Biorefinery Design in Context
Integrating Stakeholder Considerations in the Design of Biorefineries

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Biorefinery Design in Context

Integrating Stakeholder Considerations in the Design of Biorefineries

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by

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Summary

Biobased production has been presented as a sustainable alternative to the use of fossil resources. However, emerging controversies over the impacts of biofuels (on, e.g., land use, food, and energy security), made it clear that this production approach cannot be assumed to be inherently sustainable or unsustainable. Behind these controversies are unexplored uncertainties and assumptions made during the development of biofuel production, as well as limited considerations of the local context and the values of stakeholders upon its implementation. While these concerns do not necessarily relate to all biobased products, they do indicate that there are many aspects of sustainability besides those driving biobased production (i.e. the use of renewable resources, climate change mitigation), and that the relevance of some of these aspects depends on the local contexts and the values of stakeholders.

This thesis presents an approach to the development of a more sustainable biobased production. Particularly, this thesis answers the question: *"how can considerations of stakeholders and the local context be investigated and integrated into the early-stage design of biorefineries?"* To answer this main question, the research in this thesis is structured around the design process. First, the motivation of this work and a review of the literature on biorefinery design is presented in **Chapters 1 and 2**. Then, by focusing on specific stages of the design process, the research is structured from the definition of the design space (**Chapter 3**), to the design decision making (**Chapter 4**) and the evaluation of design concepts (**Chapter 5**). In **Chapter 6** the overall findings of this work are presented and integrated into a novel design approach for more sustainable biorefinery design. The presented approach not only allows to bring considerations of stakeholders' values and the project context, it also opens the space to identify tensions between stakeholders' values and sustainability aspects. By promoting the discussion of these tensions in the context of the project, the presented approach opens opportunities for responding to these tensions in the decision making for the development of biobased production.

Chapter 1 of this thesis presents the motivation and theoretical background of this work. Based on the overview of the research problem, the main research question, presented above, and the overall research approach of this work is introduced. In **Chapter 2**, sustainability methods and metrics in biorefinery design practices are analysed to identify challenges and opportunities for future improvements in the field. It is found that although efforts have been made to develop more integral sustainability analyses for biorefinery design, they are often challenged by disciplinary boundaries that yield a narrow scope of analysis, being blind to contextual settings or stakeholder perspectives. As a consequence, during the design of biorefineries there is no consideration of emerging societal concerns, value conflicts, and diverging visions of sustainability, as the ones mentioned in Chapter 1. Based on this review of the literature, it is suggested to apply a multi- and trans-disciplinary perspective, bringing inclusive and context aware approaches for integrating sustainability in the design of biorefineries.

Chapter 3 presents an approach to set the design space of biorefineries with consideration of stakeholders' values. Concepts from Value Sensitive Design (VSD) serve as the starting point for this approach, which is further developed through a case study on biojet fuel production in Southeast Brazil. Values of identified stakeholders are analysed and presented in relation to sustainability and the case study. Design propositions that considered the interaction between these stakeholders' values, sustainability, and biojet fuel production are derived and used to suggest design propositions, as context specific design principles for further design activities. Through them, it is intended that designers are prompted to actively reflect on the interaction between biorefinery systems and the socioeconomic and environmental context around them.

In **Chapter 4,** the consideration of stakeholders' values in a biorefinery design project is investigated. For this, some elements of VSD, such as the identification of relevant values and their connection to a technology's features, are brought into a biorefinery design project. Midstream Modulation (MM), an approach to promoting the consideration of societal aspects during research and development activities, is applied to promote reflection and value considerations during the design decision making. As result, it is shown that MM interventions during the design process led to new design alternatives in support of stakeholders' values, and allowed to recognize and respond to emerging value tensions within the scope of the project. In this way, the present work shows a novel approach for investigating how stakeholders' values can be supported during the design decision making part of the design process, particularly with regards to project variables that define a biorefinery technical features. Also, based on this work it is argued that not only reflection, but also flexibility and openness are important for the application of VSD in the context of biorefinery design.

In **Chapter 5** an ex-ante sustainability analysis of biojet fuel production alternatives in Southeast Brazil is presented. The analysis is based on a sustainability framework composed of sustainability aspects identified as relevant to the case study from previous engagements with local stakeholders and sustainability literature. The sustainability aspects that conform this framework are climate change, commercial acceptability, efficiency, energy security, investment security, profitability, social development, and soil sustainability. For the analysis, data from techno- and macro-economic analyses, life cycle assessments, and stakeholder and value analyses that were conducted as part of the same overall study is integrated. By identifying tensions between production alternatives and the sustainability aspects, opportunities for further developments, such as sugarcane ethanol-to-jet production in the short term, and in-house production of hydrogen and power with renewable energy are discussed. Overall, taking into consideration the perspectives of stakeholders and the context of production for the definition of a sustainability framework and the interpretation of results allows to recognize tensions between different sustainability aspects in the context of the project, and identify opportunities for further developments in the region.

In **Chapter 6** the overall conclusions from this thesis is presented as an answer to the main research question and the three sub research questions stated in Chapter 1. Particularly, it is concluded that consideration of stakeholders' values can be effectively integrated into biorefinery design practice in three ways: First, value considerations can be integrated into the definition of the design space when deriving design propositions as boundaries to the design space. Secondly, stakeholders' value can be integrated to the evaluation of alternatives when they served as basis for defining a sustainability framework. And thirdly, value considerations can be integrated into the design process when they, together with design propositions, serve as prompts for reflection during the design decision making. Additionally, the project context can be integrated in the specification and consideration of stakeholders' values (i.e. during the definition of the design space and also for prompting reflection during design decision making), and the interpretation of results in the evaluation of production alternatives. Based on these findings, a design approach to the design of biorefineries for sustainability and continuous learning is suggested. The approach is centred on integrating the perspectives of stakeholders and the local context of production along the different stages of design. For continuous improvement, the approach is suggested as an iterative process along the development of biorefineries, from conceptual to detailed design and its implementation or termination.

Although the presented work was to a large extent applied in an academic context (particularly Chapters 4 and 5), it is expected that opening the design practice to considerations of stakeholders and the context around biobased production is also the interest of the industry. This is related to the various socio-technical barriers that hinder the uptake of biorefineries, and the emerging uncertainties and acceptability issues surrounding this production approach. By bringing stakeholder and context considerations to early stage design, the presented approach can support the formation of a stakeholder network and the anticipation of socio-technical barriers, and potentially contribute to the advancement of more socially acceptable and sustainable biobased production.

Samenvatting

Biobased productie wordt gepresenteerd als een duurzaam alternatief voor het gebruik van fossiele grondstoffen. Echter, opkomende controverses met betrekking tot de effecten van biobrandstoffen (op bijvoorbeeld landgebruik, voedsel en energiegarantie) hebben duidelijk gemaakt dat voor deze manier van produceren nog niet kan worden aangenomen dat deze inherent duurzaam of niet-duurzaam is. Achter deze controverses liggen nog onontdekte onzekerheden en veronderstellingen die worden gemaakt tijdens de ontwikkeling van de productie van biobrandstoffen, evenals het negeren van de lokale context en de waarden van stakeholders bij de implementatie ervan. Hoewel deze zorgen niet noodzakelijkerwijs betrekking hebben op alle biobased producten, geven ze wel aan dat er vele aspecten van duurzaamheid zijn naast degene die biobased productie op dit moment stimuleren (het gebruik van hernieuwbare bronnen, beperking van de klimaatverandering), en dat de relevantie van sommige van deze aspecten afhangt van de lokale context en de waarden van stakeholders.

Dit proefschrift presenteert een benadering voor de ontwikkeling van een meer duurzame biobased productie. In het bijzonder beantwoordt dit proefschrift de vraag: "hoe kunnen overwegingen van stakeholders en de lokale context worden onderzocht en geïntegreerd in het vroege stadium van het ontwerpen van bioraffinaderijen?" Om deze vraag te beantwoorden, is het onderzoek in dit proefschrift gestructureerd rondom het ontwerpproces. Eerst wordt de motivatie van dit onderzoek en een overzicht van de literatuur over bioraffinage-ontwerp gepresenteerd in hoofdstuk 1 en 2. Vervolgens wordt het onderzoek gestructureerd vanuit de definitie van de ontwerpruimte door zich te concentreren op specifieke fasen van het ontwerpproces (hoofdstuk 3), tot aan de ontwerpbeslissing (hoofdstuk 4) en de evaluatie van ontwerpconcepten (hoofdstuk 5). In hoofdstuk 6 worden de algemene bevindingen van dit werk gepresenteerd en geïntegreerd in een nieuwe ontwerpbenadering voor een duurzamer bioraffinage-ontwerp. De gepresenteerde aanpak maakt het niet alleen mogelijk om rekening te houden met de waarden van stakeholders en de context van het project, het geeft ook ruimte om spanningen tussen de waarden van stakeholders en duurzaamheidsaspecten te identificeren en te verkennen. Door de discussie over deze spanningen in de projectcontext te bevorderen, biedt de gepresenteerde aanpak ook mogelijkheden om op deze spanningen te reageren in de besluitvorming voor de ontwikkeling van biobased productie.

Hoofdstuk 1 van dit proefschrift presenteert de motivatie en theoretische achtergrond van dit werk. Gebaseerd op dit overzicht van het onderzoeksprobleem wordt de voornaamste onderzoeksvraag, welke hierboven is gepresenteerd, en de algemene benadering van dit onderzoek geïntroduceerd. In hoofdstuk 2 worden duurzaamheidsmethoden en -statistieken in ontwerppraktijken voor bio-raffinage geanalyseerd om uitdagingen en kansen voor toekomstige verbeteringen in het veld te identificeren. Het is gebleken dat hoewel pogingen zijn gedaan om meer integrale duurzaamheidsanalyses te ontwikkelen voor het ontwerp van bioraffinaderijen, deze vaak worden uitgedaagd door disciplinaire grenzen. Deze grenzen leiden tot een beperkte breedte van analyse, en zijn blind zijn voor contextuele instellingen of stakeholderperspectieven. Als gevolg hiervan wordt bij het ontwerp van bioraffinaderijen geen rekening gehouden met opkomende maatschappelijke problemen, waarde conflicten en uiteenlopende visies op duurzaamheid, zoals gepresenteerd in hoofdstuk 1. Op basis van dit literatuuroverzicht wordt voorgesteld om een multi - en transdisciplinair perspectief te implementeren, welke inclusieve en contextbewuste benaderingen voor het integreren van duurzaamheid in het ontwerp van bioraffinaderijen omvat.

Hoofdstuk 3 presenteert een benadering om de ontwerpruimte van bioraffinaderijen te bepalen met inachtneming van de waarden van stakeholders. Concepten afgeleid van Value Sensitive Design (VSD) dienen als uitgangspunt voor deze aanpak, welke verder worden ontwikkeld door een case study over de productie van biobrandstoffen voor de luchtvaart in Zuidoost-Brazilië. De waarden van geïdentificeerde stakeholders worden geanalyseerd en gepresenteerd in relatie tot duurzaamheid en de case study zelf. Ontwerpproposities die de interactie tussen de waarden van deze stakeholders, duurzaamheid en de productie van biobrandstoffen voor de luchtvaart in acht nemen, zijn hiervan afgeleid en gebruikt om ontwerpproposities voor te stellen als context specifieke ontwerpprincipes voor verdere ontwerpactiviteiten. Via deze proposities is het de bedoeling dat ontwerpers worden aangespoord om actief te reflecteren op de interactie tussen bioraffinage-systemen en de sociaaleconomische en ecologische context om hen heen.

