2.825	3.002	2.99	2.361	2.516	2.344
1998	2.455	2.777	2.751	2.658	2.206	1.336	.392	-.336	-.636	-.808	-1.071	-.908
1999	-1.039	-1.123	-.95	-.88	-.596	-.339	-.478	-.739	-.967	-.97	-1.041	-1.142
2000	-1.122	-1.189	-1.09	-.397	.251	.001	-.159	-.145	-.238	-.391	-.713	-.55
2001	-.496	-.649	-.548	-.05	.282	.052	.297	.332	-.174	-.276	-.151	.033
2002	.017	-.16	-.118	.401	.886	.932	.712	1.002	.881	.979	1.076	1.156
2003	1.214	.944	.83	.413	.214	.107	.177	.309	.46	.497	.563	.362
2004	.332	.37	-.036	.358	.558	.315	.571	.617	.558	.492	.794	.684
2005	.325	.816	1.057	.626	.885	.589	.519	.343	.296	-.179	-.385	-.55
2006	-.428	-.414	-.521	-.571	.045	.526	.716	.748	.8	.939	1.272	.965
2007	.985	.537	.125	.026	.348	-.155	-.248	-.442	-1.197	-1.217	-1.155	-1.178
2008	-1.006	-1.371	-1.552	-.858	-.345	.142	.088	-.269	-.58	-.699	-.588	-.646
2009	-.714	-.69	-.705	-.106	.326	.751	1.06	1.05	.707	.883	1.107	1.059
2010	1.066	1.526	1.462	.978	.658	-.228	-1.103	-1.671	-1.879	-1.892	-1.477	-1.558
2011	-1.719	-1.544	-1.554	-1.387	-.199	-.003	-.193	-.517	-.778	-.939	-.938	-.945
2012	-.98	-.675	-.382	.11	.757	.842	1.126	.607	.316	.069	.127	.111
2013	.103	-.068	-.026	.09	.205	-.094	-.314	-.481	-.155	.115	-.053	-.234
2014	-.27	-.259	.018	.295	1.001	1.046	.915	.937	.557	.421	.754	.566
2015	.417	.464	.614	.916	1.583	2.097	1.981	2.334	2.479	2.201	2.271	2.12
2016	2.216	2.17	1.963	2.094	1.752	1.053	.352	.167	-.118	-.385	-.209	-.11
2017	-.052	-.043	-.08	.744	1.445	1.039	.456	.009	-.478	-.568	-.285	-.576
2018	-.623	-.731	-.502	-.432	.465	.469	.076	.132	.509	.468	.698	

[1] https://www.esrl.noaa.gov/psd/enso/mei/mei.html