CIRCULAR BUSINESS MODEL BASED ON INDUSTRIAL SYMBIOSIS OF MICROALGAE CULTIVATION FOR BIODIESEL PRODUCTION

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Tese de Doutorado apresentada ao Programa de Pós-graduação em Engenharia de Produção, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Doutor em Engenharia de Produção.

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À minha luz na eternidade, guerreira para todo sempre, minha mãe.
Ao meu mestre querido, prof. Rogerio Valle.

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Resumo da Tese apresentada à COPPE/UFRJ como parte dos requisitos necessários para a obtenção do grau de Doutor em Ciências (D.Sc.)

MODELO DE NEGÓCIO CIRCULAR BASEADO NA SIMBIOSE INDUSTRIAL DO CULTIVO DE MICROALGAS PARA PRODUÇÃO DE BIODIESEL

Ana Carolina Maia Angelo

Fevereiro/2019

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Paulo Sergio Salomon

Programa: Engenharia de Produção

Microalgas são uma fonte de biomassa atraente para a produção de biodiesel. Devido a vários fatores que afetam o crescimento e cultivo de microalgas, estudos focam a viabilidade técnica do cultivo com CO_2 injetado a partir de gases de combustão. Desafios ainda existentes tornam o biodiesel de microalgas distante da produção comercial, mas estes desafios podem ser superados através da produção de biomassa de microalgas como uma oportunidade de negócio quando integrada a uma planta industrial sob a ótica da Economia Circular. Este estudo tem como objetivo desenvolver um Modelo de Negócio Circular baseado na simbiose industrial de cultivo de microalgas em *raceways* para a produção de biodiesel, obedecendo a lógica de criação de valor a partir do gás de exaustão da planta industrial até o produto final: o biodiesel. A integração do Modelo de Negócio Canvas e da Pegada de Carbono foi aplicada em um caso hipotético da indústria brasileira de cimento usando dados reais, a fim de evidenciar as principais potencialidades e gargalos do cultivo de microalgas no Brasil em um contexto de precificação de carbono. As perdas de CO_2 durante o cultivo de microalgas influenciam fortemente o dimensionamento da produção de microalgas e, consequentemente, a área necessária para o cultivo, bem como a viabilidade econômica e ambiental do negócio.

Abstract of Thesis presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

CIRCULAR BUSINESS MODEL BASED ON INDUSTRIAL SYMBIOSIS OF MICROALGAE CULTIVATION FOR BIODIESEL PRODUCTION

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Microalgae are an attractive feedstock for biodiesel production. Owning to various factors affecting microalgae growth, focus has been given on studies of the technical feasibility of microalgae cultivation with CO_2 injected from industrial flue gases. However, microalgae-based biodiesel is still far from the commercial production due to various bottlenecks, which may be overcome by considering microalgae biomass production as a business opportunity when integrated with an industrial plant under the Circular Economy perspective. This study aims to develop a Circular Business Model based on industrial symbiosis of microalgae cultivation in raceway for biodiesel production, obeying the logic of value creation from waste streams from the industrial plant up to valuable final product: the biodiesel from microalgae. An integrated Business Model Canvas and Carbon Footprint analysis was applied to a hypothetical case of Brazilian cement industry using real data to assess potentialities and constraints of microalgae cultivation in Brazil in a carbon pricing context. Losses of CO_2 during microalgae cultivation strongly influence the size of microalgae production facility, and consequently the area required for cultivation, as well as the economic and environmental feasibility of the business.

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LIST OF ACRONYMS

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
CBM	Circular Business Model
CE	Circular Economy
CKD	Cement Kiln Dust
CN	Cetane Number
ELECTRE	Elimination and Choice Expressing Reality
ETS	Emission Trading System
FAME	Fatty Acid Methyl Esters
GHG	Greenhouse Gases
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
IS	Industrial Symbiosis
LCA	Life Cycle Assessment
MCDA	Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision Making
MUFA	Mono-unsaturated fatty acids
NRE	Natural Resources and Environment
OD	Optical density
PBR	Photobioreactor
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
PUFA	Polyunsaturated fatty acids
SFA	Saturated Fatty Acids
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution

1. Introduction

1.1 Research context

Although the concept of Sustainable Development is well recognised worldwide since the Brundtland Report (WCED, 1987), it is undoubtedly one of the greatest challenges the world continues to face today. This is maybe due to the fact that the concept of Sustainable Development is so broad and intangible that loses meaning (GEISSDOERFER et al., 2018).

Aiming to reach the Sustainable Development, the Circular Economy (CE) has emerged as a new paradigm that suggests a deep rethinking and redesigning of the current linear system, based on the take-make-dispose industrial model (ELLEN MACARTHUR FOUNDATION, 2015a; GEISSDOERFER et al., 2017), however with the characteristic of being a much more tangible way to organize society and economy (GEISSDOERFER et al., 2018).

A worldwide trend is leading the international community (governs, private companies, academy) to explore possible paths for the transition from the linear to the Circular Economy business models. Industrial symbiosis, originated from the Industrial Ecology, has been seen as a good strategy to advance the Circular Economy (SOeS, 2017).

Cultivation of microalgae (microscopic, oxygen-evolving photosynthetic organisms that thrive in aquatic ecosystems) is one type of activity with potential to be couple to various industrial processes within the framework of the Industrial symbiosis principle.

In this sense, microalgae cultivation can be integrated with large-scale CO_2 generating processes under the industrial symbiosis principle, which include, for example, fossil fuel-based power plants and cement factories. Therefore, environmental benefits related to CO_2 mitigation and wastewater treatment confers microalgae an important role towards Sustainable Development (LANGHOLTZ et al., 2016), and, more precisely, a promising step towards Circular Economy.

Microalgae are undoubtedly an attractive source for biofuels production. They have been seen as a potential feedstock for biodiesel production due to their high lipid content, advantages in relation to terrestrial crops regarding e.g. non-arable land requirements and high photosynthetic, and CO_2 reduction efficiencies (CHISTI, 2007;

LEE, 2011). Furthermore, biodiesel from microalgae may be the only renewable fuel to replace fossil fuels without affecting the world´s food supply (VISWANATH et al., 2010).

Microalgae cultivation under industrial symbiosis can be advantageous (eg. SORATANA & LANDIS 2011; ANDERSSON et al., 2014; UBANDO et al., 2016). However, the amounts of CO_2 generated by industrial plants require large-scale microalgae cultivation systems.

Large-scale commercial production of algal biomass often relies on open raceway ponds that require a relatively low investment in capital (CHISTI, 2016). This low investment and ease of operation make the raceways a preferable choice for microalgal biomass production for biofuels that are products with low added value.

Despite the increasing interest in microalgae as feedstock to produce biofuels and the scalability advantages through microalgae cultivation co-located with a CO_2 source, large-scale microalgal biomass production still faces challenges, mainly regarding economic viability (QUINN et al., 2013). For instance, Langholtz, Stokes, and Eaton (2016) have evaluated CO_2 co-location scenarios for large-scale microalgae cultivation. The results indicated lower benefits due to economic constraints such as the high costs of transporting the CO_2 from the industrial plant to the microalgae cultivation site.

Biodiesel from microalgae is still far from commercialization (CHEN et al., 2018). A plenty of studies have focused on microalgal biomass production for biofuel, specifically biodiesel (eg. CHISTI, 2007; MATA et al., 2010; SHARMA et al., 2012; ISLAM et al., 2013; TORRES et al., 2013; ANAHAS & MURALITHARAN, 2015), but most of them were dedicated to technical aspects such as selection of microalgae strains more appropriate for lipid extraction and downstream processes.

1.2 Problem statement

Microalgal biomass production for biofuels requires large-scale cultivation systems that still face limitations. Most of these limitations are related to economic viability that can be overcome through integrated microalgae cultivation with an industrial plant based on the industrial symbiosis principle, thus contributing not only to a decarbonized economy but also to the Circular Economy.

Therefore, this research aims to answer the question:

How to address microalgal biomass production as a business driver to advance the Circular Economy?

This includes identifying the main constraints of microalgae-based biodiesel production under an industrial symbiosis system, and a critical analysis of the feasibility of cultivating microalgae in large-scale raceway systems.

1.3 Objectives

This study aims to develop and apply a Circular Business Model based on the industrial symbiosis principle for microalgae cultivation to contribute to the transition to Circular Economy as well as to assess the feasibility of microalgal biomass production in raceways for biodiesel production in Brazil.

The specific objectives are:

- Build a conceptual Circular Business Model based on industrial symbiosis for large-scale microalgae cultivation and guidance to the private sector (enterprises) on decision-making about microalgal biomass production at large-scale;
- Identify the most appropriate microalgal strain for raceway cultivation by the application of an outranking multi-criteria method;
- Apply the model on a hypothetical case of the cement industry and analyse the microalgal biomass production under technical, economic and environmental aspects.

1.4 Relevance and originality

As CO_2 biological mitigation gains importance, the win-win situation where microalgae biodiesel production is coupled with CO_2 mitigation may amplify the strategic role of the microalgae industry worldwide (LAM et al., 2012). Despite various studies discussing the benefits and limitations of using microalgae to capture CO_2 for GHG mitigation (eg. PACKER, 2009; SAYRE, 2010; SYDNEY et al., 2010; HO et al., 2011; LAM et al., 2012; BHOLA et al., 2014), there are very few studies dedicated to investigate the concept of industrial symbiosis of microalgal cultivation with other industries.

A consultation in important scientific databases such as Scopus and Web of Science was carried out using the terms microalgae AND ‘industrial symbiosis’ as search string for paper topics (title, abstract and keywords). This search retrieved eight indexed articles (i.e. no conference papers or book chapters included), of which three have addressed industrial symbiosis in some extent:

- Soratana and Landis (2011) evaluated 20 scenarios of microalgae cultivation in closed PBR utilizing nutrients and CO_2 from synthetic sources. They also carried out an LCA of these scenarios varying the photobioreactor construction materials (glass, polyvinyl chloride, polycarbonate, polymethyl methacrylate and high-density polyethylene), the nutrients source (synthetic fertilizers and municipal wastewater), and the CO_2 injection (synthetic CO_2 and from flue gas of thermal power plant);
- Andersson et al. (2014) investigated the collaboration between an algae cultivation, biofuel production processes, a wastewater treatment plant and an industrial cluster for the purpose of utilizing material flows and industrial excess heat in Gothenburg on the Swedish west coast. Based on a biorefinery concept, the authors addressed two cases study where microalgae were cultivated in open systems for wastewater treatment and production of biogas and biodiesel;
- Ubando et al. (2016) proposed a fuzzy mixed-integer non-linear programming model to select prospective companies, called by support tenants, in an eco-industrial park in order to optimise product demand, environmental footprint and profit. The eco-industrial park of the case study considered an integrated microalgae to biodiesel plant, ethanol plant, cement factory, combined heat and power plant, and an anaerobic digestion plant.

Undoubtedly, the three studies represent an import step towards technical feasibility of microalgae cultivation for biofuel production. However, none of them represent a clear contribution to the assessment of microalgae cultivation as a business opportunity.

Moreover, although these three studies address the industrial symbiosis concept and also carried out environmental evaluations to prove the benefits of microalgae cultivation, there are no evidences of adopting the industrial symbiosis as a strategy for the circular economy, thus missing the circularity aspect. In other words, the closed loops are not a core issue in these studies.

The Circular Business Model proposed in this thesis will address, therefore, closed loops through the value creation of the industrial flue gas and waste streams by turning them into valuable outputs, such as microalgae-based biodiesel. The circularity is enhanced by using the final product, biodiesel, as input to the industry source of CO_2 to microalgae growth.

The application of this model in the cement industry is also original, because even though the use of cement-plant flue gas as source of CO_2 for microalgae cultivation has been previously addressed (eg. TALEC et al. 2013; LARA-GIL et al. 2014; 2016), it was evaluated only under small-scale, laboratorial conditions.

In addition, the relevance of this theme is corroborated by R&D projects carried on by the industry. InterCement and Votorantim Cimentos, largest cement producers in the world, have done R&D projects of CO_2 biofixation by microalgae that resulted in the construction of microalgae cultivation pilot plants coupled to the cement plants (VOTORANTIM, 2017; INTERCEMENT, 2017). However, all of these projects evaluated the microalgal biomass production in closed photobioreactors due to advantages in biomass productivity, and also based on the belief that land availability is the bottleneck for open cultivation systems such raceways.

The transformation to the Circular Economy needs leaving the linear mindset to think circular, i.e. it implies to think from linear to circular, from simple to complex, from predictive to adaptive, and from competition to cooperation. As this is not often an easy task, by developing the conceptual Circular Business Model, this thesis aims to contribute to the blooming knowledge about circular supply chain management, where all the organisational functions (marketing, sales, R&D, production, logistics, information technology, finance, and customer service) are coordinated within and across business units and organisations to close loops of materials. In summary, this research seeks to contribute to the discussion on how microalgae could become a business opportunity fostering the Circular Economy.

1.5 Structure of the thesis

This thesis is organized in six chapters, including this Introduction. **Chapter 2** brings the conceptual background on the following topics: microalgal biomass production; Circular Business Models (CBMs), including the main concepts and principles related on the Circular Economy and Industrial Symbiosis; and the ELECTRE III method, including an introduction to the Multi-Criteria Decision Analysis (MCDA). **Chapter 3** addresses the methodology used in this study with an explanation of each step in achieving the objectives. **Chapter 4** presents the conceptual CBM applied to a hypothetical case considering real scenarios of the cement industry. This application is presented in **Chapter 5**. Finally, **Chapter 6** concludes the thesis by summarizing the key challenges of microalgal biomass production as a business driver to advance a Circular Economy, as well as by suggesting further steps in order to improve the research in this field.

2 Conceptual Background

2.1 Microalgal biomass production

2.1.1 Microalgae definition

Microalgae are oxygen-evolving photosynthetic microorganisms (both prokaryotes and protists) that use sunlight, CO_2 and nutrients (nitrogen, phosphorus, ammonia and other elements) to create biomass, in which lipids, proteins, and carbohydrates can be converted and upgraded to a variety of high value-added products (cosmetics, biofertilizers, animal feed, human food, supplements, nutraceuticals, vitamins, anti-oxidants, etc) and biofuels (eg. biodiesel, biogas). More than 90% of all microalgae world production has been used for nutritional products, and the annual worldwide biomass production is around 15,000 tons (LANGHOLTZ et al., 2016).

Microalgae can be classified according to their colour and some properties related to kinds of pigments, chemical nature of storage of products and cell wall constituents. The cyanobacteria, a diverse group of prokaryotes also known as blue-green algae, can be found in marine and freshwater environments, moist soils and rocks, or as symbiotic organisms. Their main storage product is glycogen (RICHMOND, 2004).

Red algae, or Rhodophyta, represent the majority of seaweeds, and their commercial utilisation concerns agar, carrageenan and polyunsaturated fatty acids, such as arachidonic acid – an important supplement for infant development. Chlorophyta are the green algae and embrace a large group of organisms with great genetic and morphological diversity. They are primarily freshwater, but they can also be found in marine, terrestrial and subaerial environments. *Chlorella*, *Dunaliell*a and *Haematococcus* are the major green algae genera commonly used for commercial exploitation (RICHMOND, 2004).

Depending on the strain, microalgae can be grown in water from second-use sources (e.g. industrial, municipal, agricultural or aquaculture wastewater) which represent a huge advantage in terms of environmental benefits.

Several products can be produced using microalgal biomass as feedstock, including biodiesel, renewable hydrocarbons, alcohols, biogas, bioplastics, surfactants, industrial enzymes, animal feed, and human food and health. These end-products can be classified through a scale of added value and volume of production (Figure 1).

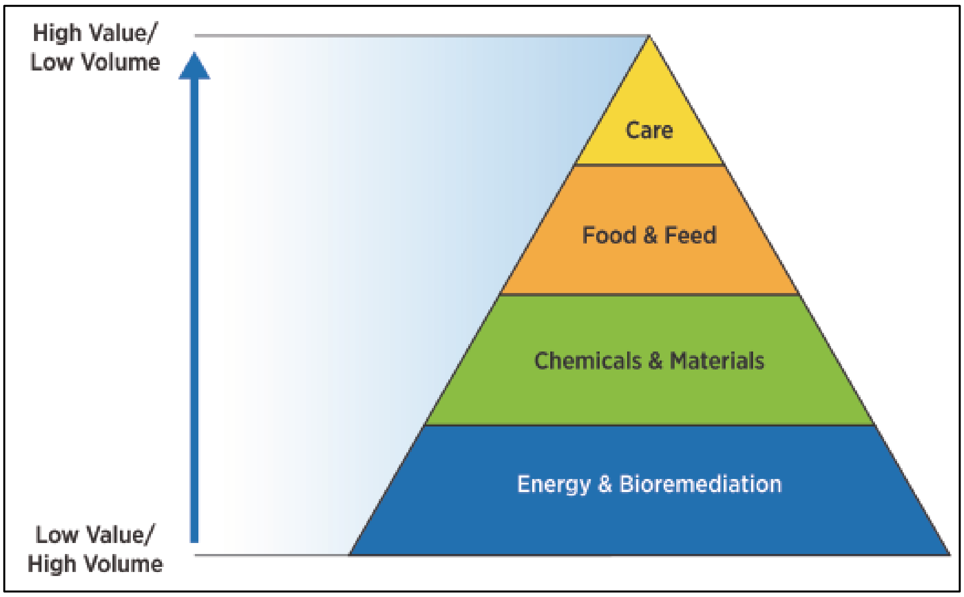


Figure 1. Value and volume pyramid for possible products from microalgae
Source: LANGHOLTZ et al. (2016).

This qualitative representation of the value and volume of products obtained from microalgae shows low added value products associated with high production volumes like energy products (e.g. biofuels) and bioremediation processes (e.g. wastewater treatment and CO_2 capture). As the added value increases, the volume of production decreases. Personal care products, including cosmetics (e.g. alguronic acid for skin treatment) and pharmaceuticals, are the higher added value, microalgae-based products and thus have low production volume. Nutraceuticals are food and feed products, including supplements to human diet (e.g. astaxanthin, omega-3 fatty acid) and ingredients for animal and aquaculture feed. Chemicals include, for example, the bioplastics, fertilizers, and enzymes lubricants (U.S. DOE 2010; HERRADOR, 2016).

2.1.2 Microalgal biomass production process

The microalgal biomass production process includes the microalgae cultivation and downstream processes such harvesting and drying (Figure 2). Regardless of the specie cultured, microalgae cultivation requires solar radiation or artificial light as energy source, water, nutrients, CO_2 and land availability.

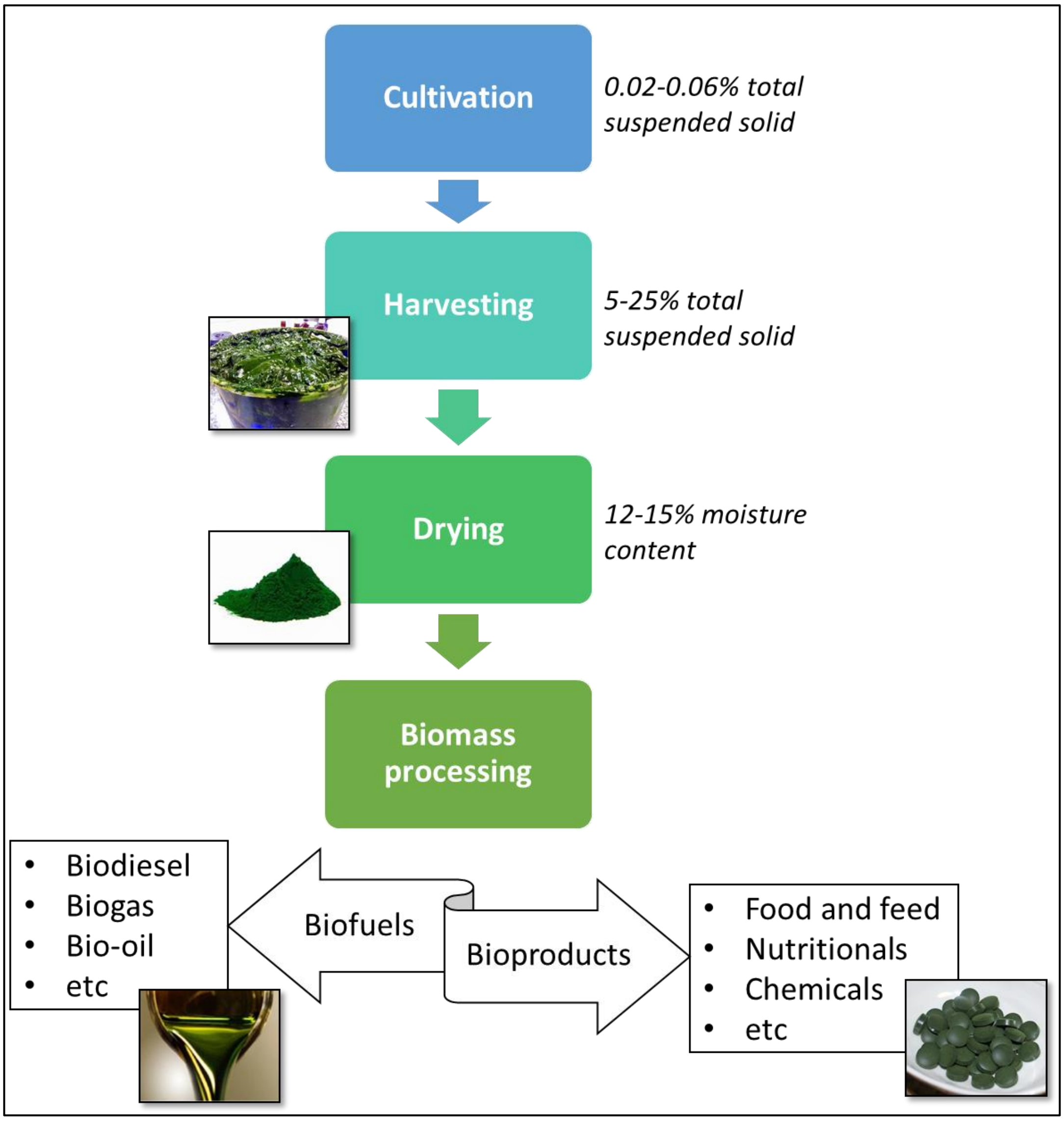
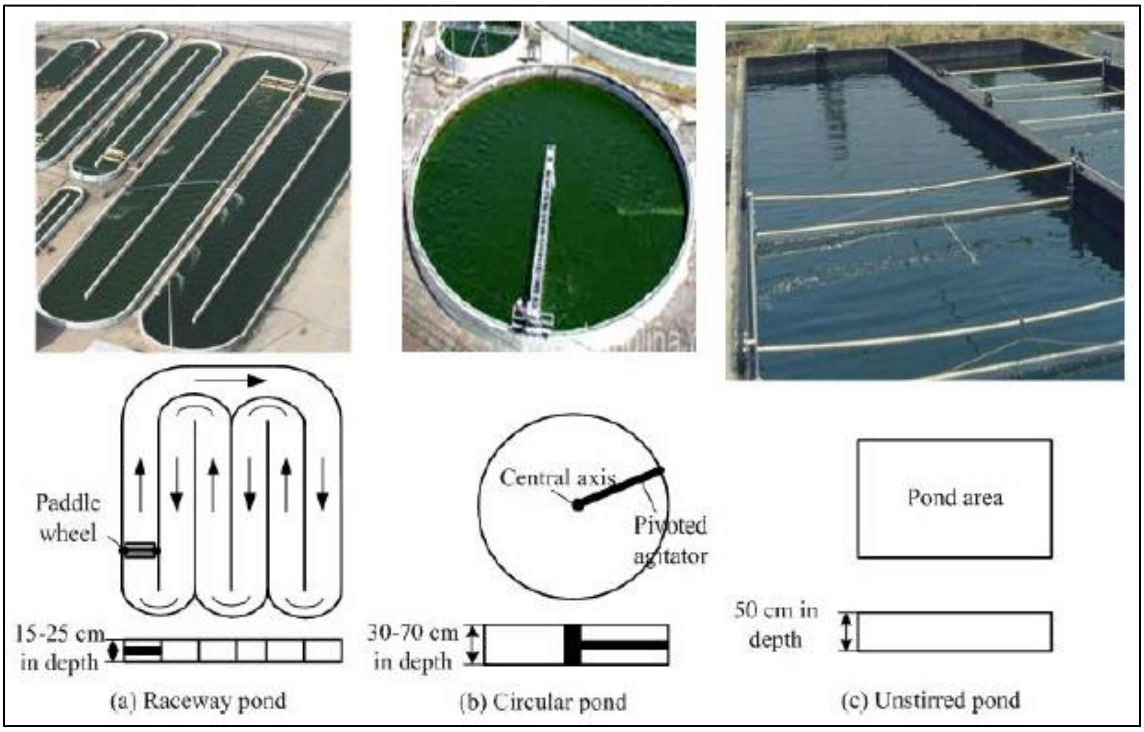


Figure 2. Microalgal biomass production process
Source: Adapted from HERRADOR (2016) and TAN et al. (2016).

i. Cultivation systems

Microalgae cultivation systems are divided into two main types: open and closed systems. Open systems, as the name suggests, comprises cultivation in open areas such as ponds and lagoons that receive direct sunlight. Closed systems consist of microalgae cultivation in transparent vessels or containers under the sun or artificial light.

There are three different designs of open ponds, namely: unstirred ponds, raceways and circular ponds (Figure 3). Unstirred ponds, with a depth of half a meter or less, are considered de most convenient ones due to their easy construction and operation. The main disadvantage is related to the high potential of contamination by e.g. viruses and bacteria, as well as other microalgae, affecting the growth of the target microalgae and the efficiency of the cultivation process. Raceways are channels in the shape of an oval, like a car raceway circuit, with a depth of 15 to 25 cm and paddles that help to circulate the water, therefore minimizing the deposition of sediments. Circular ponds can have a depth of 30 to 70 cm, with a central pivot that rotates to provide circular motion to the water.



(a) Raceway pond (b) Circular pond (c) Unstirred pond

Figure 3. Three different designs of open pond cultivation systems
Source: SHEN et al. (2009).

In closed systems, microalgae can grow under controlled conditions in photobioreactors with different designs, such as: tubular, plastic bag, airlift, and flat plate photobioreactors. Tubular photobioreactors comprises transparent vessels in a tubular shape, in which chambers are connected to a supply of CO_2 and nutrients (Figure 4).

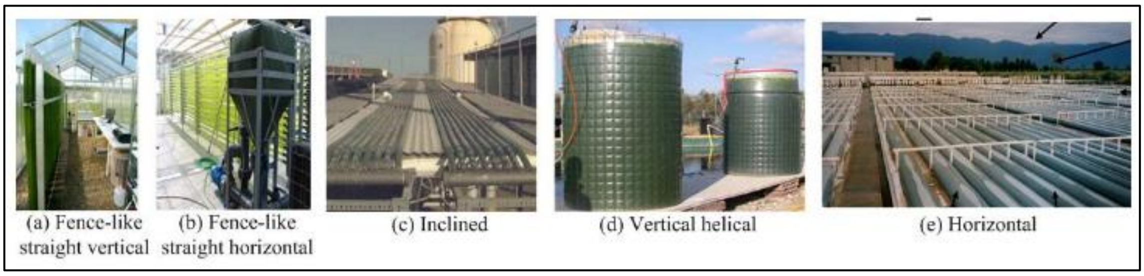


Figure 4. Different designs of tubular photobioreactors
Source: SHEN et al. (2009).

The plastic bags are made of transparent polyethylene bags. Airlift comprises cylinders made of acrylic glass, where the medium moves in a circular way by vertical bubble columns, which provides better light absorption. Although they are useful for large-scale cultivation with minimum potential of contamination, high investment and maintenance costs are required. The last type, flat plate photobioreactors (Figure 5), incurs less investment to build and maintain than the others photobioreactors due to its unique design as vertical flat plates (HERRADOR, 2016).

Figure 5. Flat plate photobioreactors designs
Source: SHEN et al. (2009).

Since the 1960s, raceway ponds are widely used in commercial production of microalgal biomass, because they show advantages compared to closed photobioreactors in terms of ease of construction and operation (CHISTI, 2016). Moreover, raceway ponds are considered the best option in terms of energy consumption and CO_2 emission (LAM & LEE, 2012). However, there are some limitations of raceways regarding the land area required, nutrients absorption efficiency and prowess to contamination. As the depth of open ponds must be kept shallow in order to ensure sunlight availability to the microalgal cells, large land areas are required. Also, nutrients can be lost during evaporation, and, as an open cultivation system, it allows other microorganisms (e.g. viruses, bacteria and protozoa) to invade and potentially inhibit the microalgal growth (HERRADOR, 2016).

These constraints may be better handled in a closed photobioreactors. Nevertheless, this type of culture vessel implies higher investment and operation costs, turning it only suitable for the production of high-value products that cannot be produced otherwise (HERRADOR, 2016). Hence, each type of culturing device has advantages and disadvantages, as summarized in Table 1. The big challenge is to manage the major difference between the two: the trade-off of cost and control (PACKER, 2009).

Table 1. Comparison between raceway and tubular photobioreactor

Aspect	**Raceway**	**Tubular photobioreactor**
Required land use area	High	Low to medium
Water loss	Very high	Low
CO_2-loss	High, depends on pond depth	Low
O_2 concentration	Usually low enough because of continuous spontaneous outgassing	Build-up in closed systems requires gas exchange device (O_2 must be removed to prevent inhibition of photosynthesis and photo oxidative damage)
Temperature	Highly variable, some control possible by pond depth	Cooling often required
Shear	Usually low	Usually high
Cleaning	No issue	Required
Contamination risk	High	Low
Biomass quality	Variable	Reproducible
Biomass concentration	Low	High
Weather dependence	High	Medium
Start-up	4-6 weeks	2-4 weeks

Source: Adapted from HERRADOR (2016) and CHISTI (2016).

ii. Harvesting

As presented in Figure 2, cultivation of microalgae to a high biomass level is followed by harvesting to separate microalgal cells from the water. There are plenty of harvesting methods (e.g. filtration, centrifugation, flocculation, sedimentation and flotation), that have advantages and disadvantages. The preferable one, or a combination of harvesting methods, depends on the microalgae species, growth medium, production rate, quality of end product and production cost (RICHMOND, 2004).

Each harvesting method (RICHMOND 2004; HATTAB et al., 2015):

Filtration

It is an efficient physical harvesting method that uses a permeable medium (typically a filter or membrane) that retains in the simplest way the microalgal biomass while allowing the liquid to pass through. It requires a pressure difference across the filter, which can be produced by pressure or gravity. Depending on the size of the membrane filters' pores, it can be a macro filtration process, micro-filtration, ultrafiltration or reverse osmosis, where the pressure required decreases as this size of pores increases.

Centrifugation

This physical method is widely used in some industries such as beverage, food and pharmaceuticals industries, and almost all microalgae species can be separated from the culture medium by centrifugation. The separation of solids occurs by means a centrifugal force. Disc stack and decanter centrifuges are the two common techniques of this method. The former is the most common industrial centrifuge used in microalgae commercial plants producing high valuable products and biofuel. Decanting centrifugation uses gravitational forces to force the solids in suspension to fall down.

Flocculation

It is a chemical harvesting method, where the cells are concentrated by coagulation. As the density increases, cells or clumps of cells settled in the bottom of the cultivation apparatus. Inorganic and organic polymers can induce the flocculation process, such as ferric sulphate, ferric chloride, aluminium sulfate amongst the inorganics, and chitosan and polyelectrolyte amongst the organics.

It must be noticed that certain stress conditions involving pH, DO content, nitrogen concentration and the amount of calcium and magnesium ions in solution can induce the flocculation in some species, a phenomenon called autoflocculation. Furthermore, there is also the bio-flocculation, where microorganisms (e.g. bacteria species) are added to the microalgal culture. The bacteria adhere to the microalgae cells causing the increase of their weight, and consequently settlement to the bottom.

Sedimentation

This method uses gravitational forces to separate solids from liquids based on density. This means that a larger difference in density would result in faster sedimentation process, while a smaller particle size would require longer time to settle out by gravitational forces.

Flotation

Flotation is a physiochemical gravity separation process, where gas bubbles pass through a liquid-solid suspension causing the microalgae to float up to the surface, then adhering to the gaseous bubbles. Dissolved air flotation, dispersed air flotation, and microbubble generation are the most common techniques. The dissolved air flotation works with a difference of pressure, starting with the reduction in water pressure that is injected into a flotation tank at atmospheric pressure. The bubbles generated from the diffuser nozzles at the bottom, thus carry the microalgae cells to the surface of the tank for collection.

By using the dispersed air flotation, a high-speed mechanical agitator and an air injection system are required to bubble formation. Microbubble generation comprises an air supply in an oscillatory flow with regular frequency, leading bubbles 10 times smaller than the conventional ones to attach to the hydrophobic cells and carry them to the surface.

Tan et al. (2016) summarized the advantages and disadvantages of various microalgal biomass harvesting methods, from those it can be highlighted:

- Centrifugation → rapid cell harvesting method that can handle most microalgal types and large volumes. As requires high capital and operational costs, mainly due to high energy consumption, it is recommended for high added value end products;
- Filtration → despite de low energy consumption, it has high operating costs. It is considered a slow harvesting process, size dependent, being most suitable for large microalgae cells;
- Flocculation followed by sedimentation → suitable for low added value end products, due to the low energy consumption and for being an inexpensive harvesting method. It is able to handle a large quantity of microalgae culture,

besides the suitability for a wide range of species. Amongst the disadvantages, there are the sensitiveness to pH level and the requirement of chemicals, that may contaminate the final product;

- Flotation → Despite being a species-specific harvesting method, it is an efficient and cost-effective method to harvest microalgae grown in wastewater. Suitable for small particles and relatively cheaper than centrifugation.

Hattab et al. (2015) reviewed and compare current techniques used for harvesting in order to identify the most efficient and economically viable for large scale processing of microalgal biomass. They identified four techniques suitable for harvesting microalgae at large scale due to their effective dewatering ability, low operational costs, suitability for numerous species, rapidness and minimal maintenance requirement: two techniques of centrifugation method (disc stack centrifuge and decanter centrifugation), the remaining two of filtration and of flocculation methods (cross-flow filtration and organic flocculation).

Although these techniques can be used alone to harvest microalgae, Hattab and co-authors recommended that the use of organic flocculation as an initial dewatering step, followed by centrifugation or filtration in order to improve the economic viability of the overall process.

iii. Drying

The harvested microalgae need to be further dried seeking to remove the remaining water content (dehydration). The most common methods are freeze drying, drum drying, spray drying and sun drying (RICHMOND, 2004). The following bullets describe each method and point out its advantages and disadvantages (RICHMOND, 2004; TAN et al., 2016):

- Sun drying → undoubtedly is the cheapest drying method as it occurs naturally depending on the weather. Although used for most crops, sun drying is not recommended to microalgae due to the high-water content in the biomass, turning it a slow drying process besides the large areas' requirement;
- Spray drying → pressure or centrifugal atomizers or gas-liquid jets are used to generate a fine spray of solution, that is put into continuous contact of hot air in

a large chamber. It is a well-established process used in food industry, with high drying efficiency and rapid process. However, it requires high capital and operational costs, hence it is more suitable for high added value microalgal products;

- Drum drying → also known as rotary drying, where a slope rotating cylinder is used to move the microalgae being dried from one end to other by gravity force. It is a fast and effective drying method, with the dual advantage of sterilizing the product and breaking the cell wall. It leads to high energy cost to run the dryer;
- Freeze drying → Also called lyophilization, the dehydrate process occurs by frozen the microalgal slurry (the biomass coming from the harvested step) and then the ice crystals are sublimed through direct exposure to warming water vapor without thawing. As it requires high capital and operating costs, it is considered an expensive method for large-scale plants, being more suitable for fine applications where high quality of product is appreciated.

All these harvesting methods differ both in the extent of capital investment and energy requirements. Hence, the selection of which method to use depends on the scale of operation and the quality of the end product (SHOW et al., 2015).

iv. Oil extraction

After the drying process, the microalgae cells are then disrupted to extract intracellular compounds, such as lipids for further biodiesel production. There are a number of methods for microalgae cell disruption that depends on the cell wall characteristics and on the end-product nature to be obtained (RICHMOND, 2004).

Oil extraction delivers two products: crude microalgae oil and algal cake. They differ from each other in their carbon and energy content. The oil can be transesterified likewise any other oil, and the cake, that is the main co-product by its volume and composition, can be used as feedstock to animal feed or to produce biogas through anaerobic digestion (FLESCH et al., 2013).

Disruption methods are classified in mechanical and non-mechanical. The most common mechanical methods are pressing, bead-milling, ultra-sound, and homogenization. The non-mechanical methods comprise mainly the use of solvents, fluids, enzymes, and osmose.

Show et al. (2015) reviewed these methods in order to examine recent advances for nutrition and biofuel production:

- Pressing → as the name suggests, this method involves subjecting the microalgal biomass to high pressure up to rupture of the cell walls and release of their contents. When used in combination with chemical solvents, oil can be extracted from biomass with 70-75% efficiency;
- Bead-milling → in this method, a vertical or horizontal cylindrical compartment (bead mills) with a motor-driven central shaft support a collection of discs or another agitating element, in which the cells of dried microalgal biomass are broken through the action, in a high-speed, of a large number of fine steel or glass beads;
- Ultra-sound → it works by applying a high-power ultra-sound that generates intensive microbubbles that grow and collapse violently (cavitation phenomenon), generating a shock wave with enough energy to disrupt the microalgal cell walls;
- Homogenization → also based on high pressure, where a high-speed liquid flow creates high shear forces that can destroy the cell walls. It is suitable at large-scale biomass production. However, the high energy requirements, thus high operation costs, this method is best used for high added value products;
- Solvent extraction methods → the use of solvents is commonly used for extraction of lipids from the cells, due to few prerequisites they should attend (insoluble in water, be ease to obtain, have low boiling point and be reusable). The mainly solvents are hexane, chloroform, acetone, benzene and cyclohexane, but a combination of chloroform and methanol is the most common organic solvent for algae oil extraction;
- Super-critical fluid extraction → in this method, substances that exhibit properties of both liquids and gases under high temperature and pressure can act as an extract solvent leaving no residues when the pressure return to atmospheric levels. The most limitation of this method is the high costs associated of investment and maintenance;

- Enzymatic extraction → enzymes are used to facilitate cell wall disruption to release oil into an appropriate solvent medium. This method is costly, but can be an alternative for using conjunctly with other methods for resistant microalgae to cell disruption;
- Osmotic shock → in this method, the addition of high concentrations of a solute or other additive (salt, substrates, neutral polymers such as polyethylene glycol, dextran) causes sudden reduction in the concentration of water across the algal cell membrane, promoting the cell rupture. Costly as enzymatic extraction, it is still not found at large-scale productions.

Due to the various methods available for downstream processes (harvesting, drying and oil extraction), a rigorous techno-economic analysis is necessary to identify the most suitable one for each step taking into account the main purpose of microalgae biomass production (RICHMOND, 2004; SHOW et al., 2015; TAN et al., 2016).

2.1.3 Successful projects of microalgae for biodiesel

Several studies pointed out the advantages of biodiesel production from microalgae biomass (eg. CHISTI, 2007; MATA et al., 2010; LAM & LEE, 2012; BEKIROGULLARI et al., 2017). Besides their advantages in comparison with terrestrial feedstocks regarding to productivity and land use (Table 2), microalgae are easy to cultivate, can use water unsuitable for human consumption (eg. wastewater) and do not need arable soil to be cultivated, thus do not compete with food crops (CHISTI, 2007; MATA et al., 2010).

Table 2. Comparison of some terrestrial sources and microalgae for biodiesel production

Crop	**Oil yield (L/ha)**	**Land area needed (M ha)**
Corn	172	1,540
Soybean	446	594
Canola	1,190	223
Oil palm	5,950	45
Microalgae (high[1] oil content)	136,900	2
Microalgae (low[2] oil content)	58,700	4.5

[1] 70% oil by wt in biomass; [2] 30% oil by wt in biomass.
Source: Adapted from Chisti (2007).

As microalgae are seen as an alternative feedstock for biodiesel production, they are the target of several investments in R&D by consortiums, private and public organizations (MATA et al., 2010). Raslavičius et al. (2018) overviewed 400 R&D projects funded by the European Union and summarized the ones that reinforce algae as a universal product which can be used in food industry, pharmacy, farming, biofuel, etc. Three projects related to microalgae biodiesel, and considered by the authors as successful projects are:

- InteSusAL (2011-2016)

  The overall objective of InteSusAL (Demonstration of integrated and sustainable microalgae cultivation with biodiesel validation) is to demonstrate an integrated and sustainable approach to produce microalgae in an industrial scale, by optimising heterotrophic and phototrophic routes, and production technologies such as raceway, PBR and fermentation in order to achieve 90-120 t of dry biomass/ha.year at an one-hectare demonstration plant located in Algarve, Portugal (Figure 6) (InteSusAl, 2016).