In hoofdstuk 4 wordt de overweging van de waarden van stakeholders in een bioraffinage-ontwerpproject onderzocht. Hiervoor worden sommige elementen van VSD, zoals de identificatie van relevante waarden en hun verband met de kenmerken van een technologie, opgenomen in een ontwerpproject voor bioraffinage. Midstream Modulation (MM), een benadering ter bevordering van de overweging van maatschappelijke aspecten tijdens onderzoeks- en ontwikkelingsactiviteiten, wordt toegepast om reflectie en waarde overwegingen tijdens de ontwerpbeslissing te bevorderen. Als resultaat wordt aangetoond dat MM-interventies tijdens het ontwerpproces hebben geleid tot alternatieven qua ontwerp ter ondersteuning van de waarden van stakeholders, en het toelaten om opkomende spanningen in het kader van het project te herkennen en daarop te reageren. Op deze manier wordt een nieuwe aanpak getoond om te onderzoeken hoe de waarden van stakeholders kunnen worden ondersteund tijdens de ontwerpbeslissing welke deel uitmaakt van het ontwerpproces. Met name met betrekking tot projectvariabelen die de technische kenmerken van een bioraffinage definiëren. Op basis van dit werk wordt ook betoogd dat niet alleen reflectie, maar ook flexibiliteit en openheid belangrijk zijn voor de toepassing van VSD in de context van het ontwerp van bioraffinage.

In hoofdstuk 5 wordt een ex ante duurzaamheidsanalyse van alternatieven voor de productie van biobrandstof voor de luchtvaart in Zuidoost-Brazilië gepresenteerd. De analyse is gebaseerd op een duurzaamheid framework dat bestaat uit duurzaamheidsaspecten die als relevant zijn geïdentificeerd voor de casestudy uit eerdere ontmoetingen met lokale stakeholders en uit literatuur met betrekking tot duurzaamheid. De duurzaamheidsaspecten die voldoen aan dit framework zijn: klimaatverandering, commerciële aanvaardbaarheid, efficiëntie, energiegarantie, investeringszekerheid, winstgevendheid, sociale ontwikkeling en duurzaamheid van de bodem. Voor de analyse zijn gegevens van techno- en macro-economische analyses, life cycle analyses en stakeholder- en waardeanalyses die werden uitgevoerd als onderdeel van hetzelfde algemene onderzoek, geïntegreerd. Door spanningen tussen productiealternatieven en de duurzaamheidsaspecten te identificeren, worden kansen voor verdere ontwikkelingen besproken, zoals suikerriet-ethanol-tot-luchtvaartbrandstof productie op korte termijn, en de eigen productie van waterstof en energie uit hernieuwbare bronnen. Over het algemeen, rekening houdend met de perspectieven van stakeholders en de context van productie voor de definitie van een duurzaamheidskader en de interpretatie van resultaten, kunnen spanningen tussen verschillende duurzaamheidsaspecten in de context van het project worden herkend en kansen voor verdere ontwikkelingen in de regio worden geïdentificeerd.

In hoofdstuk 6 worden de algemene conclusies van dit proefschrift gepresenteerd als antwoord op de hoofdvraag en de drie sub-onderzoeksvragen die in hoofdstuk 1 worden vermeld. In het bijzonder wordt geconcludeerd dat de overweging van de waarden van stakeholders effectief kan worden geïntegreerd in de ontwerppraktijk van bioraffinage op drie manieren. Ten eerste kunnen waardeoverwegingen worden geïntegreerd in de definitie van de ontwerpruimte bij het afleiden van ontwerpproposities die als grenzen kunnen fungeren voor de ontwerpruimte. Ten tweede kan de waarde van stakeholders worden geïntegreerd in de evaluatie van alternatieven wanneer deze als basis dienen voor het definiëren van een duurzaamheidskader. En ten derde kunnen waardeoverwegingen in het ontwerpproces worden geïntegreerd wanneer ze, samen met ontwerpvoorstellen, dienen als aansporingen tot reflectie tijdens de ontwerpbeslissing. Bovendien kan de projectcontext worden geïntegreerd in de specificatie en overweging van de waarden van stakeholders. Dat wil zeggen, tijdens de definitie van de ontwerpruimte en ook voor het aanzetten tot reflectie tijdens ontwerpbeslissingen, en de interpretatie van resultaten bij de evaluatie van productiealternatieven. Op basis van deze bevindingen wordt een ontwerpbenadering voorgesteld voor het ontwerp van bioraffinaderijen met het oog op duurzaamheid en continu leren. De aanpak is gericht op het integreren van de perspectieven van stakeholders en de lokale context van productie langs de verschillende fases van het ontwerp. Voor continue verbetering wordt de aanpak voorgesteld als een iteratief proces gaande de ontwikkeling van bioraffinaderijen, van conceptueel tot gedetailleerd ontwerp en de implementatie of beëindiging ervan.

Hoewel het gepresenteerde werk grotendeels werd toegepast in een academische context (met name de hoofdstukken 4 en 5), wordt verwacht dat het openstellen van de ontwerppraktijk voor overwegingen van stakeholders en de context rond biobased productie ook in het belang van de industrie is. Dit hangt samen met de verschillende sociaal-technische belemmeringen die het gebruik van bioraffinaderijen belemmeren, en de opkomende onzekerheden en problemen rond aanvaardbaarheid voor deze productiebenadering. Door stakeholder- en contextoverwegingen in een vroeg stadium in te brengen, kan de gepresenteerde aanpak de vorming van een stakeholdernetwerk en de anticipatie op sociaal-technische barrières ondersteunen en mogelijk bijdragen aan de ontwikkeling van meer sociaal aanvaardbare en duurzame biobased productie.

Chapter 1

General Introduction

1.1. Introduction

"Like all people, we perceive the version of reality that our culture communicates. Like others having or living in more than one culture, we get multiple, often opposing messages. The coming together of two self-consistent but habitually incomparable frames of reference causes un choque, a cultural collision"

"The new mestiza copes by developing a tolerance for contradictions, a tolerance for ambiguity [...] She learns to juggle cultures. She has a plural personality, she operates in a pluralistic mode—nothing is thrust out, the good, the bad, and the ugly, nothing rejected, nothing abandoned. Not only does she sustain contradictions, she returns the ambivalence into something else"

Gloria Anzaldúa, Borderlands/La Frontera

Through her writing in Borderlads/La Frontera, Gloria Anzaldúa shows the borderlands as those places where a *mezcla,* a mixture, occurs; where different beliefs, values, and ways of seeing the world are confronted within the individuals that inhabit these regions, and who, in their struggle to be, develop a new consciousness. She argues that this consciousness does not emerge on its own, but it is a result of the increased awareness and constant negotiation (a struggle) that living these multiple subjectivities, contradictions, and ambiguities implies. What she describes as the new, mestiza consciousness leads to an inclusive way of being that draws strength from the numerous possibilities that a borderland identity brings: while they are conscious of the ambiguities and contradictions, inhabitants of the borderlands have the freedom to act beyond the restrictions of a single cultural tradition.

I start with this reference to Anzaldúa's Borderlands as an analogy of the main topic of this thesis, the sustainability of biobased production. Drawing from this analogy, in this introduction chapter I will first discuss what biorefineries are, and how they come to be (or are intended to be) a biobased production center that also becomes a meeting point between different cultures from different societal and productive sectors, and scientific disciplines. Then, I will discuss sustainability as a concept that carries subjectivities as it gets specified differently, by different actors, in different contexts. To illustrate this, I will refer to sustainability controversies as they have emerged in past biofuel developments. Following this discussion, I will introduce the challenges in the design of sustainable biorefineries, which will lead to the main research question of this thesis.

The borderlands, as Anzaldúa describes them, are also illustrative of the doing of this doctoral work. Having started with the aim to contribute to the design of more sustainable biorefineries, I foresaw doing research about selecting metrics that would indicate the most sustainable option; an expectation from a BioProcess Engineer with some knowledge on Life Cycle Assessments (LCA). As this thesis progressed, however, the research quickly led to other disciplines, other theories, and other methodologies; other ways of approaching what designing more sustainable biorefineries meant. In this way, this thesis became a sort of borderland, integrating (or struggling to integrate) these different ways of seeing and understanding the ongoing research. Therefore, after introducing the motivation and aim of this work, I will present the theoretical background and research approach as an exploratory journey that led to the specific research questions that guided this work.

1.2. Motivation

1.2.1. Biorefineries

Biobased production is an approach centered on the use of biomass, including agricultural crops and residues, forest products and residues, and even bio-waste from cities and industries (de Jong and Jungmeier 2015). The processing of these biomass feedstocks to obtain products like fuels, chemicals, and materials takes places in biorefineries. While there is no single definition of what biorefineries are, they are often described as the processes, facilities, and/or processing systems through which the sugars, oils and other organic compounds in biomass feedstocks are converted to biobased products (Bauer et al. 2017).

Biorefineries are often referred to in terms of generations, depending on the type of feedstock they process: 1st generation (1G) biorefineries are those that use food crops like sugarcane and corn, while 2nd generation (2G) biorefineries are those that process non-food materials, like agricultural and forest residues (de Jong and Jungmeier 2015). Besides the feedstock type they use, biorefineries can be defined based on the route they follow as processes. In this regard, biorefineries can be described according to four main features

(Cherubini et al. 2009): *i*) *platforms*, or key intermediates (*e.g.* C5 and C6 sugars, oil, syngas), *ii*) *products* (*e.g.* bioethanol, biogas, glycerol, ethylene, lactic acid), *iii*) *dedicated feedstocks and residues* (*e.g.* sugar and oil crops, wood chips, straw, microalgae), and *iv*) *processes* (*e.g.* fractionation, extraction, hydrolysis, fermentation, gasification, pyrolysis). Therefore, the combination of these features can define a specific biorefinery, from feedstock to product (see **Fig 1**). Different compounds like chemical building blocks, fine and specialty chemicals can all be biorefinery products. However, these products imply different degrees of processing, with additional processes for products downstream in the value chain. As example, bioethanol can be an energy product and thus be an end-product *per se*, but it can also be a building block for value-added chemical production like ethyl acetate, and 1,3-butadiene (Cheali et al. 2015). In the latter case of ethanol derivatives, I refer to the biorefinery as the combination of processes and flows that pertain not only to the production of ethanol from biomass, but also the conversion to ethanol derivatives.

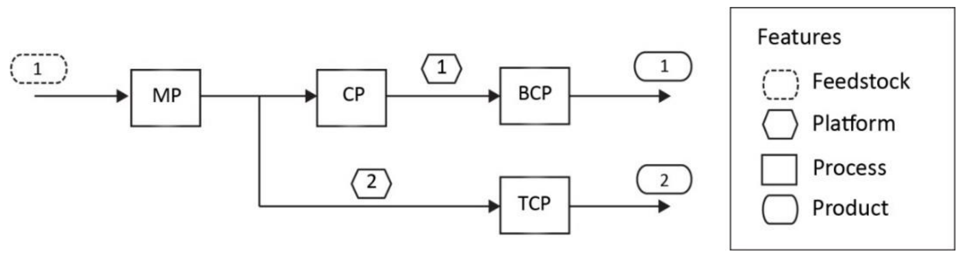

Fig. 1. Schematic example of a biorefinery as a process where a feedstock goes through mechanical processing (MP), and the resulting stream is split to go through chemical and biochemical processing (CP, BCP) to obtain a product 1, and through thermochemical processing (TCP) to obtain a product 2. Modified from Palmeros Parada et al. (2017).

For achieving the processing of biomass, biorefineries require the coordinated action of diverse stakeholders that support the production chain (see **Fig. 2**). This is in large part because there is no single actor that possesses all the capacity, in terms of knowledge and resources, to advance a specific biorefinery (Hermans Frans 2018). From a technological perspective, the most recognizable stakeholders are perhaps those directly involved with the biorefinery conversion processes, e.g. the biorefinery operating company and client companies who buy and distribute biorefinery products. Even more, as biorefineries are intended as the processing centers in biobased production, they become a confluence point of different stakeholders, a borderland that emerges from the crossing of productive sectors, government, and society, often across national boundaries. More than being a boundary object that is defined or used differently by different stakeholders, biorefineries need to bring stakeholders together, ideally to collaborate under a common objective or vision, or in alignment with their own (Bauer et al. 2017; Palgan and McCormick 2016).

Most evidently, the use of biomass as feedstock brings the chemical and process industry at intersection with the agricultural, forestry, or residue management sectors, creating a diverse array of requirements, expertise, and production cultures. For example, while in the chemical industry it is common to rely on a secure supply of feedstock with a constant quality, feedstock from the agricultural, forestry, or waste sectors can vary according to season and specific location, or be affected by unexpected weather conditions. Furthermore, while farmers plan and produce in a different way than industrial actors, there is also diversity between farmers; while some farmers have come to resemble industrial producers with high-tech machinery and large scales, others produce at a small family scale.

In addition to the stakeholders directly related to production, universities and research institutes have become active stakeholders involved in the development of biorefineries and the technologies that sustain them, in occasions in close collaboration with the industry (Kedron and Bagchi-Sen 2017; Mossberg et al. 2018). Stakeholders to biorefineries are also public actors that enable infrastructure and institutional support in the case of the government, and acceptance in the case of the public (Palgan and McCormick 2016). All of these stakeholders are not necessarily confined to a single geography, as often biobased production is developed in international ventures that seek to trade biomass or bio-products in a global context. This means that biorefineries become borderlands where different stakeholders meet, each bringing their own values and expectations with regards to biobased production. In the development of biorefineries, these values are expressed through, e.g., the visions and objectives of national governments to reduce emissions, or the interests of local farmers to access new markets. In occasions, these interests and objectives will be in tension and result in a struggle, as Anzaldúa writes about living in the borderlands.

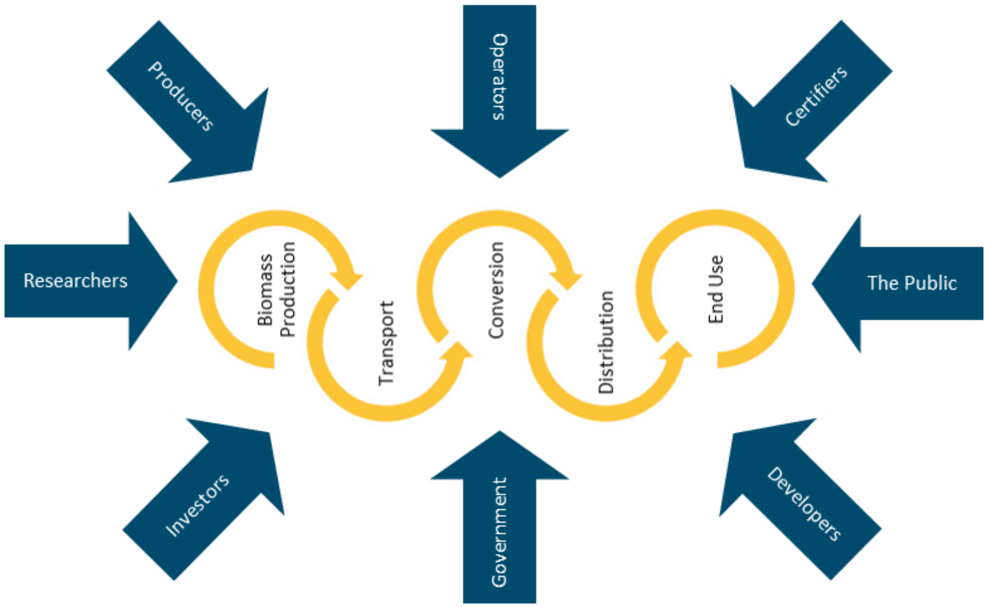

Fig. 2. Schematic representation of a biorefinery as a production chain with relevant stakeholders.

1.2.2. Sustainability implications in biobased production

Biorefineries have emerged as an alternative for the production of fuels, materials and chemicals in the transition away from fossil resources. The development of these technologies for biobased production is driven by the benefits they can potentially bring towards sustainable development. Particularly, their potential to lower greenhouse gas (GHG) emissions through the use of renewable feedstocks has been one major driver of supporting policies, like the renewable energy directive (RED) of the European Commission (European Commission n.d.) and the more recent National Biofuel Policy (RenovaBio) of Brazil (Agencia Nacional de Petroleo, Gas Natural and Biofuels 2018). Energy security has also been identified as another important driver for the development of biobased production (Pfau et al. 2014). That is, because biomass is more distributed throughout the world when compared to fossil resources, its use for energy production is expected to increase the energy security of regions with low fossil reserves or with no access to energy grids.

However, in the past decade environmental and social sustainability concerns raised controversy around biobased production. Particularly, as biofuel production grew, concerns started to emerge over unexpected emissions (Searchinger et al. 2008), and impacts on biodiversity, access to natural resources, and food security (Hoekman and Broch 2017; Nygaard and Bolwig 2017; Rosegrant and Msangi 2014). Behind these concerns are unexplored uncertainties and assumptions made during the development of biofuel production, and, in occasions, a limited perspective of the local context and the values of stakeholders. Notorious examples are Jatropha biodiesel projects in India and Ghana, in which the overlooking of some local land and biomass uses negatively impacted the food and energy security of local populations (Aha and Ayitey 2017; Baka 2013; Baka and Bailis 2014; Nygaard and Bolwig 2017). Another example is the Ecover case, where a company was seeking to develop a more sustainable biobased cleaning product. Regardless of their intentions and the efforts made for what they considered sustainable, it was found that the overlooking of some stakeholder concerns and values with regards to, e.g., the distribution of benefits and environmental risk, resulted in opposition to the project (Asveld and Stemerding 2018). While not necessarily related to all biofuels, these examples indicate that there are many aspects of sustainability besides those driving biobased production (i.e. climate change mitigation and energy security), and that the relevance of some of these aspects depends on the local contexts and the values of stakeholders.

The controversy over the sustainability of biobased production is also related to the flexibility in the sustainability concept itself. That is, while many may agree on the desirability of sustainability and on a general definition for it (e.g. “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission On Environment and Development 1987), what it actually entails and how it should be operationalized has been discussed as a subjective issue that depends on beliefs and values of those considering the concept (Hedlund-de Witt 2013; Van Opstal and Hugé 2013). This interpretative flexibility, reinforced by uncertainties most common in the early stages of development of technologies, has resulted in statements that address sustainability issues as wicked problems that engineering alone cannot resolve (Azapagic and Perdan 2014). This characteristic of sustainability becomes highly relevant as biorefinery companies and downstream industrial sectors are joined in projects by small, medium and large scale farmers, government, or other community representatives, diversifying the perspectives on what sustainable biobased production means. Looking at the Ecover case mentioned above, Asveld and Stemerding (2018) argue that involving stakeholders during the development of the technology, and particularly bringing an explicit understanding about the values and beliefs behind what they consider sustainable, could result in a design that is more acceptable for all parties.

1.2.3. The design of *sustainable* biorefineries

Engineering design typically follows sequential stages for the creation of a final design object: problem definition, conceptual and detailed design, and design specification and implementation (Goetschalckx 2011). In the problem definition stage, the boundaries of the design space are defined, making the context, objectives, requirements and constrains of the project explicit. During the design stages, several alternatives are developed and assessed according to defined criteria, in order to select promising design(s). Typically, design concepts are designed to assess the feasibility of a technology or its configuration before large investments are put into place. The best design concept from the conceptual stage is further developed in detail and subsequently brought to implementation (Warren D. Seider et al. 2008)**.** These steps can be implemented differently according to the disciplines or design approaches from which the project is addressed. For instance, these steps can be integrated to broader project development frameworks, or they can rely on different evaluation and decision making methods (see, for example, (Heintz et al. 2014; Jiao et al. 2007; Lai et al. 2018)).

In the design of biorefineries, decisions are made over variables that represent the technical features of a bio-process and/or its supply chain. From the perspective of the supply chain, typical biorefinery design variables are related to biomass type, facility location and capacity, network structure and transportation mode (Sharma et al. 2013). From the perspective of process design for biorefineries, the main variables are usually the biomass type and main product(s), as they will define the required processing and technologies (Holm-Nielsen and Ehimen 2014). For instance, a corn to ethanol process will most likely follow milling, fermentation and purification, while forest biomass to ethanol will probably go through mechanical preprocessing followed by thermochemical and/or biochemical treatments and purification steps. Additionally, critical aspects when exploring these supply chain and process variables include: (1) seasonality of raw material, like the case of sugarcane's annual *zafra* that may result in suboptimal utilization of capital in the off-peak periods; (2) market alterations across industry sectors, which are reflected in availability and cost uncertainty of biomass or biobased products; and (3) biomass moisture and the disperse availability of biomass, which accentuate the impact of transportation in biorefinery systems (Hytönen and Stuart 2011; Kamm et al. 2016; Pantaleo et al. 2013; Shabani et al. 2013).

To contribute to sustainability early in the development of biorefineries, sustainability considerations have been integrated in conceptual biorefinery design. In biorefinery design literature, this integration has been approached through assessment and optimization methods in line with the fields of supply chain and process design (e.g. Andiappan et al. 2015; Gong and You 2014; Rizwan et al. 2015). This is typically done by defining one or more indicators of sustainability, which can function as assessment criteria or optimization objectives to minimize or maximize. A common sustainability indicator brought to biorefinery design besides economic metrics, is the measure of GHG emissions of the process, production chain, or the whole life cycle of a product (Moncada et al. 2016). GHG emissions are typically measured as direct CO_2 emissions and as CO_2 equivalents that represent the amount of CO_2 that would result in the same global warming potential as a given amount of a mix of greenhouse gases.

Regardless of the contribution that these methodologies bring to their specific engineering fields, approaches in the biorefinery design literature are mostly limited to sustainability aspects that already drive biobased production, e.g. climate change mitigation and energy security (Pfau et al. 2014), rarely paying attention to societal aspects and the context around the biorefinery. These observations are derived from a review of the literature presented in detail in **Chapter 2** of this thesis, and which is the first publication of this doctoral project (Palmeros Parada et al. 2017). From this review, it was found that a narrow view of sustainability, closed to considerations of stakeholders and the context of production, predominates in biorefinery design.

Beyond academic literature, barriers to the establishment of biobased production, such as feedstock supply uncertainty and limited coordination amongst actors (Bosman and Rotmans, 2016; Kedron and Bagchi-Sen, 2017; Hellsmark and Söderholm, 2017), indicate a need for a more effective consideration of stakeholders and local contexts. There are cases of biorefinery projects developed with the explicit aim of bringing societal benefits like employment generation and rural development. An example is the Hassan Bio-Fuel Park project in India analysed by de Hoop et al. (2016) where large efforts were made to include local farmers in the production chain (e.g. visits to villages and farmers feedback events). However, a close exploration of this and other projects indicate that limited benefits and, in occasions, questionable impacts can result from assumptions about the local context, and insufficient consideration of stakeholders concerns and their practices during their development. Examples include some Jatropha projects Tanzania and

India, including the Hassan Bio-Fuel Park (Balkema and Pols, 2015; Baka and Bailis, 2014; de Hoop et al, 2016), and the Ecover case mentioned above (Asveld and Stemerdig, 2018).