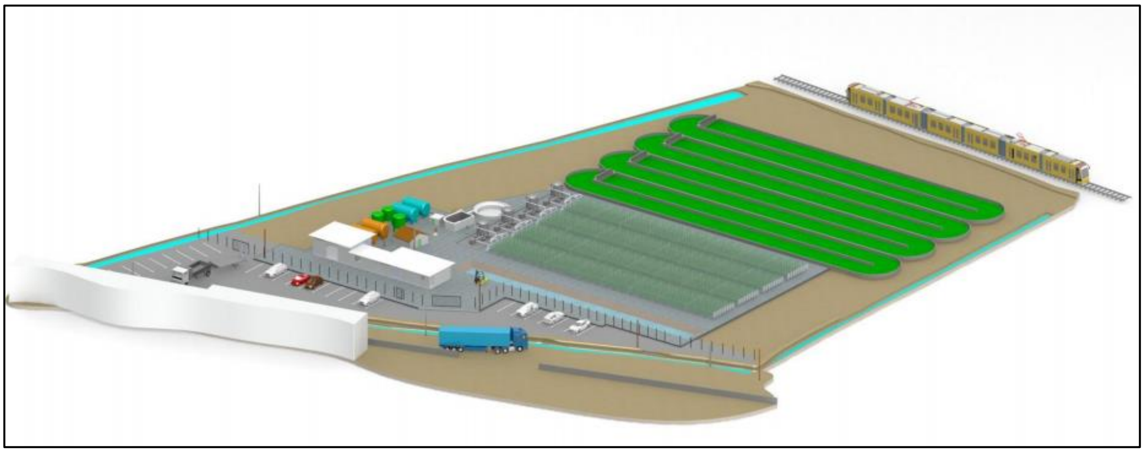


Figure 6. Demonstration plant of InteSusAl project
Source: InteSusAl (2016).

- BIOFAT (2011-2015)

  It is a microalgae-to-biofuel demonstration project that integrates all the processes from single cell to biofuel production, where PBRs were used for inoculum production, and raceways for biomass production. The innovation of this project was to scale-up the process to a 10 ha demonstration plant based on the results of two pilot plants of 0,5 ha each one (located in Italy and Portugal - Figure 7) (European Commission, 2014a).

Figure 7. General view of the plant located in Italy of BIOFAT project
Source: Tredici et al. (2016).

- All-Gas (2011-2016)

  This project aims to integrate the full production chain of microalgae to biofuels (biomass cultivation and separation, oil and other chemicals extraction, downstream biofuel production processes) on a 10 ha demonstration site with biomass yield close to 100 t/ha.year. The interesting characteristics of this project is that multiple outputs are considered (biodiesel, biogas and biofertilzers), and the residues are used as inputs. For example, wasterwater serve as source of nutrients, agricultural residues which are combusted generate the CO_2 necessary to enhance the algal yield and to generate energy (thermal energy) for drying and/or generate electricity for the system (Figure 8).

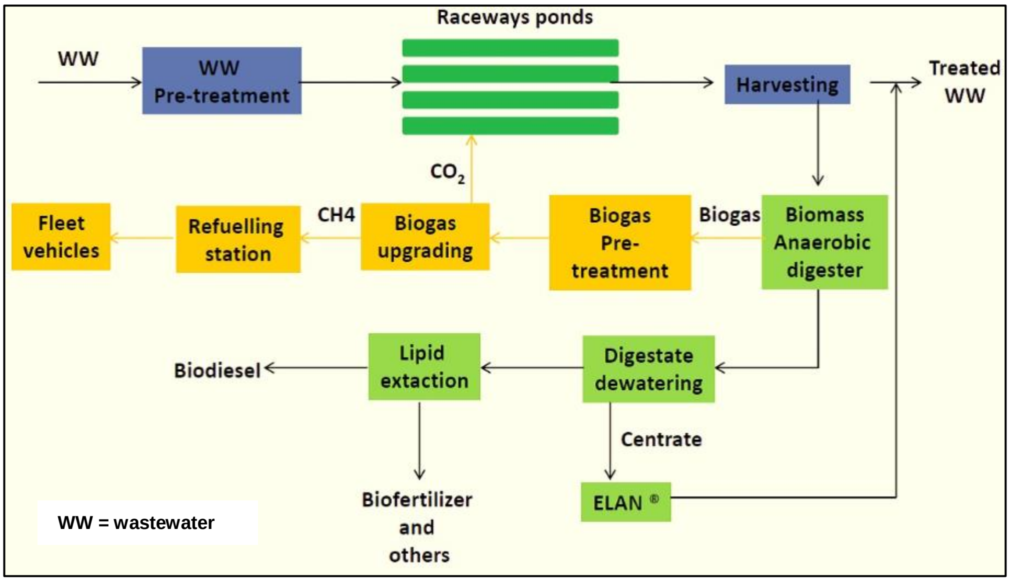


Figure 8. All-gas project flow diagram
Source: All-gas (2017).

The plant (Figure 9), located in Spain, has four raceways with a surface area of 5,200 m² each with a productivity of 100 t of biomass/ha/year, three units of dissolved air flotation for biomass separation and thickening, 2,750 m² of anaerobic digester to convert algae biomass into biomethane, and a complete biogas upgrading plant coupled to a filling station.

Figure 9. All-gas demonstration plant
Source: All-gas (2017).

Microalgae biodiesel is technically feasible (CHISTI, 2007), and all these projects reinforce the expectations of microalgae replacing fossil fuels. However, microalgae biomass is still not a viable choice for commercial biofuels production (LAM & LEE, 2012). Costs of either open ponds or PBR are expensive, and the futurist algae farms, as observed in Figure 10, may sound unrealistic (RAPIER, 2012).

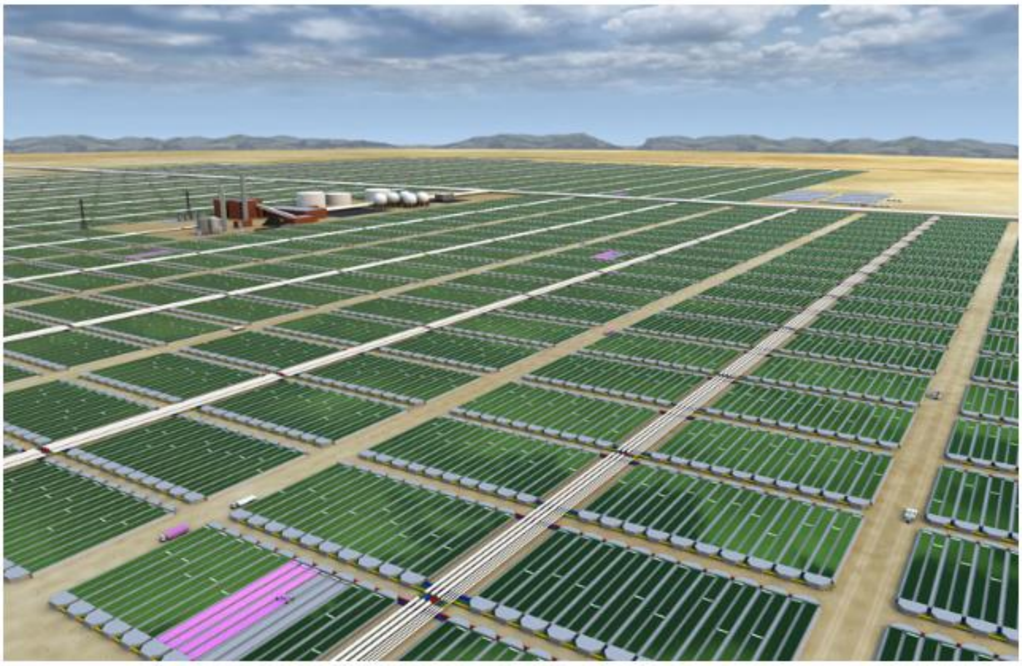


Figure 10. Computer-generated futuristic microalgae farm
Source: RAPIER (2012).

2.2 Multi-criteria Decision Analysis

2.2.1 Introduction to the multi-criteria approach

Decision-making can be a complex process aiming to establish satisfying solutions or possible compromises submitted to the judgment of a decision-maker or a group of decision-makers under a scientific base. Even when only one decision-maker is involved to the decision-making process, rarely the decision-maker has in mind only one criterion, which means that the decision-making is more often multicriteria than monocriterion. In this sense, the multi-criteria approaches have been playing an important role for analysing and structuring decision process (FIGUEIRA et al., 2005).

Multi-criteria approaches originated basically from two Schools: the European Multi-criteria Decision Analysis (MCDA), or also called French School, and the American Multi-criteria Decision Making (MCDM). While MCDA seeks to give recommendations by means the introduction of outranking relations, MCDM tries to approach an ideal solution in terms of evaluating a discrete set of alternatives by multi-attribute utility functions, linear or not (FIGUEIRA et al., 2005). To simplify, in the present thesis, the acronym MCDA will not be used in the narrow sense of being seen exclusive for European School.

Three basic concepts are involved in the MCDA: (i) alternative, that can be also called by action, and constitutes the object of the decision, which may involve a finite number of alternatives or infinite possibilities; (ii) criteria, which lead to evaluate and compare the alternatives; and (iii) problematic, that refers to the way in which the decision aid is envisage, i.e. which questions the decision aid wants to answer (FIGUEIRA et al., 2005). The latter concept is an important issue in the decision-making process because it will determine the most suitable procedure to fulfill the objective. All of them must be defined on the first step of the MCDA methodology process (Figure 11).

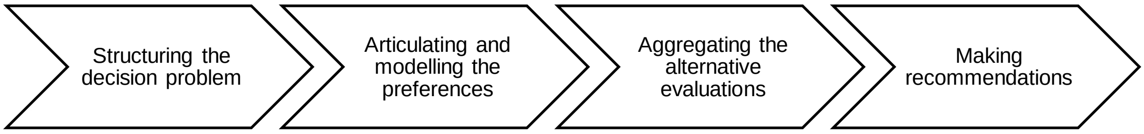


Figure 11. The process of the MCDA methodology
Source: The author based on Guitouni & Martel (1998).

Phase 1: Structuring the decision problem

The structuring the decision problem refers to the characterization of the decision-making situation, and includes the determination of the emergency of the decision, the different alternatives, the consequences, the criteria (important aspects), the quantity and the quality of information, and the stakeholders. This step is vital since the formulation of the decision problem is often more essential than its solution.

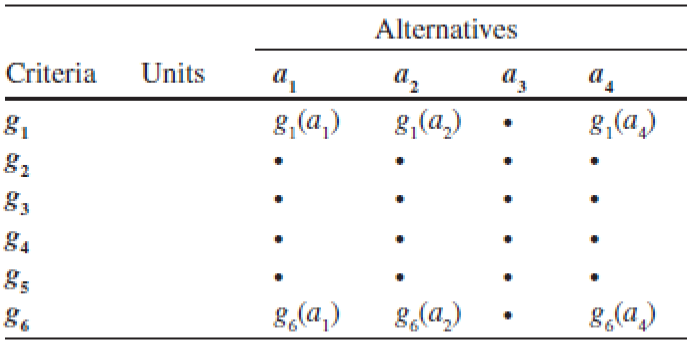
Alternative, or also called action, corresponds to the modelling situation where two distinct potential actions cannot be conjointly put into operation, supposing they are mutually exclusive. Although many authors adopt this definition, it must be notice that such hypothesis is not applicable to all real-world decision aiding contexts, where modelling several potential actions implemented conjointly seems more appropriate. The number of alternatives can be finite or infinite, depending on the objective of the decision-making (FIGUEIRA et al., 2005).

The criteria allow the evaluation and comparison of potential alternatives. The performance of each alternative in such criterion is a real number, even if it reflects a qualitative assessment, expressed by $g_j(a)$, for $j = 1,2, \dots . n.$, where n corresponds to the number of criteria and a to the set of alternatives $A = \{a, b, \dots, m\}$. A family of criteria has to be built in accordance to some statements (FIGUEIRA et al., 2005):

- each criterion should be sufficiently intelligible for each of the stakeholders;
- each criterion should be perceived to be a relevant instrument for comparing potential actions;
- the n criteria considered should all together satisfy some logical requirements such as exhaustiveness, cohesiveness and non-redundancy.

Different forms of criteria can be defined: true criterion, semi-criterion, interval criterion and pseudo-criterion. The first one is the simplest form of criterion, where no thresholds exist, and the differences between criterion performances are used to determine which alternative is preferred, leading a complete pre-order as a result. Semi-criterion allows the use of a constant 'just-noticeable difference' as a threshold, and the difference between the performance of two alternatives must exceed this threshold before one alternative is declared preferred to another. The use of this difference threshold (q) is by definition intransitive, leading a semi-order structure as a result. The interval criterion is used in terms of the creation of a variable threshold model, where the thresholds can vary with the scale of the criteria being compared. Finally, the pseudo-criterion that corresponds to the use of two thresholds – preference (p) and indifference (q), and handles with imprecision and uncertainty, since it allows the creation of an intermediary zone in which the decision-maker's information is contradictory or indeterminate (ROGERS et al., 2000).

Defined the alternatives and the consistent family of criteria, a performance matrix (or impact matrix) could be built including quantitative, qualitative or both types of information (Figure 12).



		Alternatives			
Criteria	Units	a_1	a_2	a_3	a_4
g_1		$g_1(a_1)$	$g_1(a_2)$	•	$g_1(a_4)$
g_2		•	•	•	•
g_3		•	•	•	•
g_4		•	•	•	•
g_5		•	•	•	•
g_6		$g_6(a_1)$	$g_6(a_2)$	•	$g_6(a_4)$

Figure 12. Example of performance matrix
Source: Munda (2008).

Phase 2: Modelling the preferences

The second step refers to modelling the preferences. All MCDA methods use the decision-maker(s) preferences to make recommendations, and it must be remarked that the assumptions about the preferences may affect both the MCDA process and the solution, because the decision-maker(s) can influence the decision process and also be influenced by it (Guitouni and Martel 1998). The decision-maker preferences can be clearly addressed by four elementary binary relationships considering two alternatives *a* and *b*: indifference, weak or strong preference, and incomparability (Table 3).

Table 3. Relationships between two alternatives

Relationship	Representation	Description
Indifference situation	$a\ I\ b$	Means alternative a is indifferent to alternative b
Preference situation	$a\ P\ b$	Alternative a is strictly preferred to b
Weak preference situation	$a\ Q\ b$	It is the hesitation between the indifference and preference situations, and hence there is not sure that ($a\ P\ b$)
Incomparability	$a\ R\ b$	Occurs when there is hesitation between ($a\ P\ b$) and ($b\ P\ a$), or when there is no sufficient information to compare them

Source: The authors based on Roy (1990).

The construction of the decision-makers' preferences depends on the type of criterion used. Considering two alternatives a and $b\ \in A,\ g(a)$ is the performance of alternative a in the criterion g, and $g(b)$ the performance of alternative b in the same criterion g. The preferences' structure for a true criterion is:

$$aPb \leftrightarrow\ g(a) > g(b)$$

$$aIb\ \leftrightarrow g(a) = g(b)$$

Where the indifference relation is transitive, i.e. $aIb\ and\ bIc \leftrightarrow aIc.$

For a semi-criterion (with the introduction of a positive threshold):

$$aPb \leftrightarrow\ g(a) > g(b) + q$$

$$aIb\ \leftrightarrow |g(a) - g(b)| \leq q$$

For an interval criterion (variable threshold model):

$$aPb \leftrightarrow\ g(a) > g(b) + q(g(b))$$

$$aIb\ \leftrightarrow g(a) \leq g(b) + q\big(g(b)\big)\ and\ g(b) \leq g(a) + q\big(g(a)\big)$$

For a pseudo-criterion (with introduction weak preference):

$$aPb \leftrightarrow\ g(a) > g(b) + p\big(g(b)\big)$$

$$aQb\ \leftrightarrow g(b) + p\big(g(b)\big) \geq g(a) > g(b) + q(g(b))$$

$$aIb\ \leftrightarrow g(b) + q\big(g(b)\big) \geq g(a)\ and\ g(a) + q\big(g(a)\big) \geq g(b)$$

Phase 3: Aggregation of the alternative evaluations

This third step of the MCDA methodology refers to the multi-criteria aggregation procedure, which corresponds to the problematic concept of decision-making. If the decision-making is oriented to select a single alternative, it refers to the choice problematic (P.α). If the decision-aid lies on an assignment of each alternative to one category, it refers to the sorting problematic (P.β). If the objective is to rank the alternatives, the decision-aid is related to the ranking problematic (P.γ). Each problematic has a set of suitable procedures for decision-aid. It must be remarked that these problematics are not the only possible ones (FIGUEIRA et al., 2005).

Phase 4: Making recommendations

The core objective of MCDA is to support decision-makers (eg. managers) to make better decisions, thus the last step of MCDA methodology process is to make recommendations. It should be notice that the complexity involved on the decision process and the limitations of problem structuring may lead to not the better solution but to the compromise solution. In other words, the solution is no longer an optimal one but a satisfactory one (Guitouni and Martel 1998). In most cases, the process of knowledge construction plays more an important role than the decision-making per se (FIGUEIRA et al., 2005).

2.2.2 Classification of the main MCDA methods

MCDA methods can be classified according to the aggregation procedure adopted to take into account all criteria analysed, as pointed out by (Figure 13). The main MCDA methods are briefly discussed in the following.

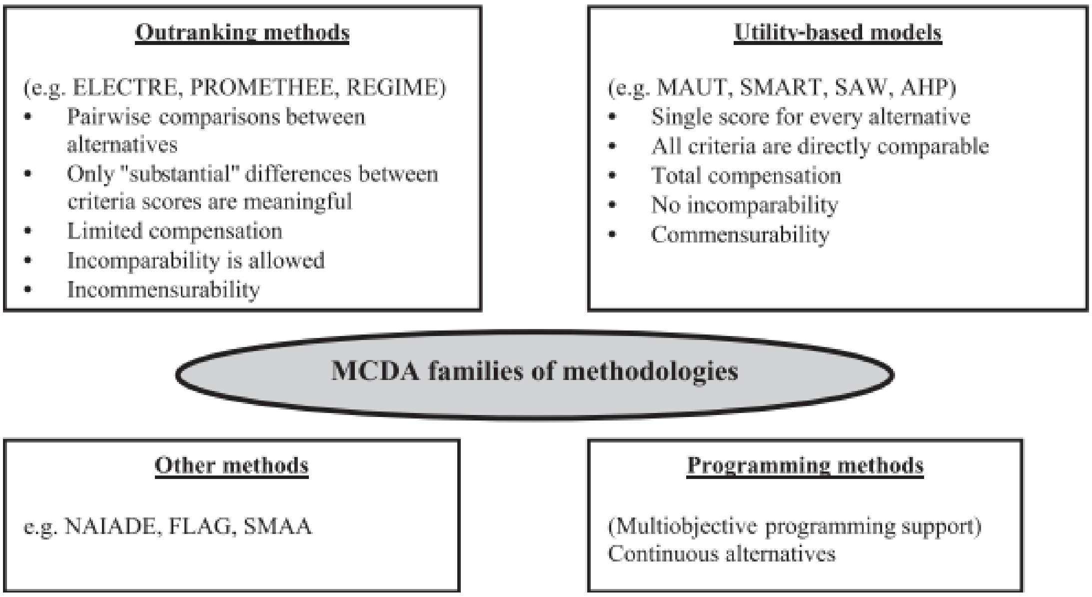


Figure 13. MCDA methods classification
Source: Polatidis et al. (2006).

The most traditional approach is that one based on utility or value-function by single synthesising criterion, in which the criteria multiplicity is reduced to a unique criterion by using formal rules mathematically structured. Several commonly used methods belong to this group, such as: TOPSIS, AHP and ANP. TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), also known as a reference point approach, is based on the concept that the alternative chosen should be the nearest to the ideal solution and farthest from the negative-ideal solution (FIGUEIRA et al., 2005).

AHP (Analytic Hierarchy Process) is the most widely applied multi-criteria method in decision-making (VAIDYA & KUMAR, 2006). Developed by Saaty (1980), the AHP is based on the creation of a hierarchical structure of criteria, sub-criteria (if they exist) and alternatives. In this method, criteria and alternatives are compared in pairs to assess the relative preference among each other, where the intensity of preference is defined with the help of a relative measurement scale called Saaty’s scale. ANP (Analytic Network Process) is a derived form of AHP that comprises the generalisation of hierarchies to networks with dependence and feedback (SAATY, 2005).

Despite these methods assume some compensability among criteria, i.e. trade-offs (ROWLEY et al., 2012; BENOIT & ROUSSEAUX, 2003; GUITOUNI & MARTEL, 1998), where a disadvantage on some criterion can be compensated by a sufficiently large advantage on another criterion, TOPSIS and AHP have been largely used in sustainable related decisions (eg. AHP: MYLLYVIITA et al., 2013; von DODERER & KLEYNHANS, 2014, AKHTAR et al., 2015; TOPSIS: SU et al., 2010; DONG et al., 2014; SEDLAKOVA et al., 2014; 2015).

The other approach is that based on a synthesizing preference relational system, which involves pairwise comparison of the alternatives on each criterion supported by well-structured mathematical rules based on discrimination thresholds and veto thresholds. Belonging to this group there are the outranking methods such as the PROMETHEE family and ELECTRE family.

The outranking methods can be considered as partially compensatory (GUITOUNI & MARTEL, 1998; ROGERS et al., 2000; BENOIT & ROUSSEAUX, 2003) or even non-compensatory methods (ROY, 2005; ROWLEY et al., 2012), what means they might be more suitable to handle problems involving sustainability.

PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) family is composed of six methods that differ from partial ranking (PROMETHEE I) to complete ranking (PROMETHEE II), ranking based on intervals (PROMETHEE III) or on continuous case (PROMETHEE IV), with constraints segmentation (PROMETHEE V) or representation of the human brain (PROMETHEE VI). All of them based on positive and negative preference flows for each alternative, according to the selected criteria preferences (weights) (BRANS & MARESCHAL, 2005).

ELECTRE (Elimination and Choice Expressing Reality) family comprises six different methods: ELECTRE I that is dedicated to choice problems, with the aim of reducing the size of a non-dominated set of alternatives; ELECTRE IS, an improved form of ELECTRE I, that uses an indifference threshold; ELECTRE II which ranks alternatives from the best to worst option, using either strong or weak relations; ELECTRE III that allows the use of pseudo-criteria and fuzzy outranking relations; ELECTRE IV, similar to the ELECTRE III, but without the use of criteria weights; and finally, ELECTRE TRI for dealing with ordinal classification problems (ROY & BOUYSSOU, 1993).

There are other methods that are not in accordance with these approaches due to their interactivity nature. An example could be found in Angelo et al. (2017), where an interactive learning oriented multi-attribute additive MCDA model using imprecise information, called VIP-Analysis, was applied in order to identify the most preferable waste management alternative in terms of environmental impacts.

Moreover, there is another approach used when the decision problem involves an infinite or a very large number of alternatives, known as Multi-Objective Decision-Making. It comprises programming methods such as multi-objective optimization and goal programming, and are in general restricted to operational decisions (AZAPAGIC & PERDAN, 2005). However, it must be remarked that, facing the multiplicity of MCDA methods, none can be considered as the best method appropriated to all decision-making situations (GUITOUNI & MARTEL, 1998).

2.2.3 ELECTRE methods

ELECTRE methods take part of the multi-criteria methods from the European School, and were developed by Bernard Roy. The first decision-aid method using the concept of outranking relation was ELECTRE, created in 1965 to solve a concrete, multi-criteria and real-world problem regarding decisions related to the development of new activities in firms. ELECTRE IS has appeared subsequently for modelling situations in which the data is imperfect.

Few years later, ELECTRE II was developed to deal with a different real-world decision-making situation: definition of an advertising plan in media planning, where magazines, newspapers, etc must be ranked from the best option to the worst. Few years later, as in the real-world the perfect knowledge is rare, ELECTRE III was introduced to deal with uncertainty and imprecision by using pseudo-criterion and fuzzy binary outranking relations.

ELECTRE IV arose to allow the rank of alternatives without using criteria importance weights. The most recent method created was ELECTRE TRI that is the only method of the ELECTRE family dedicated to sorting problematic (FIGUEIRA et al., 2005). Table 4 summarizes these methods.

Table 4. Some characteristics of the main MCDA discrete methods

MCDA method	**Reference**	**Problematic**	**Outranking relationship**
ELECTRE I	Benayoun et al., 1966	P.α	Binary (outranking, no outranking)
ELECTRE II	Roy & Bertier, 1973	P.γ	No outranking, weak outranking, strong outranking
ELECTRE III	Roy, 1978	P.γ	Fuzzy outranking relationship
ELECTRE IV	Roy & Hugonnard, 1982	P.γ	
ELECTRE IS	Roy & Skalka, 1984	P.α	
ELECTRE TRI	Roy & Bouyssou, 1991	P.β	

P.α = selection, P.β = sorting, P.γ = ranking.
Source: The author based on Roy (1991) and Rogers et al. (2000).

Both methods allow the input of ordinal, cardinal or mixed information. However, only those with fuzzy outranking relationship are able to handle uncertain or unambiguous information (GUITOUNI & MARTEL, 1998). Moreover, the incorporation of fuzziness into these methods (ELECTRE III, IV, IS and TRI), i.e. fuzzy criterion, renders greater stability or robustness facing variations in the values of certain thresholds. On the contrary, a small change in the criterion crisp values can create or destroy a relationship between two alternatives, modifying the result notably (ROY, 1991; ROGERS et al., 2000).

For decision-making related to ranking problematic, there are three options: ELECTRE II, III and IV. The choice of which method to be used pass by the choice of true or pseudo-criteria, and of to function with or without weights. In other words, if the criterion can be represented by crisp values because there is no uncertainty nor ambiguity associated with it, a straightforward model such as ELECTRE II seems favourable.

On the contrary, problems where the uncertainties inherent in criterion estimates can be significant, such as environmental problems, the choice of a fuzzy decision model as ELECTRE III might be more appropriate. Finally, the second aspect is related to the power of the criteria. In cases where no criterion is too dominant or too insignificant, ELECTRE IV must be preferred than ELECTRE III, because it is the only ELECTRE method designed, from the start, for such condition (Figure 14).

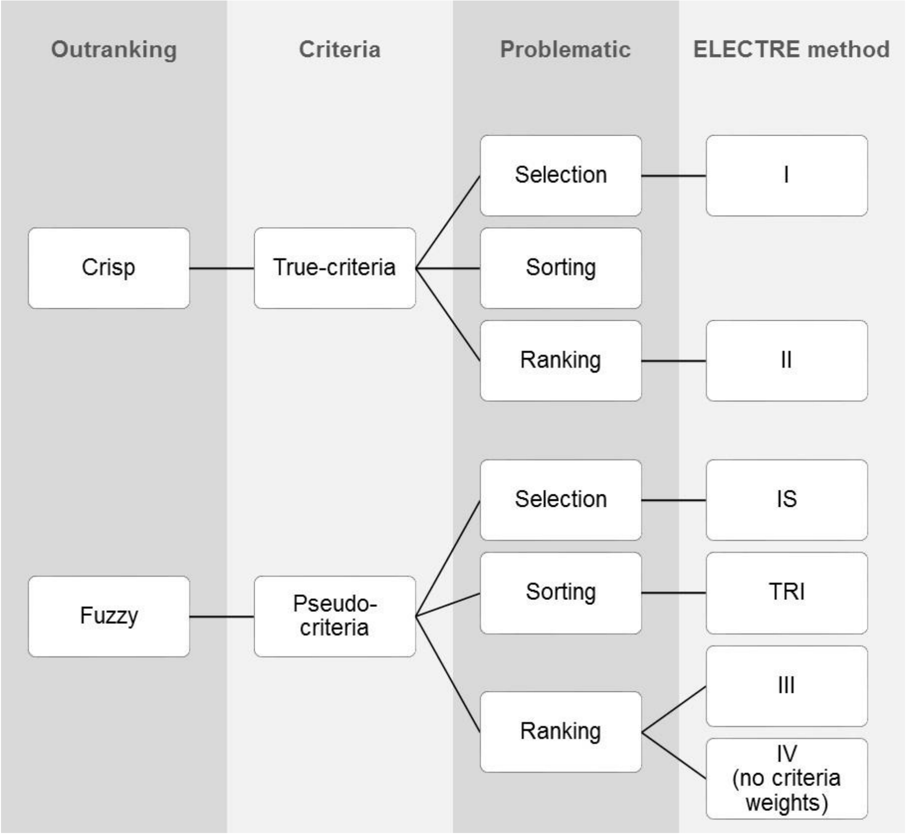


Figure 14. Choosing the most appropriate ELECTRE method
Source: The author based on Roy (1991) and Rogers et al. (2000).

Govindan & Jepsen (2016) carried out a comprehensive literature review of papers on ELECTRE or ELECTRE-based methods was performed, in order to investigate how ELECTRE family methods have been considered in various areas. Figure 15 shows the distribution of the applied papers, and it can be observed that natural resources and environmental management (NRE) is by far the most popular application area for ELECTRE methods.

As NRE is a broadly area, the authors divided it into five sub-categories (Figure 16), of which water management contains almost half of papers in NRE. The other NRE applications refers to problems related to emissions and air quality, end-of-life products and selecting of environmental indicators.

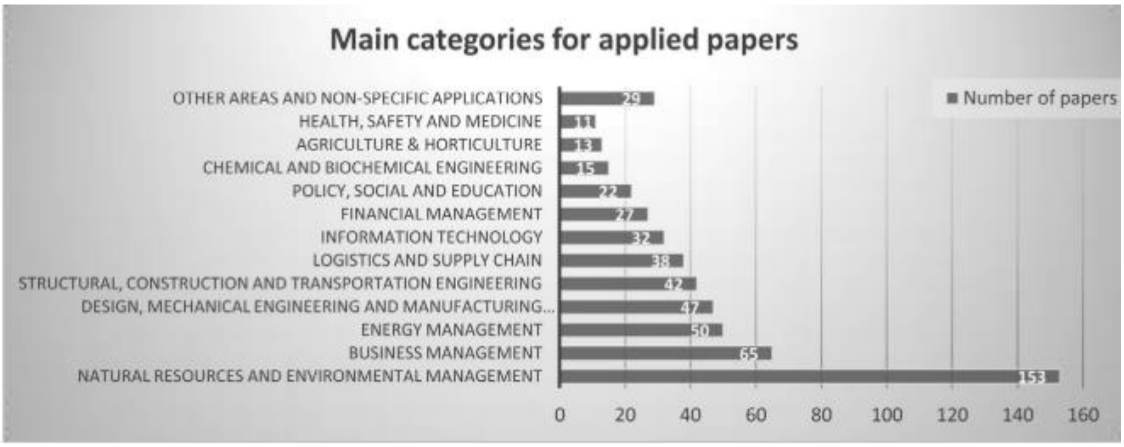


Figure 15. Application areas for ELECTRE methods
Source: Govindan & Jepsen (2016).

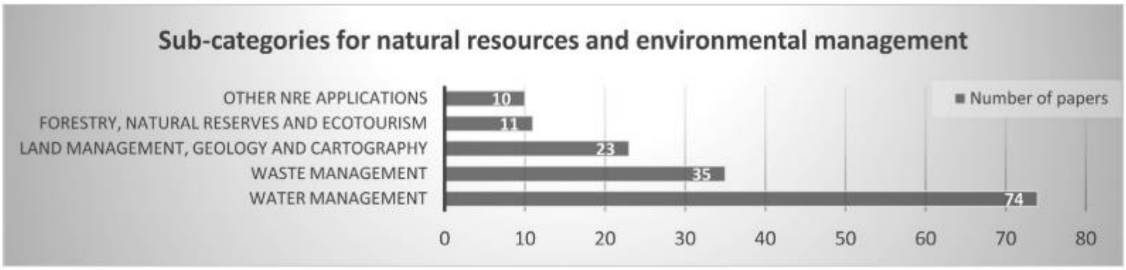


Figure 16. Sub-categories for NRE
Source: Govindan & Jepsen (2016).

Govidan and co-author also analysed the application of each ELECTRE method in relation to application areas (Table 5), pointing out ELECTRE III as the most popular of the ELECTRE methods. Therefore, the results of their review clearly show the usefulness of ELECTRE methods in the environmental area, and specially the large use of ELECTRE III in areas involving complex decision-making such energy management, chemical and biochemical engineering, policy, social and education.

Table 5. Distribution by ELECTRE method *vs.* application area

Application area	**ELECTRE method (participation %)**						**Total**
	I	**IS**	**II**	**III**	**IV**	**TRI**	
NRE total	27	1	20	39	3	10	100
Water management	30	0	33	27	3	7	100
Waste management	18	5	8	63	5	0	100
Land management, geology and cartography	30	0	0	35	0	35	100
Forestry, natural reserves and ecotourism	25	0	8	50	0	17	100
Other papers on NRE	20	0	10	50	0	20	100
Business management	38	1	6	31	4	21	100
Energy management	12	4	7	53	5	19	100
Design, mechanical engineering and manufacturing systems	46	4	14	28	6	2	100
Structural, construction and transportation engineering	34	0	11	34	6	15	100
Logistics and supply chain	46	3	15	23	5	8	100
Information technology	47	3	15	24	3	9	100
Financial management	16	3	10	23	0	48	100
Chemical and biochemical engineering	33	7	7	53	0	0	100
Policy, social and education	28	0	16	44	4	8	100
Agriculture and horticulture	31	0	15	15	0	38	100
Health, safety and medicine	50	0	8	25	0	17	100
Other areas and non-specific applications	29	0	13	48	0	10	100
Overall participation (%) of each method	**28**	**2**	**14**	**35**	**4**	**14**	**100**

Source: Adapted from Govindan & Jepsen (2016).

2.2.3.1 Description of ELECTRE III

ELECTRE III method starts by a pair-wise comparison of each alternative to the remaining ones in order to accept, reject or assess the credibility of the assertion "alternative a is at least as good as alternative b", i.e. "a outranks b" (aSb). After definition of the alternatives, the consistent family of criteria, the thresholds, the criteria weights and the performance matrix, two indices should be calculated for each criterion: concordance and discordance indices. The former expresses in what measure the performance of the alternatives a and b are in concordance with the assertion "a outranks b", and the later indicates in what measure they oppose this assertion.

Then, the partial concordance indices are aggregated taking into account the weights (expressed as importance coefficients) for construction the fuzzy outranking relationships of each pair of alternatives. These outranking relationships - denoted by a credibility index $\sigma(a, b)$ – express in what measure aSb using both concordance and discordance indices for each criterion analysed. The ranking of alternatives is presented as a final partial pre-order resulted from the two distillations by applying the ranking algorithm (Figure 17).

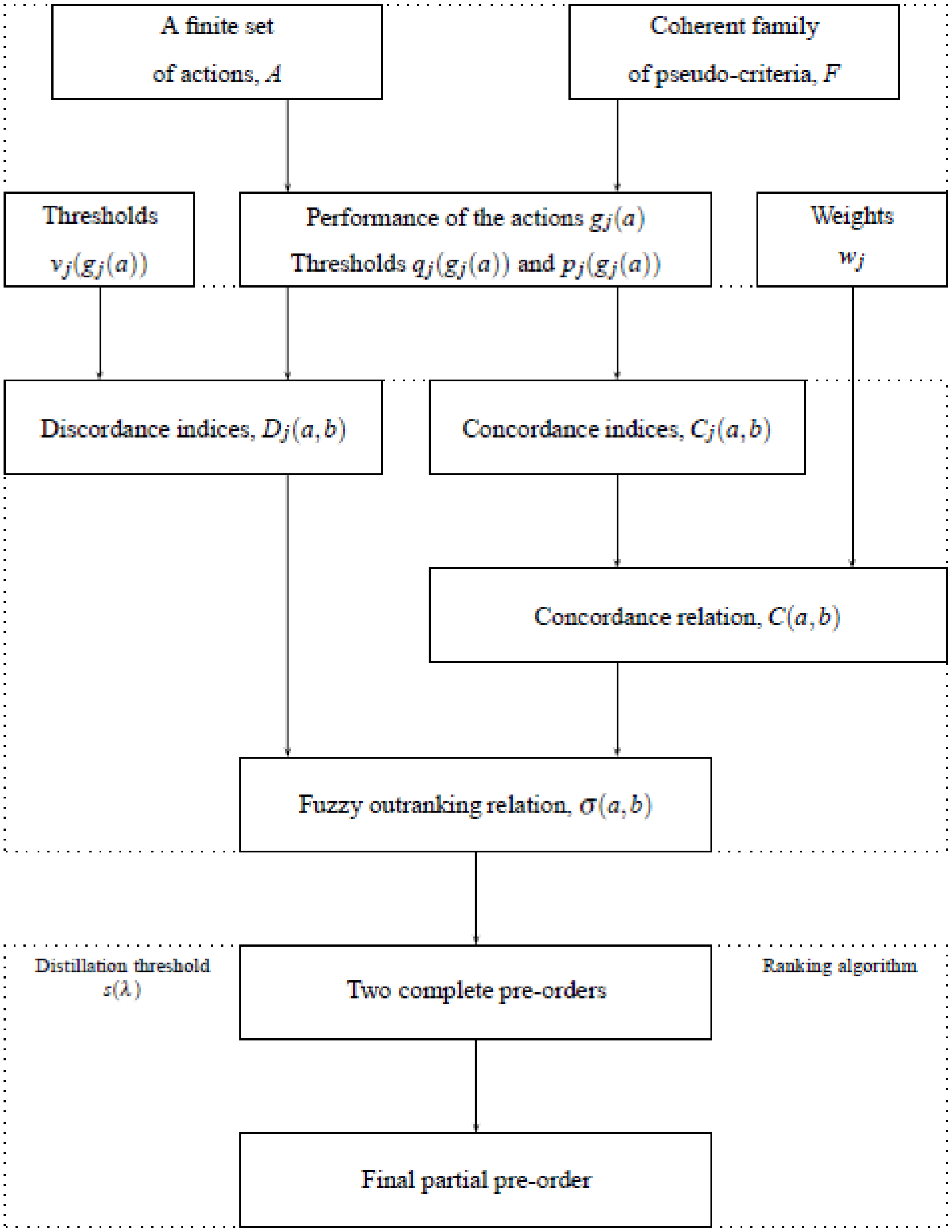


Figure 17. General structure of ELECTRE III
Source: Dias et al. (2006).

As mentioned before, ELECTRE III uses pseudo-criteria by the adoption of three thresholds: preference, indifference and veto. Each threshold can be expressed as an affine function of the performance: $\alpha \times g(a) + \beta$, where $g(a)$ is the performance of the alternative a on the criterion g. The coefficients α and β must be specified by the decision-maker. If $\alpha \neq 0$, the threshold varies as a function of the performance. It is important to notice that both coefficients must not return a negative value for the threshold.

The outranking relationship of each pair of alternatives is thus analysed by assuming these thresholds. For instance, a and b are indifferent (aIb) if the difference between the performance of these two alternatives is smaller than the indifference threshold (q). The alternative a is weak preferred to b of the difference of their performances is between the thresholds of indifference (q) and preference (p). The strictly preference occurs when the difference of their performances is greater than the preference threshold (p). Finally, the pseudo-criterion also allows the incomparability of alternatives when this difference surpass the veto threshold (v) (Figure 18).

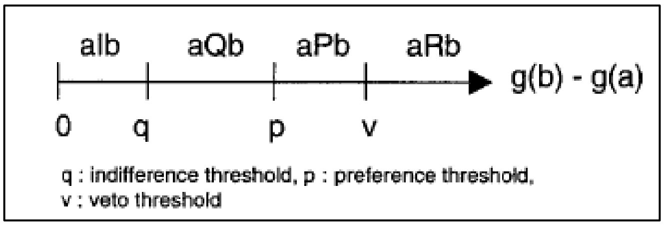


Figure 18. Outranking relationships between two alternatives
Source: Benoit & Rousseaux (2003).