Thus, to contribute to the development of more sustainable biorefineries, the main research question of this doctoral work is *how can the perspectives of stakeholders and the local context be investigated and integrated into the early-stage design of biorefineries?*

1.3. Theoretical Background

Based on the previous sections, to design for sustainability there is a need to open up to different methodologies and fields of knowledge, as already discussed by Azapagic and Perdan (2014), in order to address the contextual implications of biobased production and the values of stakeholders on which different sustainability judgements are based (Asveld and Stemerding 2018). In this section, theoretical perspectives and methods for analyzing sustainability and societal implications of production systems, technologies, and policies are presented, and discussed in relation to the main research question.

1.3.1. Sustainability Assessments

In the sustainability field, numerous sustainability frameworks for various systems have been developed, such as the frameworks by the Roundtable on Sustainable Palm Oil (RSPO) and the Forest Stewardship Standard (FSS). These frameworks are typically intended for certification of existing production chains and are extensive on the issues they address, providing details on how to use methods and indicators to quantify effects on specific sustainability aspects. These frameworks are focused on specific sectors (e.g. forestry, agriculture), or on specific objectives, like organic agriculture, fair trade, and climate change (Scarlat and Dallemand 2011). Additionally, some frameworks have been developed specifically for biobased production, like the Global Bioenergy Partnership, and typically cover aspects related to land use change, water, biodiversity, and greenhouse gas emissions, and may be in alignment with national or regional policies (Ramirez-Contreras and Faaij 2018).

However, while some of these frameworks have become broadly used in the industry, they tend to be generically defined for any system within their scope (i.e. palm oil) or face limitations in the contextualization from a global definition (Marin-Burgos et al.

2015; Schut and Florin 2015). Having a range of sustainability aspects or indicators to apply to all situations can make the analysis results easier to communicate and compare, however it also results in a limited capacity to reflect local realities. The need for taking into consideration the context in sustainability frameworks is related to: First, different stakeholders in different regions will have different interests and priorities based on the values of the group they represent, as illustrated by the case of the national interpretation of the RSPO framework (Marin-Burgos et al. 2015), and as discussed for sustainability in **Section 1.2.2.** Secondly, the characteristics of the local environment affect the relevance and the way to measure relevant sustainability impacts. This second point is discussed in detail by Efroymson et al. (2013), who demonstrates how variables behind sustainability effects on, e.g. soil and climate, vary across locations, and that effects are therefore better predicted by selecting indicators according to the location. These points are further underlined by observations that global frameworks emphasize agro-industrial production and fail to recognize impacts for smallholders, as observed for some small scale biofuel projects in Mozambique (Schut and Florin 2015).

To bring the perspectives of stakeholders and the consideration of local realities, some participatory sustainability frameworks have been developed. These frameworks have been used to evaluate and compare the sustainability performance of development projects and policy alternatives. In these frameworks, the input of stakeholders has been used to select relevant sustainability aspects or criteria, and to give importance weights to selected criteria and rank alternatives (Wang et al. 2009). In some cases, stakeholders input is processed through multi-criteria decision analysis (MCDA) approaches that include weighting and ranking methods (Kurka and Blackwood 2013). For example, Talukder et al. (2018) detail a MCDA framework to assess and compare the sustainability of agricultural system alternatives that uses the input of stakeholders to weigh different sustainability aspects, and to normalize and rank the performance.

While these participatory frameworks are open to the input of stakeholders and experts, they can lead to misleading conclusions that depend on methodological choices (Jacobs et al. 2014; Steele et al. 2009). This limitation is related to the use of stakeholders' input to select or weight criteria and indicators from pre-defined lists. Such approach clearly narrows the type of issues addressed by such frameworks, or the way they are evaluated is not necessarily in alignment with the local context. A second point is related to the normalization, weighting, and ranking methods that are usually applied to treat data, for example, with multi-criteria decision making methods. While these approaches can be practical for contrasting options, information is inherently lost, potentially hiding the meaning of a difference in scores between sustainability aspects or alternatives. Additionally, if two or more sustainability aspects are quantified, one can also question if the scores for different aspects are comparable. For example, it is hard to say whether or not an alternative with a given amount of emissions and a given production cost is more desirable than another alternative with less emissions but higher cost. When these impacts are normalized and aggregated an equivalence between incommensurable aspects is wrongly assumed. Overall, the use of these approaches to treat assessment results can yield conclusions that depend on methodological choices instead of reflecting how alternatives perform with regards to the considered sustainability aspects.

Furthermore, when developed in the scope of development and policy options for bioenergy and biofuels, sustainability frameworks have a limited consideration of societal aspects, as in the design of biorefineries discussed in **Section 1.2.3**; and when they do cover societal aspects their focus has been on management and/or governance practices (Pashaei Kamali et al. 2018). Thus, sustainability analyses related to biobased production have a limited consideration of societal aspects, or they are distant to the scope of the design of biorefineries, i.e. variables of biobased processes and their supply chains such as feedstock types, technologies, and scale. That is, while these type of frameworks can be useful for evaluating or guiding the implementation of biobased production, this type of assessment can only provide a limited insight into how specific biorefinery features affect the sustainability performance of biorefineries, or how it can be improved. For example, aspects such as labour conditions, and training and education are included as social aspects in some of these frameworks but the relationship between these sustainability aspects and the features of biorefineries or technologies has not been explored.

1.3.2. Technology and Society

The fields of Engineering Ethics, and Science and Technology studies, address the relationships between technological developments and society. Theoretical and methodological developments in these fields have been based on the understanding that technological developments can then influence society according to the features of the technology, the context in which they are deployed, and the stakeholders and values around the technology (see, for example, Doorn et al. 2013; Koops et al. 2015; van den Hoven et al. 2015). To ensure positive impacts or prevent negative impacts of a technology on society, some approaches in these fields seek to involve stakeholders and consider societal values and perspectives in the development of technologies. For example, Constructive Technology Assessment (CTA) is an early-stage approach for the assessment of a technology early in its development, with the aim to provide knowledge and orientation for its implementation in society (Fleischer and Grunwald 2008; Rip and Robinson 2013). Midstream modulation (MM) is an approach applied to broaden R&D practices to considerations of ethical, legal and social aspects during decision-making (Flipse et al. 2013). By contrast, Value Sensitive Design (VSD) is a design approach that aims to actively consider stakeholder's values in the design process of a particular technological product by enhancing features that positively relate to stakeholder values, and vice versa (Friedman et al. 2008). These approaches seek to bring engagement about societal and ethical issues during the development of technologies, proactively seeking to bring stakeholders' values or concerns to this process. Therefore they seem promising for addressing sustainability in the design of biorefineries.

VSD has four characteristics that make it particularly interesting for the purpose of this thesis: 1) It is meant for use at the level of projects to obtain a design that integrates stakeholder values; thus, it could lead to a value sensitive biorefinery concept. This is in contrast to other approaches, like CTA, that focus more broadly at the development of a technological sector or domain (e.g. nanotechnology, synthetic biology); 2) it proactively seeks to bring considerations of stakeholders, and their direct involvement, in the design of a technological product; 3) through an understanding of how the features a technology (or variables in the design stage) relate to stakeholders' values, VSD supports the integration of stakeholders' values in a design; 4) VSD uses terminologies common in the engineering field (e.g. design requirements) that can facilitate communication and understandings between VSD and engineering researchers. Therefore, VSD is proposed in this thesis not only to analyse relevant sustainability issues taking into account the values of stakeholders and the societal context of implementation, but rather to constructively incorporate these aspects into a biorefinery design.

VSD is typically carried out considering the iteration of three main studies: 1) conceptual investigations where relevant stakeholders and value concepts are identified, 2) empirical investigation where identified stakeholders are approached to study their understandings and concerns related to relevant values, 3) technical investigations in which the way in which the technology features and mechanisms relate to the relevant values is investigated. As part of this investigation, it has been suggested that values can be "translated" into design requirements as going down a value hierarchy (van de Poel

2013): values stand at the top of the pyramid, in the middle of the pyramid are norms that imply or restrict an action (objectives, goals, constraints) for the sake of the values above them. The understanding of such conceptions can be used to define design requirements to satisfy the values and norms above the, or even metrics to use for evaluation. Thus, a VSD approach can help to incorporate the conceptions of sustainability by stakeholders into the design of biorefineries.

However, the application of VSD for technological systems, such as biorefineries, is not easily deduced from previous experiences. VSD has been mostly applied for the design of information technology and human-computer interaction technological products, which are in direct contact with end users (for a review refer to Davis and Nathan 2015). By contrast, biobased products are often industrial products that are farther away from the end user, and imply a broad diversity of stakeholders as mentioned in **Section 1.2.1**. Furthermore, going from conceptual to detailed design stages for biorefineries can take many years of development. As a consequence, at early stages of development there is limited availability of information and involvement of stakeholders is difficult when their roles and interests in the biorefinery are uncertain or tenuous. By contrast, in later stages of development when there is less uncertainty, the capacity to change the project is limited as investments for, e.g. piloting or demonstrations projects, have been made.

1.4. Research Approach

This research project started with a review of the literature on sustainable biorefinery design (**Chapter 2**), which allowed to define the main resarch question of this thesis metnioned above: *how can the perspectives of stakeholders and the local context be investigated and integrated into the early-stage design of biorefineries?* To answer this quesiton, and considering the theoretical background presented in **Section 1.3**, three sub-research questions (RQ) were defined in the scope of biorefinery design, from problem definition to the evaluation and selection of a final design concept.

- *RQ 1 - What is an effective way to bring into biorefinery design practice considerations of stakeholder values in relation to the project context, and prior to the generation of design concepts?*

The approach to answer this question was taken from the perspective of VSD and the value hierarchy discussed above (van de Poel 2013). As this question is in the scope of the design problem definition of biorefineries, when the design space is defined, the approach was to investigate stakeholders' values, and seek to derive norms as objectives and constraints that could facilitate a value integration in later design activities. For this, the production of biojet fuel in Southeast Brazil was explored as case study. The exploration started with a stakeholder analysis taking a generic biofuel value chain as a guide, which allowed to identify potential stakeholders relevant to the project. Based on interviews with some stakeholders, a value analysis was performed in the context of the project. The value analysis, with a close understanding of the project variables, served as a basis to define design propositions, which are project specific, and flexible design boundaries to guide subsequent design activities. As a result, the presented design space investigation is proposed as an approach to integrate sustainability considering the context of the project and its stakeholders in the early stages of design.

From this work, the hypothesis that reflection over the design propositions could guide the subsequent design for the integration of stakeholders' values was derived. When looking closely into VSD literature however, it was found that the generation of alternatives and the decision-making over variables that form part of the design process had not been systematically studied for the integration of values. Therefore, the need to systematically investigate the integration of stakeholders' values during the generation of design alternatives and decision making led to the following research question.

- *RQ 2 - How can considerations of stakeholder values in relation to the project context, as analyzed in RQ 1, be integrated in the design decisions that define biorefinery concepts?*

For exploring this research question, MM was applied to promote reflection about stakeholders' and their values during a design project. MM was selected as it has been shown to successfully raise reflection and result in a change of practices in R&D decision-making with considerations beyond those normal to R&D (Flipse et al. 2013; Schuurbiers 2011). To put this into practice, MM was applied after a design space investigation for a project, as investigated for the previous research question. For this, MM was adapted to the design context, focusing on promoting reflection about stakeholder values in the scope of variables and the design decision making. This work was done in close collaboration with a group of designers working in a bioplastics biorefinery design project. This research work not only demonstrates the integration of stakeholders' values in design decisions, but also shows the potential to use MM as a structured technical investigation of VSD. Additionally, it is argued that reflection, openness and flexibility allow to discuss and respond to emerging value tensions in early stages of biorefinery design.

- *RQ 3- How can stakeholders' values and the local context of biobased production be considered in the evaluation of biorefinery alternatives for sustainability?*

The assessment of alternatives is an important part in the design of biorefineries. Sustainability has been integrated in biorefinery design assessments with the limitations discussed in **Section 1.2.3** (i.e. no inclusion of stakeholders nor the consideration of the context of the biorefinery, and limited consideration of societal issues). While there are sustainability frameworks for evaluating biofuel and bioenergy development and policy alternatives that are open to the involvement of stakeholders, these also face some limitations for the purpose of this work as discussed in **Section 1.3.1**, i.e. relying on predefined lists of sustainability aspects and/or indicators, processing stakeholders' input through aggregation approaches that are prone to methodological biases, or the covered social aspects have a limited scope on design alternatives).

Therefore, looking back at the results from RQ1 and RQ2, the approach to answer this third research question was to develop a sustainability framework for assessing the performance of biorefinery alternatives. Engagements with local stakeholders and the sustainability literature were taken as a reference to define sustainability aspects of relevance, seeking to include emerging societal aspects in the context of the biorefinery and in the scope of design. The framework was used to evaluate alternatives for the production of biojet fuel in Southeast Brazil, as a continuation of the case study in RQ1. The performance of evaluated alternatives was presented individually for each sustainability aspect, with no aggregation nor normalization of results. Rather, for their analysis, results for the different alternatives were put into contrast, allowing to identify sustainability tensions between different aspects and production alternatives, and opportunities for further developments.

1.5. Readers' Guide

Chapter 2 is a literature review and critique of how sustainability has been considered and incorporated in methodologies for the design of biorefineries is presented. Through this critique, challenges and opportunities in biorefinery design practices are identified, and serve as motivation for the main research question of this work. To investigate the main research question, three sub-questions, i.e. RQ 1, RQ 2 and RQ 3, were specified in the scope of the design process (see Fig. 3). Chapters 3 and 4 address RQ 1 and RQ 2 in the scope of the definition of the design space and the generation of design alternatives as described in **Section 1.4**. For answering RQ1, the case of a potential biojet fuel biorefinery in Southeast Brazil is investigated. For answering RQ2, Chapter 4 explores the integration of stakeholders' values in the design decisions of an ongoing design project for the production of biobased plastics. Then, Chapter 5 addresses RQ 3 with regards to the evaluation of production alternatives for the biojet fuel case study presented in Chapter 3. Finally, in Chapter 6 the overall results of this thesis are discussed, and conclusions are derived in response to the presented research questions. Based on these reflections, some recommendations for further research are formulated.

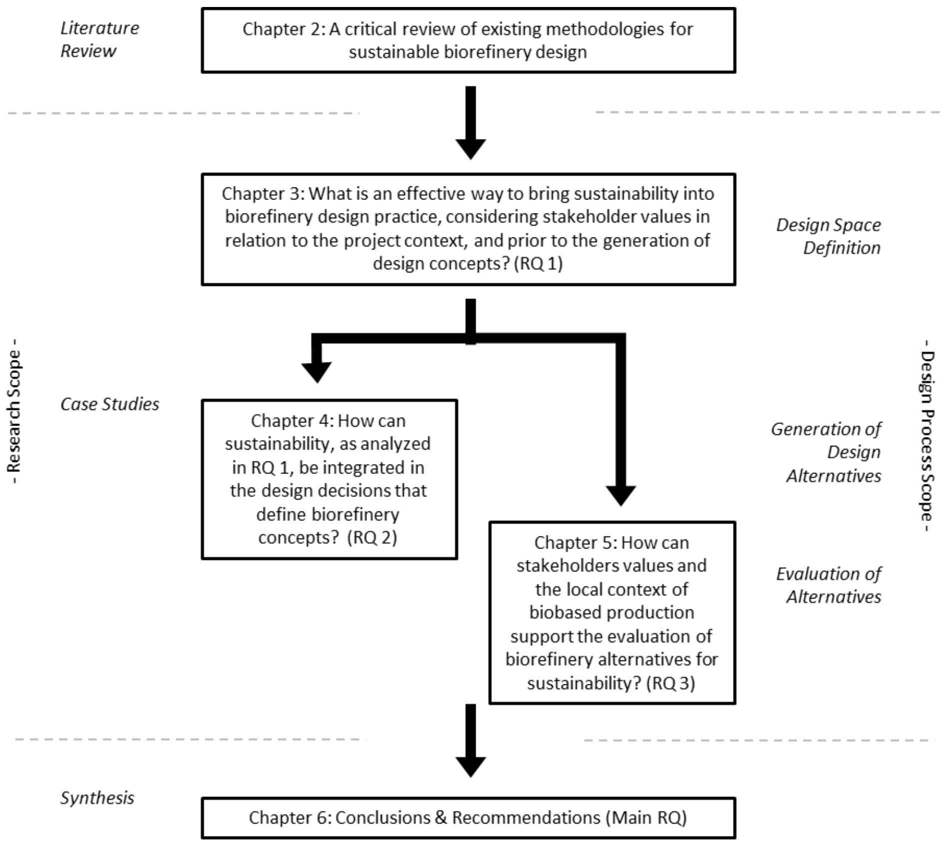

Fig. 3. Scheme of the thesis outline and scope of the different chapters with regards to the design process (right) and the thesis research project (left). **RQ**: Research question.

1.6. Author contributions

All chapters have been written by the author of this dissertation, and chapters 2 through 4 have been co-authored as indicated in pages 39, 87, 117 and 153. The author of this thesis was responsible for the conception of the research, field work, analysis and interpretation of results, conclusions, and writing of Chapters 2 through 4. The author planned the research for Chapter 5 together with the co-authors, and she conducted the research except for the soil sustainability part. She wrote most of the manuscript and structured the contributions of other co-authors. The work in Chapter 5 draws data from previously published material as it is the final stage of a large research project initiated and organized by some of the co-authors. All co-authors of chapters 2 through 5 contributed with critical revisions of the research plan and development, analysis, and conclusions.

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Chapter 2

Sustainable biorefineries, an analysis of practices for incorporating sustainability in biorefinery design

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2.1. Introduction

The biobased economy has been promoted as a sustainable alternative for replacing fossil resources in the production of energy, chemicals and materials. In this context, biorefineries are being developed as technological means for the transition to this economic approach, opening the possibility to add value to biomass through a more sustainable production. However, controversies related to the actual sustainability impacts of biobased products have been raised in the last years (Condon et al., 2015; Rosegrant and Msangi, 2014). As result, sustainability has become a central topic for the development of the bioeconomy and future biorefinery systems. A clear example are the sustainability criteria that the European Commission has set for domestic and imported bioenergy in order to receive government support or to count in national renewable energy targets (Tom et al., 2012).

Sustainability of biobased products is increasingly monitored and evaluated through certification schemes that measure impacts of biobased production (European Commission, n.a.). However, considering sustainability criteria during the design stage of biorefineries could result in alternative design options and consequently have a significant influence in improving their overall performance. This observation is reflected in the extensive and broad academic work on sustainable biorefinery design, from, for example, a sustainability assessment of an electrolysis-enhanced biomass to liquid fuel process (Bernical et al., 2013) to evolutionary algorithms for bioenergy supply chain optimization (Ayoub et al., 2009) and life cycle optimization methods for the design of sustainable product systems and supply chains (Yue et al., 2013). Consequently, concepts and methods used in these studies vary significantly, and are sometimes conflicting among different sources.

Recent publications have attained to analyse conceptual and methodological developments towards sustainable biorefineries. However, these studies are limited to, for instance, sustainability issues generally associated with biorefineries (Azapagic, 2014), or specific methodologies and methods used in certain disciplines, like optimization frameworks for biorefinery supply chains (Eskandarpour et al., 2015), assessment methodologies of biorefinery value chains (Parajuli et al., 2015) and process integration approaches for sustainable biorefineries (El-Halwagi, 2012). Regardless of the importance that these studies have in their academic niche, e.g. optimization in supply chain, sustainable biorefinery design is not restricted to a single discipline, or to a single design approach. The work in this chapter takes presents a broader overview on advances for sustainability incorporation in biorefinery design, across disciplines and research areas related to design. As part of this review, current design practices, methods and metrics for sustainable biorefineries are analysed with regards to different aspects of sustainability, including environmental and societal impacts, and stakeholder participation. From this analysis, challenges, needs and opportunities for further development and research on design practices are identified with the aim to contribute towards the development of sustainable biorefineries.

2.2. Concepts and Definitions

In the reviewed literature some concepts from different research areas are used in different ways. Therefore we discuss the most relevant concepts to present a coherent analysis of the reviewed literature. When necessary, contrast with similar concepts is presented to avoid ambiguities.

2.2.1. Biorefinery

The biorefinery concept has been used to refer to the biomass processing facility only (NREL, 2009), and also to biomass processing in a broader sense. The International Energy Agency (IEA) states that "biorefining is the sustainable synergetic processing of biomass into a spectrum of marketable food & feed ingredients, products (chemicals, materials) and energy (fuels, power and heat)" (IEA Bioenergy, 2014). Thus, through this definition, IEA describes the concept as a process, a facility or a cluster of facilities integrally covering the upstream, midstream and downstream processing of biomass (de Jong and Jungmeier, 2015).

Biorefineries are usually referred to as of 1st or 2nd generation according to the feedstock used as raw material. 1st generation (1G) biorefineries are those that use food crop resources such as corn sugar and vegetable oil, while 2nd generation (2G) biorefineries are those that process non-food materials, such as agricultural residues, wood and energy crops typically high in lignocellulose (Guo et al., 2015). Biorefineries that use algae biomass as feedstock have been referred to as 3rd generation (3G) biorefineries (Parajuli et al., 2015). The most established type of biorefineries are 1G, while 2G and 3G are still under development due to technical or economic challenges (Gerssen-Gondelach et al., 2014). As an illustration, ethanol biorefineries processing US corn and Brazilian sugarcane lead the global production with contributions of 58% and 25% respectively (Renewable Fuels Association, 2014), whereas cellulosic ethanol only started commercial operations in 2014 (Service, 2014).

Biorefineries can be further defined as systems based on four main features (Cherubini et al., 2009): i) platforms, such as sugars, oil and syngas; ii) energy and material products, like bioethanol, glycerol, lactic acid; iii) dedicated feedstocks and residues, e.g. forest residues, sugar and oil crops; and iv) processes, such as fermentation, gasification and pyrolysis. Then, the combination of these four features defines a specific biorefinery system, from feedstock to product.

2.2.2. Supply Chain

Supply chain refers to the link of actors and operations that allows the flow of materials from producer to consumer, passing through processes that convert these materials into products (Goetschalckx, 2011). Given the diversity of operations involved, the supply chain is often a network of different actors that may include convergent and divergent flows (Goetschalckx, 2011; Sharma et al., 2013).

Typically, a biorefinery supply chain includes five stages: feedstock production, feedstock logistics, conversion (or production), product distribution and product end-use (Liu and Eden, 2014). However, in the biobased economy the supply chain is sometimes specified as biomass supply chain, which indicates the biomass-to-conversion plant part of the chain, as described by Sharma et al. (Sharma et al., 2013). These supply chain stages are coordinated through supply chain management (SCM) to ensure an efficient product delivery to customers at a minimum cost to the system (Sharma et al., 2013; Yan et al., 2012).

In biorefinery research, supply chain and value chain are sometimes used interchangeably; however these two concepts have different implications (Holweg and Helo, 2014). Value chain refers to the value aspect of the chain, sometimes conveyed as demand originated at the customer side, while supply chain typically refers to the flow of materials from supplier to final customer (Andrew, 1999; Ramsay, 2005). Hence, while value chain activities focus on effective value creation considering also product innovation and marketing, supply chain activities are centred on the efficient delivery of materials

(Feller et al., 2006). Additionally, in some aspects supply chain stages can also overlap with the biorefinery system (for instance, separate pre-treatment and fermentation facilities as part of decentralized supply chains); however, these two concepts refer to different aspects of the biorefinery, as illustrated in Fig. 2.1. In this chapter, the term “biorefinery project” is used to generically refer to both the biorefinery system and its supply chain.