The concordance index is a fuzzy index $C(a,b)$ measuring which indicates the truth of the assertion “alternative a is at least as good as b on criterion g_j”. If $C(a,b) = 0$, the assertion is false. On the contrary, $C(a,b) = 1$ indicates it is the full truth. This index is the sum of the partial concordance indices $C_j(a,b)$ on each criterion weighted by the weights (w_j), presented as follows:

$$C(a,b) = \frac{\sum_{j=1}^{n} w_j c_j(a,b)}{\sum_{j=1}^{n} w_j}$$

Where $C_j(a,b)$ ca be represented graphicaly as given in Figure 19, from which it is possible to observe:

- $C_j(a,b) = 0$ (zone 1) when
    - $\boldsymbol{g_j}(\boldsymbol{b}) > g_j(a) + p(g_j(a))$ that means alternative b is strictly preferred to a on criterion g_j

- $0 < C_j(a,b) < 1$ (zone 2) when

    - $g_j(a) + q(g_j(a)) < \boldsymbol{g_j(b)} < g_j(a) + p(g_j(a))$ that means alternative b is weakly preferred to a on criterion g_j

- $C_j(a,b) = 1$ (zone 3) when
    - $g_j(a) \leq \boldsymbol{g_j(b)} \leq g_j(a) + q(g_j(a))$ that means alternative b and a are indifferent on criterion g_j

- $C_j(a,b) = 1$ (zone 4) when
    - $\boldsymbol{g_j(b)} \leq g_j(a)$ that means the performance of alternative a is better than the performance of b

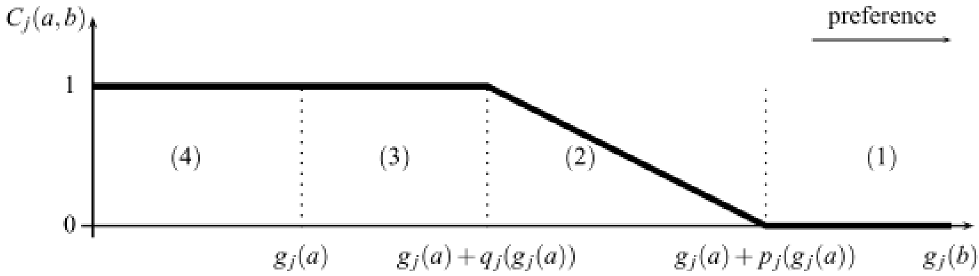


Figure 19. Concordance index between two alternatives a and b
Source: Dias et al. (2006).

The discordance index $D_j(a,b)$ indicates if the criterion g_j is more or less discordant with the assertion a outranks b. The graphic representation is given in Figure 20, where:

- $D_j(a,b) = 0$ (zone 1) when
    - $g_j(b) - g_j(a) \leq p(g_j(a))$ that means the peformances of alternatives a and b on criterion g_j do not reject aSb
- $0 < D_j(a,b) < 1$ (zone 2) when
    - $p\left(g_j(a)\right) < g_j(b) - g_j(a) < v(g_j(a))$ that means the peformances of alternatives a and b on criterion g_j weakly reject aSb
- $D_j(a,b) = 1$ (zone 3) when
    - $g_j(b) - g_j(a) > v(g_j(a))$ that means the peformances of alternatives a and b on criterion g_j reject aSb

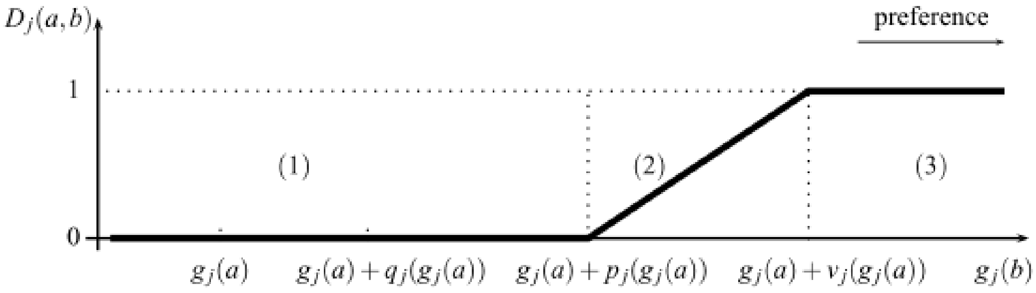


Figure 20. Discordance index between two alternatives a and b
Source: Dias et al. (2006).

Using both concordance and discordance indices, the outranking relation is then defined as a credibility index $\sigma(a,b)$, which represents in what measure aSb. When there is no discordant criterion, $\sigma(a,b) = C(a,b)$. The credibility index value decreases in the presence of one or more discordant criteria, and $\sigma(a,b) = 0$ when $D(a,b) = 1$ in conformity with the veto effect, whatever the weight of the criterion. Thus, the credibility index can be calculated as follows:

$$\sigma(a,b) = \begin{cases} C(a,b) \\ C(a,b) \times \prod_{j \in \bar{F}(a,b)} \frac{1 - D_j(a,b)}{1 - C(a,b)} \end{cases}$$

If $\bar{F}(a,b) \neq \emptyset$, where $\bar{F}(a,b)$ is the set of criteria for $D_j(a,b) > C(a,b)$.

The degrees of credibility are consolidated in the Matrix of Credibility. It must be remarked that the way of the credibility index is constructed excludes the possibility of compensation between criteria, i.e. that a big loss in one criterion might be compensated by a number of small gains on the remaining criteria (DIAS et al., 2006).

Everything presented so far in this section refers to the phase of construction of the outranking relationship. The next phase concerns to the exploitation of the relationship, in which two pre-orders are built by means two antagonist procedures: upward and downward distillations. A final partial pre-order is then built resulting the intersection of these two pre-orders.

The downward distillation, also called descending distillation, starts with the best alternative and finishes with the assignment of the worst one. On the contrary, in the upward distillation, or ascending distillation, the ranking process starts with the worst alternative and finishes with the best one.

Both distillations need a distillation threshold function $s(\lambda) = \alpha\lambda + \beta$, which is used to make successive cuts of the fuzzy outranking relations in order to obtain crisp outranking relations. The distillation coefficients' values can be defined by the decision-maker, however some standard values are recommended: $\alpha = -0.15$ and β = 0.30 (ROY & BOUYSSOU, 1993). The pre-orders are stablished by the following proceed:

- A succession of crispy outranking relationships is built from the credibility matrix $[\sigma(a,b)]$;
- A set of cut-off levels $\lambda_k \in [0{,}1]$ and a distillation threshold function $s(\lambda) = \alpha\lambda + \beta$ are defined;
- A crispy outranking relation $S_A^{\lambda_k}$ is obtained:
  - $a\, S_A^{\lambda_k}$ b $\Leftrightarrow \begin{cases} \sigma(a,b) > \lambda_k \\ \sigma(a,b) > \sigma(b,a) + s(\sigma(a,b)) \end{cases}$

  which means that the assertion aSb will be taken into account if it is more significative than the opposite bSa;

- The power of an alternative is calculated in terms of how much this alternative outranks all the others, and the weakness in terms of how much this action is outranked by all the others, where:
  - $P_A^{\lambda_k}(a)$ is the power of alternative a;
  - $f_A^{\lambda_k}(a)$ is the weakness of alternative a;
- The relative positions of each alternative are obtained by the difference between the power and the weakness of the alternative:
  - $q_A^{\lambda_k}(a) = P_A^{\lambda_k}(a)$ -$f_A^{\lambda_k}(a)$
  - $q_A^{\lambda_k}(a)$ is the qualification of alternative a;
  - $\lambda_1$is the first fixed cut-off level.
- The selected alternative is, in the set of alternatives to rank A, the best one obtained from a subset A which has the maximum qualification (descending distillation $\overline{D}_1$) or the worst alternative obtained from those which has the minimum qualification (ascending distillation $\underline{D}_1$):
  - $\overline{D}_1 = \left\{a \in A \mid q_A^{\lambda_1}(a) = \bar{q}_A = \max q_A^{\lambda_1}(x)\right\}$
  - $\underline{D}_1 = \left\{a \in A \mid q_A^{\lambda_1}(a) = \underline{q}_A = \min q_A^{\lambda_1}(x)\right\}\ \forall x \in A$

- At the end of the k steps of the first distillation, a first subset of A which will constitute the first or the last class of one of the two pre-orders is thus selected, where:
    - $\bar{C}_1$ is the first class of the descending distillation, and
    - $\underline{C}_1$, the last class of the ascending distillation;
- In the remaining subset of alternatives from A after the first distillation, the qualification of each alternative must be calculated again until all the alternatives are ranked.

Two complete pre-orders are thus resulted at the ending of the ascending and descending distillations. In each of them, the alternatives are ranked in a set of equivalence classes, which must contain at least one alternative. The intersection of these pre-orders results the final rank which provides the comparisons between alternatives or even possible incomparability, considering such statements:

- An alternative a is considered better than b if in at least one of the distillations, a is better than b, and in the other distillation, a is at least as well ranked as b;
- An alternative a is different to b if both belong to the same equivalence class in the two pre-orders;
- The alternatives a and b are incomparable if a outranks b in the ascending distillation and b outranks a in the descending distillation or *vice-versa*.

Details about the ranking algorithm can be found in Dias et al. (2006) and Rogers et al. (2000). In the former, there is also an illustrative example to present the software modelling. In addition, the later has case studies from which it is possible to observe in detail the ELECTRE III methodology and its usefulness.

2.3 Circular Business Models

2.3.1 Introduction to the Circular Economy

The Circular Economy (CE) has been seen as an alternative approach to the current economic model, based on a linear production system influenced by the strong consumption of goods and services. In other words, the CE aims to look beyond the current take-make-dispose industrial model, which starts at the natural resources extraction and ends with the waste disposal at landfills (ELLEN MACARTHUR FOUNDATION 2015a). Despite the various studies dedicated to understand the CE concept (GEISSDOERFER et al. 2017; KIRCHHERR et al., 2017; PRIETO-SANDOVAL et al., 2018), there is a consensus that the CE represents a new paradigm of production and consumption of goods and services (PRIETO-SANDOVAL et al., 2018).

According to the Ellen MacArthur Foudation, a global thought leader commited to accelarate the transition to a circular economy, the CE can be defined as an economy aimed to redefine growth, focusing on positive society-wide benefits by providing multiple value-creation mechanisms which are decoupled from the consumption of finite resources. It is based on three principles: (i) preserve and enhance natural capital, by controlling finite stocks and balancing renewable resource flows (eg. replacing fossil fuels with renewable energy); (ii) optimise resource yields, by keeping products, components and materials in use at the highest utility level; and (iii) foster system effectiveness by revealing and designing out waste and pollution (ELLEN MACARTHUR FOUNDATION 2015a). These three principles can be graphically observed in the CE system diagram (Figure 21), also known as butterfly diagram, focused on the biological and technical closed loops.

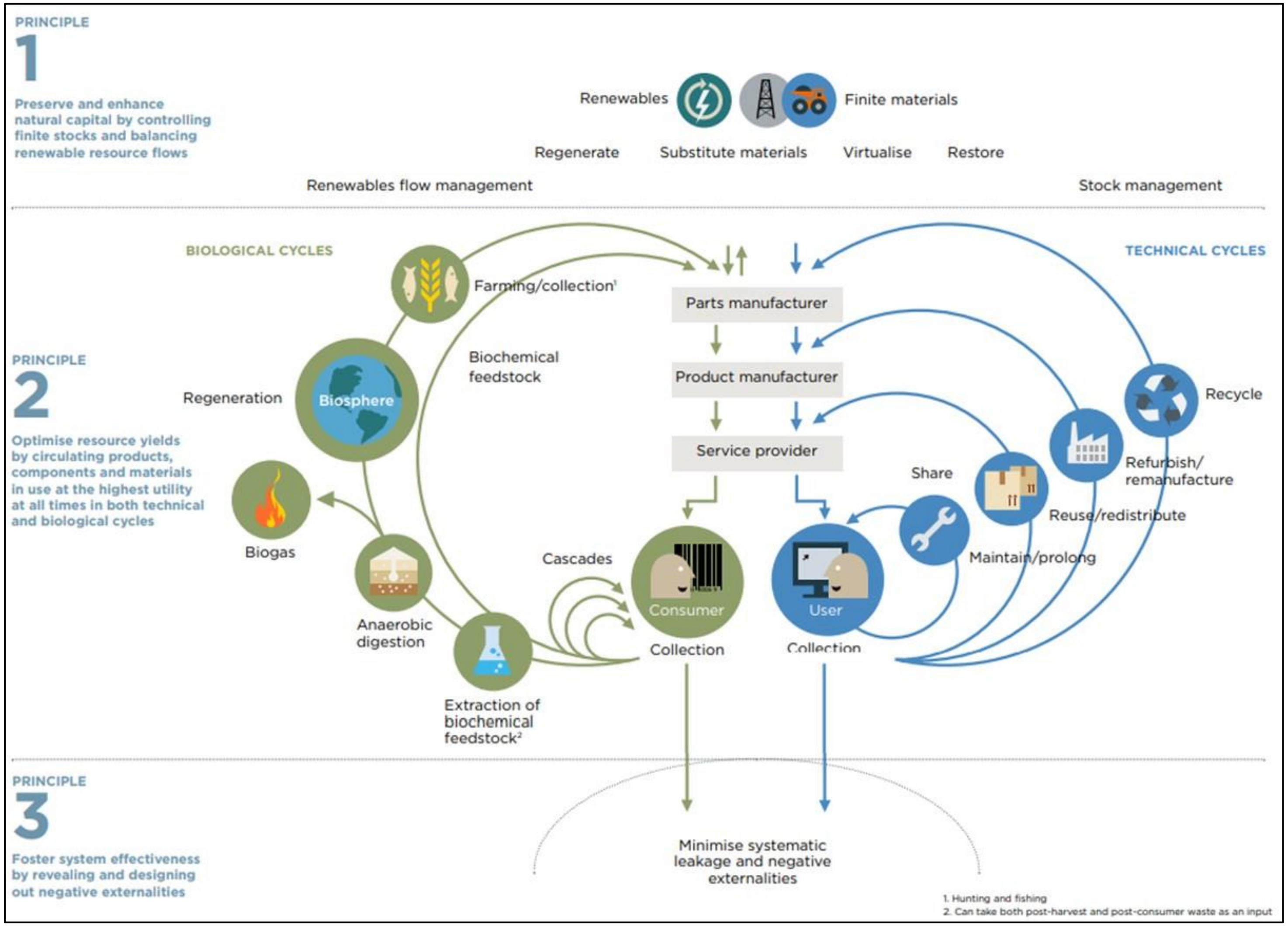


Figure 21. The Circular Economy Diagram
Source: Ellen MacArthur Foundation (2015).

It must be remarked that the transition to a circular economy goes beyond the reduce the negative impacts of the linear economy. As a regenerative system in which resource, waste, emission and energy leakage are minimised by slowing, narrowing and closing material and energy loops, the CE represents a systemic shift towards long-term resilience, business and economic opportunities generation, and environment and social benefits provision, in terms of seeking the effective work at all scales – for large and small business, for organisations and individuals, globally and locally (ELLEN MACARTHUR FOUNDATION, 2017; GEISSDOERFER et al., 2017).

Figure 22 depicts the complexity of the CE model, where materials are recovered from products at the end of the product's life cycle, connecting wastes to resources. Furthermore, the CE model has the production and the use of renewable energy as one of the constituent principles (van BUREN et al., 2016).

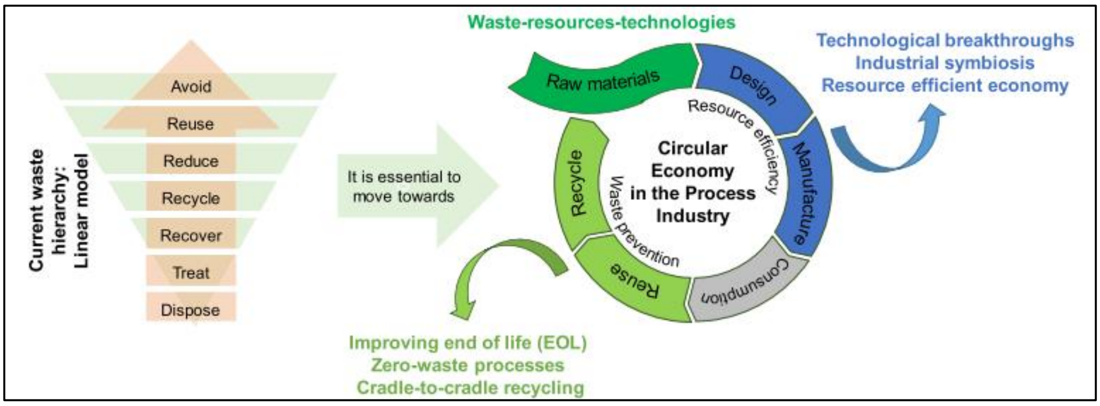
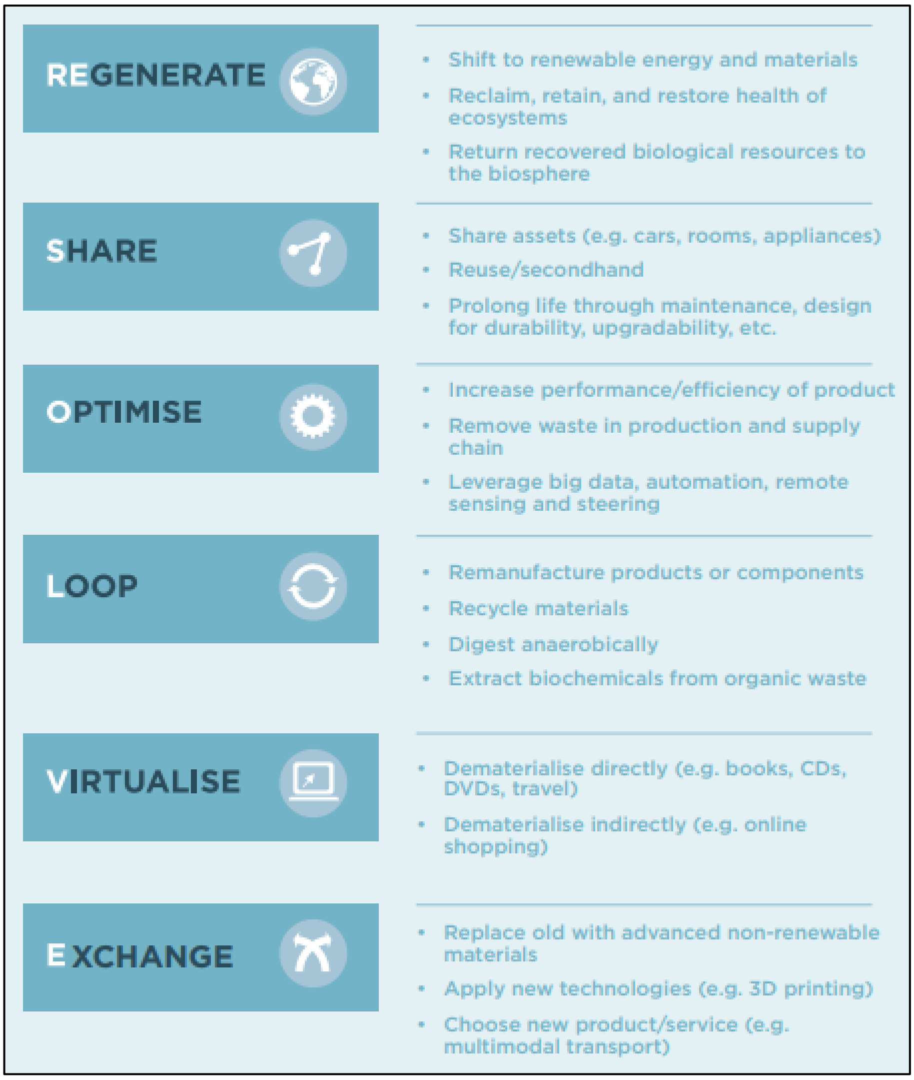


Figure 22. Differences between linear and circular economy models
Source: Garcia-Herrero et al. (2017).

There are a variety of actions that can be adopted by businesses and governments in order to transition to a circular economy, such as: regenerate, share, optimise, loop, virtualise, and exchange. All of them together comprise the ReSOLVE framework proposed by Ellen MacArthur Foundation (Figure 23) (ELLEN MACARTHUR FOUNDATION, 2015b).



REGENERATE
- Shift to renewable energy and materials
- Reclaim, retain, and restore health of ecosystems
- Return recovered biological resources to the biosphere

SHARE
- Share assets (e.g. cars, rooms, appliances)
- Reuse/secondhand
- Prolong life through maintenance, design for durability, upgradability, etc.

OPTIMISE
- Increase performance/efficiency of product
- Remove waste in production and supply chain
- Leverage big data, automation, remote sensing and steering

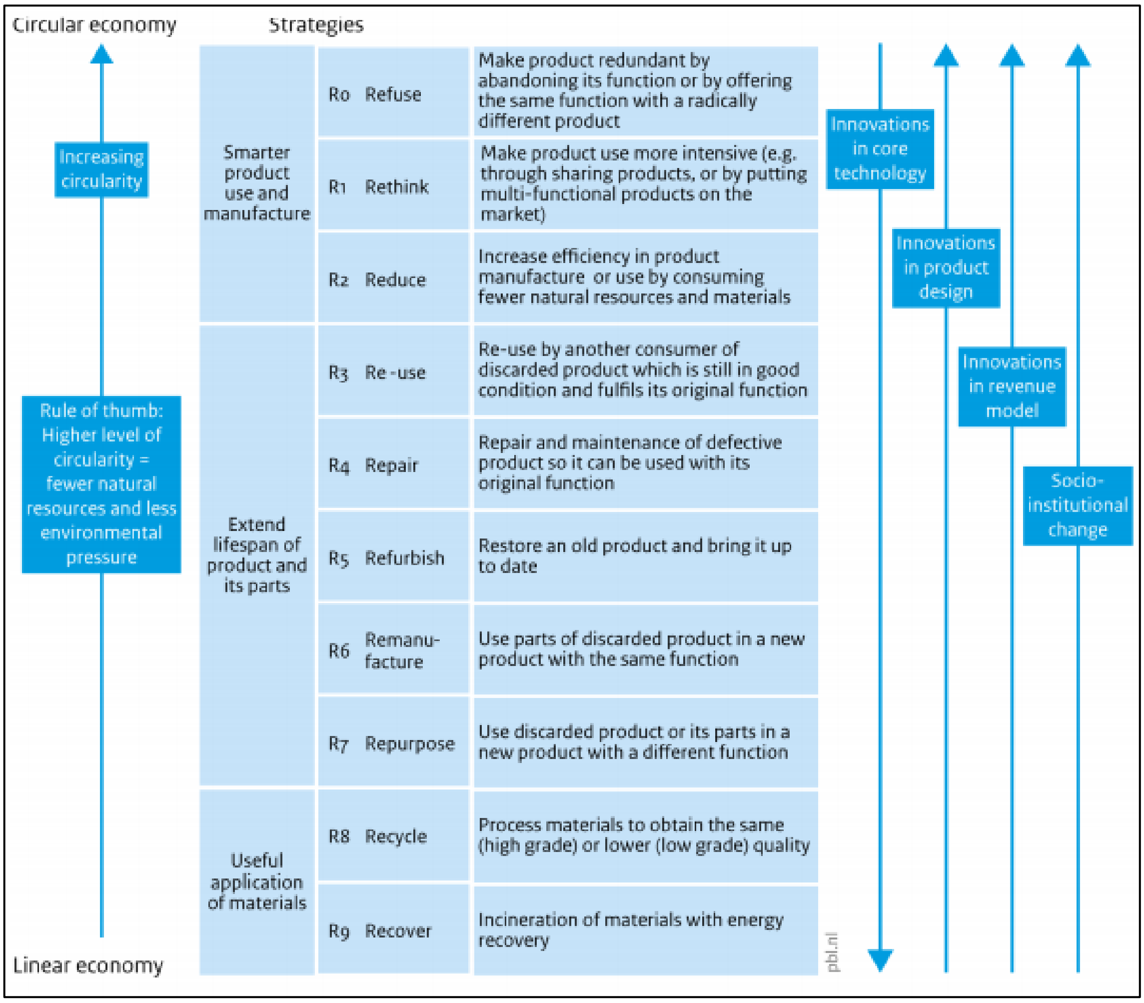
LOOP
- Remanufacture products or components
- Recycle materials
- Digest anaerobically
- Extract biochemicals from organic waste

VIRTUALISE
- Dematerialise directly (e.g. books, CDs, DVDs, travel)
- Dematerialise indirectly (e.g. online shopping)

EXCHANGE
- Replace old with advanced non-renewable materials
- Apply new technologies (e.g. 3D printing)
- Choose new product/service (e.g. multimodal transport)

Figure 23. The ReSOLVE framework
Source: Ellen MacArthur Foundation (2015b).

In addition, there are the R frameworks that have been used for decades not only in academia but also by practitioners as the ‘how-to’ of CE (KIRCHHERR et al., 2017). In other words, there are various gradations or options for circularity represented by a sequence of Rs. Besides the well know 3R and 4R frameworks, there is the 9R framework (Figure 24) which may be considered the most nuanced R framework used to express the different gradations of circularity (van BUREN et al., 2016), and thus circular strategies (POTTING et al., 2017).



Strategies		
Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intensive (e.g. through sharing products, or by putting multi-functional products on the market)
	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	R3 Re-use	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function
	R4 Repair	Repair and maintenance of defective product so it can be used with its original function
	R5 Refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 Recover	Incineration of materials with energy recovery

Figure 24. Circular strategies within the production chain
Source: Potting et al. (2017).

By observing the 9Rs, several strategies exist in order to reduce the consumption of natural resources and materials, as well as the waste generation, and can be applied in order of priority according to their level of circularity. In this sense, Refuse and Reduce are the strategies with high circularity, while Recycle and Recover are those with lower circularity.

There is another approach that considers three areas of action and seven pillars of CE (Figure 25), and is used by the French Environment and Energy Agency (ADEME) to monitor the CE. The first area 'supply from economic stakeholders' comprises sustainable supply chains, eco-design of products and procedures, industrial and territorial ecology (as known industrial symbiosis), functional economy. The area of action 'consumer demand and behaviour' considers reuse, repair and recycle as strategies to extend the product lifespan, besides actions about responsible consumption.

Finally, the third area ‘waste management’ comprises the recycling of materials and organic waste (SOeS, 2017).

Figure 25. The three areas of action and seven pillars of CE
Source: SOeS (2017).

Moreover, the transition to a circular economy must occur at the three levels of the CE system: the macro, the meso and the micro system. The first means operating at city, region, nation level or beyond; the meso level refers to the eco-industrial parks; and the micro to products, consumers and individual enterprises (KIRCHHERR et al., 2017). All of these frameworks and strategies presented so far in this section highlight the multiple facets of the CE concept and thus the different degrees of circularity adopted by companies as pointed out by Urbinati et al. (2017).

2.3.2 Circular Business Model description

Business models play an import role to manage complexity since they allow to create understanding about aspects, actions, and relationships that are of interest to enterprises, governments, and stakeholders in general. They are the basis for improving the current business structure and operations, and for experimentation with innovations and new business concepts (NEUBAUER, 2011). In other words, business models can be seen as simplified representations of elements of the complex organisational system and their interrelation (GEISSDOERFER et al., 2018).

Although the term business model was already in use in the 1960s, only in the early 2000s the number of studies mentioning term became expressive, associated to the rise and diffusion of commercial activities on the internet (e-commerce) (RICHARDSON, 2008; NEUBAUER, 2011). Recently, the business models gained special attention from practitioners, policy makers and researchers due to their usefulness for helping companies to operate economically in a circular economy (ELLEN MACARTHUR FOUNDATION, 2015b; NUßHOLZ, 2017), being seen as a key tool to implement the changes required by this new paradigm (GEISSDOERFER et al., 2018).

Circular Business Models (CBM) have emerged to describe business models suited for the CE by incorporating circular strategies not only into the organisation but also beyond its boundary, since these strategies require more holistic and radical changes. Therefore, CBM refers to how a company creates, captures, and delivers value by improving resource efficiency, extending useful life of products and parts, closing material loops (NUßHOLZ, 2017), shifting from a carbon-based energy system to a renewable one, reducing the dependence of virgin materials and increasing the adoption of sustainable production practices (URBINATI et al., 2017).

Despite the widespread use of CBM, no common understanding of the concept still exists, which may create a risk of using the concept in an arbitrary manner with no conceptually difference from the linear business models (NUßHOLZ, 2017). Moreover, some authors consider CBM as a class of or generic strategy for sustainable business models (BOCKEN et al. 2013; GEISSDOERFER et al. 2018). In this respect, Figure 26 highlights the transition from the linear business model to the circular one.

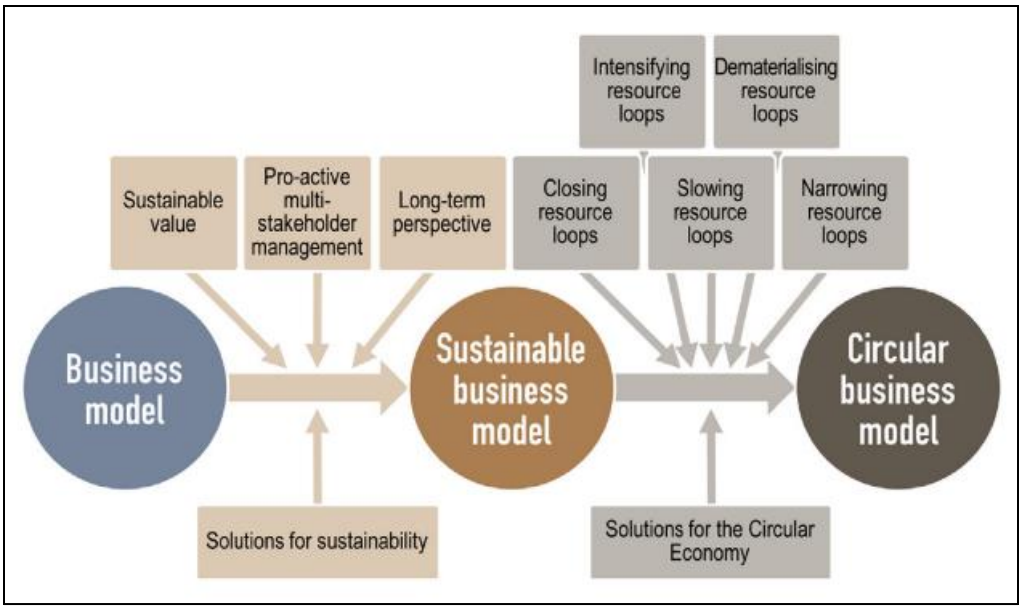


Figure 26. Traditional, sustainable and circular business models
Source: Geissdoerfer et al. (2018).

Among the prerequisites for a successful business model, some are pointed out (NEUBAUER, 2011):

- Representing a better way than existing alternatives;
- Offering more value to a discrete group of customers;
- Completely replacing the old way of doing things and becoming the standard for the next generation of companies;
- Shifting existing revenues among companies or even creating new, incremental demand;
- Creating strong competitive advantage by changing the industry's economies and/or by making replication difficult.

Faced with the non-existing a common concept of CBM, Nußholz (2017) proposed a definition of CBM from the perspectives of resource efficiency and business model innovation, based on elements of the Business Model Canvas. According to the author, adjusting the configuration of business model elements provides a more systemic approach for aligning the value creation logic of the company with circular principles, in terms of changes in material flows. This means that these elements can be configured in such a way that they help to overcome potential barriers to implementation of these strategies.

2.4 Industrial Symbiosis

2.4.1 Concept

Industrial symbiosis (IS) takes part of the Industrial Ecology concept and it is related to achieve competitive advantage involving exchange of flow of materials, energy, water, and/or by-products based on geographic proximity among organizations for both environmental and economic benefit (CHERTOW, 2000). As the name suggests, IS builds on the notion of biological symbiotic relationships that could be seen in nature, where different species exchange materials or energy in order to create mutual benefits.

At simplest view, IS consists of a place-based exchanges among different entities, in which business strive for a collective benefit greater than the sum of individual ones that could be achieved by acting alone. Eco-industrial parks are the most concrete example of this concept and its gains (CHERTOW, 2000).

Despite resource exchanges may have been implemented a long time ago (eg. waste exchanges between unrelated organizations come from the 19th century), the term of IS was been first used in 1989 (CHERTOW, 2000), bringing the notion to provide valuable use for industrial wastes.

The geographic proximity is a key factor for IS, however the network can be encouraged even in the absence of this geographic proximity depending on logistics costs compared to the financial benefit of the IS collaboration. In this sense, current trends in the implementation of IS focus on the following types of collaboration (ISIE 2015):

- By-product exchanges → converting waste into valuable productive resources;
- Waste heat recovery → turning energy losses into revenue by designing inter-firm energy cascading systems using heat exchangers and heat pumps;
- Shared infrastructures → mainly for water purification and supply, and energy production by cogeneration;
- Shared waste management → infrastructure for handling and sorting and for developing innovative recycling technologies and value chains;
- Shared services → such as like security, training, catering, meeting rooms, etc.

All of these types of IS can be represented graphically in Figure 27.

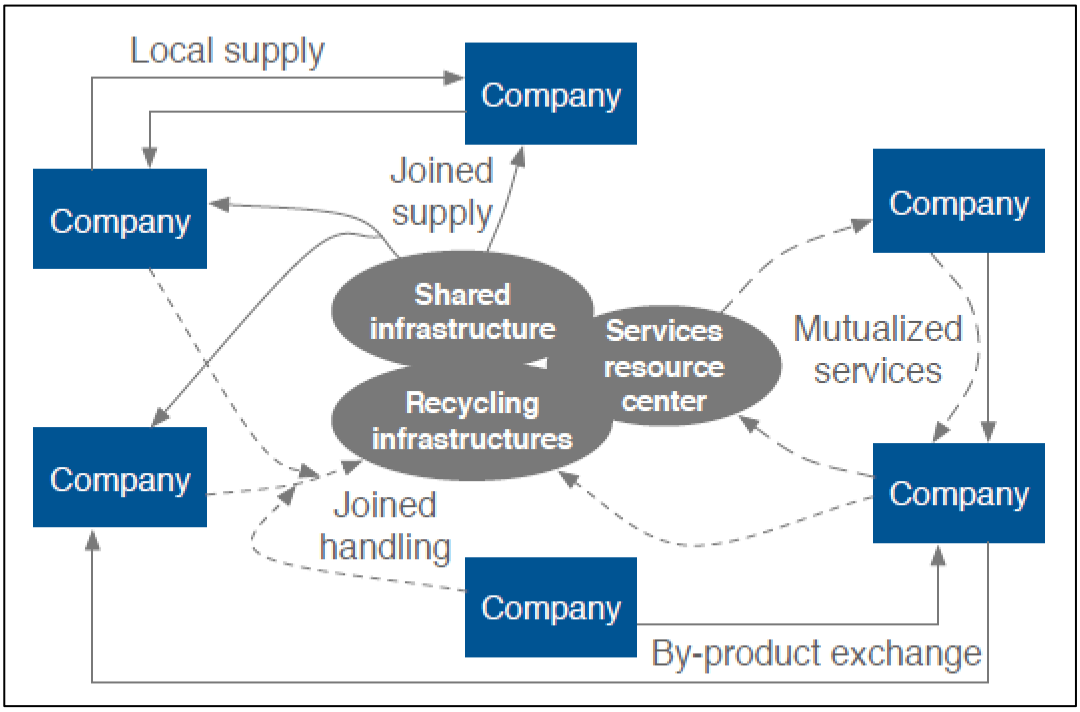


Figure 27. Representation of the different types of IS
Source: ISIE (2015).

Undoubtedly, IS may lead several environmental benefits due to it enables several actions regarding to energy efficiency, recycle wastewater, recover solvents, and reuse waste streams, beyond other nonmaterial based linkages such as jointly planning transportation networks, sharing office and facilities, information, or security services (CHERTOW, 2000). However, it must be remarked that IS does not only encompasses material and energy exchange, but also offers a plausible means of building cooperative relations across business (CHERTOW & EHRENFELD, 2012).

2.4.2 The Kalundborg Symbiosis

The first model of IS is an eco-industrial park developed in Kalundborg - Denmark, in the early 1970s, in which an oil refinery, power station, gypsum board facility, and a pharmaceutical plant shared water flows, steam, electricity, and lots of residues that became feedstocks in several processes (Figure 28).

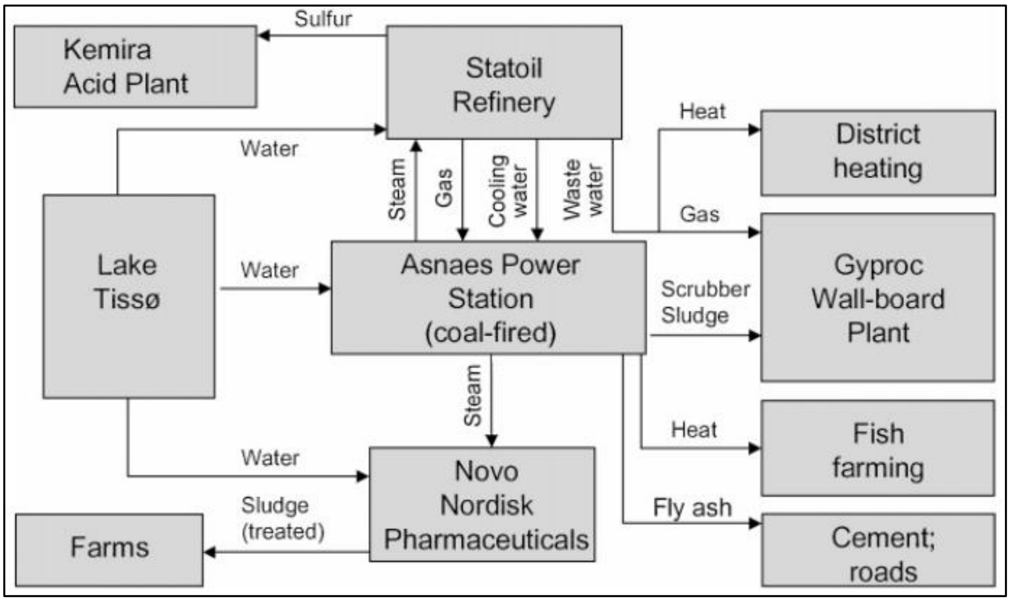


Figure 28. First model of IS - an eco-industrial park in Kalundborg
Source: Chertow (2000).

This first model of IS still works and became one of the most important IS in the world, known as Kalundborg Symbiosis. Over the past six decades, Kalundborg Symbiosis has evolved organically, with the creation of joint projects when the collaboration was beneficial, but ending when the business case became unfavourable (ELLEN MACARTHUR FOUNDATION, 2018).

Nowadays, Kalundborg Symbiosis is built on core values (eg. trust, confidentiality, openness, equality and cooperation) that make it possible to renew and strengthen the partnerships, connecting flows of energy, water and materials, at the same time promoting the symbiotic mindset to others on all geographical scales, from local to global (ELLEN MACARTHUR FOUNDATION, 2018). This business strategy is presented in Figure 29.

Figure 29. The Kalundborg Symbiosis business strategy
Source: Ellen MacArthur Foundation (2018).

Figure 30 presents the current Kalundborg Symbiosis network flow that is made up 25 different streams, including energy, materials and water emanated from six private organisations and three of public sector. All of these organisations act on a partnership strengthened by shared values and aided by the fact that none competing directly to each other.

An interesting point of this symbiotic model is that it has changed the business model of the power company called Ørsted, that was to produce electricity with the excess steam as a by-product, to the steam of being the primary product and comprising most of their income. This clearly illustrates how business models can be changed and innovated, reaping economic and environmental benefits (ELLEN MACARTHUR FOUNDATION, 2018).

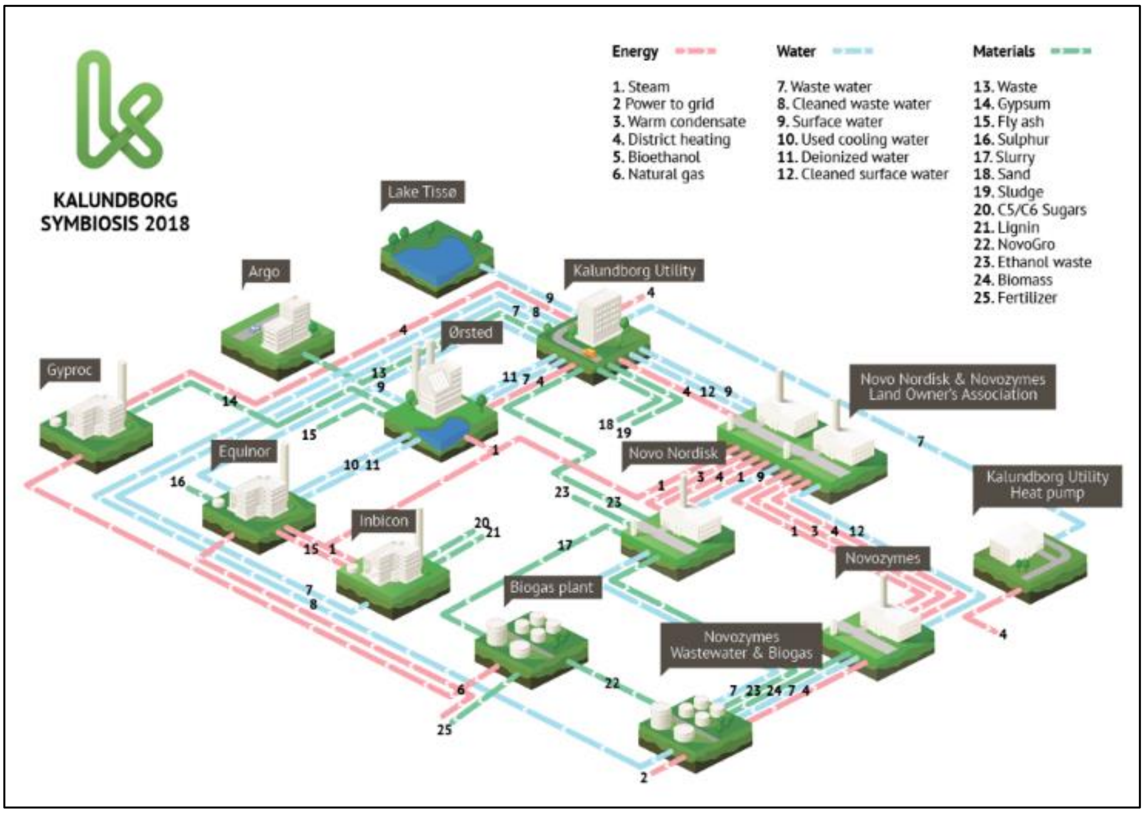


Figure 30. The current Kalundborg Symbiosis model
Source: Ellen MacArthur Foundation (2018).

Furthermore, the Kalundborg Symbiosis is as an effective example of how IS can act as a path to the Circular Economy model by improving operational and economic performance as well as environmental performance in situations where resource exchanges can be efficiently achieved.

2.4.3 Industrial symbiosis over the world

IS is currently being implemented in many countries worldwide, driven by various public and private players (ISIE 2015), reflecting the growing recognition of the benefits resulted through the collaboration based on IS. Chertow & Ehrenfeld (2012) pointed out ten examples of well-studied industrial symbiosis projects (Table 6).

Table 6. Top-10 examples of Industrial Symbiosis worldwide

#	**Name of symbiosis**	**Facilities involved**	**Materials involved**
1	Kalundborg, Denmark	Coal-fired power plant, pharmaceuticals, gypsum board, oil refining, fish faming	Water, wastewater, sulfur, steam, sludge, fly, ash, yeast and organic residues
2	Guayama, Puerto Rico	Coal-fired power plant, pharmaceuticals, chemical refining	Wastewater, condensate, steam, ash
3	Campbell Industrial Park, Hawaii	Coal-fired power plant, oil refining, cement, water reclamation, recycling	Wastewater, waste oil, steam, ash, shredded tires, activated carbon
4	Guitang Group, China	Sugar refining, alcohol, pulp and paper mill, cement, alkali recovery, agriculture	Sludge, alcohol, fertiliser, alkali
5	Ulsan, Korea	Oil, chemicals, incineration, metal processing, paper mill	Wastewater, biogas, steam, metal
6	Kwinana, Australia	Coal-fired power plant, chemicals, fertiliser producer, cement, construction, oil refining	Organic waste, sludge, acid, ash, dust, chemical catalysts, organic waste, energy production
7	Styria, Austria	Sawmills, mining, textiles, chemicals, power plant, board industry, plastic production, ceramic industry, cement plant, material dealers, iron manufacturing, agriculture associations	Ash, plastics, sludge, iron scrap, wood and paper, heat, petrol coke, slag, dust, oil
8	Tianjin Economic Development Area, China	Pharmaceuticals, food and beverages, electronics, machinery, others	Water, metals, chemical substances, ash, organic residues
9	Rotterdam Harbor, The Netherlands	Chemicals, cement, oil refining, incinerator	Heat, energy
10	UK Industrial Areas	Coal-fired power plant, plastic, rubber, plastic recycling, paper mill, chemicals, food and fish processing, metals, furniture	Steam, electricity, technology, waste carpets, fuels, edible oil, electronic waste

Source: Adapted from Chertow & Ehrenfeld (2012).

It can be observed the diversity of IS configurations and materials exchanged. In a broader view, these exchanges mean the conversion of negative environmental externalities in the form of waste into positives environmental externalities such as the benefits of waste deviation from landfills and reducing pollution (CHERTOW & EHRENFELD, 2012).

On a research perspective China is by far the country that received the most attention in IS academic research and continues to grow rapidly as shown in Figure 31 (CLIFT & DRUCKMAN, 2016).

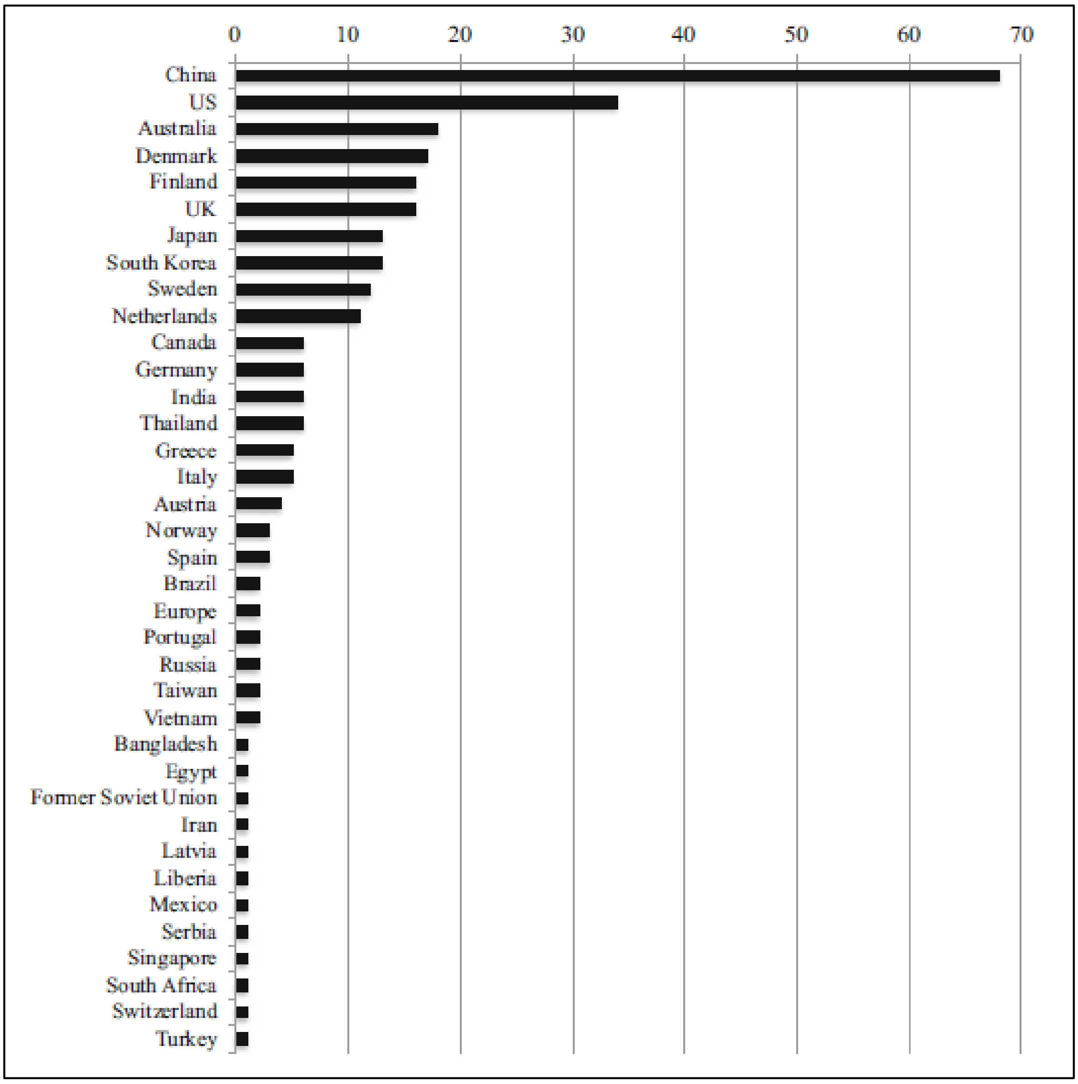


Figure 31. Countries features in 286 academic papers on IS from 1995 to 2014
Source: Clift & Druckman (2016).

Regarding the practical application of IS, there is the National Industrial Symbiosis Program (NISP) promoted by the International Synergies, a world leader in the application of facilitated IS projects at company, local, regional and national levels.

The NISP model has been exported to more than 20 countries worldwide at national and regional level (Figure 32). In Brazil, the state of Minas Gerais implemented the NISP model, called Programa Mineiro de Simbiose Industrial in Portuguese, in order to promote a deeply change in organisations' culture seeking the Sustainable Development.

The participants (organisations-members) share information and knowledge in periodic workshops, in which opportunities of synergies are identified resulting in mutual benefits. To date, more than 280 opportunities of IS were identified through this

Program, involving 317 private organisations, resulting in a contribution to avoid the disposal of 140,000 t of residues in landfills and the use of 195,000 t of virgin resources, besides 87,000 t of GHG emissions reduced (PMSI, 2018).

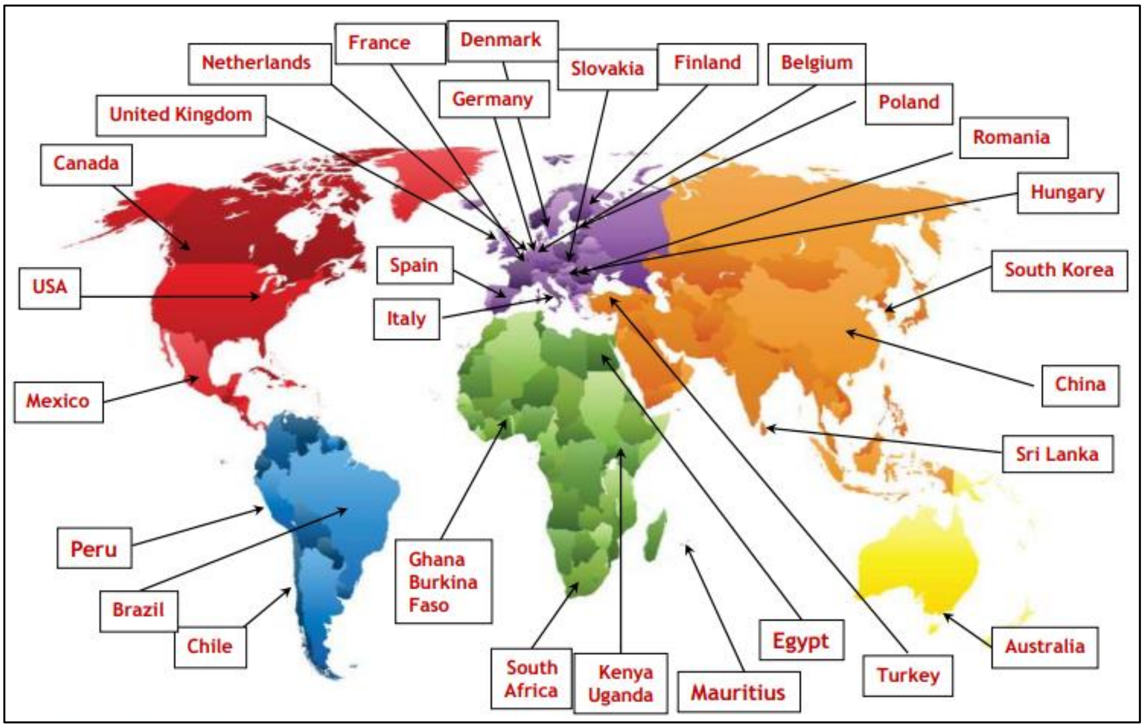


Figure 32. National Industrial Symbiosis Program over the world
Source: Laybourn (2015).

In the European Union, the IS is strongly seen as driver to the Circular Economy on European Commission Directives (eg. EUROPEAN COMMISSION, 2012; 2014b) by promoting the resource efficiency and low-carbon economy, including more sustainable products and limiting the environmental impacts of resource use and optimisation of industrial processes. In addition, the Roadmap to a Resource Efficient Europe strongly promotes turning the waste into resources not only by the sustainable management of all resources but also by a cross-industrial residue utilisation and novel symbiosis initiatives and products (EUROPEAN COMMISSION, 2011).

3. Methodology of the research

This research consisted in five steps:

i. Planning;
ii. Contextualizing;
iii. Developing;
iv. Applying;
v. Concluding.

Planning refers to the problem statement and definition of research objectives. Contextualizing is look for background information. The Circular Business Model is constructed in the developing phase based on the information collected in contextualizing phase. The next step is thus applying this model in order to improve it and test its effectiveness. Finally, conclusions are provided as well as recommendations for future research in the field.

All these steps are detailed in the flow chart of the research process presented in Figure 33.

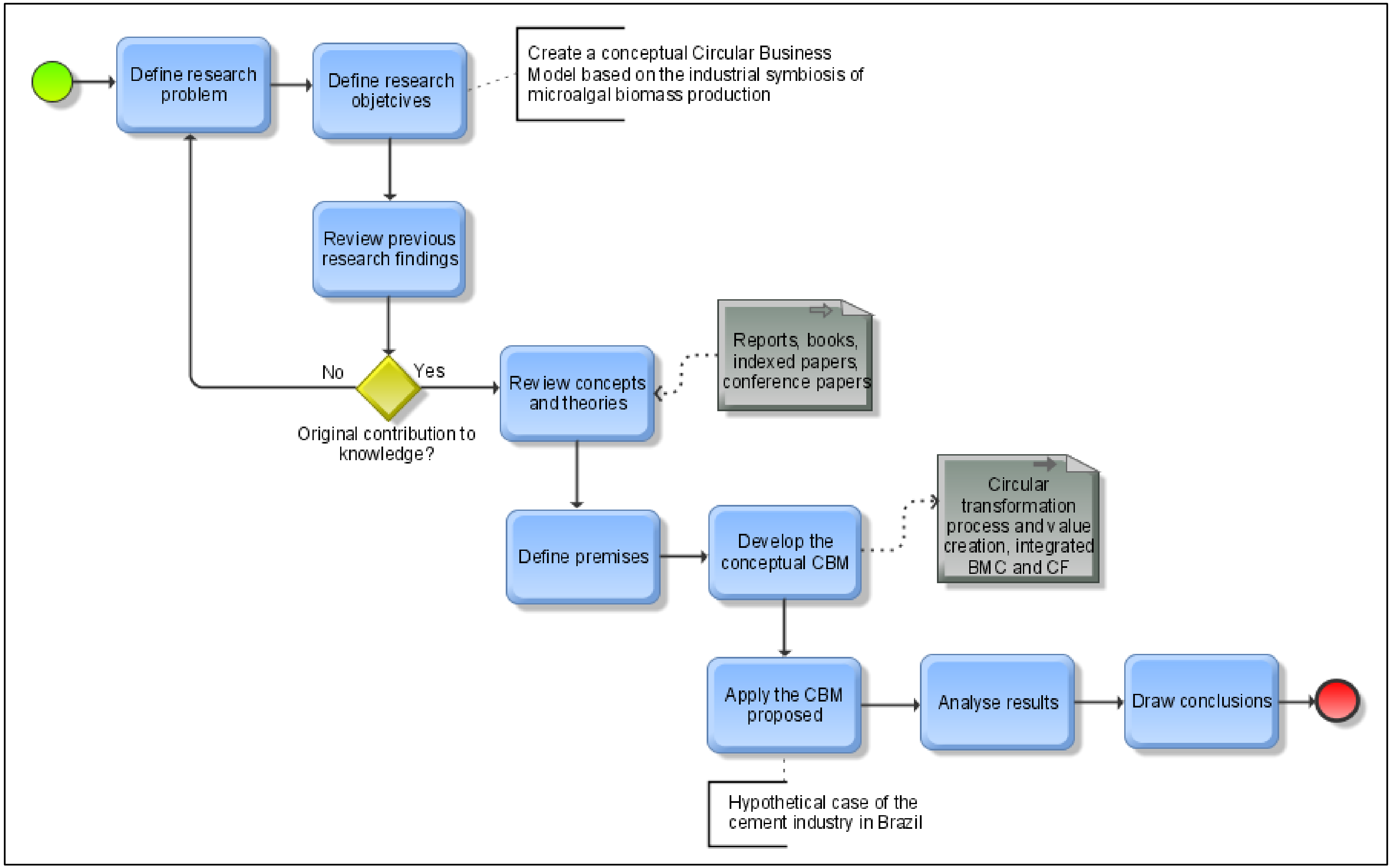


Figure 33. The research process
Source: The author.

To carry out this research, the first step was to define the research problem after a review on published documents, including reports and articles. This research is grounded on the concepts of Sustainable Development, Circular Economy, biofuels and industrial symbiosis. Microalgae-based biodiesel meets all of these concepts; hence it was established as research object.

A mind map was built to help structuring information and comprehend the connections about microalgae cultivation (Figure 34). Then, the research objectives (general and specific objectives) were established, lied on the microalgae cultivation under industrial symbiosis principle.

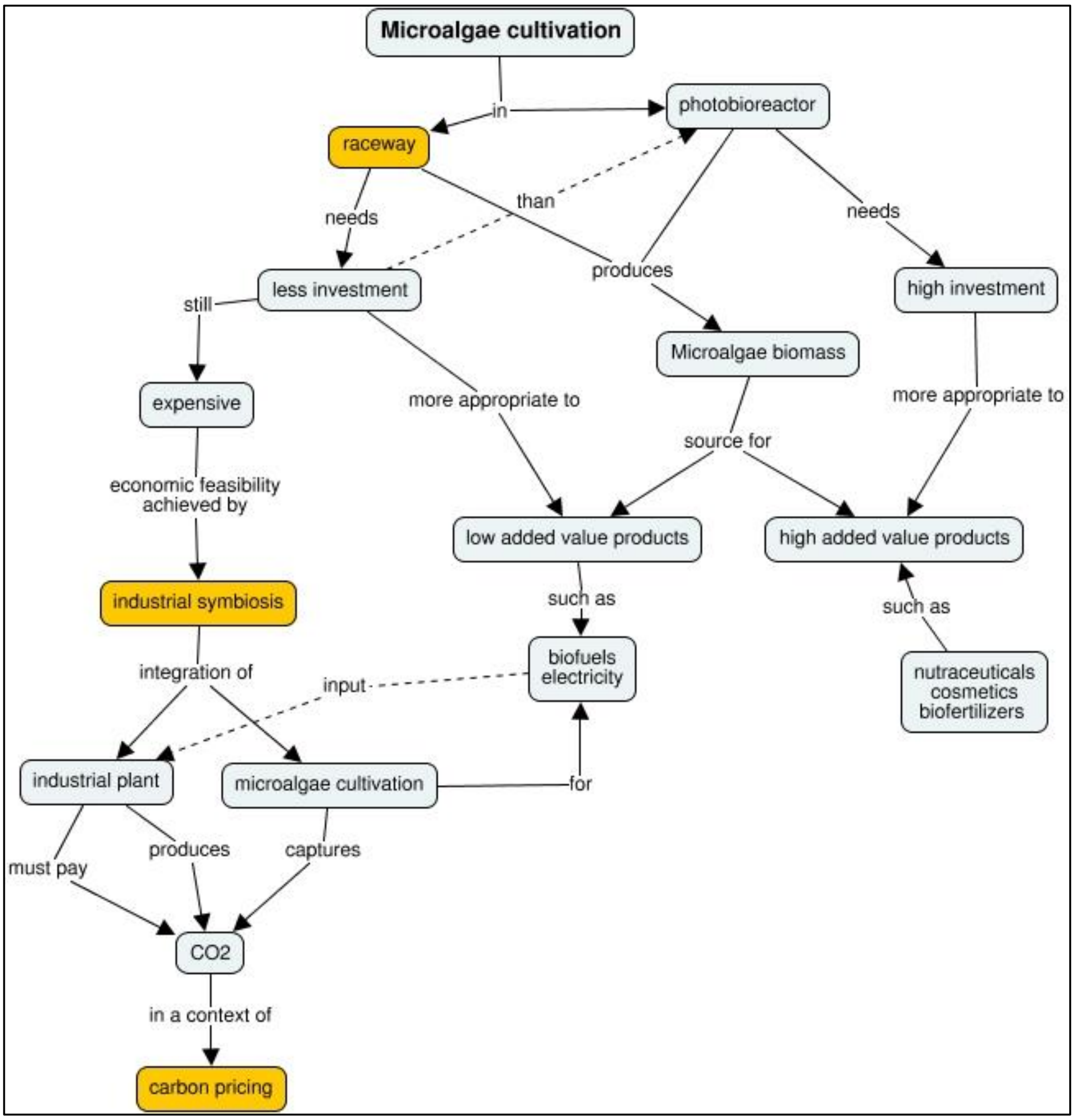


Figure 34. Mind map of microalgae cultivation
Source: The author.

An investigation on previous research findings was performed by consultation on important scientific databases such as Scopus and WoS. The results of the review adopting the search strings “microalgae” AND “industrial symbiosis” endorse the originality of this research. Furthermore, the lack of studies regarding microalgae cultivation using cement-plant flue gas as source of CO_2, the application case chosen, also corroborated such originality.

A theoretical background was built to support the development of the Circular Business Model proposed. The concepts and theories came from books, reports, articles in indexed journals, and conference proceedings. The next step was to define the assumptions of the model proposed. The mind map presented in Figure 34 also contributes to this definition, since microalgae-based biodiesel is a low added value product, thus requires microalgal biomass production with low costs of operation and investment, enhanced by cultivation in raceway.

Although less expensive than cultivation in closed systems such photobioreactors, raceways need high investments that can be amortized by using industrial flue gas as source of CO_2 and waste streams as source of nutrients, achieved by an integration of microalgae cultivation with industrial plants in terms of industrial symbiosis. This integration becomes more attractive in a context of carbon pricing, where microalgae capture the CO_2 that would be taxed. So, carbon pricing is assumed as premise to the Circular Business Model proposed.

As precise information is needed to ensure good decisions related to new investments projects, and the adoption of Circular Economy mainly depends on the willingness of companies (URBINATI et al., 2017), a guidance was developed considering crucial aspects related to microalgal biomass production: strain and site selection.

Multi-Criteria Decision Analysis (MCDA) was used in the process of microalgal strain selection, since it could be a difficult task due to the necessity of addressing several information from different nature (qualitative and quantitative data). ELECTRE III, an outranking method, was chosen to rank the strains seeking identify that most suitable for large-scale cultivation in raceways. A consultation of experts was carried out in order to establish criteria weights for strain selection.

A total of seven experts were asked for their opinion about the importance coefficients of each criterion previously defined as resulted from a review of literature. A 4-point scale was adopted where the importance increases through the scale, i.e. 1 means low importance; 2, medium importance; 3, high importance; and 4 means essential. Five experts were participants of the Algae Biomass Summit 2016 held in Phoenix, Arizona - USA and two are Brazilian experts.

Two of the five experts consulted in the Algae Biomass Summit are noteworthy researchers in microalgae field: a research assistant Professor of the University of Texas at Austin and curator of UTEX Culture Collection of Algae; and an assistant Professor of Istanbul Microalgae Biotechnologies Research and Development Center. The former is a co-author of multiple patents based on the development of cyanobacteria as sources for biofuel feedstocks, and the later works with microalgae and cyanobacteria species as feedstock for third-generation biofuel production.

With the aim of bring some different point of view, a research scientist of a San Diego-based American energy company (Sapphire Energy), that produces crude oil made from algae, was consulted. Two Ph.D. students whose research focused on biodiesel from microalgae were also consulted. One from University of Toledo and the other from the Arizona State University.

The two Brazilian experts consulted are two noteworthy Professors in this field, with vast research regarding to microalgal production in open raceways for biodiesel production. One is senior researcher at the Agronomical Institute of Paraná (IAPAR); and the other is from the University of Campinas (UNICAMP), São Paulo state.

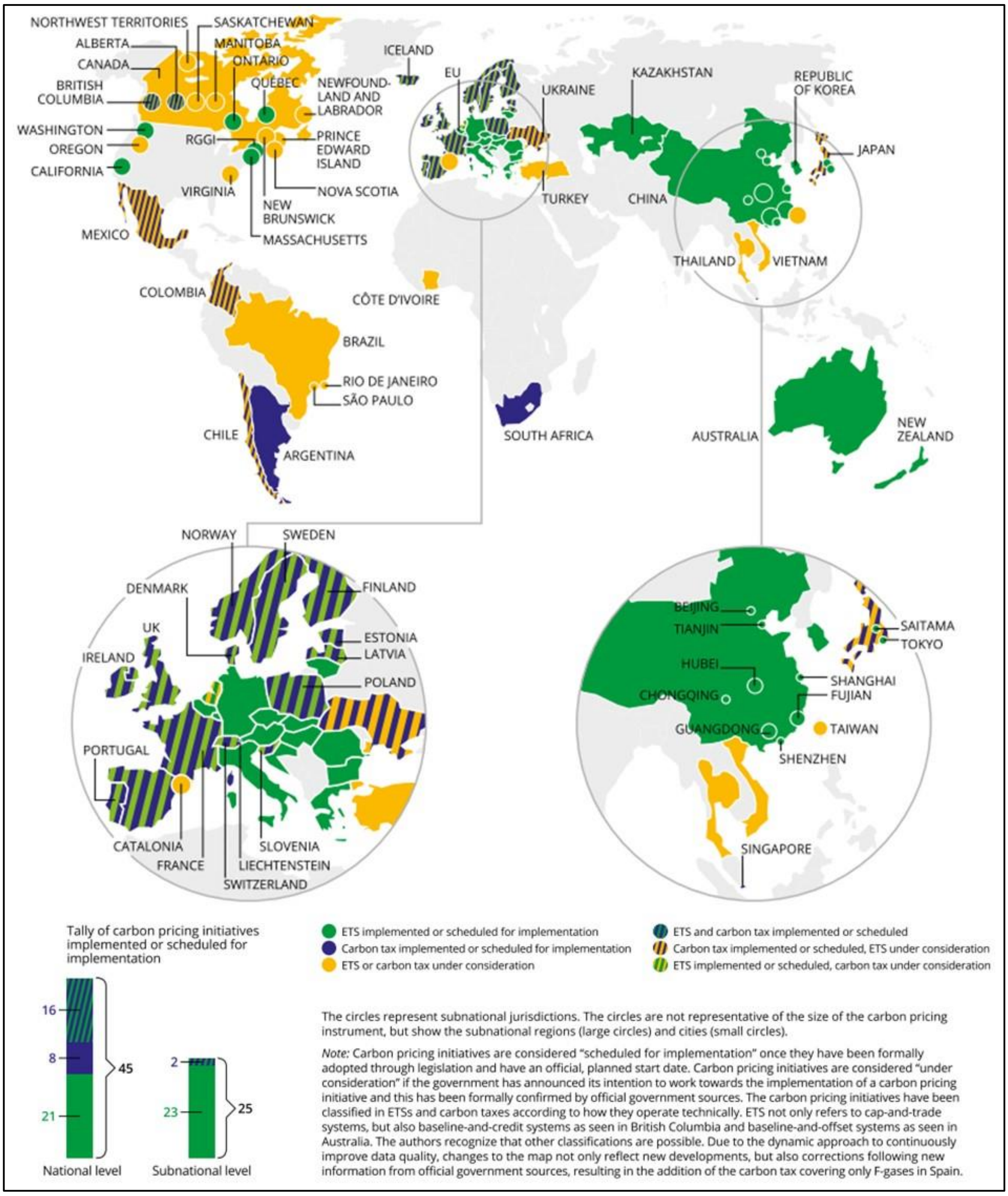
In order to translate this Circular Business Model into valuable information for decision-making for managers, two well recognized support decision tools (Business Model Canvas and Carbon Footprint) were used in an integrated manner. Business Model Canvas (OSTERWALDER and PIGNEUR, 2010) was chosen due to it enables ease communication to managers, as it presents relevant information graphically, while Carbon Footprint (ISO, 2013) allows the evaluation of environmental impacts in terms of climate change.

The model is applied considering a hypothetical case of the cement industry in Brazil. Real data from the sector were used, as well as CO_2 emissions and cement production scales. Scenarios were defined in order to evaluate the sensibility of microalgal biomass production under variations in the CO_2 source. Finally, conclusions are drawn from these results and recommendations for future research are provided.

Model premise: Carbon pricing

Carbon pricing means to put an explicit or implicit price on GHG emissions generated by a company, facility or jurisdiction, i.e. to specify a monetary value at each tonne of CO_2e sent to the atmosphere. The increasing prevalence of carbon pricing in climate change discussions means that put a price on carbon has become one of the most important strategies to reduce GHG emissions since the world has undertaken to put efforts to fight climate change after the Paris Climate Conference (COP21) in 2015.

According to the State and Trends of Carbon Price Report, several countries are planning or considering the use of carbon pricing as a tool to meet their commitments under the Paris Agreement, and then 51 carbon pricing initiatives have been implemented or are scheduled for implementation (Figure 35), which represents around 20 percent of global GHG emissions - 11 $GgtCO_2e$ (THE WORLD BANK, 2018).



The circles represent subnational jurisdictions. The circles are not representative of the size of the carbon pricing instrument, but show the subnational regions (large circles) and cities (small circles).

Note: Carbon pricing initiatives are considered "scheduled for implementation" once they have been formally adopted through legislation and have an official, planned start date. Carbon pricing initiatives are considered "under consideration" if the government has announced its intention to work towards the implementation of a carbon pricing initiative and this has been formally confirmed by official government sources. The carbon pricing initiatives have been classified in ETSs and carbon taxes according to how they operate technically. ETS not only refers to cap-and-trade systems, but also baseline-and-credit systems as seen in British Columbia and baseline-and-offset systems as seen in Australia. The authors recognize that other classifications are possible. Due to the dynamic approach to continuously improve data quality, changes to the map not only reflect new developments, but also corrections following new information from official government sources, resulting in the addition of the carbon tax covering only F-gases in Spain.

Figure 35. Carbon pricing initiatives around the world
Source: The World Bank (2018).

Based on the polluter pays principle, the main purpose of carbon pricing is to stimulate cost-effective emissions mitigation by employing an Emissions Trading System (ETS) or carbon tax, but the results may be beyond a carbon market since carbon pricing revenues can be used to support policymakers, particularly in developing countries. For instance, China has pointed out the stimulation of low-carbon innovation as an additional objective, including production process improvement and optimization; Chile used a carbon tax as part of a set of environmental taxes in order to reduce the negative environmental and health impacts from fossil fuel use sector (THE WORLD BANK, 2018).

In Brazil, although carbon pricing has been under discussion by the government as a climate policy potential instrument since 2011 (CEBDS, 2016), it is still on an exploratory phase. Regarding the private sector, over 30 major Brazilian companies are leading their own ETS simulation, and on a voluntary basis, several companies are using carbon pricing as a decision support tool, called internal carbon pricing, to discover new business opportunities which may encourage the adoption of production systems towards GHG reduction (The World Bank, 2018). Therefore put a price on carbon generates not only business opportunities for mitigation but also technological innovation for low-carbon economy (CEBDS, 2018).

An important initiative regarding a future carbon market in Brazil is a platform (operating since 2014) that simulates an emissions trading system with a voluntary panel of 23 companies (e.g. O Boticário, ArcelorMittal, Gerdau, Intercement, Petrobras, Ternium, Votorantim, etc). The transaction takes place through the BVRio Environmental Exchange trading platform using fictitious financial resource (EPCents - Ec$, where Ec$ 1.00 = R$ 1.00) - more information in www.bvrio.com and www.gvces.com.br.

Regarding the countries that have official implemented some mechanism of carbon price, the majority adopted the carbon tax. As could be observed in Table 7, the price levels vary widely.

Table 7. Carbon prices implemented (nominal prices US$/tCO$_2$e)

City/Country/Region	**Carbon price (US$/tCO$_2$e)**	**Mechanism type**
Sweden	139	Carbon tax
Switzerland	101	Carbon tax
Norway	64	Carbon tax (upper value)
France	55	Carbon tax
Denmark	28	Carbon tax (fossil fuels)
	25	Carbon tax (F-gases)
Korea	21	ETS
European Union	16	ETS
California	15	Carbon tax
Beijing	9	ETS (pilot initiative)
Portugal	8	Carbon tax
Chile	5	Carbon tax

Source: The author based on The World Bank (2018).

4 The Circular Business Model proposed

4.1 General description

As discussed in section 2.3, CBMs differ from conventional methods in their value creation and delivered element that is to close resource loops. Based on the industrial symbiosis principle, the CBM proposed aims to close resource loops, where waste streams are transformed into valuable resources, which return to the generation source as input, closing the loop (Figure 36).

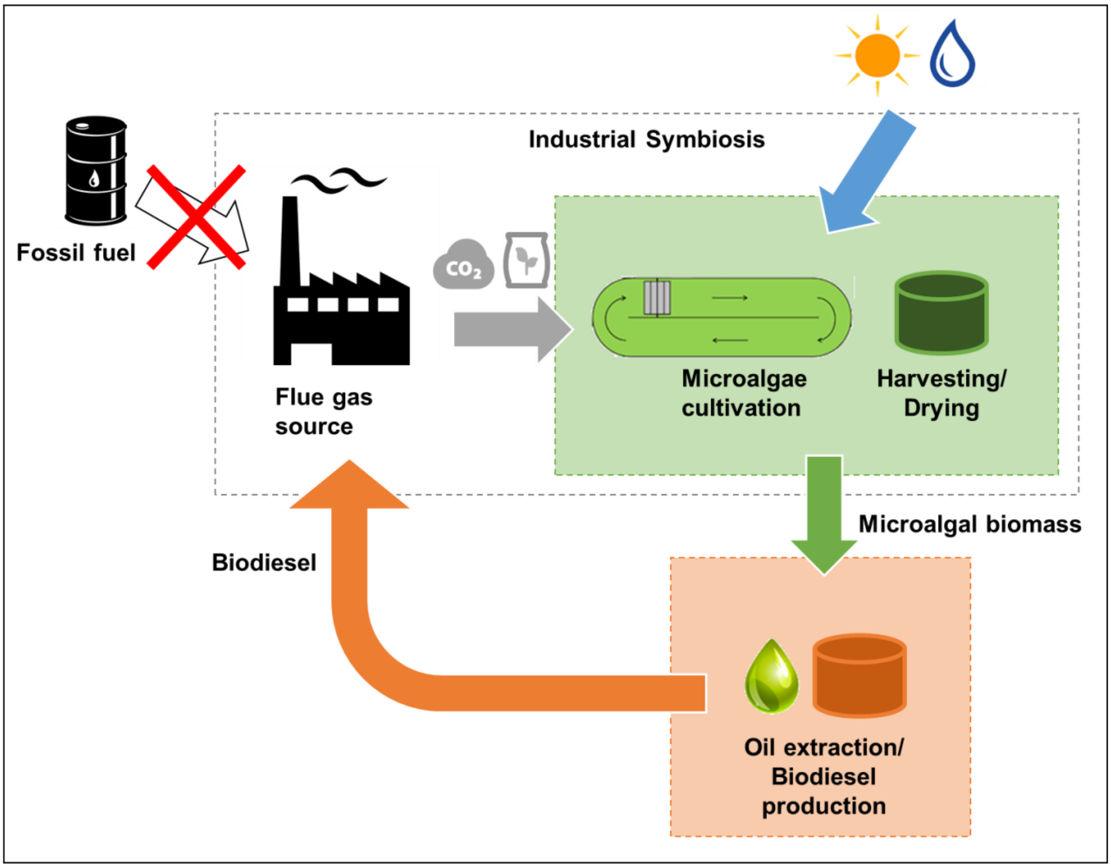


Figure 36. CBM based on the industrial symbiosis of a microalgae cultivation for biodiesel production
Source: The author.

In this model, a microalgae cultivation facility is co-located near to an industrial source of flue gas, from which the CO_2 is used as input to grow microalgal biomass associated with solar radiation, water, land and nutrients supply. In some cases, it is also possible to use waste streams (e.g. dust, wastewater) from the industry plants as source of nutrients. The biomass harvested and processed is then used as feedstock for biodiesel production, i.e. as resource in the industry, therefore returning to the industrial plant.

This represents a CO_2 recycling with environmental benefits not only due to the CO_2 biofixed but also reduces the fossil fuel consumption replaced by the microalgae-based biodiesel, hence avoiding CO_2-eq as expected in the CE paradigm.

In order to enable the comprehension of all main processes involved for value creation from waste streams up to microalgae-based biodiesel, the CBM proposed must be translated into a value chain (Figure 37). Developed by Michael Porter in 1985, a value chain is a set of activities addressed by an organization to deliver its products to customers.

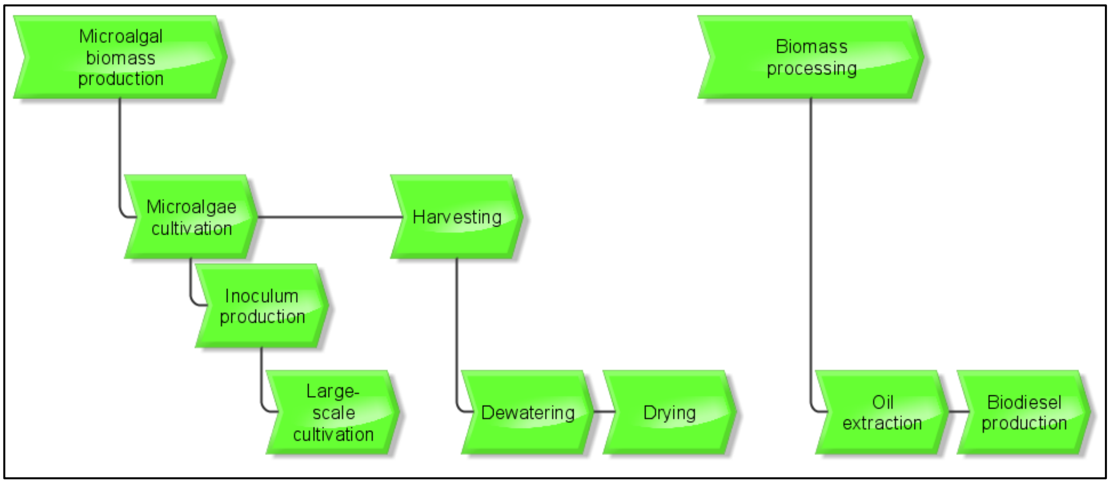


Figure 37. Microalgae-based biodiesel value chain
Source: The author.

Notwithstanding the value chain offers a systematic view of how value is created through processes, in CBMs the value creation has to be circular (GEISSDOERFER et al., 2018), which is not properly represented in a conventional linear value chain. This value creation of the CBM proposed could be represented clearly in terms of a circular transformation process (Figure 38).

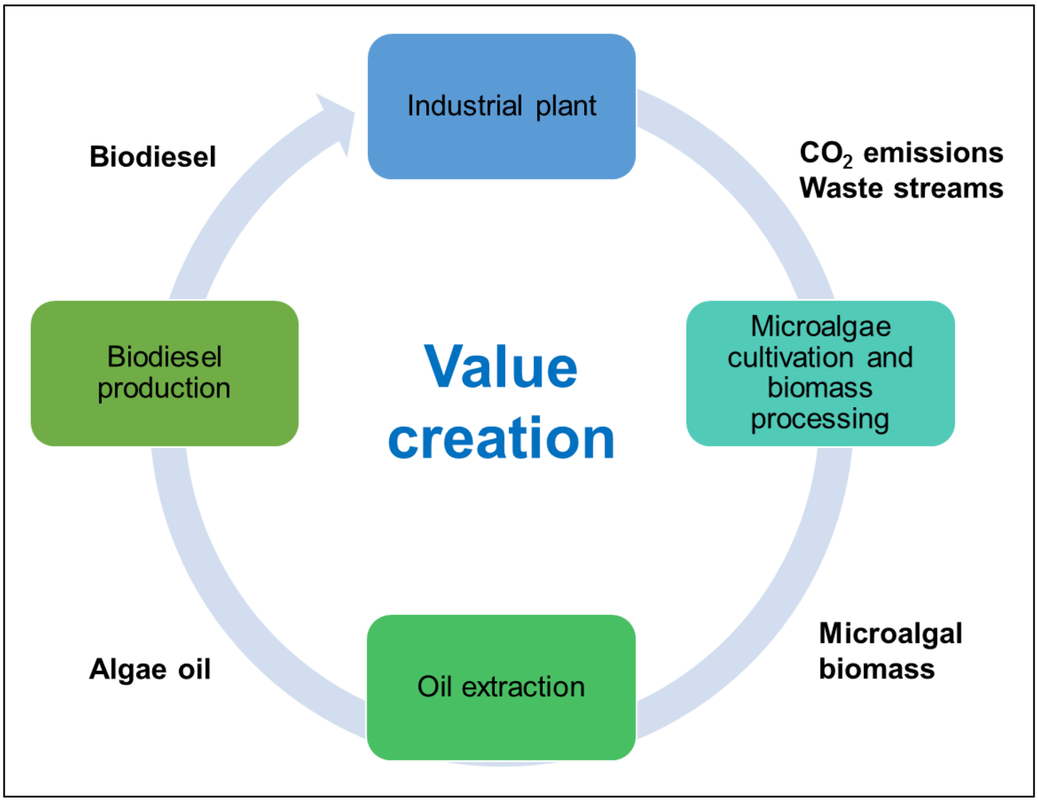


Figure 38. The circular value creation of the CBM proposed
Source: The author.