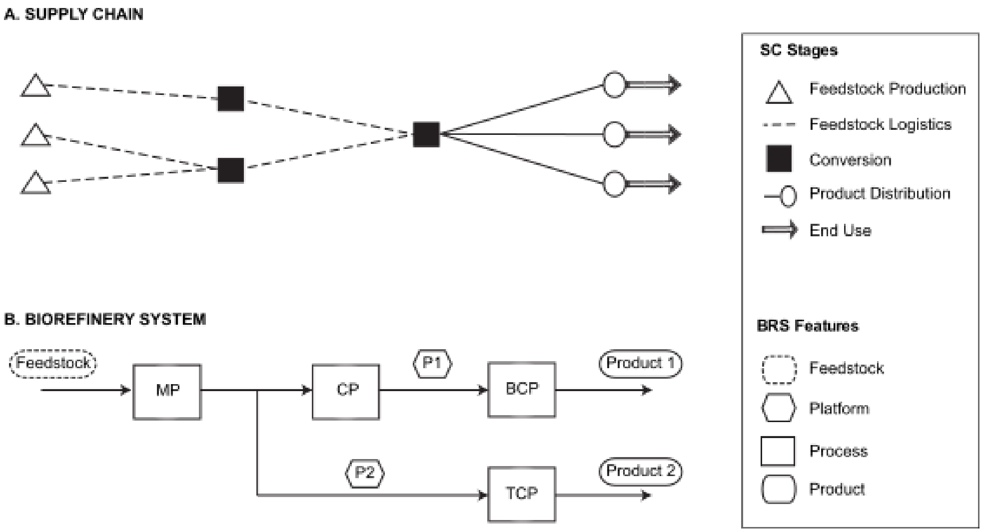

Fig. 2.1. Schematic example of a biorefinery project (supply chain and biorefinery system): As part of the supply chain (SC), feedstock from several locations is transported to distributed and centralized conversion centres, from which products are distributed to reach the final consumer and be used (A). In the biorefinery system (BRS), it is illustrated that feedstock pre-processing is mechanical (MP), and that chemical (CP), biochemical (BCP) and thermochemical (TCP) conversions are used to process two platforms (P1: Platform 1, P2: Platform 2) into two products (B).

2.2.3. Life Cycle

The life cycle of a product is defined as “consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal” (ISO, 2006). In contrast to a biorefinery system, supply chain and value chain, the life cycle concept typically refers to the scope of analysis of a system. Thus, a product’s life cycle refers to a system that starts with raw material extraction from the environment, like water or fossil oil, it covers any transportation, manufacturing and use of the product, and it ends with waste management related to the product’s disposal (Shabnam et al., 2012). A life cycle that considers these stages can also be referred to as a cradle-to-grave life cycle (Eskandarpour et al., 2015). A cradle-to-gate life cycle, indicates a system boundary until the production stage, while cradle-to-cradle refers to a life cycle that includes reuse, recovery or recycle of a product or its parts (Silvestre et al., 2014).

2.2.4. Design in Engineering

Design activities involve strategic decisions that will specify aspects of a project. After these decisions are taken, decisions at tactical and operational levels are made for design implementation. From strategic to tactical and operational levels, the space and the time scale of these decisions are reduced: on one side strategic decisions affect the project in long time scales, while operational level decisions affect the project in short time scales. Thus, broad strategic decisions are taken with the creation of design concepts that yield facilities and long term contracts, while narrower tactical and operational decisions are taken to plan and operationalize the design in shorter timeframes.

The design of biorefinery projects is based on different engineering disciplines, including supply chain and process engineering. These areas have in common an engineering-based design approach that follows sequential stages: problem definition, conceptual and detailed design, and design specification and implementation (Goetschalckx, 2011). Differences in these steps may arise according to disciplines or design approaches.

2.2.4.1. Supply Chain Design

Supply chain design is approached as the strategic planning or synthesis of a supply chain network, heavily relying on the use of models. Common modelling approaches in supply chain design are linear programming (LP) as sets of linear equations with continuous variables, and mixed-integer linear programming (MILP) that also considers integer variables (Yan et al., 2012). Nonlinear programming (NLP) and evolutionary algorithms are less commonly used than MILP and LP, as illustrated in the review on supply chain design by De Meyer et al. (2014).

Design variables for biorefinery supply chains are related to biomass selection, the capacity and location of facilities, and transport means for raw materials and products (Sharma et al., 2013) (Goetschalckx, 2011; Sharma et al., 2013; Yan et al., 2012). Since some of these strategic variables often have little impact on the distribution and use of biorefinery products, these later stages are sometimes not considered in supply chain models (Giarola et al., 2012), which already require large computational capacities (Yue et al., 2014).

2.2.4.2. Process Design

The aim of process design is to strategically synthetize the chain of sub-processes and conditions that will result in a complete production process. This strategic designing often follows a sequence from less to more detailed stages, which may combine product, process and equipment design (Dieudonné et al., 2012; Seider et al., 2010).

Research on process design is often focused on three activities: process synthesis, integration and optimization. In process synthesis, the process superstructure and sub-processes are created, often through a hierarchical decomposition of the process (Grossmann and Guillén-Gosálbez, 2010; Moncada et al., 2014) or other systematic approaches like the forward-backward approach (El-Halwagi, 2012) and synthesis algorithms for heat exchange and reactor networks (Grossmann and Guillén-Gosálbez, 2010; Seider et al., 2010). Integration, on the other hand, may relate to feedstock integration, process intensification, and energy and mass integration (Moncada et al., 2014). Optimization, on the other hand, can be approached by repeated simulations such as in sensitivity analyses, or with mathematical programming as for supply chain design. Combinations of mathematical programming with synthesis approaches have also been developed for optimization-based design (Grossmann et al., 1999; Grossmann and Guillén-Gosálbez, 2010). However, optimization algorithms integrated in simulation software, in combination with heuristics, are the most common way for process optimization in practice (Seider et al., 2010).

2.2.5. Sustainability

The Brundtland report (World Commission on Environment and Development, 1987) sparked the interest in sustainability by stating that "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Hofer and Bigorra, 2008). From this classic definition it is derived that sustainable development does not impair the quality of life of future generations "here and elsewhere" (de Vries and Petersen, 2009). Sustainability, as a twin notion to sustainable development, has been considered to englobe the integral balance of three dimensions: economic, environmental and social, where poor performance related to one could hinder performance on the others (Kemp and Martens, 2007; Leadership Council of the Sustainable Development Solutions Network, 2013).

Biorefinery systems have often been considered inherently sustainable due to the renewability of biomass. However, this has been recently refuted given that sustainability is not founded exclusively on renewability or on the environmental dimension (Pfau et al., 2014). Therefore, it is acknowledged that for the development of sustainable biorefinery projects all dimensions of sustainability must be taken into account, which implies, for instance, considerations on by-product valorisation, erosion, food security, land use, property rights, among others (Azapagic, 2014; Cambero and Sowlati, 2014; Rai et al., 2010).

The interpretation of sustainability remains a debatable subject even if definitions as the one presented above are widely accepted. This is largely related to: 1) the fact that environmental and economic aspects are quantitative, while social sustainability is often measured in qualitative terms; and 2) the flexibility of the sustainability concept, which is often reduced to subjective interpretations derived from the norms and values of individuals who seek to implement it (de Vries and Petersen, 2009; Hedlund-de Witt, 2013; Janeiro and Patel, 2014; Kemp and Martens, 2007; Van Opstal and Hugé, 2013). The latter relates to differences in worldviews, which has been studied in relation to the bioeconomy (see De Witt et al. 2015). For example, the use of genetically modified (GM) crops for biomass production can be viewed as a technology allowing a production of low-input, high-yielding, “sustainable” biomass resources, while from a different perspective the same technology is seen as a threat to biodiversity, health or farmers self-sufficiency, and is hence considered a risk to “sustainability” (Hedlund-de Witt, 2014; Lotz et al., 2014). In biorefinery projects this subjectivity becomes highly relevant as a large diversity of stakeholders, including the chemical and agricultural industries, government and non-governmental organizations, is often involved in their development.

2.2.5.1. Concepts for Evaluating Sustainability

Evaluations of performance in relation to sustainability can be used as a tool for designing or assessing biorefinery projects. These evaluations are often based on the use of indicators that represent the severity of the project’s impact on a specific aspect of sustainability according to the evaluation method. For instance, methods for the environmental life cycle assessment (LCA) methodology consider indicators like infra-red radiative forcing and phosphorus concentration for the climate change and eutrophication impact categories (Goedkoop et al., 2013; Institute for Environment and Sustainability, 2010). In some assessment methods, environmental or social mechanisms are used to relate so-called midpoint impact categories to endpoint impacts or damages. Thus, CO2 emissions can be used directly as a stand-alone indicator for environmental performance, they can also be accounted together with other GHG emissions through their global warming potential as impacts on global warming (midpoint level). Additionally, global warming impacts can be further evaluated as damages on human health (endpoint-level) through mechanisms related to, for instance, alterations in disease frequency and population displacements, (Goedkoop et al., 2013). Furthermore, some impacts cannot be quantified or are better described by qualitative features, especially when dealing with impacts on society (Benoit and Vickery-Niederman, 2011). In these cases, indicators of qualitative nature may be used to relate the project to impact categories through semi-qualitative analyses, for instance with 1 to 10 scales (Wu et al., 2014).

Indicators, methods and methodologies can address one, two or three of the dimensions of sustainability (i.e. economic, environmental and social). Considering this dimensionality aspect, assessment tools can be considered as mono-dimensional (1D), bi-dimensional (2D) or tri-dimensional (3D). Thus, 1D relates exclusively to economic, environmental or social impacts; while 2D covers either socio-environmental, socio-economic, or economic-environmental impacts; and 3D relates to an integral sustainability in its three dimensions (Fermeglia et al., 2009; Sikdar, 2003). Furthermore, metrics based on mass and energy balances directly have also been used to describe the efficiency or technical performance of a project. These indicators are sometimes considered as a measure of economic and environmental sustainability impacts of a project given their relationship to resource use and operational cost, and are often used for sustainable process design or in energy analyses (Kalinci et al., 2013; Ojeda et al., 2011; Ruiz-Mercado et al., 2011; Wall and Gong, 2001; Zvolinschi et al., 2007).

2.3. Methodology of Literature Review

This systematic literature review is based on a literature search done in the multidisciplinary database web of knowledge. The search terms used as queries were biorefinery related (biorefinery, biofuels, bioenergy, bioproduct, bioplastics), design related (design, evaluation, assessment, optimization) and sustainability. The time period was defined from 2005 to present time (mid-2015). The mid-2000s is considered a reasonable point to start finding sustainability approaches, and a way to limit the number of papers that would otherwise be mostly focused on economic or environmental aspects only. The query results were screened through title and abstract analysis, yielding a sample of 78 papers related to the design of sustainable biorefinery projects, marked with an asterisk (*) in the reference list.

According to this systematic literature search, this review covers current practices for sustainable biorefinery design. Although not all existing approaches are covered in this literature sample, the analysis is enriched with references known in the field, identified through snow-ball sampling and expert recommendations and yielding 84 papers (the time frame of these was not restricted). Furthermore, this review is focused on methods and metrics for integrating sustainability in the design phase of biorefinery projects as applied or proposed in the reviewed literature. Therefore, research papers on the evaluation of existing biorefineries are not necessarily part of the reviewed literature.

The analysis on the incorporation of sustainability in the design of biorefinery projects is elaborated in two parts: first, methods and metrics for evaluating sustainability are analysed according to sustainability dimensionality (i.e. economy, environment and society) and efficiency (i.e. energy, exergy and mass); then the incorporation of these method and metrics is analysed according to the relevant design activities (e.g. as an assessment of a base case or as an objective of optimization) and stakeholder inclusion. From this analysis, the most important challenges and opportunities for sustainable biorefinery design are identified and discussed in Section 2.5.

2.4. Results and Discussion

The section covers the findings on the incorporation of sustainability in the design of biorefinery projects. In section 2.4.1, methods, impact categories and indicators of sustainability used in the reviewed literature are analyzed according to sustainability dimensionality and the use of efficiency metrics. Then, an analysis of how sustainability is, or is intended to be, incorporated in the designing of biorefineries is presented in section

2.4.2. Also a review on how different perspectives have been considered in the design for these projects is presented as part of section 2.4.2.

2.4.1. Sustainability in Biorefinery Project Design

Sustainability considerations have increasingly been incorporated in biorefinery design, as indicated by the number of publications in the last years (see Fig. 2.2A.) However, most of the publications consider impacts on the economic and environmental dimensions of sustainability, while the social one is often omitted. Furthermore, efficiency indicators have also been used in combination with metrics that fall in the dimensionality classification (except in (De Meyer et al., 2015; Peralta et al., 2010) that use only efficiency metrics). These efficiency indicators are used to describe the efficiency of a project mostly in relation to energy, as presented in Fig. 2.2B.

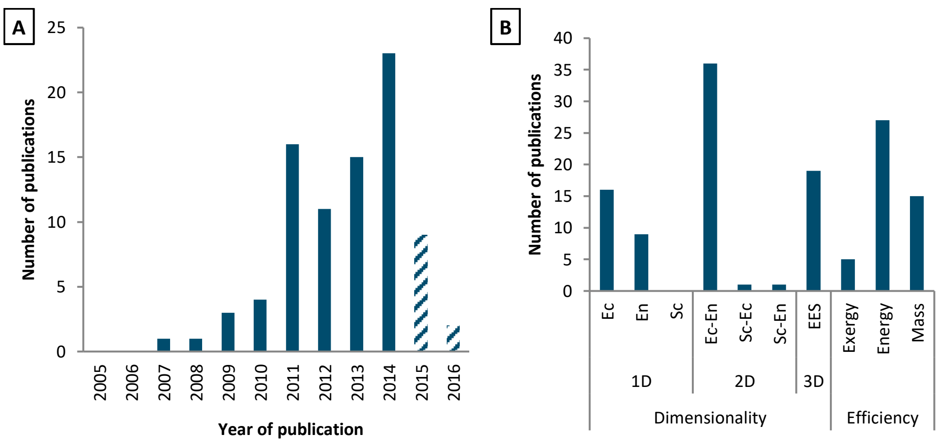

Fig 2.2. Overview of the 84 reviewed publications. A: Number of publications per year. The dashed bar represents the number of publications only until mid-2015 when the search was performed. B: Number of reviewed publications according to the dimensionality and efficiency metrics. The frequency of efficiency metrics is not exclusive as they are often used in combination with others (e.g. a 1D publication that considers environmental sustainability, energy and exergy efficiency metrics is accounted in the "1D En", "Exergy" and "Energy" bars). Ec: Economic, En: Environmental, Sc: Social, EES: Economic, Environmental and Social. See section 2.3 Methodology of Literature Review for details on the search.

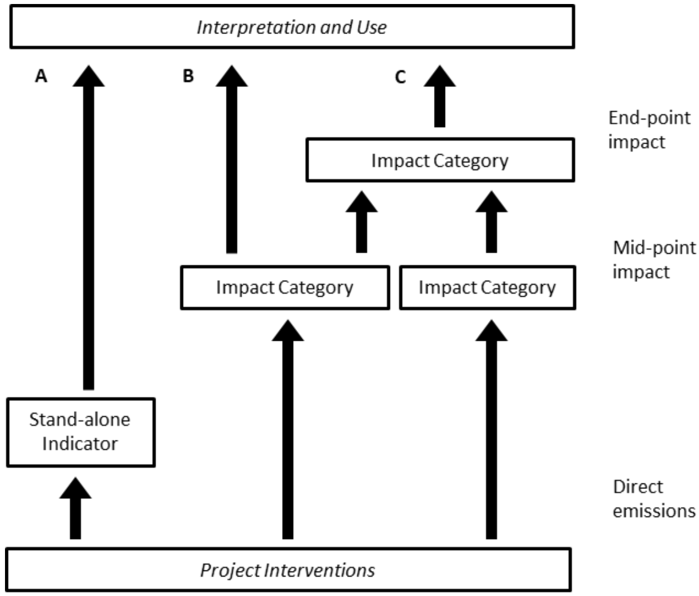

Fig. 2.3. Schematic representation of how project interventions (i.e. emissions, resource use, products) are analysed for the incorporation of sustainability for biorefinery design. The impact of project interventions on different aspects of sustainability has been analysed and expressed as (A) direct stand –alone indicators (e.g. CO2 carbon emissions, total energy use), (B) impact categories that combine different indicators or use mechanisms to express emissions as midpoint impacts (e.g. global warming impact as the sum of greenhouse gas emissions' global warming potential relative to that of CO2 in a given time frame), and (C) impact categories that combine different impacts at the midpoint level (e.g. human health impacts estimated from impacts on climate change, particulate formation, human toxicity, etc.). Typically, studies following the approach described in C are based on well-known assessment methods like the LCA Ecoindicator-99.

Incorporation of sustainability aspects in design of biorefinery projects has been done through different metrics and methods. In this review, these are categorized as stand-alone indicators, impact categories and methods that cover different dimensions of sustainability. Then, as schematized with line A in Fig. 2.3, in some cases indicators are interpreted or used directly in design activities, e.g. CO2 emissions as indicator in an optimization framework for the identification of optimal bioenergy sources (Iakovou et al., 2012). In some cases, several indicators are combined or analysed through specific mechanisms to represent impact categories that are then used in design, (see line B in Fig. 2.3). For instance, Cheali et al. (2015) use a process cost and environmental impact category (PCEI), calculated as a combination of efficiency and process specific indicators, in an optimization framework for the design of a lignin upgrading biorefinery. In the work of

Tock and Marechal (2012), GHG emissions, normalized to CO2 equivalents based on global warming potentials (GWP), are used for process design as a measure of the contributions to the climate change environmental impact category. Furthermore, in the studies where endpoint LCA methods were used, impact categories are further analysed as endpoint impacts or damages to for instance, human health (Fig. 2.3, line C). In this result section, we discuss midpoint and endpoint impact categories together to avoid further complications with the analysis, however, when necessary for discussion, this aspect is mentioned.

2.4.1.1. Economic Sustainability

The economic dimension of sustainability is often considered in the design of biorefinery projects, mostly through profitability or techno-economic analysis (TEA) where technical aspects of engineering projects are analysed in economic terms. Indicators used in economic analyses in the reviewed papers are numerous, as shown in Fig. 2.4. However, these metrics are mostly related to three topics: costs, profits and margins, and value of investment. Out of these three, the most common economic indicators are production cost, gross profit and net present value (NPV), (Fig. 2.4).

Costs indicators are a measure of economic performance often used to compare biorefinery alternatives for producing a given product or processing a particular raw material. For example, Coleman et al. (2014), compare the production cost of different microalgal fuel production systems and locations combining biomass assessment and logistics models. However, costs metrics per se do not reflect the economic performance of the project since expected revenues are not considered for their calculation.

Profit, on the other hand, is an indicator based on costs and revenues, and can thus be used for comparisons of systems with different products. For example, Ng et al. (2015) use gross profit as an objective function for optimization-based design, in which different systems of product alternatives and related processes are evaluated. Furthermore, when differences in capital requirements among different alternatives are expected to be minor or when capital costs are not yet known, a gross operating margin can be used as indicator of economic potential at the early-stage of a project. An example of the latter case is the study by Field et al. (2013), where an operational cost model is used to investigate design trade-offs and alternative uses of biochar for bioenergy production, where differences in capital cost are expected to be minimal. Evidently, this type of high-level analysis is suitable when exploring different concept alternatives and data availability is an issue, but it cannot be taken as a realistic indication of the economic potential of a project.

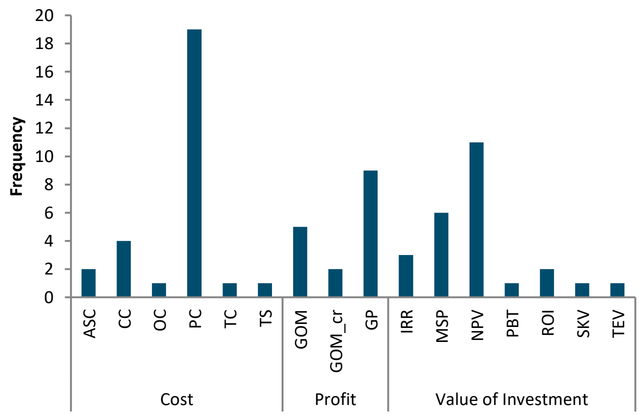

Fig. 2.4. Frequency of use and topic of economic indicators found in the 84 reviewed papers. Economic indicators used as part of impact categories are excluded from this figure. ASC: Actual sequestration cost, CC: capital cost, OC: operating cost, PC: production cost, TC: transportation cost, TS: total savings, GOM: gross operating margin, GOM_cr: credited gross operating margin, GP: gross profit, IRR: internal rate of return, MSP: minimum selling price, NPV: net present value, PBT: payback time, ROI: return on investment, SKV: stakeholder value, TEV: total economic value. See the Appendix I for the list of indicators and their definition.

Other indicators are those related to the investment value of a project. For example, NPV is a measure based on cash flows of the project throughout a future period of time under a defined discount rate. This metric is useful for estimating the value of long term projects and can also be a communication tool with business teams. Although this type of metrics can be very sensitive to considered discount rates or other assumptions (Seider et al., 2010), it is still widely used in the reviewed literature (see Fig. 2.4). For example, in the work by Karschin and Geldermann (2015), NPV is used as an economic indicator given the well-defined conditions of the system (i.e. fixed electricity prices). Another common metric for economic potential is the minimum selling price (MSP), price at which a product would yield a defined profitability. This metric has been used to evaluate the potential competitiveness of a process in the market, as part of their techno-economic analysis. For instance, Tan et al. (2016) conclude that their process for the production of high-octane gasoline from biomass is potentially cost-competitive to conventional fossil alternatives, making it an interesting option for further research. Zhu et al. (2013) also use MSP to evaluate the economics of processing algal biomass residues into liquid fuels, and find that it is competitive with conventional fuel prices only with large-scale centralized facilities supported by a neighbouring large-scale algae production site.

Policy benefits or taxes on emissions and resource use are also considered for evaluating the economic performance of project alternatives under different policy scenarios. For example, in the optimization model developed by Kantas et al. (2015), penalty costs for water usage and CO2 emissions are accounted as operating costs when these are higher than predefined limits. However, given the unpredictability of these measures, such analyses carry uncertainties with large impacts on the project set-up. For example, in the same study (Kantas et al., 2015) it was found that the optimal raw material mix for the biorefinery can change considerably under different CO2 penalty costs, having significant impacts on biomass cost, supply contracts and processing technology.