The value creation is thus constructed as the output of one process and input for another process. In other words, the value is added in the transformed resources after each transformation process, starting with the flue gas and waste streams from the industrial plant and resulting in biodiesel, which then returns to the industrial process as an input.

The boxes in the figure 38 are the macro-processes of the microalgae-based biodiesel value chain that can be associated with each part of the CBM: the industry, the microalgae cultivation facility and the biodiesel production plant. Any part represents a dual role in the value creation process: customers that receive inputs, and suppliers that deliver outputs. In this sense, an important characteristic of a CBM is that the first supplier of the value chain is also the customer of the final product, resulted from the circularity of the transformation process.

4.2 The integrated model approach

The overall objective of any business model, circular or not, is providing a consistent logical picture of the business that helps to guide the myriad choices involved in a decision-making (RICHARDSON, 2008). Roughly speaking, a business model can be seen as a narrative of how the business works. In other to construct this narrative, an integrated CBM is proposed (Figure 39).

The step-by-step integrated model enables to address and put in evidence relevant aspects of the microalgae-based biodiesel production under the industrial symbiosis principle. In the planning phase (step 1), microalgal strain selection and the co-location opportunity for locating the raceway must be examined.

The next step is the input-output modelling obeying the logic of the circular value creation from the industrial flue gas and waste streams, to microalgal biomass, to algae oil, to biodiesel. The input-output modelling allows the dimensioning of microalgae cultivation, consequently the microalgal biomass production in relation to the CO_2 and nutrients availability from the industrial plant, thus supporting the decision-making with technical information of the CBM.

Finally, the third step refers to picture the business by integrating the Business Model Canvas and Carbon Footprint in order to evaluate the viability of the business. Key elements are described seeking the systemic comprehension of the CBM proposed through a logical sequence provided by the Business Model Canvas. Taking into account that environmental benefits are one of the drivers of the Circular Economy, hence the CBM, the potential environment impacts of the CBM is carried out by Carbon Footprint analysis.

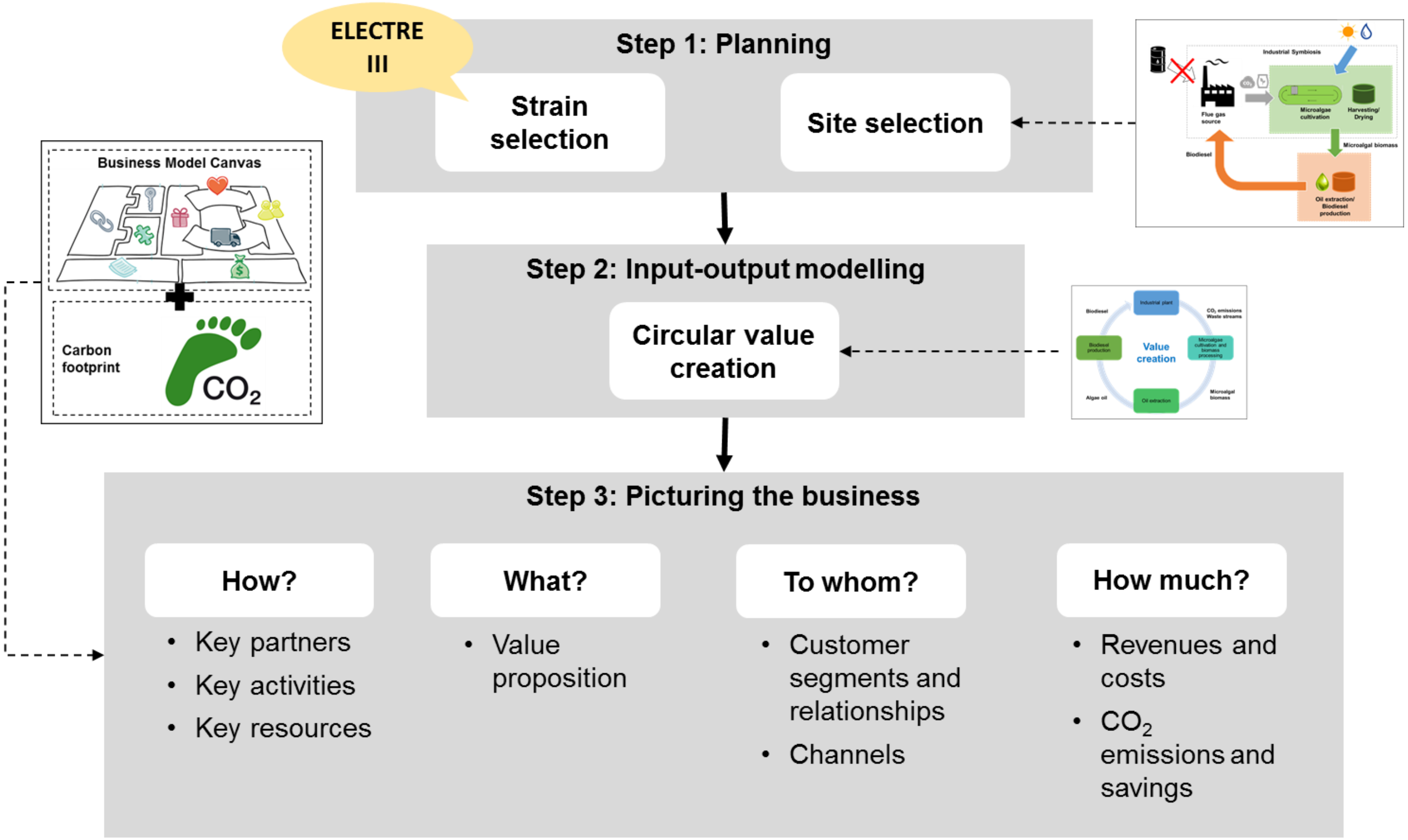


Figure 39. The integrated Circular Business Model proposed
Source: The author

4.3 Step 1: Planning

4.3.1 Microalgal strain selection

As microalgal strain can affect every step of the microalgae supply chain (LANGHOLTZ et al., 2016), strain selection is considered an important issue for a large-scale microalgae cultivation. Moreover, each specie has different physical, chemical and biological properties that must be taken into account.

Several studies have evaluated the potential of microalgal strains for biodiesel production (RODOLFI et al., 2009; TALEB et al., 2015; LIU et al., 2011; BEACHAM et al., 2014; NWOKOAGBARA et al., 2015; HE et al., 2016; JOSEPH et al., 2016; ISLAM et al., 2013). Most of these studies evaluated the microalgae performance under laboratory conditions, and rarely in open pond systems.

One such exception is the study by He et al. (2016) that analysed five microalgae concerning their growth, lipid accumulation and fatty acid profiles, and chose two for scale-up and culture in raceway due to their stronger environmental adaptability, high lipid productivity and better biodiesel qualities. It must be remarked that strains might have different performance when cultivated in outdoor ponds compared to laboratory under particular incubation conditions due to e.g. contaminations, and daily and seasonal temperature and light fluctuations.

Therefore, challenges facing microalgal strains selection for biodiesel production involve not only evaluation of their performance on a non-laboratory scale, but also the criteria that are relevant to the decision-making process. Although this might allow the best choice, it also often results in evaluating a plethora of criteria, turning the analysis too complex and difficult, needing the adoption of a multi-criteria approach.

A logical sequence of steps must be followed when adopting a multi-criteria approach. Figure 40 presents the processes of the strain selection. It starts with the definition of alternatives, i.e. definition of the strains that will be considered in the hall of possibilities for microalgal biomass production.

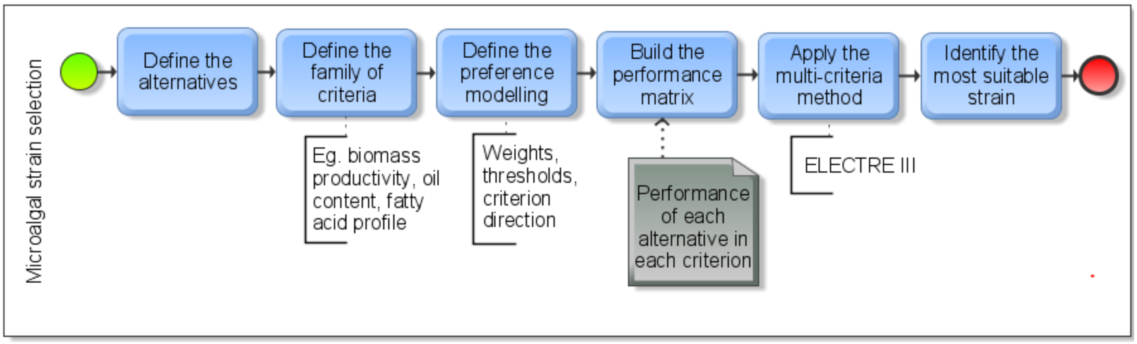


Figure 40. Guidance for microalgal strain selection
Source: The author.

i. Definition of the criteria family

The success of decision-aid crucially depends on the family of criteria adopted to the analysis. In general, adopting few criteria may oversimplify the decision process, while using a large number of criteria may reduce the influence of each one criterion. In fact, a consistent family of criteria is built when the criteria considered all together satisfy some logic requirements such as: exhaustiveness or completeness, cohesiveness, and non-redundancy (ROY & BOUYSSOU, 1993):

- Exhaustiveness → consider every important aspect for the analysis, i.e. the criteria adopted should cover all that is to be measured;
- Cohesiveness → the coherency between partial and global preferences, i.e. partial preferences must be consistent to the global preferences. For instance, if an alternative a is considered better than b, taking into account all the criteria, the same judgment must be to an alternative c, which is judged at least as good as a on every criterion;
- Non-redundancy → do not consider unnecessary criteria in the analysis, to do not take into account redundant consequences.

Several aspects can influence microalgae cultivation performance, since biological characteristics of each strain/specie are more or less adapted to technical and environmental factors of the culture system. Most studies to date have focused on looking for strains with faster growth rate, great oil production and easier cultivation. For instance, Nwokoagbara et al. (2015) evaluated six microalgae strains concerning their growth rate, lipid content, fatty acid profile and ease of harvesting, which was assumed as directly proportional to the energy consumption rates of the harvesting methods.

Ahmad et al. (2015) considered the fatty acid profile, some criteria related to lipids, such as oil concentration, oil content, oil production rate and oil yield, and ease of cultivation in terms of economic criteria such as biomass harvesting cost and nutrient cost. Although they did not apply a MCDA method, Song et al. (2013) evaluated the potential of ten microalgae strains for biodiesel production considering growth rate, biomass concentration, lipid productivity and favourable biodiesel properties based on the fatty acid profile.

As the biodiesel quality depends on the content and composition of fatty acids (HOEKMAN et al., 2012; ISLAM et al., 2015), this issue was also well handled by Islam et al. (2013), when they assumed to minimize saturated fatty acids (SFAs) and to maximize mono-unsaturated fatty acids (MUFAs) and polyunsaturated fatty acids (PUFAs), besides other criteria (eg. lipid content and fatty acid content) used in their multi-criteria analysis using PROMETHEE method. Joseph et al. (2016) also evaluated SFAs, MUFAs and PUFAs, added to biomass productivity, lipid content, and lipid productivity of five diatoms.

Despite the possibility of using several criteria for microalgae strains selection, some characteristics, such as growth rate, lipid/oil content, fatty acid profile, robustness, resistance to contamination and biofouling propensity, are considered the most important ones to evaluate which specie is better for biodiesel production (VISWANATH et al., 2010).

A consistent family of criteria must be built with non-redundant criteria and with no prejudice to the completeness of the analysis. Therefore, five criteria were defined as relevant for evaluating microalgae performance in raceway cultivation:

- growth performance;
- lipid content;
- fatty acid profile
- ease of harvesting; and
- resistance to contamination.

ii. Preference modelling

The next step is the definition of decision-maker preferences. It involves the definition of the importance weights, criterion thresholds and the criterion direction (maximize or minimize). Weighting has a critical role in MCDA, since it may introduce subjectivity in the decision- making process and it generally represents the adoption of trade-offs among criteria that leads to some kind of compensation. Due to the non-compensatory aggregation procedure of ELECTRE III, the method proposed to be used, the weights in it are interpreted as importance coefficients and not relative weights, which represent substitution rates, i.e. the trade-offs.

For the five criteria selected, weights were stablished reflecting experts' view by the application of a simple and straightforward procedure, using a 4-point scale. A total of seven experts, including participants of the Algae Biomass Summit 2016 and Brazilian researchers, were asked for their opinion about the importance of each criterion (Table 8), and then the final weights were obtained through majority, i.e. the most frequent value assigned for each criterion, since the average would not always reflect the experts' or decision makers' estimates, being pragmatically undesirable (HOKKANEN & SALMINEN, 1997; GRECO et al., 2016).

Table 8. Importance weights of the criteria provided by experts

Criteria	**Experts**							**Final weights**
	E1	E2	E3	E4	E5	E6	E7	
Growth performance	4	3	3	3	3	3	4	3
Lipid content	3	4	3	4	4	4	3	4
Fuel quality of biodiesel	1	4	4	3	4	4	3	4
Ease of harvesting	2	2	3	2	2	4	3	2
Resistance to contamination	3	2	4	4	3	2	3	3

1 = low importance, 2 = medium, 3 = high importance, 4 = essential.

It must be remarked that, besides those criteria, the experts consulted have pointed out the importance of other aspects at large-scale microalgae cultivation such as tolerance to temperature variation, pH control and genetic stability of the culture. Several studies addressed these aspects, corroborating that importance (eg. MAROUBO et al., 2018; Z. WANG et al., 2018; BLANCO et al., 2013; Q. WANG et al., 2018).

iii. Performance matrix

After the alternatives, criteria and preference modelling, the performance matrix could be built including quantitative, qualitative or both types of information (Figure 41). As the ELECTRE III does not need to enter normalized values of performances, the choice of the units of scale of values is not an issue.

<table>
<tr><th>Alternative/ Criterion</th><th>1. Growth performance</th><th>2. Lipid content</th><th>3. Fuel quality of biodiesel</th><th>4. Ease of harvesting</th><th>5. Resistance to contamination</th></tr>
<tr><td>Criteria weights</td><td>3</td><td>4</td><td>4</td><td>2</td><td>3</td></tr>
<tr><td>Strain 1</td><td rowspan="4" colspan="5"><i>Performance of each strain in each criterion
(quantitative and qualitative data allowed)</i></td></tr>
<tr><td>Strain 2</td></tr>
<tr><td>(...)</td></tr>
<tr><td>Strain M</td></tr>
</table>

Figure 41. The performance matrix (strains x five criteria)
Source: The author.

iv. ELECTRE III application

The input data can be processed in the ELECTRE III software available for download at https://www.lamsade.dauphine.fr. It is also possible to run the ELECTRE III method on Python or R code[1]. ELECTRE III is thus used in this work to establish the degree of dominance of one microalgae strain over another, resulting in a ranking of the microalgae strains cultivated experimentally in an open raceway system.

The ELECTRE III method was chosen due to its ability to deal with inaccurate, indefinite and uncertain criteria that are inherent to complex decision processes by the use of pseudo-criterion and thresholds of preference and indifference, introducing the idea of fuzzy outranking relations (GRECO et al., 2016). Moreover, although ELECTRE III has not yet been applied to the task of selecting microalgae strains, it is largely used in environmental studies, which includes waste and water management, among others (GOVINDAN & JEPSEN, 2016).

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[1] https://cran.r-project.org/web/packages/OutrankingTools/OutrankingTools.pdf

As ELECTRE III uses pairwise comparison to outrank the alternatives. Assuming for instance two alternatives *a* and *b*, the alternative *a* is considered better than *b* if in at least one of the distillations *a* is better than *b*, and in the other distillation, *a* is at least well ranked as *b*. On the other hand, these two alternatives are considered indifferent to each other if they belong to the same equivalence class in the two pre-orders (ROGERS et al., 2000). The incomparability occurs when alternative *a* is better ranked than *b* in the ascending distillation and *b* is better ranked than *a* in the descending distillation or *vice-versa*.

The results are presented either in the form of the outranking graph or in the form of the ranking matrix, that are results of the intersection of the complete descending and ascend distillations. In other words, the microalgal strains are ranked from the best to worst enabling the decision-maker choose the most preferred one.

4.3.2 Site selection

Site selection lies on the co-location of a microalgae cultivation system (raceway) with an existing industrial facility (eg. power plant, cement factory) for the purpose of utilizing its waste, resulting in benefits to either or both co-located operations. Roughly speaking, site selection means looking for the industrial symbiosis opportunities.

Figure 42 presents the flowchart that can be applied to support the decision for choosing the co-location opportunity for large-scale microalgae cultivation, since it represents an important issue for large-scale microalgae cultivation due to it may reduce costs by allowing the use of waste as resources (eg. CO_2, residues, wastewater).

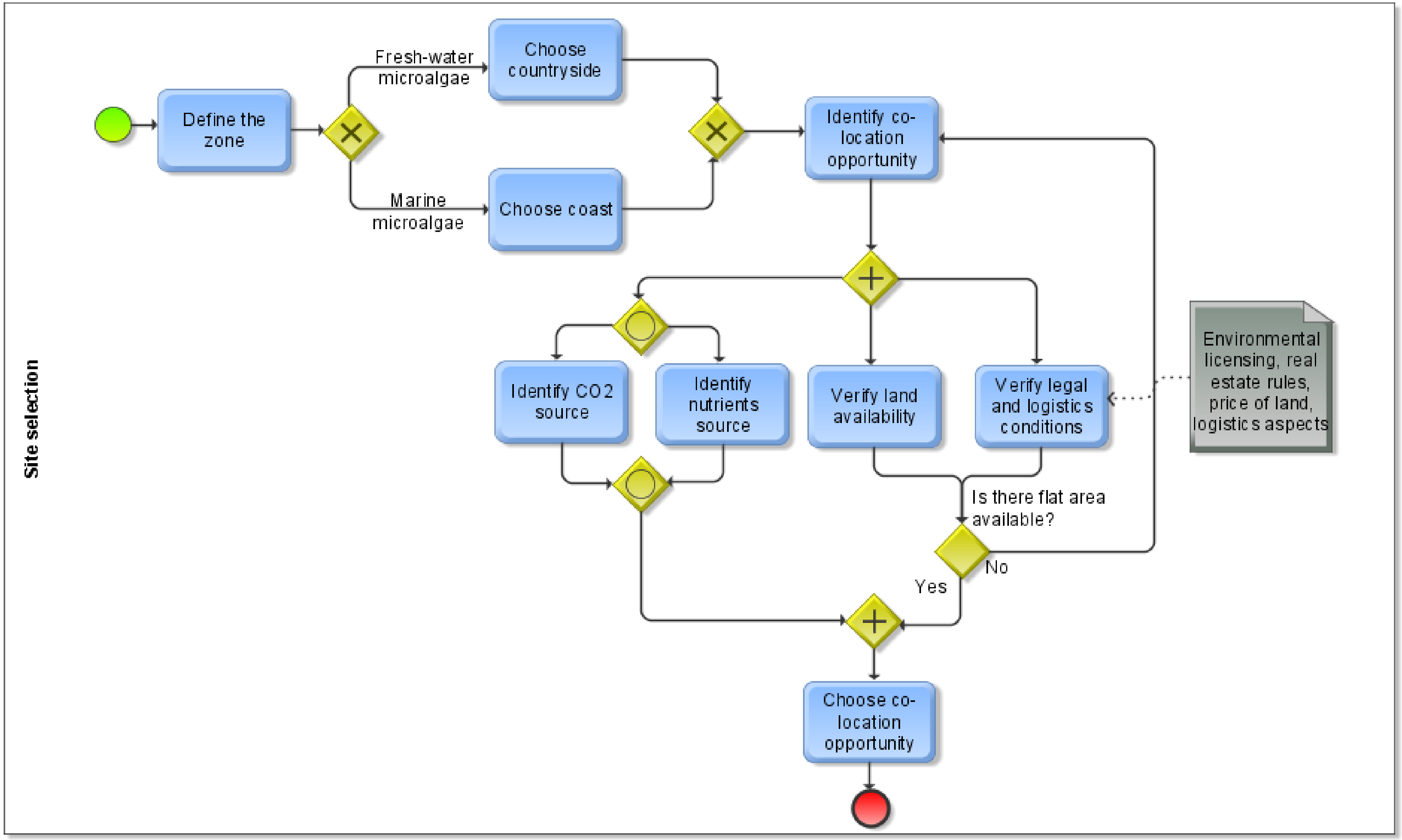


Figure 42. Guidance for site selection
Source: The author.

The site selection process starts with the definition of the zone for microalgae cultivation which must be taken into account if CO_2 source is located on the coast or not. So, if the strain selection process resulted in a freshwater microalga, the resource co-location opportunity must be in the countryside. On the contrary, a marine microalga implies choosing the coast zone.

After defining the area zone, the co-location opportunity must be identified by considering the waste streams. It means the preferred option is that both CO_2 and nutrients were available at the same industrial plant. In parallel with that, the site selection should consider flat land availability since the microalgae cultivation in raceways requires extensive areas.

Figure 43 illustrates the partition of land use in Brazil, where pasture areas represent a significant portion of the land (198 million hectares). It must be remarked that there is a large quantity of degraded land or land in process of desertification in Brazil - about 140 million hectares of degraded land, of which 30 million are pasture areas under some stage of degradation, with very low productivity for animal feed (CGEE, 2016). This clearly represents potential areas for microalgae cultivation.

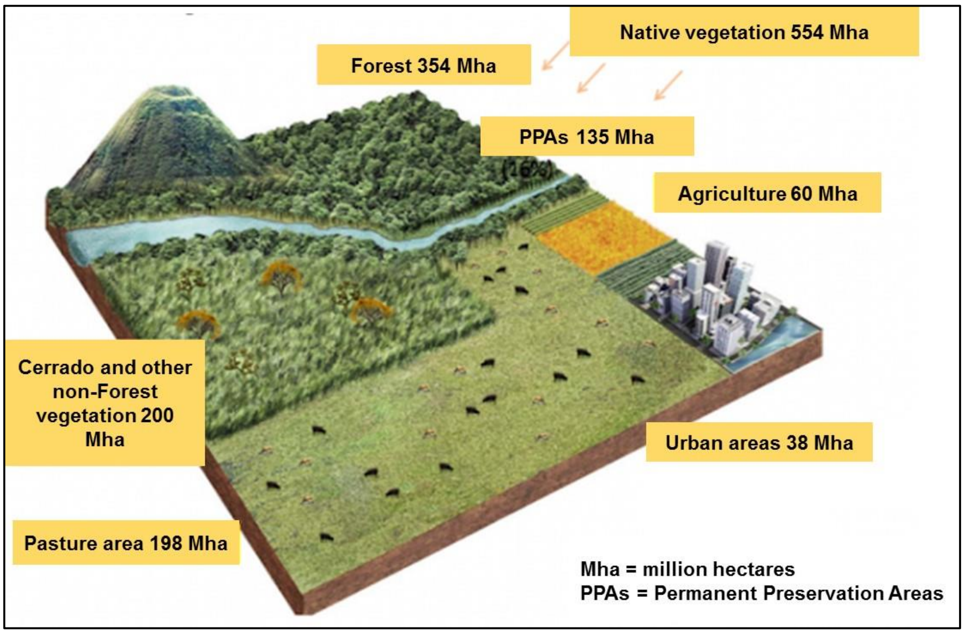


Figure 43. Land use in Brazil
Source: Adapted from Brasil Agrícola (2013).

Another issue to be considered refers to legal aspects and logistics. It is important to ensure that the chosen area complies with all legal requirements for building and operating the microalgal biomass production. Furthermore, the logistics must be analysed in terms of resources supply and product delivery. The IS facility closed to biodiesel production plant is recommended to reduce logistics costs. The volume of biodiesel will determine the transport option (pipeline or road transportation).

The transport of CO_2 from the industrial plant to the microalgae cultivation facility can be done through pipelines. Benemann & Oswald (1996) considered 2.4 km as maximum economically feasible distance for piping CO_2. However, Quinn et al. (2013) adopted 4.8 km as the economically preferable transport distance in their analysis, indicating concrete pipe as the most economically solution among the variety of pipe options commercially available.

Although not addressed by the guidance for site selection, climate conditions may represent a critical issue. Climate aspects such as temperature, insolation, windspeed, relative humidity, precipitation and evapotranspiration might be relevant when producing microalgal biomass in open systems (RESURRECCION et al., 2010; QUINN et al. 2013).

Moody et al., (2014) have evaluated the global biofuel potential from microalgae by modelling lipid productivity under climatic variables of atmospheric pressure, cloud cover, wind speed, wind direction, temperature, and solar radiation. Results corroborated Brazil’s potential for microalgal biomass production (Figure 44).

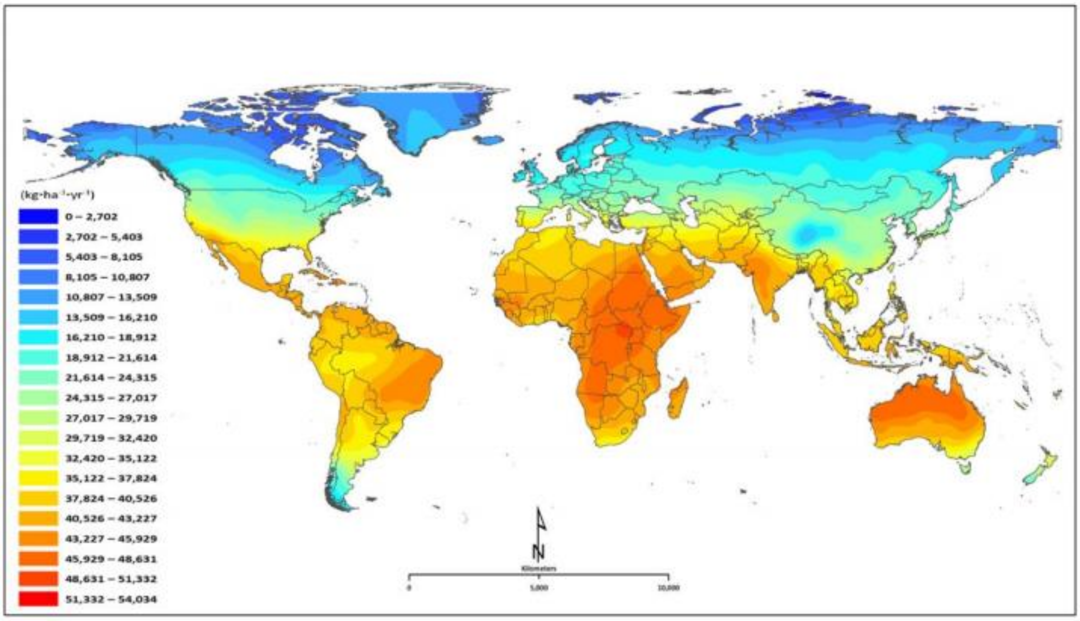


Figure 44. World map of the biomass productivity potential from microalgae
Source: Moody et al., (2014).

Therefore, from a climate-resource-perspective, Brazil has favourable conditions for microalgae become the main source of biofuels (Embrapa Agroenergia 2016). This means that, for microalgae cultivation located anywhere in Brazil, the climate conditions are minimally favourable.

4.4 Step 2: Input-output modelling

An input-output modelling is based on the concept of transformation process, where inputs are transformed to outputs (goods, services or mixed). Inputs comprise transformed resources and transforming resources. The former are the resources treated, transformed or converted in the process (feedstocks, materials, etc). The resources which act upon the transformed resources are the transforming resources (facilities and staff) (SLACK et al., 2002).

So, the input-output modelling has to address both transformed and transforming resources. It is recommended carrying out the modelling obeying the circular value creation logic, account at first the main transformed resources, and then the results could be used in the dimensioning the microalgal cultivation facility.

The availability of CO_2 and nutrients will define the scale of microalgal biomass production, consequently the volume of oil and biodiesel. At simplest, model parameters from previous studies that investigated microalgae performance under a variety of conditions could be used to estimate the outputs of each transformation process.

More important than to have precise values, it is to know which factors influence the microalgae growth and how the influence occurs. Because the overall microalgae performance can be affected by several factors including environment and biological factors, and operational conditions (KUMAR et al., 2010), especially in outdoor cultures which there are more exposure to a variety of changes in environmental conditions (RICHMOND, 2004).

Light, temperature, pH, salinity, nutrients, and dissolved oxygen (DO), levels of toxic elements (eg. heavy metals) are the most relevant environmental factors that can affect the growth of microalgae. Among biological factors that inhibit microalgal growth, the most relevant ones are related to the contaminants, i.e. microorganisms different from the cultured species (viruses, bacteria, etc), leading to predation and competition (KUMAR et al., 2010).

Table 9 summarizes the most relevant factors (causes) to each effect into the overall performance of microalgae cultivation, and their relationship in order to understand how each factor influences the respective effect. The direction means if the cause and effect have the same direction of change (+) or opposite direction (-). In other words, the direction is associated to the notion of direct or inverse relationship between cause-effect.

Table 9. Relationship description between cause and effect into microalgae performance

Effect	Cause	Relationship	Direction
Growth rate	Light intensity	Microalgal activity usually rises, with increasing light intensity up to 400 µmol/m²s	+
	Temperature	Higher temperatures generally accelerate the metabolic rates of microalgae	+
	High pH	The increase in pH can inhibit microalgal growth	-
	Low pH	Decreasing pH of the medium results in low productivity	+
	Salinity	Introduction of salinity may reduce the overall biomass productivity	-
	CO_2 concentration	The increase in CO_2 concentration can lead to higher biomass productivity	+
	Dissolved oxygen (DO)	DO supersaturation (excessive DO) can inhibit microalgal growth	-
	Heavy metals	Heavy metal are potent inhibitors of microalgal photosynthesis	-
	Nutrients requirement	Carbon, nitrogen and phosphorus are important elements required for microalgal nutrition	+
	Contaminants	Predation, viruses, bacteria and competition are biological factors that limits the microalgae productivity	-
Oil content	Nitrogen supply	Nitrogen limitation can result in more lipids production	-
	Salinity	The increase in salinity may result in slight increase of total lipid content	+
	Lipid production	Lipid production results in more oil content	+
Contaminants	pH	The increase in pH can be beneficial for inactivation of patogens	-
pH	CO_2 concentration	The increase in CO_2 concentration can decrease pH	-
Microalgae physiology	Heavy metals	Heavy metal induces morphological changes in the microalgal cells resulting physiological incompatibility	-

Source: The author based on Richmond (2004); Kumar et al. (2010); Sharma et al. (2012).

Each factor can be considered as cause of an effect related to the microalgae performance as schematized in the causal loop diagram presented in Figure 45.

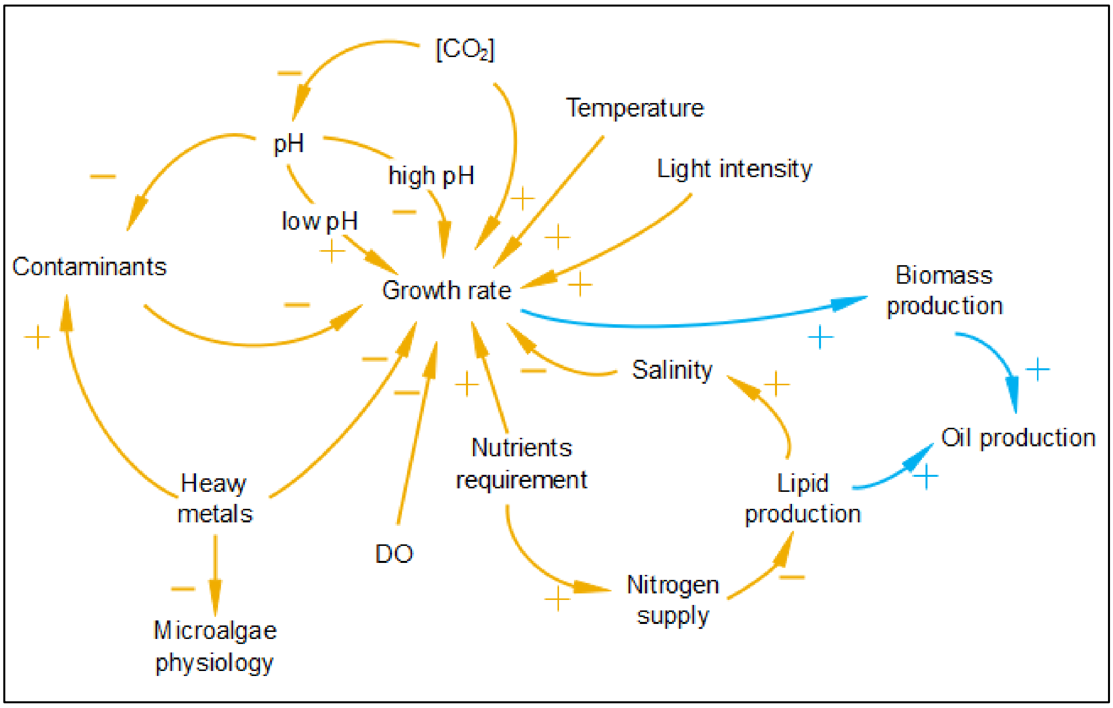


Figure 45. Cause-effect relationship diagram of microalgae performance
Source: The author.

Depending of the flue gas composition and the source of nutrients, one factor could be more critical than other. Understand how these factors affects the microalgal biomass production is crucial, because most of these factors are manageable in the cultivation system.

Regarding the transforming resources, mainly regarding facilities, the raceway dimension is the most critical issue, since it could be the bottleneck of the overall system as it is directly related to the land availability. If available area is a constraint in the decision-making, all the dimensioning of the microalgal biomass production must take into account this constraint and not only the CO_2 and nutrients availability.

4.5 Step 3: Picturing the business

4.5.1 Business Model Canvas

The Business Model Canvas has already addressed in a circular economy context, as can be observed in the CBM proposed by Nußholz (2017) and discussed in section 2.2.2. By considering a business model as the rationale of how an organization creates, delivers and captures value, Osterwalder & Pigneur (2010) proposed nine basic building blocks that show the logic of how an organization intends to make money. The nine blocks cover the four main areas of a business (customers, offer, infrastructure and financial viability), and build-up the well-known Business Model Canvas (Figure 46).

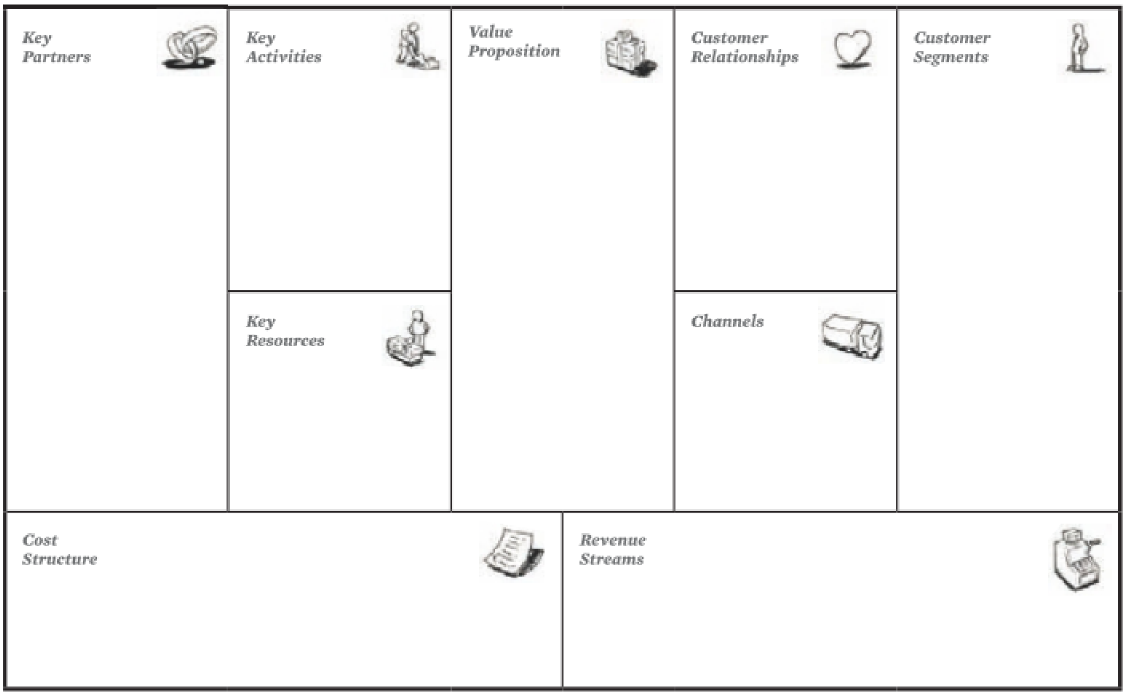


Figure 46. The Business Model Canvas
Source: Osterwalder & Pigneur (2010).

As customers comprise the heart of any business model, the first building block is the *customer segments*, in which different groups of people or companies an enterprise aims to reach are defined. The second block is the *value propositions*, where the bundle of products and services that create value for a specific customer segment must be described. The value proposition can be understood as the reason why customers turn to one company over another, and could be quantitative (price, speed) or qualitative (design, customer experience, convenience).

Channels comprise the third block building, which describes how a company communicates with and reaches its customers to deliver the value proposition. The *customer relationship* building block aims to describe the relationships a company establishes with its customers (acquisition, retention, upselling). Considered the arteries of a business model, the building block *revenue streams* represents the cash a company generates from each customer, from which costs must be subtracted to create the earnings.

Another important building block is the *key resources*, where the most important assets required to make a business model work are described. They allow an enterprise to create and offer the value proposition, reach markets, maintain relationships with customers, and earn revenues. The *key activities* building block describes the most important things a company must do to make its business model work.

In order to survive, companies must create alliances to optimize their business models, reduce risks, or acquire resources. This represents the *key partnerships* that is the eighth building block, which describes the network of suppliers and partners that make the business model work. Finally, the last building block is the *cost structure* that aims to describe all the costs incurred to operate the business model, including fixed and variable costs, economies of scale and scope.

4.5.2 Carbon Footprint

The carbon footprint, it is the sum of greenhouse gas emissions (GHG) and removals in a system, expressed as CO_2 equivalents, and based on the relevant processes within life cycle. The CO_2e of a specific amount of GHG is calculated as the mass of a given GHG multiplied by its 100-year time horizon global warming potential (GWP) given by the Intergovernmental Panel on Climate Change (IPCC), through characterization factors (ISO, 2013).

It can be calculated based on the Life Cycle Assessment (LCA) methodology using the single impact category of climate change, following the international standards ISO 14040 and 14044 for LCA studies. So, the carbon footprint analysis is carried out through the four iterative phases of an LCA: goal and scope definition, inventory analysis, impact assessment, and interpretation or results.

The goal and scope definition include identifying the decision context, the intended applications, the system boundary, the function unit, assumptions, limitations, among others. The inventory analysis comprises all the data collection for further impact assessment, which represents the translation of emissions to potential environmental impacts. Finally, the results are interpreted for decision-making (ILCD, 2010).

4.5.3 The integrated Business Model Canvas and Carbon Footprint

The integrated approach joins all the structure of the Business Model Canvas and its nine buildings blocks with two other blocks regarding the Carbon Footprint. The idea is to put on the same frame all the relevant aspects of the CBM proposed in terms of technical, economic and environmental dimensions.

Figure 47 shows how the tripartite CBM can be shown by this integrated approach.

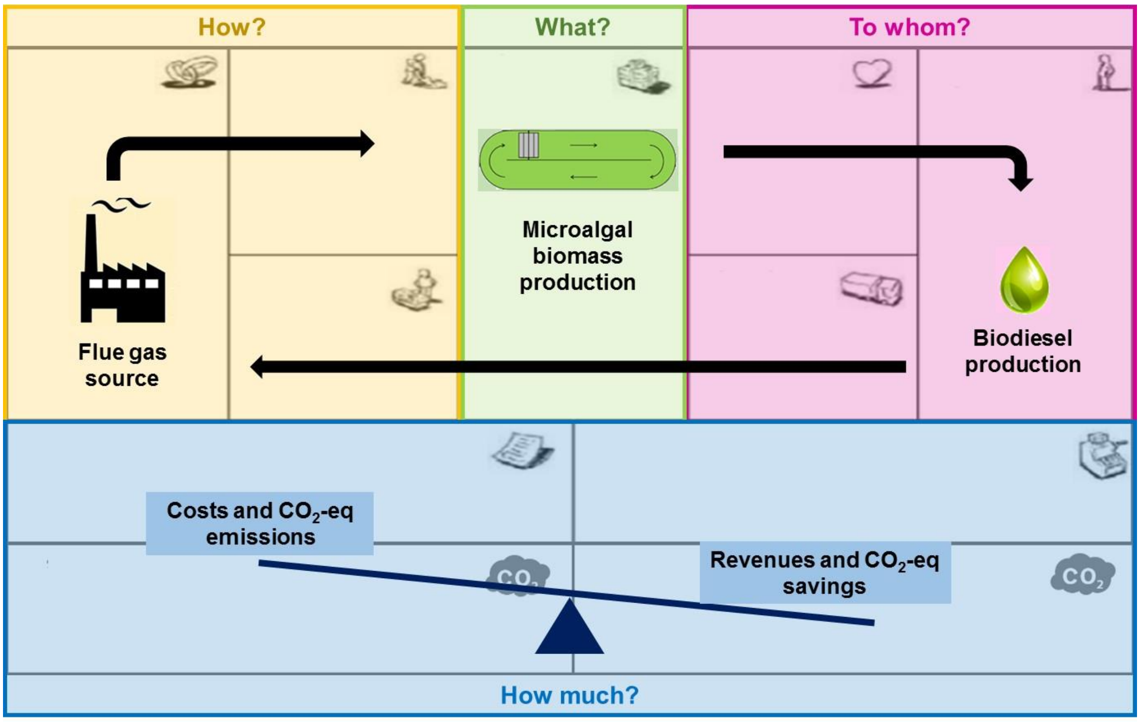
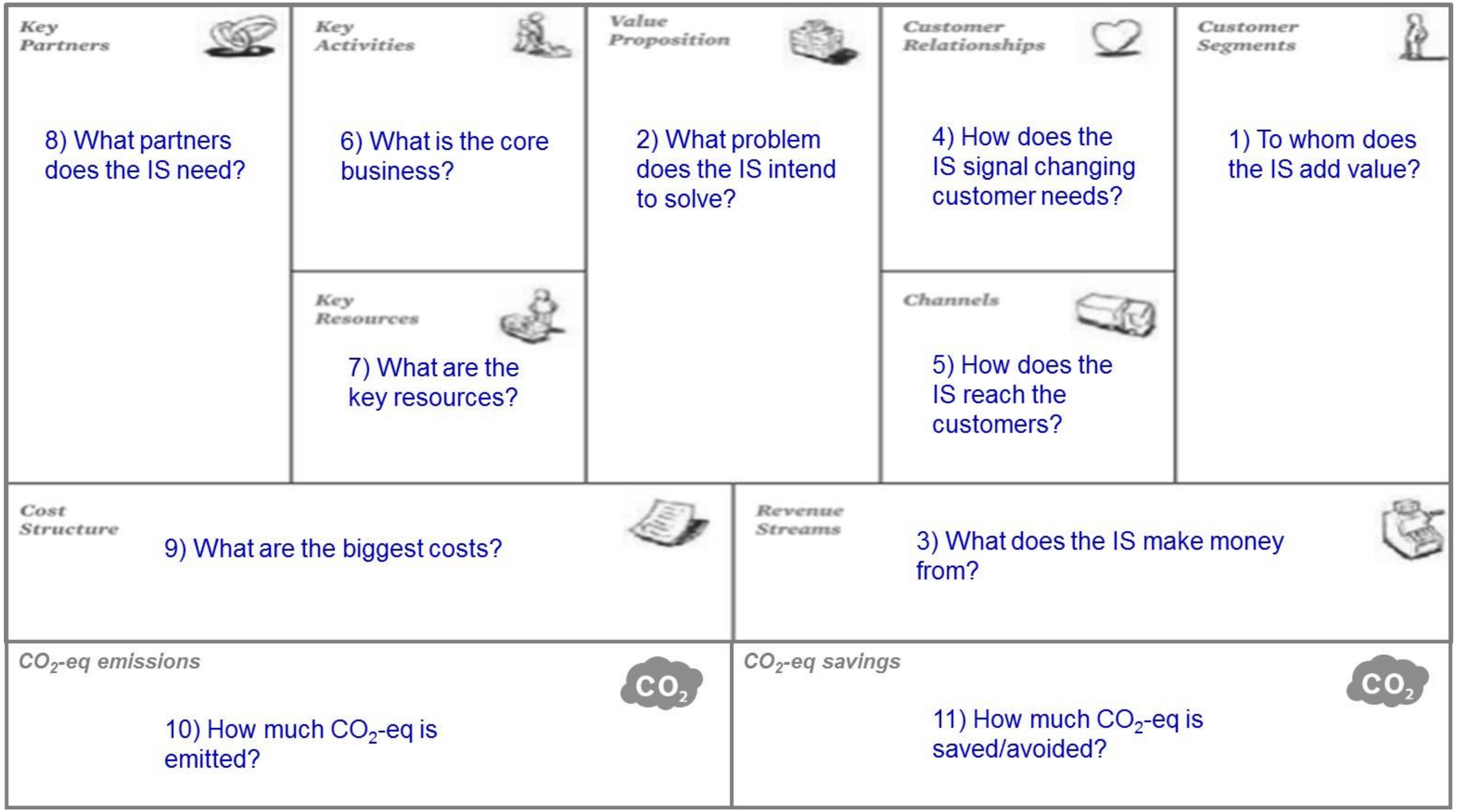


Figure 47. CBM in the integrated Business Canvas Model and Carbon Footprint
Source: The author.

So, the integrated approach comprises eleven building blocks, that could be addressed by answering the questions presented in Figure 48.



8) What partners does the IS need?

6) What is the core business?

7) What are the key resources?

2) What problem does the IS intend to solve?

4) How does the IS signal changing customer needs?

5) How does the IS reach the customers?

1) To whom does the IS add value?

9) What are the biggest costs?

3) What does the IS make money from?

10) How much CO_2-eq is emitted?

11) How much CO_2-eq is saved/avoided?

Figure 48. Step-by-step of the integrated Business Model canvas and Carbon Footprint
Source: The author.

5 Application in the cement industry

5.1 Potentialities of the cement industry

The industrial sector (related to the emissions generated by industrial processes that do not result from fuel burning) represents 7% of the total Brazilian GHG net emissions (Figure 49). Despite this modest contribution, industrial process emissions should be under discussion when new GHG reduction targets will be defined in 2025, as a result of the National Policy on Climate Change (PNMC) implemented in 2009 by federal law (Brasil 2009) in which mechanisms are stablished in order to achieve GHG reduction targets on a voluntary bases (CEBDS, 2018).

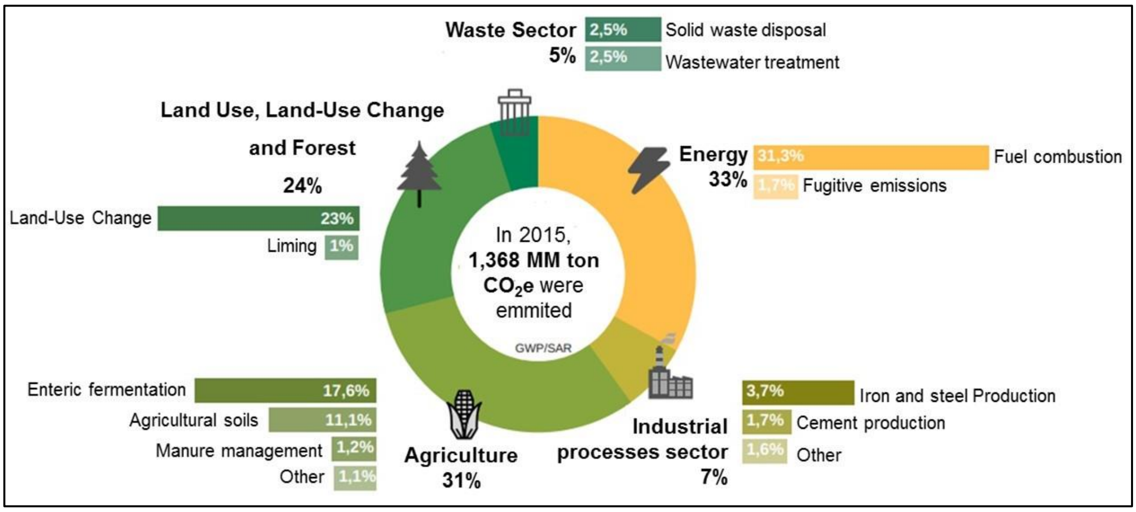


Figure 49. Contribution to GHG emissions by sector in Brazil (2015)
Source: Adapted from SIRENE-MCTI (2017).

As observed in Figure 49, two sectors are responsible for most GHG emissions of industrial processes in Brazil: iron and steel production, and cement production. Together they contribute over 75% of total industrial processes GHG emissions. Among these emissions, there are carbon dioxide (CO_2), methane gas (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (CF_4 e C_2F_6) and sulfur hexafluoride (SF_6), from which CO_2 is the most GHG emitted (Figure 50), pointing out the importance of implementing strategies for carbon capture such as integrated microalgae cultivation into these industrial processes. All of them are characterized into CO_2e based on IPCC characterization factors[2].

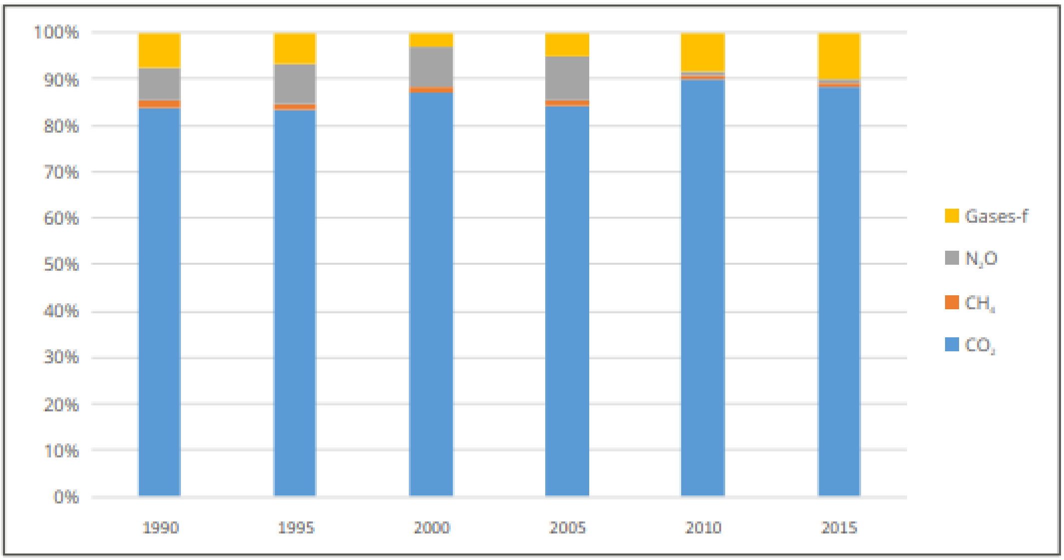


Figure 50. GHG participation by type of gas from industrial processes in Brazil
Source: MCTIC (2017b).

A Report published by the Ministry of Science, Technology, Innovation and Communication (MCTIC) in 2017 concerning GHG mitigation options in key sectors in Brazil shows the industrial sector leading the cost-effectiveness ranking of these sectorial options, where the cement industry is in the top of this rank with the best cost-benefit strategy (Table 10).

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[2] GWP/SAR – 1995 <https://www.ipcc.ch/ipccreports/sar/wg_I/ipcc_sar_wg_I_full_report.pdf>.

Table 10. Top 10 GHG mitigation options in Brazil

#	**Sector**	**Mitigation options**	**Potential of mitigation ($MTCO_2e$)**	**Total costs (US$ MM)**	**Cost-effectiveness index[1]**
1	Industry (cement)	Fuel Exchange	1.0	1.0	1.0
2	Industry (iron and steel production)	Heat recovery efficiency	14.7	14.3	1.0
3	Industry (iron and steel production)	Fuel Exchange	4.1	4.0	1.0
4	Industry (other sectors)	Fuel Exchange	2.4	3.0	1.3
5	Energy (refining)	Electrical efficiency in engines	1.2	7.9	6.6
6	Industry (chemicals)	Heat recovery efficiency	1.4	9.7	6.9
7	Municipal Solid Waste Management	Biogas degradation in landfills	20.8	234.6	11.3
8	Industry (cement)	Heat recovery efficiency	2.8	31.7	11.3
9	Energy (refining)	Efficiency in hydrogen consumption	3.9	55.0	14.1
10	Industry (other sectors)	Efficiency in heat and steam recovery	7.1	117.4	16.5

[1] Ratio between total costs and potential of mitigation.

Source: Adapted from MCTIC (2017a).

The Technology Roadmap of Low-Carbon Transition in the Cement Industry has set some strategies for CO_2 emissions mitigation of the cement sector worldwide by improving energy efficiency of cement kilns, switching to less carbon intensive fuels, reducing the clinker to cement ratio, and implementing innovative technologies such as carbon capture (IEA and CSI 2017).

Despite the efforts made in order to reduce the consumption of fossil fuels, electricity, and CO_2 emissions (Figure 51) (VAN OSS & PADOVANI, 2003; WBCSD, 2012a), carbon capture technologies must be adopted to make the cement industry more sustainable due to the nature of the calcination process, which generates considerable amounts of CO_2 (WBCSD 2012b, LARA-GIL et al., 2016).

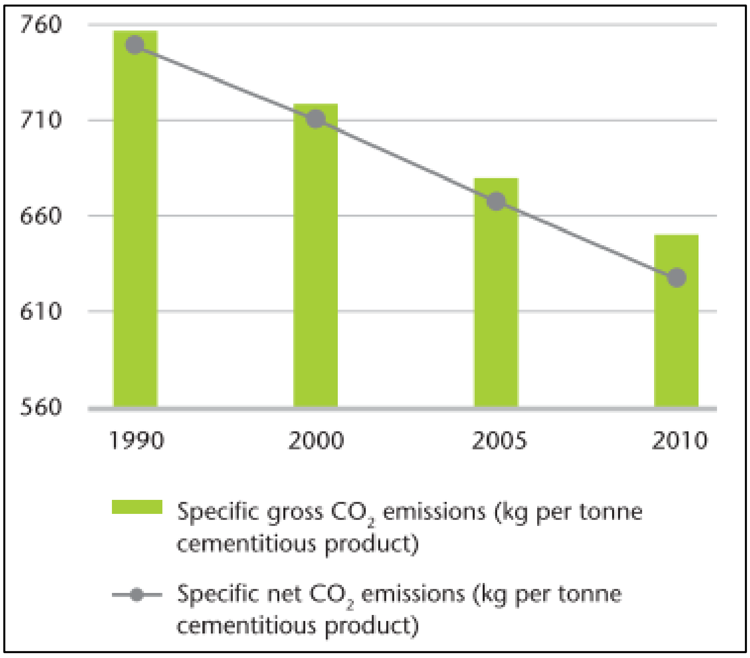


Figure 51. Reduction of specific CO2 emissions of the cement global sector (24 major cement producers)
Source: WBCSD (2012b).

In this sense, the feasibility of using flue gas from a cement plant as a source of CO_2 for microalgae cultivation has been analysed in the literature (Table 11) and by some cement companies, such as InterCement and Votorantim Cimentos.

Table 11. Studies that analysed the feasibility of microalgae cultivation using cement flue gas

Study	Objective	Microalgae	Cultivation system	Scale
Talec et al. (2013)	Evaluate the feasibility of using cement-plant flue gas as a source of CO_2 for microalgae cultivation	*Dunaliella tertiolecta*[1] *Chlorella vulgaris*[2] *Thalassiosira weissflogii*[1] *Isochrysis galbana*[1]	Closed photobioreactor	Laboratorial (2 L)
Lara-Gil et al. (2014)	Determine the toxicity of NOx and SOx flue gas components from cement plants	*Desmodesmus abundans*[2]	Erlenmeyer flasks	Laboratorial (125 mL)
Lara-Gil et al. (2016)	Develop a strategy against toxicity for microalgae considering flue gas components at concentrations close to maximum values	*Desmodesmus abundans*[2]	Closed photobioreactor	Laboratorial (3 L)

[1] Marine.
[2] Freshwater.
Source: The author.

In a partnership between Santa Maria Federal University (UFSM), São Carlos Federal University (UFsCar) and Algae Biotechnology, the InterCement, one of the 10 largest cement producers in the world, has been developed a R&D project related to CO_2 biofixation by microalgae since 2013. In 2017, a pre-industrial scale pilot plant (Figure 52) was built in the state of São Paulo, Brazil, for tests related to CO_2 biofixation, animal nutrition, human health and effluent treatment (INTERCEMENT, 2017).

Figure 52. Microalgae cultivation in PBRs in the pre-industrial scale pilot plant
Source: InterCement (2017).

Another example is seen in a carbon sequestration project that has been developed in a partnership between Votorantim Cimentos and Pond Technologies in Canada, at St Marys unit, where microalgae capture carbon to transform it into biomass, which can be used as a source of essential oils, protein for animal feed and fuel for potentially use in the kiln's company - the last option reinforces the approach of circular economy presented Figure 53 (VOTORANTIM, 2017).

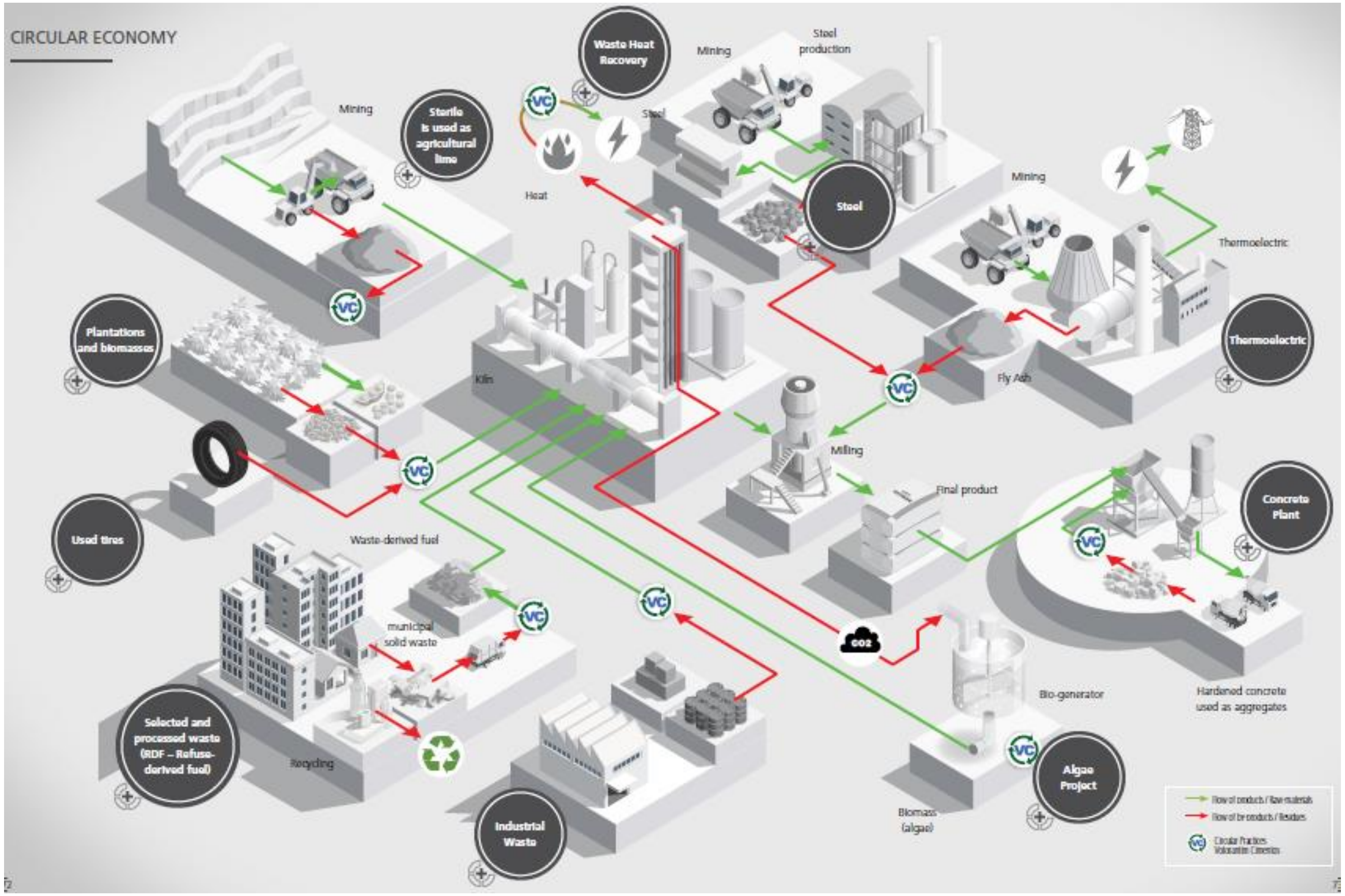


Figure 53. Schematic integration of the Algae Project by Votorantim Cimentos
Source: Votorantim (2017).

In 2016, a demonstration plant was built with the capacity of capturing 100 kg of CO_2 per day, producing a daily amount up to 50 kg of dry microalgae, and it works as an algal biorefinery located on St Mary’s site with a 25,000 L photobioreactor that uses LED lights and receivers CO_2 emissions by a pipeline directly from the cement kiln (Figure 54) (CHURCH, 2017).

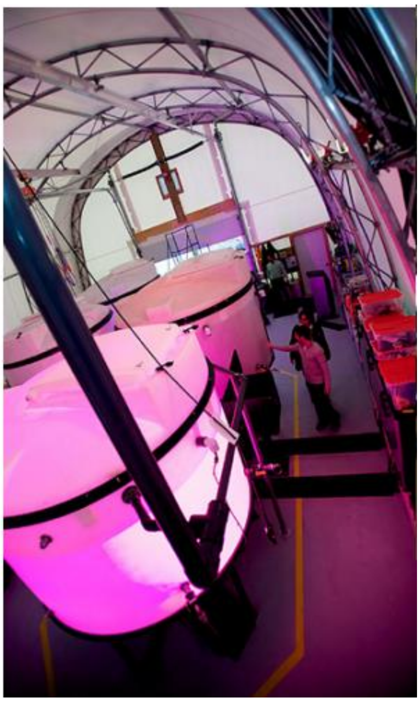


Figure 54. Algae Project at the St Mary's site, Ontario, Canada.
Source: Votorantim (2016).

In addition to the capture of CO_2 from the flue gas, the industrial symbiosis of a microalgae production facility with cement factory offers additional advantages due to the possibility of using the kiln dust, that is a residue from the calcination process, as nutrient source required for microalgae growth (Figure 55).

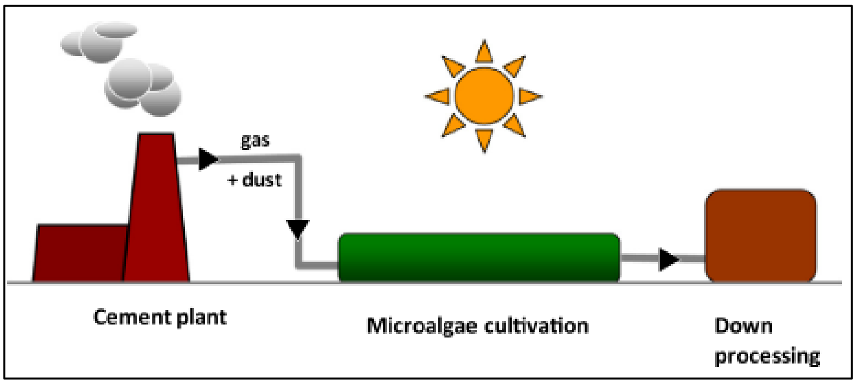


Figure 55. Industrial Symbiosis of cement plant and microalgae cultivation facility
Source: Talec et al. (2013).

5.2 Step 1: Planning

5.2.1 Microalgal strain selection

In order to identify the most suitable microalgal strain for cultivation in raceways for biodiesel production, fifteen potential candidates were analysed through ELECTRE III, taking into account culturability criteria and lipid content and quality of each strain.

Alternatives definition

Thirty-three microalgal strains were initially investigated. Five are chlorophytes isolated from a lagoon in Paraná State, southern Brazil and belong to the Culture Collection of Microalgae of the Agronomical Institute of Paraná, Brazil (IPR). One strain was purchased from the University of Texas Culture Collection (UTEX), Austin, USA. Six are diatom strains isolated from marine waters off the Brazilian coast and 21 chlorophytes isolated from an interdunal lake system in Brazil (FISTAROL et al., 2018) were also used. The latter belong to the Culture Collection of Microorganisms at Federal University of Rio de Janeiro, Brazil (CCMR). It must be remarked that the suitability of these species for biodiesel production has been extensively evaluated in the literature (eg. SHARMA et al., 2012; DASSEY et al., 2014; JOSEPH et al. 2016).

All microalgae were grown first in the inoculation phase at laboratory scale, and the successful ones progressed to the cultivation in plastic bags and then to open tanks (raceways). Cultures were scaled-up for 7 to 12 days in 10, 100, 1,000 and 10,000-mL flasks subsequently. Strains that grew and reached the 10 L flasks in good condition were cultivated in 100 L bags, and then finally grown for 12 to 15 days in the raceways (Figure 56).

The raceway system is located at the Agronomic Institute of Paraná (IAPAR), in the municipality of Londrina, northern area of Paraná state in southern Brazil (23°21’17”S; 051°09’53”W) and was built based on the typical configuration design addressed by Chisti (2016). It comprises four elongated, narrow and shallow tanks: two with capacity for 1,500 L each, and two with capacity for 3,000 L each (Figure 57 and Table 12).

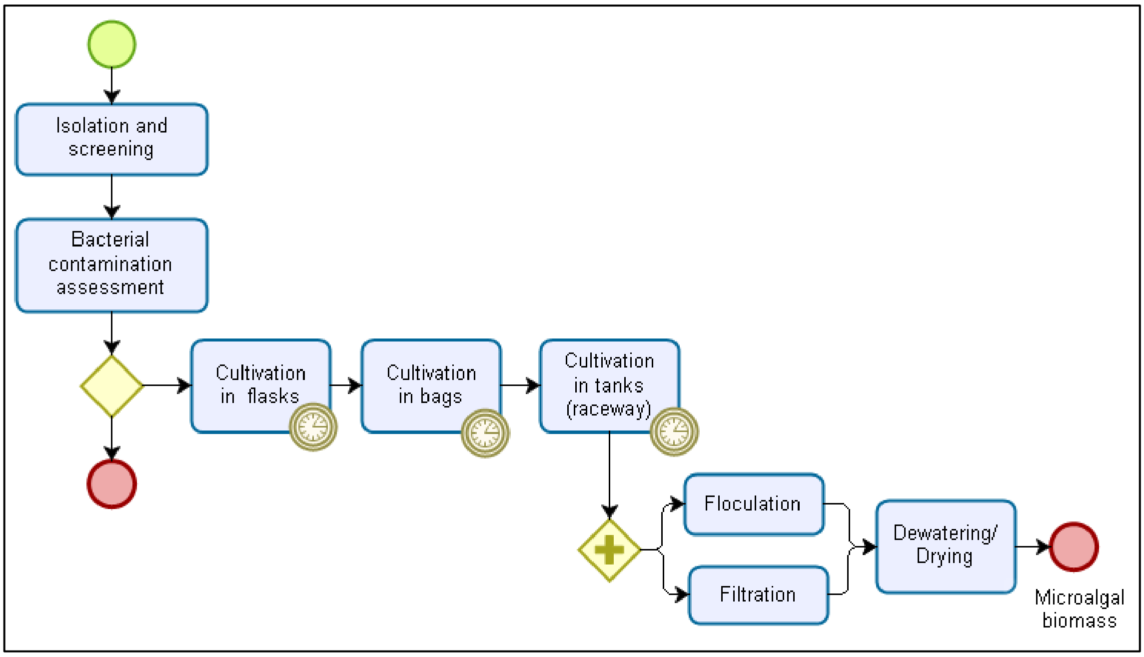


Figure 56. Cultivation process from lab-scale to the raceway
Source: The author.

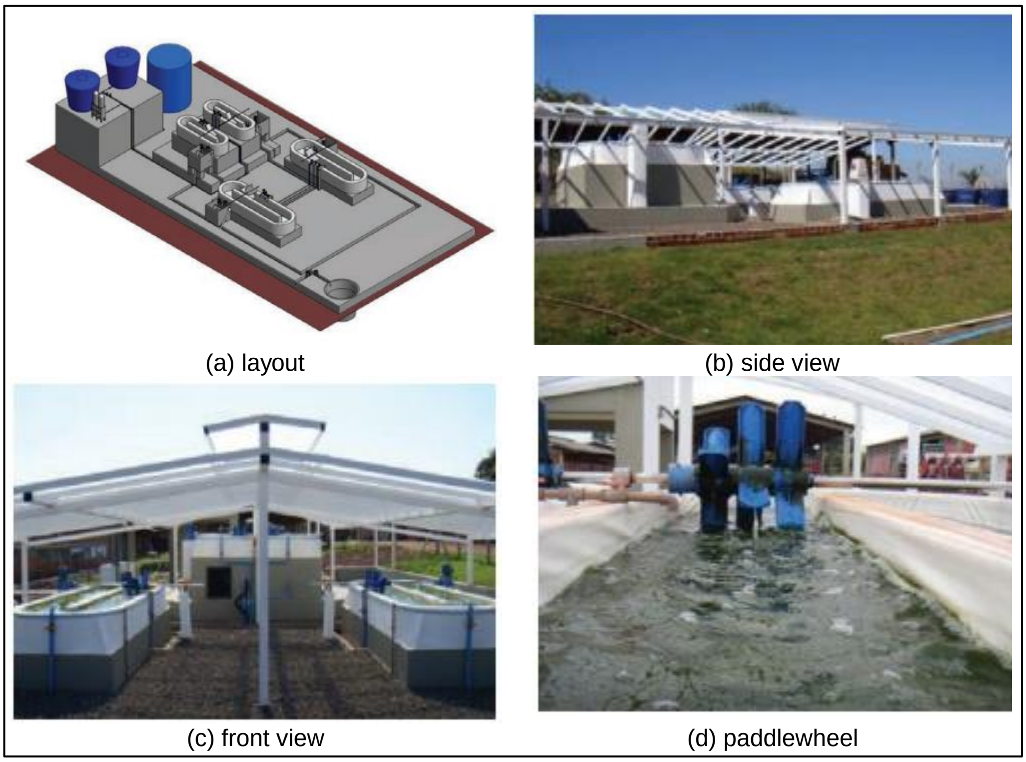

(a) layout
(b) side view
(c) front view
(d) paddlewheel

Figure 57. The raceway facility at IAPAR
Source: Adapted from Souto & Gatti (2014).

Table 12. Main characteristics of the raceway system at IAPAR

Characteristics	**Raceway**	
	Capacity of 1,500 L	**Capacity of 3,000 L**
Quantity (un.)	2	2
Central wall length (m)	2.20	3.50
Channel width (m)	0.60	0.80
Depth[1] (m)	0.70	0.70
Membrane composition	Polyvinyl chloride (PVC)	

[1] Different from the water level, which is 0.40 m.

Source: Adapted from Souto and Gatti (2014).

From the 33 strains cultivated, 18 remained at the initial phase of inoculation due to several reasons, such as adherence to the walls of the culture vessels, apparent viscosity or simply poor or non-growth, and thus were considered inadequate to the raceway. Seven strains reached the tank cultivation and the other eight reached the antecedent phase – cultivation in 100-L bags.

As the main focus is to identify the best microalgae strain for lipid production under open pond system conditions, the 15 strains that reached at least the 100L bag phase were selected as alternatives to the MCDA method. Figure 58 presents the scheme of alternatives selection and Table 13 shows each alternative to be analysed in the multi-criteria method.

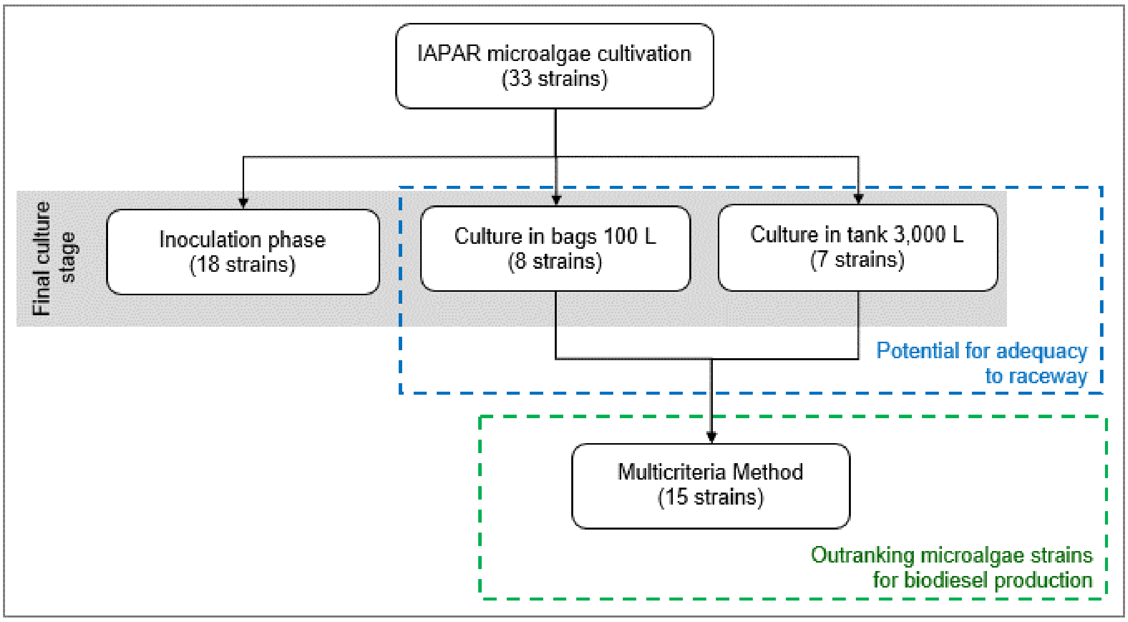


Figure 58. Rationale for strain selection as alternatives to the MCDA method
Source: The author.

Table 13. Alternatives (microalgal strains) analysed in the study

Alternative	**Strain code**	**Group**	**Taxon**
A0001	CCMR0089	Chlorophyta[1]	*Chlorella* sp.
A0002	CCMR0193		N.I.
A0003	CCMR0090		*Desmodesmus perforatus*
A0004	CCMR0194		*Scenedesmus rubescens*
A0005	CCMR0029	Diatom[2]	*Navicula salinicola*
A0006	CCMR0031		*Nanofrustulum shiloi*
A0007	CCMR0032		*Pseudostaurosira brevistriata*
A0008	CCMR0033		*Nanofrustulum shiloi*
A0009	CCMR0036		*Nanofrustulum shiloi*
A0010	IPR7104	Chlorophyta	*Chlorella* sp.
A0011	IPR7116		*Chlorella* sp.
A0012	IPR7115		*Chlorella* sp.
A0013	IPR7117		*Chlorella* sp.
A0014	IPR7151		*Chlorella* sp.
A0015	IPR1185		*Neochloris oleoabundans*

N.I. means that the specie has not yet been identified; Microalgae isolated from: [1]Lençois Maranhenses, Maranhão State, Brazil; [2]Archipelago of Abrolhos, Bahia State, Brazil.

Criteria definition

For the five criteria suggested in section 4.3.1, a group of sub-criteria is adopted (Table 14).

Table 14. Criteria and sub-criteria adopted in the study

Criterion	**Sub-criterion**	**Unit**	**Preference direction**
C1: Growth performance	SC1: Performance after application of yeast extract	4-point scale	Maximize
	SC2: Final biomass	O.D.	Maximize
C2: Lipid content	SC3: Oil content	% of dry matter	Maximize
C3: Fuel quality of biodiesel	SC4: SFA	%	Minimize
	SC5: PUFA		Maximize
	SC6: MUFA		Maximize
	SC7: Cetane number	-	Maximize
C4: Ease of harvesting	SC8: Ease of cultivation and harvesting	4-point scale	Maximize
C5: Resistance to contamination	SC9: Resistance to contamination	4-point scale	Maximize

SFA: saturated fatty acid; PUFA: polyunsaturated fatty acid; MUFA: monounsaturated fatty acid. O.D.: optical density at 750nm.
Source: The author.

The growth performance is evaluated in terms of the final biomass concentration measured by optical density at the final culture stage (bags or tanks), and of the response to the yeast extract application, which has been suggested to be an important supplement for the build-up of microalgal biomass, i.e. for its efficient growth (AZMA et al., 2011; PARK et al., 2012). Both sub-criteria have the preference direction set to maximize. The lipid content means the oil content expressed as fatty acid methyl esters

(FAME) detected by gas chromatography coupled to mass spectrometry. FAMEs were analysed using a whole biomass transesterification procedure as described at Johnson and Wen (2009).

A C4:0-C24:0 FAME mixture (Sigma Aldrich) was used as standard. Pentadecane (Sigma Aldrich) was used as internal standard for all samples. FAME profiles were determined using gas chromatography coupled to mass spectrometry GCMSQP2010 Plus (Shimadzu, Japan) and DB5-MS column (25 m × 250 µm ID × 0.25 µm df). The fuel quality of biodiesel is affected by the composition of fatty acid profile, represented by SFAs, MUFAs and PUFAs. Cetane number (CN) for each strain was calculated based on FAME profiles according to Lapuerta et al., (2009) and Tong et al., (2011). Despite the fact that the CN can be influenced by fatty acid profile, it was also considered in the analysis because it is directly related to the combustion of fuel, indicating the ignition delay time that means the time between injection and ignition.

Moreover, each fatty acid may has a different impact on CN as evaluated by Islam et al., (2015), that revealed positive relationship between MUFA and CN, and by contrast the negative correlation between MUFA and CN. The ease of harvesting was assumed as a qualitative criterion based on the judgment of the cultivation and harvesting process in the experimental raceway by a 4-point scale (very easy, easy, difficult, very difficult).

Finally, the resistance to contamination was also evaluated on a qualitative 4-point scale based on when (i.e. in which culture phase) the contamination occurred. For instance, considering that the final culture stage could be either in bags or tank, if the contamination occurred at the bag culture stage, the resistance to contamination is considered very low. If it happened in the raceway stage, the resistance is considered as low. On the other hand, if there was no contamination in the raceway, the resistance is very high, and in the bag, the resistance is high (Table 15).

Table 15. Rationale for resistance of contamination

Final stage of culture	**Resistance to contamination**
Contamination	
Bags	Very low
Raceway (tanks)	Low
No contamination	
Bags	High
Raceway (tanks)	Very high

Source: The author.

The decision matrix

As ELECTRE III does not need to enter normalized values of performances, the choice of the units of scale of values is not important. So, the performance of each alternative in each criterion can be seen on the decision matrix (Table 16). SC1, SC8 and SC9 are qualitative sub-criteria expressed by a 4-point scale. The sub-criterion SC1, related to the microalgae performance after application of yeast extract, can be expressed by: 0, that means no application of the yeast extract; 1, when the extract had a negative impact to the microalgae growth; 2, when the extract application had no influence in the growth; and 3, when the microalgae grew up. The SC8 refers to the ease of harvesting and can be expressed by: 1 – very hard, 2 – hard, 3 – easy, and 4 – very easy. The SC9 is related to the resistance of contamination and the scale adopted was: 1 – very low resistance, 2 – low, 3 – high, and 4 – very high.

Table 16. Decision matrix of the strains investigated

Sub-criterion	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9
Weight	3	3	4	4	4	4	4	2	3
Unit	Qualitative[1]	cells mL^{-1}	% of dry matter	%	%	%	-	Qualitative[2]	Qualitative[3]
Alternative									
CCMR0089	1	0.384	12.999	92.527	4.546	2.297	62.807	3	2
CCMR0193	3	0.438	15.072	86.603	3.575	9.822	62.677	4	2
CCMR0090	3	3.147	21.322	66.012	4.005	29.983	59.829	4	2
CCMR0194	3	0.394	15.081	85.911	3.607	10.482	62.201	4	2
CCMR0029	0	0.330	13.980	92.433	4.293	3.274	62.885	3	3
CCMR0031	0	0.248	17.036	91.243	3.762	4.995	64.083	3	1
CCMR0032	0	0.389	13.740	92.752	4.409	2.839	63.952	3	1
CCMR0033	0	0.366	14.670	90.695	3.485	5.820	63.199	3	1
CCMR0036	0	0.425	12.949	93.039	4.235	2.726	63.195	3	1
IPR7104	3	2.362	17.966	76.792	3.103	20.105	61.354	4	2
IPR7116	3	1.584	15.956	87.812	3.844	8.343	64.188	4	2
IPR7115	3	1.241	13.260	93.101	4.197	2.702	63.726	3	1
IPR7117	3	1.295	16.483	84.352	4.119	11.529	63.129	3	1
IPR7151	3	1.177	12.931	92.312	4.677	3.011	63.445	3	1
UTEX1185	3	1.736	16.429	87.369	3.672	8.958	63.804	3	1

[1] 0 = not applied, 1 = negative impact to the growth, 2 = indifferent, 3 = positive impact to the growth.

[2] 1 = very hard, 2 = hard, 3 = easy, 4 = very easy.

[3] 1 = very low, 2 = low, 3 = high, 4 = very high.

ELECTRE III results

The ELECTRE III results can be presented in the form of the outranking graph (Figure 59 and Figure 60), that are results of the intersection of the complete descending and ascend distillations. The strain CCMR0090 (*Desmodesmus perforatus*), isolated from an interdunal shallow lake system in the tropical area of northeast Brazil (2°29´09”S; 043°07`41”), ranked at the first position, followed by three strains of *Chlorella* sp. isolated from Paraná State (IPR 7104, 7116 and 7117).

The environment from were strain CCMR0090 was isolated presents harsh conditions of high temperatures and fluctuating lake level (FISTAROL et al. 2018) which might have contributed to its adaptability and good performance to culture conditions from laboratory level up to the raceways. Moreover, the genus *Desmodesmus* and its close relative *Scenedesmus* are widely used for biotechnological purposes as they are easy to isolate and maintain, as well as to grow in large volume systems (Nagappan and Verma 2016).

The two others Brazilian clorophytes (strains CCMR0193 and CCMR0194) were indifferent at fifth position, and incomparable to the strain UTEX1185. The best ranked diatom was *Navicula salinicola* strain CCMR0029 at the sixth position incomparable to the *Chlorella* sp. strain IPR 7115. They are followed by the strain IPR 7151 (*Chlorella* sp.*)* at seventh position and the diatom *Nanofrustulum shiloi* (strain CCMR0031) at eighth position. The strains CCMR0089 (*Chlorella* sp.) and CCMR0033 (*Nanofrustulum shiloi)* are indifferent at the ninth position, followed by the two latest diatoms (CCMR0032 and CCMR0036). Table 17 summarizes the final ranking.

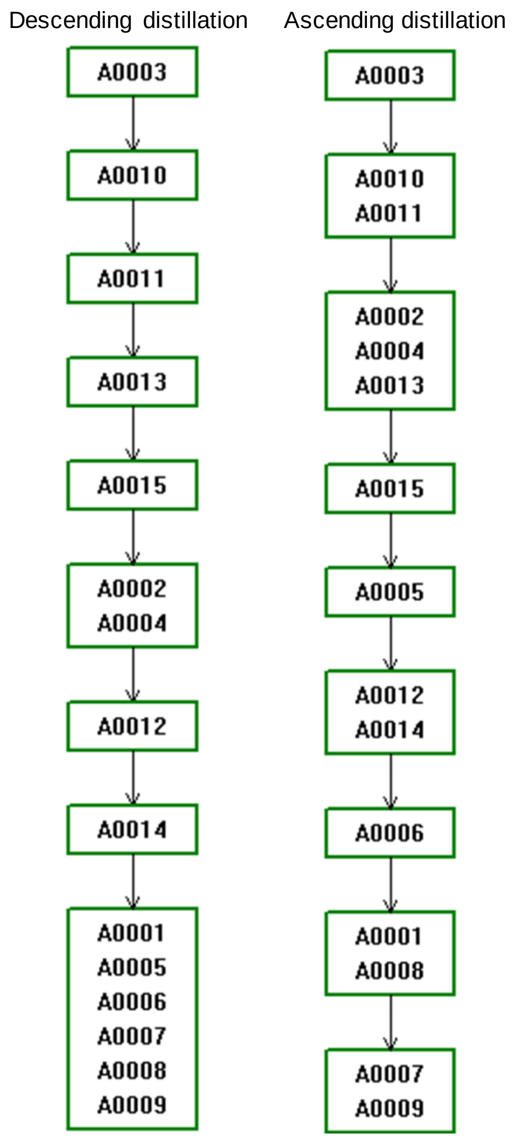


Figure 59. Descending and ascending distillations

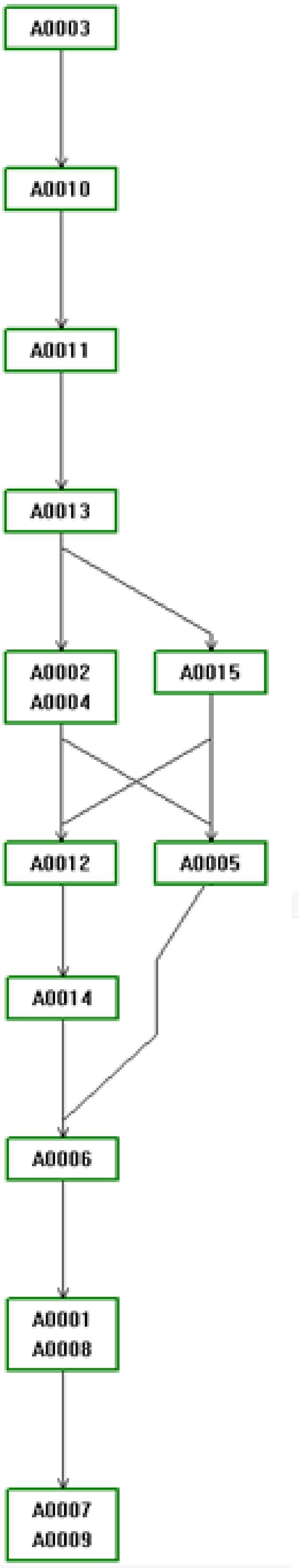


Figure 60. Graph of the final ranking

Table 17. Final ranking of the 15 microalgal strains analysed

Ranking	Alternative	Strain code	Taxon
1	A0003	CCMR0090	*Desmodesmus perforatus*
2	A0010	IPR7104	*Chlorella* sp.
3	A0011	IPR7116	*Chlorella* sp.
4	A0013	IPR7117	*Chlorella* sp.
5	A0002	CCMR0193	N.I.
	A0004	CCMR0194	*Scenedesmus rubescens*
	A0015	UTEX1185	*Neochloris oleoabundans*
6	A0005	CCMR0029	*Navicula salinicola*
	A0012	IPR7115	*Chlorella* sp.
7	A0014	IPR7151	*Chlorella* sp.
8	A0006	CCMR0031	*Nanofrustulum shiloi*
9	A0001	CCMR0089	*Chlorella* sp.
	A0008	CCMR0033	*Nanofrustulum shiloi*
10	A0007	CCMR0032	*Pseudostaurosira brevistriata*
	A0009	CCMR0036	*Nanofrustulum shiloi*

Source: The author.

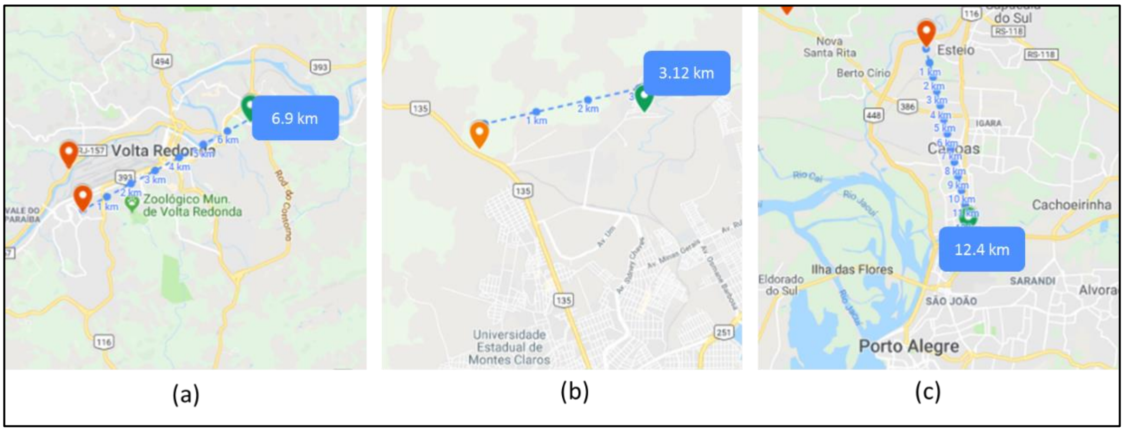
5.2.2 Site selection

As shown in the previously section, a freshwater microalgal strain was ranked at first position, amongst the microalgal strains investigated at IAPAR, being the most suitable strain for raceway cultivation for biodiesel production. In this sense, the co-location opportunity for IS does not need to be at coast, as required for cultivation of marine microalgae.

Based on the guidance for site selection presented in Figure 42, the co-location opportunity should obey availability of resources for microalgae cultivation, including CO_2, nutrients, water, land and climate conditions. Regarding CO_2, nutrients and feeding water, the cement production plants meet the requirements. As discussed in section 4.2.2, Brazil has favourable climate conditions and land availability for large-scale microalgae cultivation in raceways.

So, the decision-point for site selection could be the proximity of the cement factory to the demand, i.e. the distance from the IS to the biodiesel production plant. Figure 61 shows the distribution of cement factories and biodiesel production plants in Brazil. Few opportunities could be observed because cement plants are concentrated in the southeast region and biodiesel plants in the centre-south and south regions. Figure 62 highlights the main opportunities by considering the distance in a straight line up to 15 km between a cement factory and a biodiesel production plant.

Figure 61. Co-location opportunities – cement plants x biodiesel plants
Source: The author based on data from SNIC (2018) and MME (2017).



(a) (b) (c)

Figure 62. The three main co-location opportunities
Source: The author.

Two of the three co-location opportunities identified are in the southeast region. The first one (Figure 62a) is located in the countryside of Rio de Janeiro state. The second

(Figure 62b) is in the city of Montes Claros, Minas Gerais state, where flat areas are scarce due to the relief characteristics of the terrain. The third opportunity (Figure 62c) is located in the south region, Rio Grande do Sul state, near to an important petroleum refinery (REFAP).

The following maps (Figure 63 to 65) show the land availability of each selected co-location opportunity. It is important to emphasize that the green location icons representing the cement factory and the biodiesel production plant can reflect approximated locations. The highlighted areas indicate potential locations for microalgae cultivation nearby the cement manufactory.

Figure 63. Potential area for microalgae cultivation in Volta Redonda, RJ
Source: The author.

Figure 64. Potential location for microalgae cultivation in Montes Claros, MG
Source: The author.

Figure 65. Potential location for microalgae cultivation in Canoas, RS
Source: The author.

All these areas are potential locations identified only by observing land availability through Google Maps. However, it must be noticed that the choice of which area the microalgae cultivation facility will be located in has to be in accordance with legal aspects, environmental licensing, real estate rules, price of land, besides logistics requirements such as transport of CO_2, of algae oil and biodiesel.

5.3 Step 2: Input-output modelling of the Value Chain

5.3.1 Cement manufacturing process overview

The cement is produced through a closely controlled combination of processes (Figure 66 and Figure 67) that begins with the raw material extraction, which is composed mainly by limestone and clay.

Figure 66. Cement manufacturing value chain
Source: The author based on Votorantim (2016a).

Figure 67. Cement manufacturing processes at a plant
Source: Votorantim (2016a).

The material is extracted from mines and transported to the cement plant, to a specific place called pre-blending yard, where occurs the pre-homogenization process (1). In this phase, the quality is analysed and the limestone composition is drawn in terms of content of calcium, silicon, iron and aluminium.

In the flour mill (2), the limestone is ground with clay, that is rich in silica, iron and aluminium – essential to the quality of cement, and specific additives, such as ferrous and aluminic ores. As final product of this process, the flour is then stored in special silos to be sent to the rotary kiln, where the calcination process occurs, i.e. the clinker production (3).

The clinkerization is an energy intensive process, the temperature inside the kiln reaches 1450ºC. Clinker comes out of the process as grey balls that, after cooled (4) to less than

200ºC, are grinded and mixed with small amounts of gypsum and limestone in order to obtain the final product – the cement (5), ready for transport to the market (6) (VOTORANTIM, 2016a; ABCP, 2018).

5.3.2 Flue gas as source of CO_2 for microalgae biomass production

Flue gas (or exhaust gas) can be used as a source of CO_2 for microalgae cultivation, and several studies have been discussed the benefits and limitations to use algae to capture CO_2 as a method for GHG mitigation (eg. PACKER, 2009; SAYRE, 2010; SYDNEY et al., 2010; HO et al., 2011; LAM et al., 2012; BHOLA et al., 2014).

As the cement industry is a large contributor to GHG emissions and with huge quantities of CO_2 emitted, an increasing number of studies in the literature have focused on biofixation of CO_2 from cement flue gas (eg. TALEC et al., 2013; LARA-GIL et al., 2014; OLOFSSON et al., 2015; LARA-GIL et al., 2016). However, an important issue of CO_2 biofixation is related to the toxicity of the exhaust gas, because it does not contain only CO_2.

In the case of cement flue gas, there are also significant ammounts of other elements such as nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter. Notwithstanding these constituents may inhibit the growth of microalgae, some of them can be used as nutrients for certain species (DOUSKOVA et al., 2009; TALEC et al., 2013; LARA-GIL et al., 2014), reinforcing not only the importance of the microalgal strain selection step but also the possibility to adopt a sustainable low cost cultivation strategy in the industrial symbiosis model, since nutrients supply may be costly in large-scale cultivation systems (VAN DEN HENDE et al., 2012).

In addition, the cement kiln dust, considered a flue gas component, can be used to regulate the microalgae culture pH and also as nutrients source, solving a problem of disposal for the cement industry (LARA-GIL et a., 2016). However, it contains heavy metals (e.g. Cadmium, Lead, Mercury that can be potentially toxic for microalgae growth (VAN OSS & PADOVANI, 2003). Figure 68 presents a schematic industrial symbiosis of microalgae biomass and cement production, where the cement flue gas and kiln dust (outputs from the cement plant) are used as inputs to the microalgae production facility.

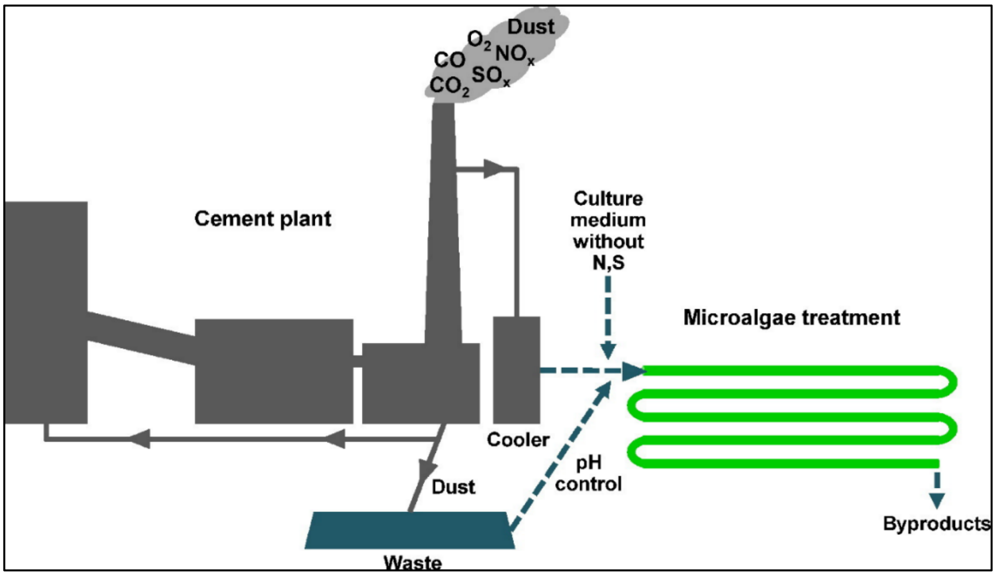


Figure 68. Schematic industrial symbiosis of microalgae production and a cement plant
Source: Lara-gil et al., (2016) (graphical abstract).

5.3.3 Input-output modelling

The IS system is presented as an input-output modelling obeying the logic of value creation from the cement manufacturing waste streams until the biodiesel final product. Three scenarios were assumed considering different annual scales for cement production and CO_2 losses during microalgae cultivation. According to Scheller (2010), small-scale plants produce 750,000 t of cement per year and large-scale plants, 2 million t of cement. The modelling parameters are presented as follows (Table 18).

Table 18. Parameters assumed for input-output modelling

Parameter	**Value**	**Reference***
Annual cement production	750,000 t (scenario 1) 2,000,000 t (scenario 2 and 3)	Scheller (2010)
CO_2 emissions (Brazilian average)	0.585 t CO_2/t cement	Intercement (2010)
Cement kiln dust (CKD) generation	67 g/t cement	Votorantim (2016b)
Raceway dimensions	12 m wide 82 m long 0.30 m deep	Chisti (2007)
Raceway area	978 m²/pond	Calculated
Raceway work volume	293 m³/pond	Calculated
Microalgae volumetric productivity	0.117 kg/m³day	Chisti (2007)
Dilution rate	0.25 per day	Chisti (2007)
Flow rate of harvesting	73.25 m³/day	Calculated
CO_2 fixed by microalgae	1,833 t CO_2/t biomass	Chisti (2007)

* Calculated values are detailed in Appendix A.
Source: The author.

Assuming that microalgal biomass contains 50 wt% of elemental carbon and all this carbon is derived from CO_2, 1.833 t of CO_2 is required to produce 1 t of microalgal biomass (CHISTI, 2007). The amount fixed by microalgae added to the losses to atmosphere due to open cultivation system result in the total amount of CO_2 that must be injected to microalgae cultivation facility.

Large-scale microalgal biomass production often uses continuous culture during daylight. This means carbon dioxide must be fed continually during daylight hours (CHISTI, 2007), and feeding and harvesting processes must stop at night (CHISTI, 2016). Assuming 12:12 h the light and dark periods for microalgae cultivation (RASLAVIČIUS et al., 2018), and CO_2 losses about 80% that is the amount expected to be lost at large-scale cultivation in raceways using flue gas (CHISTI, 2016).

Despite the majority in literature points out huge CO_2 losses during microalgae cultivation in raceways, these losses can be substantially reduced by a controlled feeding using a well-designed supply system as suggested by de Godos et al. (2014). Collet et al. (2015) reviewed 41 studies that carried out a Life Cycle Assessment of microalgae production systems, and identified 44% of the total studies about raceway systems took into account these losses - on average 18% of the injected CO_2.

Therefore, besides considering the different cement production scales, the scenarios adopted also address these opposite situations of CO_2 losses during microalgae cultivation, where scenario 3 represents the case of the largest potential of microalgae cultivation.

- Scenario 1 → 750,000 t cement /year and 80% CO_2 losses;
- Scenario 2 → 2,000,000 t cement/year and 80% CO_2 losses;
- Scenario 3 → 2,000,000 t cement/year and 18% CO_2 losses.

Figure 69 shows the CO_2 mass balance of the industrial symbiosis with a cement plant, including the CO_2 streams emitted to atmosphere, injected and captured by microalgae. The stream indicated by (a) points out CO_2 fixed by microalgae around 10% of the total emitted by the industrial plant, while (b) a CO_2 biofixation about 40% of the total emitted by the cement plant.

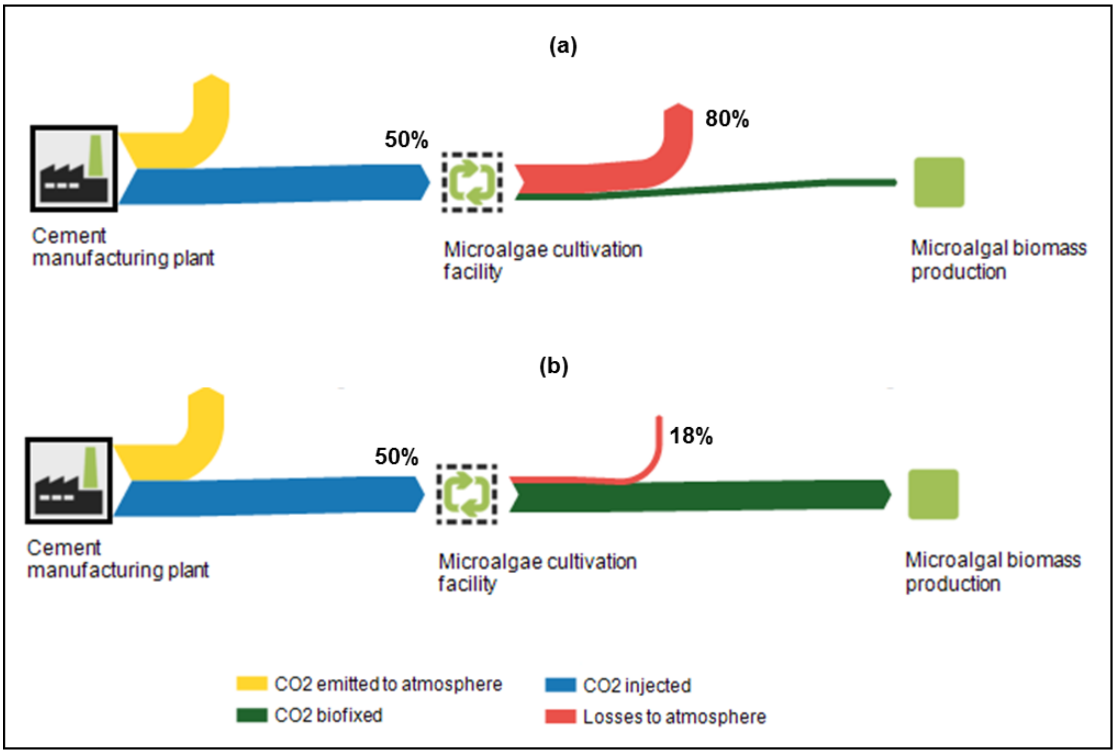


Figure 69. CO_2 mass balance of the industrial symbiosis with cement plant with 80% (a) and 18% (b) of CO2 losses during microalgae cultivation
Source: The author.

Assuming that for each ton of cement produced, 585 kg of CO_2 are emitted, the total emissions for small-scale cement plants (750 kt/yr) are about 438,750 t CO_2 per year. For large-scale plants (2,000 kt/yr), the emissions reach 1,170,000 t CO_2. Taking into account the CO_2 fixed by microalgae and other parameters presented in Table 18, it is possible to estimate the area required for cultivation, the total of microalgal biomass produced, and finally the algal oil and biodiesel volume generated (Table 19).

Table 19. Input-output modelling of each scenario analysed

	Scenario 1	**Scenario 2**	**Scenario 3**
Cement manufacturing plant			
Annual cement production (t)	750,000	2,000,000	2,000,000
Annual CO_2 emissions (t CO_2)	438,750	1,170,000	1,170,000
Annual CKD[1] generated (t)	50.3	134.0	134.0
Microalgae cultivation and biomass production			
CO_2 injected to microalgae cultivation facility (t CO_2/day)	601.0	1,602.7	1,602.7
CO_2 losses during cultivation process (t CO_2/day)	480.8	1,282.2	288.5
CO_2 captured by microalgae kt CO_2/day)	120.2	320.5	1,314.2
Dust requirement (kg CKD/day)	36.0	96.1	393.9
Microalgal biomass production (t biomass/day)[2]	65.6	174.8	716.9
Number of ponds (unit)	2	5	21
Total land area required (m²)	1,868	4,981	20,424
Raceway total volume (m³)	560	1,494	6,127
Algal oil production and biodiesel conversion			
Algal oil production – oil content 21% wt (t oil/day)[3]	14.0	37.3	152.9
Biodiesel production (t biodiesel/day)[4]	13.3	35.5	145.6

[1] Cement Kiln Dust.

[2] 1.833 t CO_2/t biomass.

[3] Considering maximum efficiency rate.

[4] 1.05 t algae oil/t biodiesel.

Calculation details can be found in Appendix A.

Source: The author.

The dimensioning of microalgae cultivation plant and biomass production obeyed the modelling addressed by Chisti (2007; 2016) and the parameters presented in Table 18. By observing the results for the three scenarios analysed, land use only can be considered a constraint on an IS with large-scale cement production plants associated to high efficiencies of CO_2 biofixation, as represented by scenario 3.

It is well known that the oil content in microalgae can exceed 80% by weight of dry biomass, and oil levels of 20-50% are quite common (CHISTI, 2007). Seeking a more realistic approach for raceway cultivation, the percentage considered in the modelling was 21% since it refers to the oil content of the most preferred microalgal strain identified by the strain selection process presented in section 5.2.

Water loss through evaporation can be significant at raceways (CHISTI, 2007), and the assessment of this evaporative water may be quite complicated because it highly depends on environmental conditions. In tropical regions, the average freshwater evaporation rate could be around 10 L/m².day (CHISTI, 2016), which suggests huge amount of daily water loss on each scenario evaluated.

So, even with a well-managed water resource through water recycling after drying process, fresh water is needed to feed the raceway to compensate water evaporation, which clearly may represent a constraint for large-scale microalgae open cultivation when there is no reliable and low-cost water supply.

Regarding the CKD used as source as nutrients for microalgae growth, in scenarios 1 and 2, all the quantity required can be easily supplied by the amount generated in the cement plant. In scenario 3, the amount required surpass the dust availability, which implies in external nutrients feeding.

The microalgal biodiesel can be used as input to cement manufacturing process. Converting the demand[3] of fossil fuel to produce the cement, 105.5 kg of biodiesel are required to produce 1 t of cement. So, the biodiesel produced in each scenario analysed can be fully consumed in the cement manufacturing. It must be emphasised that cement kilns can operate on 100% biomass, which means that microalgal biomass could be directly used. However, there some limitations because organic materials have low calorific values, and cement kilns require fuels with high calorific values (WORRELL & KERMELI, 2013).

5.4 Step 3: Integrated Business Model Canvas and Carbon Footprint

The CBM of the industrial symbiosis of a microalgae biomass production facility with a hypothetical cement plant based on real data can be expressed by the integrated Business Model Canvas and Carbon Footprint. The application of these integrated tools is described by answering the following questions.

- **To whom does the CBM add value?**

The answer of this question refers to the first Canvas's building block *customer segments*. As the CBM proposed is based on the industrial symbiosis of microalgae cultivation for biodiesel production, biodiesel production plants represent the main customer by means a B2B[4] approach.

In Brazil, 51 biodiesel production plants are authorized to produce (Figure 70). In 2017, 37 of them were responsible for more than 4,29 million m³ of biodiesel, which

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[3] 3.8 GJ/t cement (Worrell and Kermeli 2013) and 1 GJ = 27.76 t biodiesel.

[4] Business to business.

represents about 56.2% of the total capacity (Table 20). This means that there is sufficient installed capacity to attend further demand required by the increase of the biodiesel mixture in the fossil diesel. As off 2017, the compulsory addition was 7% and in March 2018 it increased to 10%.

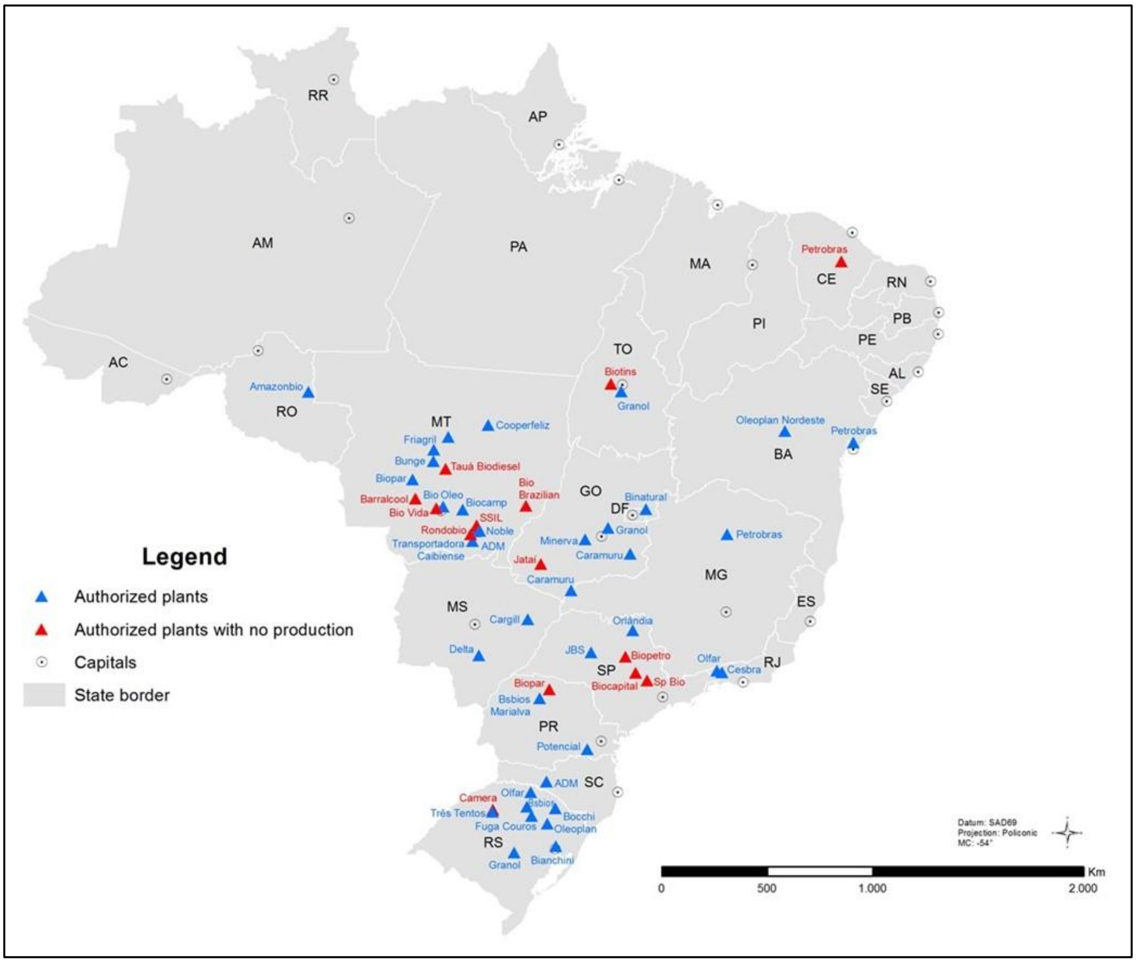

Figure 70. Infrastructure for biodiesel production (2017)
Source: ANP (2018).

Table 20. Brazilian biodiesel capacity *versus* production - 1,000 m³ (2017)

Brazilian Region	**Capacity**	**Production**	**Utilisation**
North	241.6	7.8	3%
Northeast	455.4	290.9	64%
Central-west	3,026.3	1,896.3	63%
Southeast	994	334.1	34%
South	2,918.3	1,762.2	60%
Total Brazil	**7,635.6**	**4,291.3**	**56%**

Source: ANP (2018).

Soybean oil is the main feedstock for biodiesel production in Brazil, followed by animal fats (Figure 71). As discussed in section 2.1, microalgae are by far more productive than terrestrial crops such soybean. So, in order to estimate the potential demand of microalgal biodiesel, the volume of biodiesel made from soybean oil could be replaced for microalgal oil as substitute product, which represents 3,072,446 m³ per year (reference 2017).

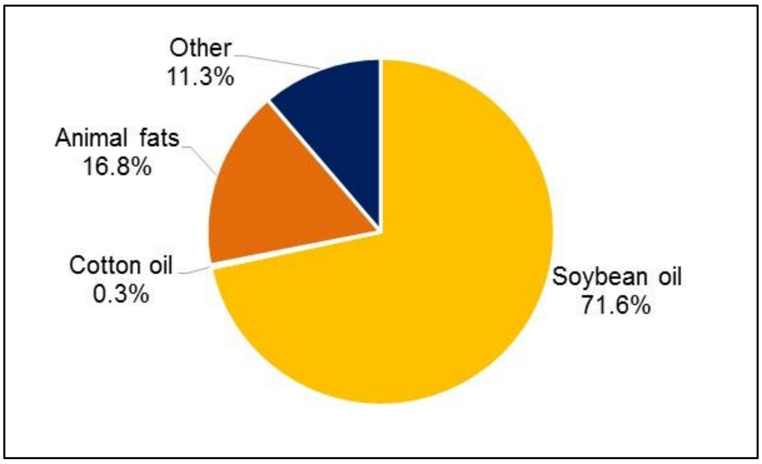

Figure 71. Feedstocks for biodiesel production in Brazil (2017)
Source: The author based on ANP (2018).

Although the CBM proposed focus on biodiesel, it must be remarked that there are various market segments for microalgal biomass since it could be used for chemicals, animal feed, among others applications. This was briefly discussed in section 2.1.

- **What problem does the CBM intend to solve?**

The answer of this question refers to the *value proposition*, which may refer to price, speed of service, design, among others identified as added value by customers. As the microalgae biomass production under industrial symbiosis concept can be considered a circular economy strategy, the value proposition refers to the main purpose of this strategy, which is to create value from waste by turning existing waste streams into useful and valuable products or inputs for other production system.

So, the proposition is to create value by recycling of cement flue-gas and cement kiln dust into microalgal biomass to be used as feedstock for biodiesel production. Besides the positive contribution to society and environment, in a CE value is created along the value chain, in which customers become suppliers and *vice-versa*. So, the value capture can be expressed by the tangible benefits for both parts of this tripartite CBM (Figure 72).

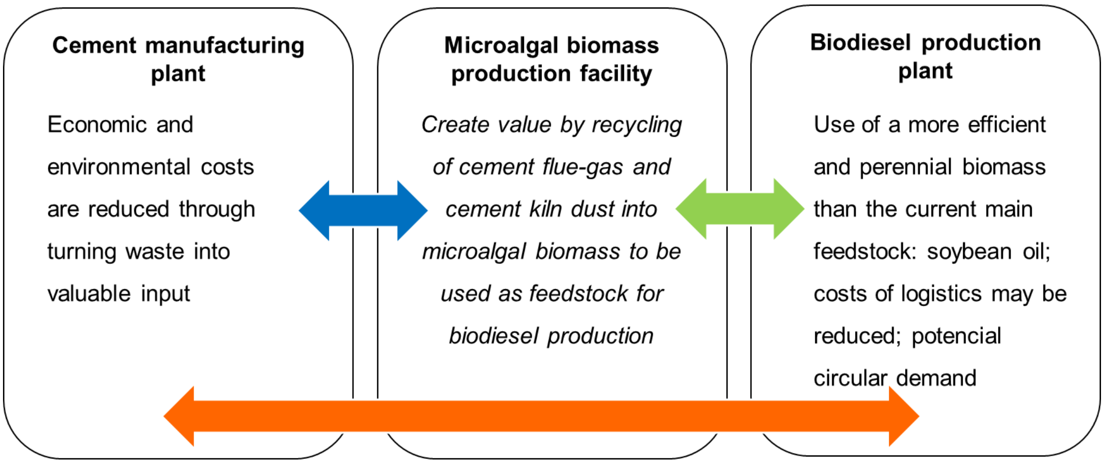

Figure 72. Value proposition and value capture of the tripartite model
Source: The author.

A special attention should be given to the fact that changes in the value proposition might occur due to economic and market interests that may divert the microalgal biomass to other purposes (more profitable) than biodiesel, thereby compromising the circularity of the model. This must be discouraged by a strong and strategic relationship between the companies of the tripartite model.

- **What does the IS make money from?**

From the revenue streams. The mainly revenue stream comes from the sale of the microalgae oil to the biodiesel mill. There is also an option of selling the cake obtained after oil extraction process to farmers for animal feed.

The microalgae oil price is defined according to the competition-based price, that is a pricing method in which prices of competitor products are used as benchmark instead of the own costs. Therefore, the revenues from the sale of oil are calculated based on the soybean oil average price in domestic market for 1 ton of oil: 2,698.66 BRL - 12% ICMS tax-included (ABIOVE, 2018).

Regarding the microalgae cake, the price is highly dependent on the price of the meal on the animal feed market (Flesch et al. 2013). In Brazil, soybean meal is the most important ingredients used in animal feed (ABIOVE, 2018). So, the average price of 1 ton of soybean meal in the domestic market will be used as benchmark to the microalgal cake: 954.64 BRL - 12% ICMS tax-included 8.4% (ABIOVE, 2018).

Table 21 summarizes these potential revenue streams for each scenario.

Table 21. Annual revenue streams (thousand BRL)

Product	Scenario 1	Scenario 2	Scenario 3
Oil[1]	13,770.8	36,722.2	150,560.9
Cake[2]	17,975.3	47,934.2	196,530.1
Total	**31,746.1**	**84,656.4**	**347,091.1**

[1] 21% oil content, 100% efficiency, 2017 average price of soybean oil in Brazilian domestic market 2,698.66 BRL per ton - 12% ICMS tax-included.

[2] 2017 average price of soybean meal in Brazilian domestic market 954.64 BRL per ton – 8.4% ICMS tax-included.

Source: The author.

It is important to note that not all of the oil extraction processes are compatible with the animal feed use of the co-product algal cake. If the oil is extracted from the microalgae biomass using chemical solvents (e.g. hexane), it may remain in the cake after the process rendering the product toxic to animals. Furthermore, flocculants can be hard costly to remove from the remaining biomass. Hence, the sale of algae cake for animal feed seems only feasible when using mechanical downstream processes. One option could be processing this co-product to produce electricity through anaerobic digestion (FLESCH et al., 2013).

- **How does the IS signal changes customer needs and how does it reach the customers?**

Based on the principle that a partnership has to be developed in the CBM, these questions can be answered.

Different to the usual relationship of customers acquisition or retention by offering services added to the products sold (ex. extended warranty), the relationship established in this CBM is more related to the strategic partnership built among the cement plant, the microalgae production facility and the biodiesel mill. All of them are connected physically by geographical proximity and strategically by shared values.

In practice, this means more than long-term contracts established. It must be a strong relationship in which all the players must work together, sharing knowledge and creating a sustainable development in the companies by means of responsible use of resources, compromise to the R&D, and encouragement of organisational competences that take into account not only economic benefits but also the environment and social ones, according to the Kalundborg Symbiosis acts.

- **What is the core business?**

Answering this question implies identification of the IS key activities, i.e. the most important things that have to be done to make the CBM works. These actions represent the core business required to create and offer the value proposition. In this respect, the key activities are those required to achieve the IS value proposition that is to create value from waste, and maintain the circularity of the business model.

They comprise the activities associated with the availability of inputs and with the delivery the product to the costumer, hence associated with operations management and logistic which involve the following:

i. Feeding administration for microalgae growth;
ii. Harvest of the microalgal biomass;
iii. Extraction of lipids;
iv. Processing algae oil to become biodiesel;
v. Distribution of biodiesel as feedback to the system.

The fifth activity, although being responsibility of the customer (biodiesel production plant), is crucial because it is the one that ensures the circularity of the model. The others activities are the core business of the IS and must be combined in order to ensure an efficient CO_2 and cement kiln dust recycling into valuable output - the microalgal biodiesel.

Furthermore, R&D is a key activity not only for seeking the continuous improvement of the system but also for enhancing the mutual benefits of this model through new symbiosis possibilities.

- **What are the key resources?**

The resources can be classified into transformed resources and transforming resources. Similar to the key activities' principle, the key resources are those most important assets required to make the CBM works besides the primary resource that is the flue gas.

Physical resources correspond the majority of the key resources, i.e. the transforming resources that allow to offer the value proposition. They comprise not only the microalgal cultivation assets and biomass processing infrastructure (e.g. raceways, machines) but also the logistics infrastructure, which starts with the feed of CO_2 and nutrients from the cement plant to the microalgae production facility, and finishes with the biodiesel distribution to the cement plant (e.g. pipelines). This type of business also requires intellectual resources that may be operationalised by R&D projects, in order to continuously improving the system efficiency.

- **What partners does the IS need?**

The major challenge of an industry that generates large quantities of flue gas in adopting biofixation process by microalgae is that producing microalgal biomass is far from its core business, i.e. the industry has no competencies to this type of business, and thus must develop new skills. This could be a hard process because it involves changes in the culture, performance, etc.

In this regard, this circular business may be formed through a joint venture agreement where the CBM parties agree to work together for mutual benefit with the specific ownership. This type of business arrangement has been successfully adopted by several companies due to minimise risks, access to resources and develop new capabilities (DELOITTE, 2016), also having great advantages for small- and medium-sized enterprises (SMEs) (LU and BEAMICH, 2006).

One of the companies that became a reference in the microalgae sector is TerraVia, which resulted from a joint venture among Solazyme and the agribusiness company Bunge. In 2012, these two companies built a share commercial-scale production facility in Brazil to produce algae oil-sugarcane based, in order to reach three target markets: fuels and chemicals, nutrition and personal care. More information could be found in the TerraVia website (http://terravia.com/).

Therefore, the cement factory should create this type of partnership with companies whose competencies benefits the value creation from the cement waste streams through microalgae cultivation. Producers of inoculum or biotechnology companies are potential candidates for this integration.

- **What are the biggest costs?**

Microalgae oil can be only considered an alternative feedstock for biodiesel production when its production total cost (including costs of cultivation, harvesting, drying and lipid extraction) is equal or lower than the traditional feedstock vegetable oils and animal fats (CHEN et al., 2018).

Target costing is used for carrying out the costs' estimation. This strategy seeks to determine the maximum allowable cost for oil algae production, taking into account its selling price and then deducting the desired profit. As discussed before, soybean oil price is used as benchmark for pricing the algae oil, since it is a substitute product.

Assuming 15% of contribution margin and the algae oil target price based on soybean oil average price in the domestic market, the target cost is calculated as follows (Table 22).

Table 22. Target cost calculation for 1 ton of algae oil

Parameter	**Value (BRL per ton of algae oil)**	**Reference**
Target price (no tax included)	2,374.82	Adapted[1] from ABIOVE, 2018
B. Desired profit (15%)	256.22	Assumed
Target cost (A-B)	2,018.60	Calculated

[1] 12% ICMS tax-included, São Paulo city, 2017 average soybean oil price = R$ 2,698.66/t.
Source: The author.

Therefore, the 2,018.60 BRL of target cost for producing 1 ton of microalgae oil represents the maximum allowable total cost of production, which includes costs of all processing steps from microalgae cultivation up to the algae oil extraction. From this value, it is possible to estimate the costs of each process by adopting allocation parameters.

For a long time, the results of a paper[5] published in 1996 have been used as baseline data for microalgal biofuels cost predictions turning it the most cited source of cost

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[5] Benemann, J.R., Oswald, W.J., 1996. Systems and economic analysis of microalgae ponds for conversion of CO2 to biomass. DOE/PC/93204 – T5.

modelling (SLADE & BAUEN, 2013). The cost modelling parameters of this study were updated by Nagarajan et al. (2013) in order to evaluate the feasibility and profitability of algae biodiesel using more accurate costs and realistic efficiencies for microalgae cultivation in raceways, and process involving centrifuge for simultaneous biomass harvesting and oil extraction.

The allocation parameters were defined based on this updated study. Two types of costs can be addressed: capital costs and operating costs. The former refers to the one-time expenditure of the microalgae production plant, while operating costs are those monthly running costs related to the operation of a business.

Table 23 summarizes the allocation parameters for operational costs.

Table 23. Allocation parameters (%) of operational costs

Process/ Item	**Operating costs (%)**
Cultivation	46.6
Downstream processes	13.3
Labour	17.9
Maintenance	22.6
Capital charge[1]	0.0
Total	**100.0**

[1] 15% of total cap. Invest, not applied for the case study analysed.
Source: The author based on Nagarajan et al. (2013).

Most of the operational costs refers to energy consumption (power for paddle wheels, centrifugation, water and flue gas supply). Nutrients represent the majority of cultivation operational costs, which can be easily reduced by using the cement kiln dust of source of nutrients. Maintenance and labour are also relevant issues in the operational costs.

Despite Nagarajan and co-authors considered 15% capital charge ratio of total capital investment, it was assumed 0.0% because it is supposed that all the investment can be covered by the savings generated from the CO_2 avoided through microalgae cultivation in a carbon pricing context.

So, for each scenario analysed in section 5.3, the biggest operating costs are:

Table 24. Annual operating costs of each scenario (thousand BRL)

Process/ Item	**Annual operating costs (thousand BRL)**[1]		
	Scenario 1	**Scenario 2**	**Scenario 3**
Cultivation	4,795.5	12,788.0	52,430.7
Downstream processes	1,337.0	3,565.3	14,617.9
Labour	1,838.8	4,903.5	20,104.3
Maintenance	2,329.3	6,211.4	25,466.7
Total operation costs	**10,300.6**	**27,468.2**	**112,619.7**

[1] Target cost per ton of algae oil: 2,018.60 BRL; annual algae oil production: sc.1 = 3,609.22 t, sc.2 = 9,625.59 t, sc.3 = 39,460.84 t.
Source: The author.

For estimating the capital costs, it was assumed the values resulted from the updated study carried out by Nagarajan and co-authors with some adjustments (eg. excluding costs related to anaerobic digestion lagoon, transesterification process to produce biodiesel, among others).

Table 25 summarizes the parameters used for total capital investment estimation.

Table 25. Values used as parameters for capital cost estimation

Process/ Item	**Monetary value (USD/ha)**	**%**
Cultivation	50,257.5	53.8
Downstream processes	22,747.7	24.4
Infrastructure	6,024.4	6.4
Land cost[1]	14,375.0	15.4
Total	**93,404.2**	**100.0**

[1] Cost of land in Brazil per ha: 57,500 BRL Ramos & Navarro (2018).
Source: Adapted from Nagarajan et al. (2013).

Amongst the capital costs, those regarding cultivation include costs of site preparation, soil compaction, pond levees and geotextiles, paddle wheels, flue gas supply and CO_2 diffusers, water and nutrient supply. Infrastructure concerns buildings, roads and drainage. Downstream processes include the investment with harvesting, drying and oil extraction processes (eg. decanter centrifuge, instrumentation and machinery).

The cost of land can represent a crucial issue, which may compromise the project of the investment. As it varies from place to place, the highest cost was considered in this analysis in a conservatory way. According to 2017 data from FNP Informa Economics, Pará State has the cheapest cost of land per hectare (10,000 BRL), while in São Paulo State the cost was around 40,000 BRL, and in Paraná state, the more expensive one, 57,5000 BRL (RAMOS & NAVARRO, 2018).

Nagarajan and co-authors also consider in the capital costs an engineering and contingency ratio of 10% on direct capital costs, and the working capital of 25%, calculated in relation to net operational costs. Therefore, based on these ratios and the values of

Table 25, the total costs of investment for each scenario are presented in Table 26:

Table 26. Total capital investment of each scenario

Process/ Item	Total capital investment (thousand BRL)[1]		
	Scenario 1 (0.19 ha)	**Scenario 2 (0.50 ha)**	**Scenario 3 (2.04 ha)**
Cultivation	37.6	100.1	410.6
Downstream processes	17.0	45.3	185.8
Infrastructure	4.5	12.0	49.2
Total direct capital costs	**59.1**	**157.5**	**645.6**
Eng. & contingency (10%)	5.9	15.8	64.6
Land costs	10.7	28.6	117.4
Working capital (25%)	2,575.1	6,867.1	28,154.9
Total capital investment (A)	**2,650.8**	**7,068.9**	**28,982.6**
Annual savings from CO_2eq on carbon pricing[2] (B)	**1,755.0**	**4,680.0**	**19,188.0**
Difference (B-A)	**(895.8)**	**(2,388.9)**	**(9,794.6)**

[1] Exchange ratio assumed: 0.25 USD/BRL.
[2] Considering US$ 10/t CO_2eq.
Source: The author.

It must be remarked that carbon pricing is considered in this study as driver for microalgae cultivation under an industrial symbiosis approach. As presented in section 3.1, carbon price varies widely and could reach levels upper than US$ 100/tCO_2e. It was assumed a carbon price cap of US$ 10/tCO_2e to estimate the savings resulted from the CO_2 biofixation. Brazilian industry has proposed this value as price ceiling for the first phase of the gradual implementation of a carbon market in the country (CEBDS, 2018).

The savings calculation must consider all the emissions which contribute to the climate change (methane - CH_4, nitrous oxide - N_2O, and carbon dioxide - CO_2) by the use of GWP factors. However, although cement flue gas comprises several compounds (e.g. NOx, SO_2, particulate matter, mercury, VOCs[6], dioxins and furans, heavy metals), none are GHG emissions except the CO_2 whose GWP is equals 1. So, the estimation was calculated based on the amount of CO_2 fixed by microalgae cultivation taking into account its price cap.

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[6] Volatic Organic Compounds.

The results presented in Table 26 shows little difference between the capital investment required and the annual savings of carbon pricing, which represent a payback time of 1.5 year, which can be considered as a rapid payback (EiiF, 2012), confirming the feasibility of investing on a microalgae cultivation for biodiesel production in an industrial symbiosis with a cement plant. Furthermore, a sensitive analysis showed a carbon price around US$ 15/t CO_2eq as break-even point for the scenarios evaluated.

- **How much CO_2e is emitted and avoided?**

The carbon footprint assessment taking into account the GHG emissions of each scenario modelled in section 5.3.3. The assessment bases on the ISO 14040 and 14041 of Life Cycle Assessment.

The function unit adopted is “one-year production of microalgae-based biodiesel under industrial symbiosis with a cement manufactory”. Figure 73 shows the product system where the processes covered by the assessment are depicted.

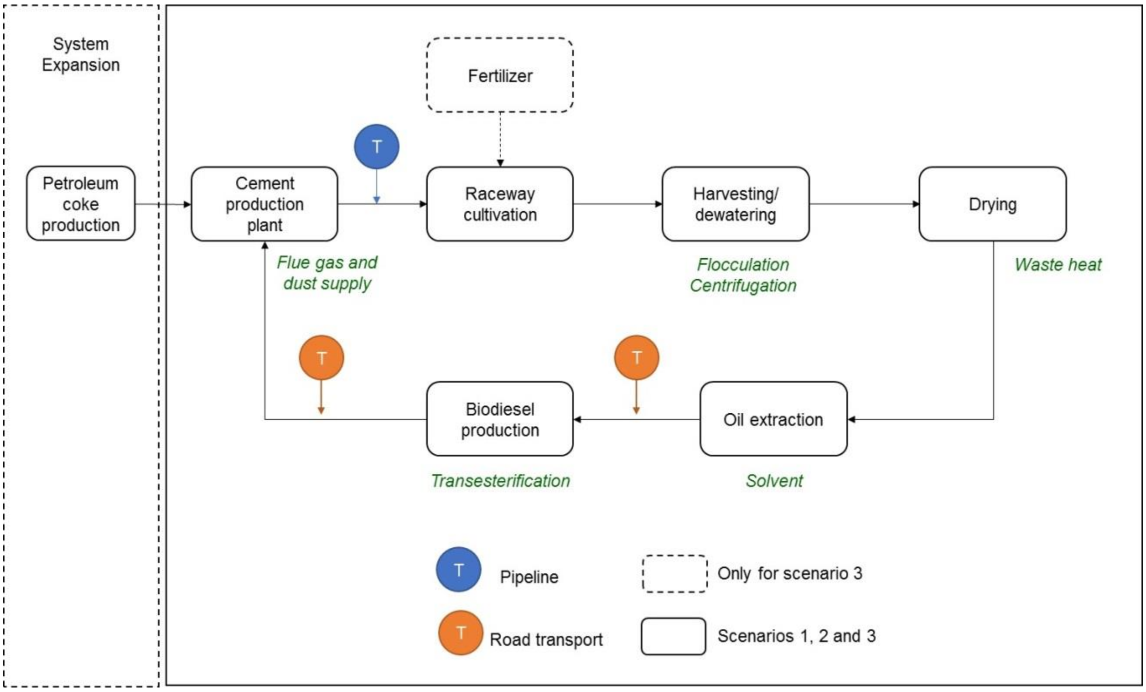

Figure 73. Product system for carbon footprint assessment
Source: The author.

A review of LCA studies in microalgae field carried out by Collet et al. (2015) indicated that the infrastructure for microalgae cultivation does not contribute significantly to the environmental impacts when compared to other processes of microalgal biomass production (e.g. dewatering and drying). However, the energy required for mixing the medium as well as the energy for flue gas injection, and the polyvinylchloride (PVC) lining may be relevant elements of cultivation process (ZAIMES & KHANNA, 2013), hence they were considered in this assessment.

Regarding to CO_2 and nutrients supply, pre-treatment of the cement flue gas for removal and deliver pure CO_2 to the medium was not considered in this assessment since microalgae can tolerate cement flue gas directly with no need of treatment or removal of particulates (LARA-GIL et al., 2014; LARA-GIL et al., 2016; TALEC et al. 2013; OLOFSSON et al. 2015). The use of fertilizer (urea, superphosphate and potassium chloride) as source of nutrients for microalgae growth was only considered in scenario 3, where the cement dust available in the cement plant cannot supply all the cultivation medium.

The harvesting process considers two phases according the pathway adopted by Zaimes & Khanna (2013). Aluminum sulfate usage refers to the flocculation of microalgae post-cultivated, from which the biomass is agglomerated to facilitate the dewatering process in a centrifuge. The microalgae harvested is then dried using the waste heat from the co-located cement plant, hence excluding the necessity to take into account the use of energy for drying.

The relevant flow adopted for oil extraction from the dried microalgal biomass was based on Lardon et al. (2009), who considered a counter-current circulation of a solvent (hexane) by taking into account the losses during the process. Finally, the microalgae-based biodiesel is produced through the transesterification using methanol as solvent. Table 27 summarizes the parameters used for the inventory analysis.

Table 27. Parameters used for inventory analysis

Parameters	**Inventories**	**Reference**
Energy for mixing (paddlewheels)	18.0 kWh/ha.day	Zaimes & Khanna (2013)
PVC membrane liner for cultivation area	8.55 t/ha	
Energy for flue gas injection	22.2 kWh/ t CO_2	Kadam (2002)
Aluminum sulfate	100 g/m³	Zaimes & Khanna (2013)
Energy for dewatering (centrifugation)	8 kWh/m³	Clarens et al. (2011)
Urea (N fertilizer)	0.023 kg/kg microalgae	Lardon et al. (2009)
Superphosphate (P fertilizer)	0.009 kg/kg microalgae	
Potassium Chloride (K fertilizer)	0.004 kg/kg microalgae	
Hexane loss	2 g/kg microalgae	
Methanol	114 g/kg biodiesel	

Life cycle data for all these parameters were taken from the Ecoinvent database 3.4. Table 28 presents the correlated processes and their contribution to climate change by means the indicator GWP 100a measured in CO_2 equivalents according to characterization factors of IPCC[7] (2007).

Table 28. GWP 100a of Ecoinvent activities (kg CO_2e)

Activity name	**Scope**	**Unit**	**GWP (kg CO_2e)**
Transport, freight, lorry>32t	RoW	t.km	0.0926
Pipeline construction, natural gas, low pressure	RoW	km.yr	1,983.35
Electricity, production mix	BR	kWh	0.21307
Polyvinylchloride production, suspension polymerisation	RoW	kg	1.9093
Aluminium sulfate production, powder	RoW	kg	0.74486
Urea production, as N	RoW	kg	3.3349
Single superphosphate production	RoW	kg	2.4545
Potassium chloride production	RoW	kg	0.51381
2,5-dimethylhexane-2,5-dihydroperoxide production	GLO	kg	4.8507
Methanol production	GLO	kg	0.61846

RoW – Rest of World, BR – Brazil, GLO – Global.
Source: Ecoinvent (2017).

It must be notice that there is no specific data for pipelines for flue gas or CO_2 supply in Ecoinvent database. The pipeline of natural gas at low pressure was chosen since it is a potentially feasible option for establishing a pipeline network for transporting CO_2 (EUROPEAN UNION, 2011). In addition, the emissions from the transport freight of Ecoinvent do not take into account the mix of biodiesel in the fossil diesel as in Brazil.

Each scenario has a different reference flow to fulfil the function unit, from which the inputs of life cycle inventory can be estimated (Table 29) based on the parameters of Table 28.

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[7] The ILCD 1.0.8 2016 midpoint method was used. More information in https://www.openlca.org/wp-content/uploads/2015/11/ILCD_2011_v1_0_10_method_update_in_openLCA_LCIA_methods_pack_1_5_6_v1.1.pdf.

Table 29. Inventory (inputs) based on the function unit adopted.

Flow	Scenario 1	Scenario 2	Scenario 3
Reference flow to fulfil the function unit			
Produced biodiesel (t)	4,859.84	12,959.58	53,134.28
Inventory (inputs)			
Flue gas injected[1] (t)	1,462,500	3,900,000	3,900,000
Energy for flue gas supply (MWh)	32,467.50	86,580.00	86,580.00
Energy for mixing (MWh)	1.23	3.27	13.42
Raceway area (ha)	0.19	0.50	2.04
PVC liner (t)	1.60	4.26	17.46
Urea - N fertilizer (t)	N.A.	N.A.	408.92
Superphosphate - P fertilizer (t)	N.A.	N.A.	160.01
Potassium chloride - K fertilizer	N.A.	N.A.	71.12
Hexane (kg)	10.21	27.22	111.58
Energy for centrifugation (MWh)	409.10	1,090.93	4,472.81
Methanol (kg)	554.02	1,477.39	6,057.31

1 Assuming 15% of CO_2 content in a cement flue gas (Olofsson et al. 2015); N.A. = not applied.

As distance could be a critical aspect in a IS model, each opportunity of co-location identified in section 5.2.2 should be considered in the assessment. Table 30 summarizes the distances of each co-location and the mode of transport adopted.

Table 30. Distances assumed in the modelling

Patch	Mode	Co-location distances (km)		
		A	B	C
From cement mill to microalgae production facility[1]	Pipeline	4.0	1.9	4.8
From microalgae production facility to biodiesel mill	Road	7.9	2.0	12.6
From biodiesel mill to cement plant		8.2	2.3	15.8

Distances based on Google Maps; co-locations: A – RJ, B – MG, C – RS.
[1] Correction factor 1.3452.

The distance between the cement plant and the microalgae production facility, whose flue gas will be transported by pipeline, is assumed about 35% upper than the straight-line distance since pipelines do not always follow straight lines by the application of an accurate correction factor for the Brazilian context (GONÇALVES et al., 2014). As both algae oil and biodiesel will be transported by road, the distances considered are the values suggested by Google Maps with car option. However, that possible mobility limitations regarding road transport in these localities were not taken into account.

By aggregating all these values with the GWP indicators of Table 31, the total GHG emissions of each scenario are as follows:

Table 31. Carbon footprint of one-year of microalgae-based biodiesel produced in an IS with a cement plant (kg CO_2e)

Process	**Scenario 1**	**Scenario 2**	**Scenario 3**
Cultivation			
Flue gas supply	6,917,850	18,447,601	18,447,601
Mixing (padwheels)	261	697	2,859
PVC	3,049	8,132	33,341
NPK fertilizer	-	-	1,793,015
Downstream processes			
Aluminum	7	19	78
Centrifugation	87,167	232,444	953,021
Hexane	50	132	541
Transesterification			
Methanol	343	914	3,746
Total GHG emissions	**7,008,727**	**18,689,939**	**21,234,202**

Source: The author.

Table 32. Carbon footprint by co-location opportunity (kg CO_2e)

Process	**Scenario 1**	**Scenario 2**	**Scenario 3**
Pipeline construction			
A	7,933		
B	3,768		
C	9,520		
Transport of algae oil			
A	3,733	9,955	40,817
B	945	2,520	10,333
C	5,954	15,878	65,100
Transport f biodiesel			
A	3,690	9,841	40,349
B	1,035	2,760	11,318
C	7,111	18,963	77,746
Total GHG emissions			
A	**15,357**	**27,730**	**89,100**
B	**5,749**	**9,049**	**25,419**
C	**22,585**	**44,361**	**152,367**

Co-location A – RJ, Co-location B – MG, Co-location C – RS.
Source: The author.

By observing the GHG emissions of the co-location opportunities identified in Rio de Janeiro, Minas Gerais and Rio Grande do Sul state, the worst option is C (RS state) which has the highest distances between the cement plant, microalgae production facility and the biodiesel mill. In a conservatory way, this option is thus considered to estimate the total carbon footprint of each scenario evaluated taking into account CO_2e emissions and savings/avoided (Table 33).

Table 33. Net GHG emissions of one-year microalgae-based biodiesel production in an IS with a cement plant (t CO_2e)

Process	**Scenario 1**	**Scenario 2**	**Scenario 3**
Production	7,009	18,690	21,234
Logistics	23	44	152
Total GHG emissions	**7,031**	**18,734**	**21,387**
CO_2 captured during cultivation	(43,875)	(117,000)	(479,700)
CO_2 losses during cultivation	175,500	468,000	105,300
CO2e avoided by product substitution	(375)	(1,000)	(4,098)
Net GHG emissions	**138,281**	**368,735**	**(357,112)**

Values in parentheses are negative values (avoided emissions).
Source: The author.

As suggested by the CBM proposed, the biodiesel from microalgae must be used in the cement plant as product substitute of fossil fuel. Petrol coke is the most fuel used for cement production, hence it was chosen to be substituted proportionally to volume of biodiesel.

Considering the lower caloric power values of biodiesel and petrol coke, 9.00 kcal/kg and 8.39 kcal/kg respectively (ANP, 2015), it is possible to estimate the quantity of petrol coke potentially substituted by biodiesel in each scenario evaluated. Thus, the GHG avoided emissions was calculated taking into account the GWP 100a indicator of Ecoinvent database for 1 kg of petroleum coke produced in a typical oil refinery RoW (0.0719 kg CO_2e).

All these emissions are presented graphically in Figure 74, from which it is possible to observe that the overall performance of the CBM proposed in terms of potential impacts to climate change is strongly affected by the performance of microalgae cultivation, i.e. the efficiency in CO_2 captured and lost to the atmosphere during the cultivation in an open system of raceway.

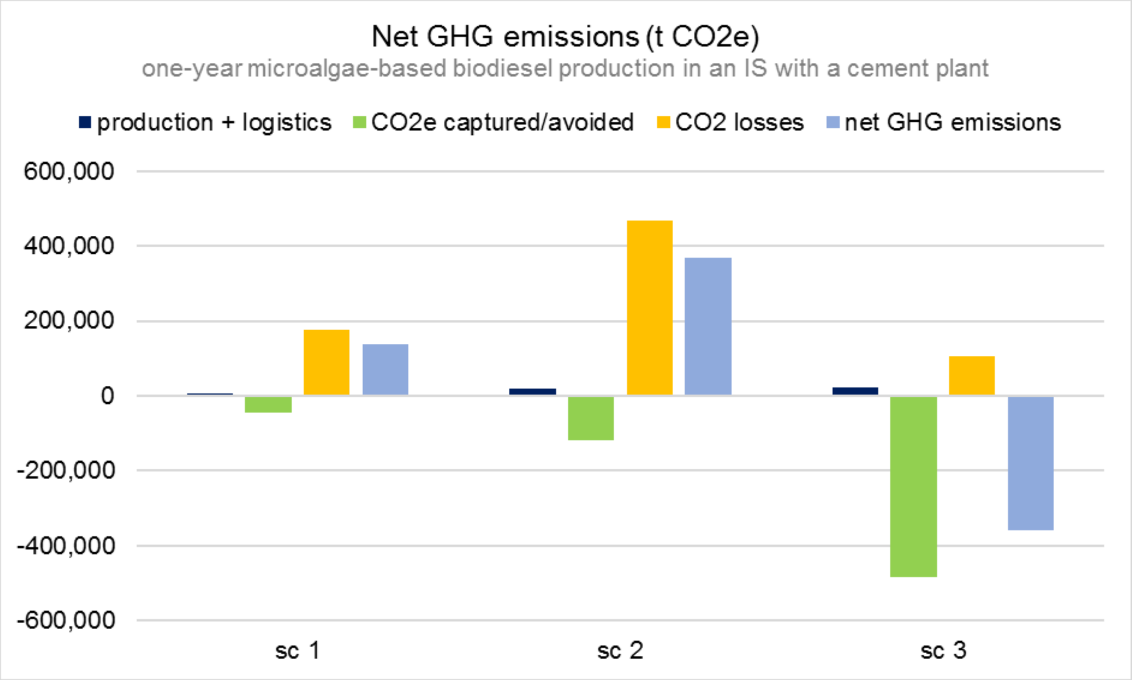

Figure 74. Carbon footprint of one-year microalgae-based biodiesel in an IS with a cement plant
Source: The author.

The following figure summarizes the main aspects of each building block of the integrated CBM of the microalgae-based biodiesel production from an industrial symbiosis model of a cement plant and a microalgae production facility.

These eleven elements provide an overall picture of the business, where it is possible to put on evidence the main constraints and potentialities of microalgae biomass production for biodiesel.

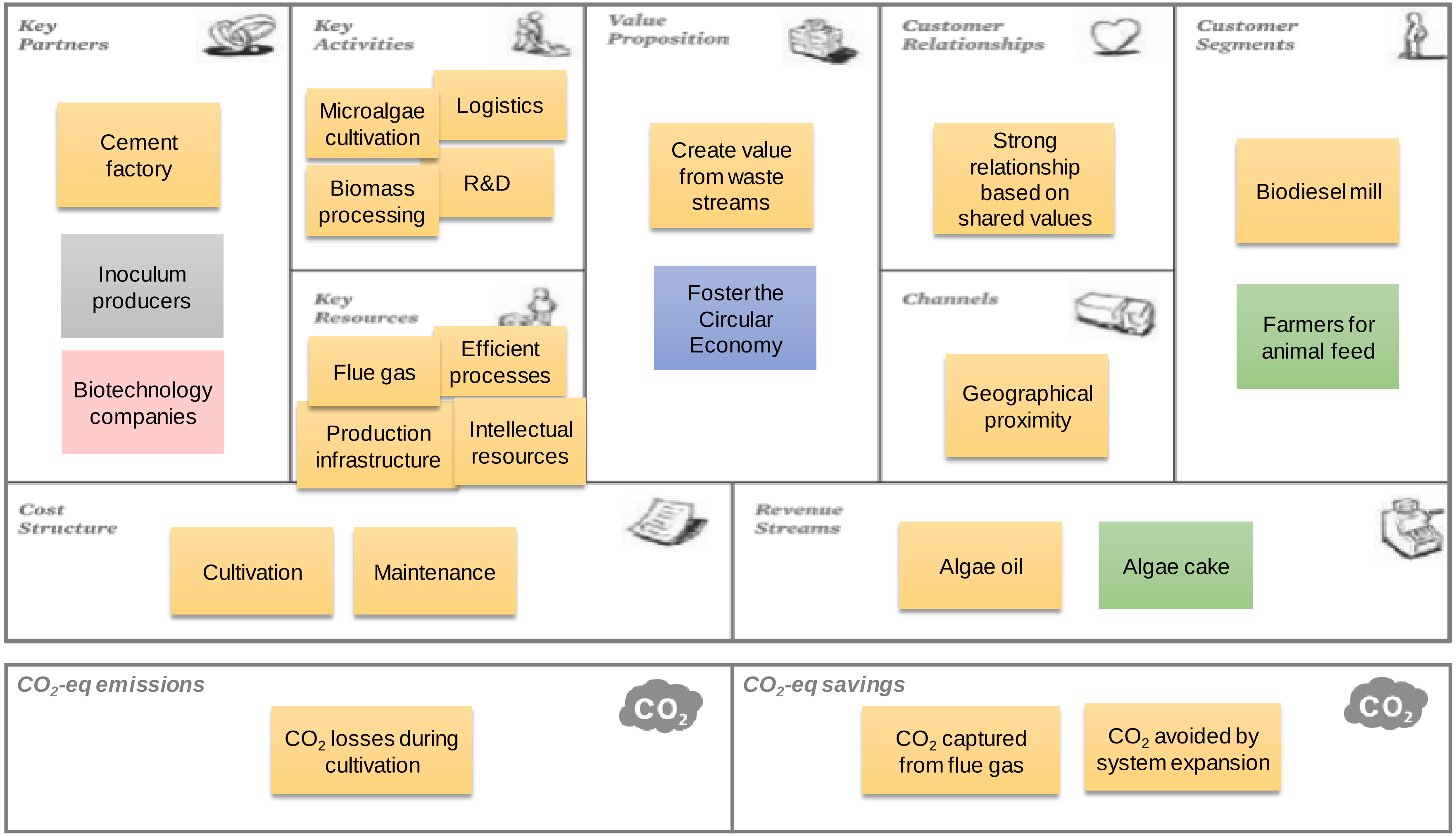

Figure 75. Integrated model of hypothetical case of industrial symbiosis with a cement plant
Source: The author.

6 Conclusion and future recommendations

On the belief that the key to climate change is the Circular Economy, and microalgae represent a sea of opportunities on this new paradigm, the central problem addressed in this thesis is how to turn microalgal biomass production a business driver to advance the Circular Economy. A CBM was proposed, based on microalgae large-scale cultivation in raceways for biodiesel production under an industrial symbiosis system.

Different from previous studies that focused on assessing the technical feasibility of microalgae cultivation in industrial symbiosis, the aim of this research is to contribute towards microalgae business opportunities. The main conclusion that can be drawn is that microalgal biomass production at large-scale raceways for low-added value products such as biofuels is encouraged by the circular value creation promoted by the CBM.

This circular value creation bases on closed loops, in which waste streams are transformed into valuable products like microalgae-based biodiesel, financially encouraged by savings from CO_2 of industrial flue gases captured during microalgae cultivation in a carbon pricing context.

Microalgae cultivation fed with flue gas from industrial plant (e.g. coal-based power plants) as a mean to recycle CO_2 has been extensively investigated. This integrated production pipeline makes microalgae cultivation a promising step towards Circular Economy since it leads to one of the most important strategies of Circular Economy: the industrial symbiosis.

Owing to the various factors affecting microalgae growth performance, scientific literature has focused on examine technical aspects regarding microalgae cultivation with flue gas feeding. On one hand, this represent an important step towards technical feasibility of microalgal biomass production at large-scale. On the other hand, challenges of commercial microalgae-based biodiesel still remain.

A typical industrial symbiosis model was built considering the integration of a microalgae cultivation facility with an industrial plant. The circularity was addressed by joining a biodiesel production plant into the model, that will supply the microalgae-based biodiesel to the industrial plant, from which it is possible to see the circular transformation process and value creation. A theoretical background was built to support the development of this model, which considered critical aspects for microalgae cultivation, mainly in raceway, such as strain selection and site selection. A guidance taking into account these constraints was proposed.

The elements ensuring microalgae as business opportunity were addressed through the nine building blocks of the well-established business model named Business Model Canvas. As a circular model, the circular transformation process, resulted from the value creation from the flue gas (waste streams) up to the microalgae-based biodiesel, could be translated into these nine elements, providing a clear approach of how to make microalgae a real strategy fostering the Circular Economy.

As the minimum requirement of any circular economy strategy is to result into environmental benefits, a Carbon Footprint analysis is proposed to be adopted in an integrated way with the Business Model Canvas. By this integration, both GHG emissions and savings could be taken into account.

This model was applied in a hypothetical case of the Brazilian cement industry considering real data from the sector. Despite the limitations of the application of the CBM in the cement industry, the results are valuable in light of providing a guidance to the private sector on decision-making about microalgal biomass production at large-scale, which includes to identify the main constraints of microalgae-based biodiesel under an industrial symbiosis system, and a critical analysis of the feasibility of cultivating microalgae in raceways.

Regarding strain selection, fifteen microalgae strains were evaluated through an outranking multi-criteria decision method, ELECTRE III that provided a ranking indicating the most preferable ones for raceway cultivation under some criteria such as growth performance, lipid content, quality of biodiesel, ease of harvesting and resistance to contamination.

All these criteria were weighted by importance coefficients resulted from seven experts' consultation from relevant international and national institutions. They considered lipid content and quality of biodiesel the most important criteria, followed by microalgae growth performance and resistance to contamination. Ease of harvesting received the lowest importance due to the diverse of techniques available to enhance good efficiencies.

ELECTRE III results pointed out *Desmodesmus perforatus*, isolated from a tropical area in northeast region of Brazil, in the first position, followed by three strains of *Chlorella* sp. isolated from Paraná State, in the southern region of Brazil. These results put on evidence the strong adaptability and good performance of Brazilian strains in open cultivation systems such as raceway.

One critical point of microalgae cultivation at large-scale open raceways refers to land area requirement. Cement factories generate large amounts of flue gas, which requires huge areas of raceway for microalgae growth under flue gas feeding. Therefore, it is imperative that the site selected for microalgae cultivation considers flat land availability nearby the cement plant besides legal and logistics aspects, such as real state rules and regulatory structure, environmental licensing, price of land, flue gas supply, algae oil distribution, among others.

Taking into account a distance up to 15 km between cement plants and biodiesel mills (supply and demand), three co-location opportunities were identified through Google Maps: one in the city of Volta Redonda, other in Montes Claros and another in the city of Canoas. The first ones are in southeast of Brazil, Rio de Janeiro and Minas Gerais State respectively, and the later in south region, in Rio Grande do Sul State.

In each locality, land availability was observed up to 5 km from the cement plant, which suggests potential location for construction of the microalgae production facility. The smallest area identified comprises more than 10 ha, while the largest one, more than 100 ha. Further investigation is recommended to investigate the real feasibility of these localities in terms of technical, financial and regulatory aspects.

Carbon dioxide losses to atmosphere during microalgae cultivation might be significant under flue gas feeding in open raceways, thus directly affecting the dimensioning of the microalgae cultivation facility. Three scenarios were evaluated considering the amount of flue gas available and CO_2 losses. Two distinct cement plant production scales were considered: small plants with capacity of 750,000 t of cement per year, and large-scale plants with 2,000,000 t of capacity; and two values for CO_2 losses: the expected one for open cultivation systems with flue gas injected (80% losses), and an optimistic value (18% losses) that can be achieved through adjustments in operation efficiencies of flue gas feeding and microalgae growth performance.

Scenario 1 represented a low CO_2 captured situation, with 80% of losses and supply of flue gas generated by a small cement plant. Scenario 2 evaluated a medium CO_2 biofixation, considering 80% of losses and flue gas came from a large-scale cement plant. Scenario 3 represented the situation with high CO_2 capture, by adopting only 18% of losses of a flue gas fed from the large-scale cement plant.

An input-output modelling, obeying the logic of value creation from the cement flue gas until the final product microalgae-based biodiesel, was carried out taken into consideration a typical raceway design and productivity rates from the literature. The amount of biodiesel produced was estimated considering the oil content of *Desmodesmus perforatus*, previously identified as the most preferred strain for raceway production.

The results indicate that dimensioning of the microalgae production facility is strongly affected by CO_2 losses in the cultivation plant. However, land availability cannot be considered a bottleneck for microalgae cultivation in Brazil since the area required in scenario 3, around 2 ha, is easily fulfilled by the potential co-locations identified in site selection. Therefore, from a land resource perspective, Brazil has potential areas for microalgae cultivation. It must be remarked that, despite this availability, studies dedicated to analyse land use change as well as its potential impacts on environment are essential.

The results of this input-output modelling also allowed the evaluation of microalgae cultivation under industrial symbiosis as business opportunity based on the analysis of eleven elements of the integrated Circular Business Model proposed: (i) customers of the industrial symbiosis, (ii) value proposition, (iii) revenue streams, (iv) relationship with customers, (v) customers' reach, (vi) core business, (vii) key resources, (viii) strategic partners, (ix) costs composition, (x) CO_2e emissions and (xi) CO_2e emissions avoided.

The results of the analysis of each element above, for instance revenues, operational and capital costs, cannot be used directly to support decision on investments because they are based on specific assumptions and simplest parameters used to turn feasible the input-output modelling. Despite this, by taking into account these elements, it is possible to get an overall picture of the business, and evaluate the potentialities and constraints associated to biodiesel from microalgae in Brazil on an industrial symbiosis model. The quality of microalgae-based biodiesel taking into account the Brazilian environment and conditions should be investigated by further research.

Carbon pricing has a crucial role to encourage microalgae-based biodiesel in Brazil since the flue gas captured by microalgae cultivation represents potential savings in terms of monetary values that can be used as investment on the industrial symbiosis model. It is important to note that an industrial symbiosis model is more than the physicality of any co-location site, it must be focused on resource reuse and how to achieve it technically, economically, and most important behaviourally.

In this sense, the integrated Circular Business Model proposed also allows to know and create the roots of a successful industrial symbiosis model: good planning, strong relationship based on trust, shared values and no competition among the actors involved, besides a strong management capability focused on operational efficiencies and continuous improvement, in order to maintain the circularity of the model.

This model delivers diverse areas of interest in research field. From a resource-optimisation perspective, this model could be analysed seeking maximise resource usage, operational efficiencies mainly regarding to microalgae cultivation process, and also the use of waste streams besides the flue gas (e.g. waste steam) for drying the microalgal biomass, that is an energy intensive process.

Nutrients can be a critical issue for microalgal biomass production at large-scale plants due to the cost of fertilizers and huge amounts required. So, in cases different to the cement industry, when the flue gas cannot be used also as a source of nutrients, industrial wastewater must be taken into consideration by the Circular Business Model.

Moreover, it is imperative to evaluate if circular strategies are fulfilling their primary objectives that is to reduce negative externalities in the environment or even promote environmental benefits. In this sense, robust environmental assessments likewise Life Cycle Assessment are recommended to identify and quantify potential environmental impacts of these strategies through impacts categories besides the climate change. A special attention must be given to land use change and its externalities in biodiversity, as well as in water footprint, that can be a critical issue when fresh-water microalgae are produced.

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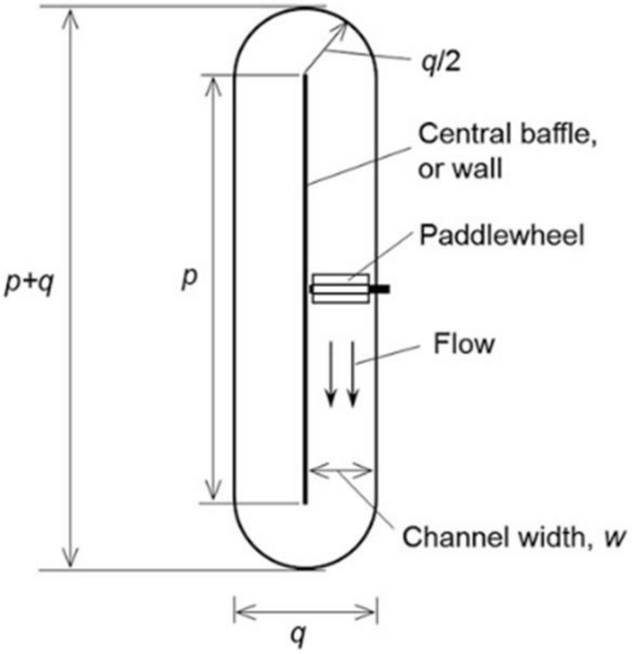
Appendix A

- **Definition of raceway area and work volume:**

Based on the typical raceway design used for microalgae cultivation and the following formulas (Chisti, 2016), the area required for one pond is 978 m² and the work volume is 293 m³.



Where: $q = 12.30\,m$ and $p + q = 82.15m$

Figure 76. Typical raceway design and its dimensions
Source: The author based on Chisti (2016).

$$A = \frac{\pi q^2}{4} + pq = \frac{\pi 12.3^2}{4} + [(82.15 - 12.30)x12.30] = 978\ m^2$$

$$V = Ah = 978x0.30 = 293\ m^3$$

- **Definition of flow rate to feed the raceway:**

The flow rate to feed the raceway is calculated based on the dilution rate. It is important to note that, in a continuous flow operation, the harvesting process must occur at a rate equals to the feed flow rate (CHISTI, 2016).

$$D = \frac{Q_f}{V}$$

$$0.25 = \frac{Q_f}{293}$$

$$Q_f = 73.25\ m^3/day$$

- **Definition of microalgal biomass concentration in the broth leaving the raceway:**

Considering the volumetric productivity of biomass adopted by Chisti (2007) and the following formula of a continuous flow operation suggested by Chisti (2016), the final biomass concentration is:

$$P_v = \frac{Q_f x_b}{V}$$

$$0.117 = \frac{73.25 x_b}{293}$$

$$x_b = 0.47\ kg/m^3.day.pond$$

- **Definition of cement kiln dust (CKD) consumption:**

According to Lara-Gil et al. (2016), the CKD required for seven days of cultivation is 450 ppm, i.e. 450 g of CKD for 1 m³ of microalgae broth. So, the annual CKD required for 293 m³, in tonnes, is:

$$CKD = 293x0.00045x\frac{365}{7} = 6.88\ t/yr.pond$$