These economic metrics used in the reviewed literature generally reflect the performance of the project on microeconomic terms, mostly to analyse costs and profits related to the project. Some authors have discussed that this type of analysis on its own does not represent economic sustainability, calling for analyses on the project's potential to add value to the economy (Keller et al., 2015; Wood and Hertwich, 2013; Zamagni et al., 2013). This macroeconomic benefit perspective is rarely addressed in the reviewed literature, and is included only in the assessment work by Gheewala et al. (2011), where the increase in gross domestic product and tax revenues to the region in relation are used for quantifying the human development and total value categories in their assessment of a biorefinery project.

2.4.1.2. Environmental Sustainability

Environmental sustainability has been included in the design of biorefinery projects through methods that indicate expected environmental impacts of the project. Interestingly, EcoIndicator99 (EI99) is the only LCA method referenced in the reviewed literature. This finding is in agreement with the fact that EI99 is a method based on endpoint damage functions presented as a single indicator, making it simple to implement (Goedkoop and Spriensma, 2001; Institute for Environment and Sustainability, 2010). For example, Santibañez-Aguilar et al. (2014) used the eco-indicator directly as environmental optimization objective for the planning of multiproduct biorefinery projects. As the authors discuss, by using this single indicator, the entire range of environmental impacts related to the project's life cycle, and an indication of social impacts through the analysis of damages to human health, are included in the analysis. However, this method has the limitation that most categories are modelled based on the European situations (except global categories like climate change and ozone depletion), and may thus not be adequate for cases with other geographical scope (Goedkoop and Spriensma, 2001; Institute for Environment and Sustainability, 2010). This method characteristic is not addressed in the reviewed papers, some of which are based on non-European contexts.

Another systematic approach for the inclusion of the environmental dimension in biorefinery design is the WAR algorithm. This method is used to determine the potential environmental impact of a chemical process (Li et al., 2011) through impact categories related to global atmospheric and local toxicological effects (Young et al., 2000). Some of the impact categories in the WAR and EI99 methods are similar, like ozone layer depletion in EI99 and the ozone depletion potential in the WAR algorithm (Goedkoop and Spriensma, 2001; Young et al., 2000). However, while in the WAR algorithm impact categories are directly normalized and weighed for obtaining a single index, EI99 impact categories are further analysed as endpoint impact categories (i.e., human health, ecosystem and resources), and are then normalized and weighted into a final indicator. This endpoint-midpoint difference has been discussed in relation to LCA methods and summarized as a trade-off between certainty at the midpoint level, and relevancy or ease of use at the endpoint level (Bare et al., 2000).

These methods for environmental assessment have also been applied in separate analyses along the main design method of the study. For instance, Gebreslassie et al. (2013a) and Wang et al. (2013) present economic-environmental optimization based on the combination of NPV and GWP as objective functions, where EI99 is applied only on found optimum design alternatives and is not part of the developed optimization framework itself. Thus, the design is synthetized considering climate change as the only environmental topic. Yet, given that the results of these optimization frameworks are presented as Pareto sets of solutions, the separate EI99 assessment is actually useful to analyse the trade-offs between different solutions, and thus include a broader environmental analysis.

However, environmental considerations have mostly been incorporated in biorefinery design through the inclusion of stand-alone indicators and impact categories, i.e. indicators and impact categories that are not part of an established method like the EI99 and WAR algorithm. These metrics are mostly related to the climate change topic. That is, from the papers that covered any environmental issue, about two thirds were related to GHG emissions and global warming (GW). This predominance of climate change related metrics is shown in Fig. 2.5, where stand-alone environmental indicators used directly for biorefinery design activities are presented.

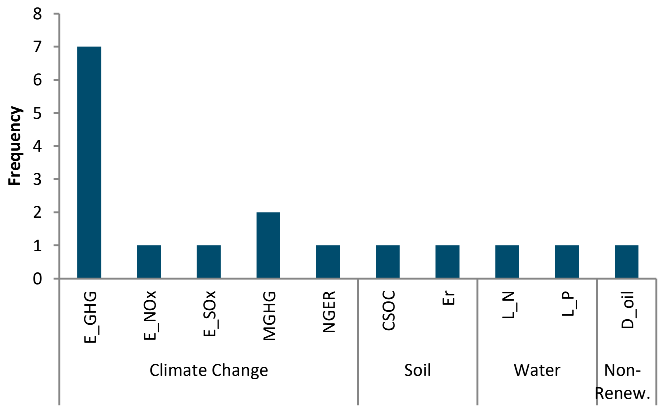

Fig. 2.5. Frequency of use and topic of stand-alone environmental indicators found in the 84 reviewed papers. E_GHG: Greenhouse gas emissions, E_NOx: nitrogen oxides emissions, E_SOx: sulphur oxides emissions, MGHG: mitigation of greenhouse gases; NGER: net greenhouse gas emission reduction; CSOC: change in soil organic carbon; Er: erosion; L_N: nitrogen leaching; L_P: phosphorus leaching; D_oil: Petroleum oil use displacement. See the Appendix I for the list of indicators and their definition.

Global warming or climate change impacts are often considered in design as an impact category on environmental sustainability, derived from GHG emissions related to the biorefinery project. These emissions are accounted as CO2 equivalents, often in reference to the IPCC global warming potential (GWP), and are sometimes estimated with the use of models and databases, like the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model. For instance, in the work by Zamboni et al. (2011), a life cycle GWP is used for a "life cycle optimization" design approach of biorefinery projects. Thus, the author includes environmental and economic objectives to optimize a biorefinery project, which are further analysed regarding relevant legislation limits for biofuels, also expressed in GWP terms.

In some cases, CO_2 emissions are interpreted directly as impacts on environmental sustainability, and sometimes they are simplified by considering only CO_2 emissions in certain parts of the project. For example, Sharma et al. (2011) and Shastri et al. (2011) estimated GHG emissions from CO_2 emissions related to production, utility generation and transportation. This simplification approach might be handy for high level estimations; however it must always be taken into account that GHG emissions are relevant in all stages of the biorefinery project (Efroymson et al., 2013). Furthermore, emissions from agricultural stage can be far from negligible, with large GHG emissions due to, for instance, land use changes (Akgul et al., 2012) and high fertilizer dosages (Fan et al., 2013).

The pronounced incorporation of GHG and GWP in biorefinery design (Fig. 2.5), may be due to the biofuels potential for reducing GHG emissions, considered one of the main drivers for biofuel development (Azapagic, 2014), with greenhouse emission criteria in policies like the EC Biofuels and Bioliquids Sustainability Scheme and the Renewable Fuel Standard in the US (United Nations, 2014). However, environmental sustainability is not only affected by global warming and climate change, but by many other phenomena, like biodiversity losses, soil erosion and eutrophication, which are often context specific and could be critical in the development of biorefinery projects (Efroymson et al., 2013). Although some metrics related to these topics have already been used to include these issues in biorefinery project design, such as the nitrogen losses and erosion indicators, the use of this type of metrics remains limited as shown by number of publications in which these are used (see indicators related to soil and water topics in Fig. 2.5).

2.4.1.3. Social Sustainability

The social dimension of sustainability, in contrast to the economic and environmental ones, has been modestly considered in the design of biorefinery projects. That is, out of the 84 papers reviewed in this study, social sustainability was included at the indicator level in only three papers, as summarized in Fig. 2.6 (Akgul et al., 2012; Kempener et al., 2009; Schaidle et al., 2011) (multidimensional metrics that include the social dimension of sustainability are similarly scarce and are discussed in the next section). This low regard for social issues in biorefinery design is in line with other engineering practices, which have only recently started to consider the social aspects of new product developments (i.e. the “who and why” of the social aspects, as complimentary to the “what and how” of the technical aspects in socio-technical engineering design (Seider et al., 2010)). This minor attention for impacts on society in biorefinery design might be due to the historically long disengagement between the social and the natural and engineering sciences. Yet, some of the review publications do cover topics in the social sustainability domain; food and energy security at the indicator level, and education and life expectancy at the category level, as discussed below (see Fig. 2.6).

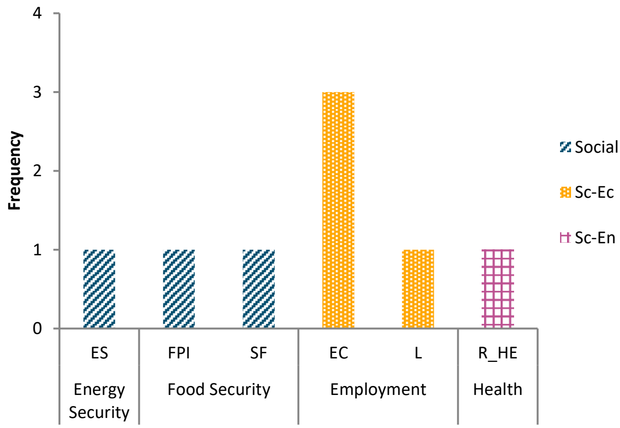

Fig. 2.6. Frequency of use and topic of stand-alone social, socio-economic (Sc-Ec) and socio-environmental (Sc-En) indicators found in the 84 reviewed papers. ES: Energy security index, FPI: food price increase, SF: sustainability factor, R_HE: human exposure risk, EC: employment creation, L: labour requirements. See the Appendix I for the list of indicators and their definition.

Food security is an important issue for the bioeconomy since both food and biobased materials are produced from biomass, and thus require land. Although recent studies state that food and biobased production do not necessarily compete for resources, and that there can even be synergies amongst both industries, this still depends on how bioeconomy research, projects and policies are developed (Souza et al., 2015). For example, food security is addressed by Schaidle et al. (2011) through a semi-quantitative indicator that considers the feedstock type used in the biorefinery project, based on the fact that cellulosic feedstock is considered to have a low impact on food prices relative to corn. Food security has also been incorporated in optimization-based design with the use of a sustainability factor constraint, which limits the use of domestic biomass for biofuel production (Akgul et al., 2012). Thus, the limitation on biomass for fuel is considered to address the competition for land that otherwise would take place between fuel and food production. These two metrics address the food security topic, which has been scarcely addressed in biorefinery design, in a simple manner. However, the simplification of complex situations, like in the case of the bioeconomy, should be complemented with other strategies for food security, as these metrics alone do not define possible synergies between food and biobased production (Osseweijer et al., 2015).

Energy has strong implications of economic and political importance related to, for instance, modern production means and technologies, and long distance transportation. Energy can also have an impact on social development, as illustrated by an increase in the Human Development Index (HDI, related to education, health and wealth levels) with increasing energy use up to about 100 GJ/person/year at 80% - 90% HDI (Souza et al., 2015). With its more distributed nature (in comparison to fossil resources), biobased production has the potential to increase energy security in regions that are currently dependent on foreign energy resources or regions that even today are energy deprived (Nuffield Council on Bioethics, 2011). Also, bioenergy is an alternative to fossil resources when other renewables are not an options, e.g. in marine and aviation transportation (Dale and Ong, 2014). However, as discussed in Souza et al. (2015), bioenergy developments need to be dealt with congruent policies and management practices that ensure sustainable energy access and affordability. This point can also be brought to the design stage of biorefinery projects, where feedstock, scales, product portfolios, etc., are decided. In the reviewed literature, energy security in the design of biorefineries has been included through the maximization of an energy self-sufficiency indicator. This indicator expresses energy provision by a biorefinery project relative to demand in the project's geographical region (Kempener et al., 2009). The inclusion of an energy security indicator can be perceived already as a step forward for including sustainability concerns related to the bioeconomy. However it should be noted that this metric does not address issues of involvement of local communities or industries that might perceive no difference in, for instance, a change from fossil to biobased energy. Interestingly, the authors use the metric in an optimization framework that is combined with an agent-based modelling approach to analyse and assess bioenergy networks, including local organizations responses along the duration of the project.

Other metrics used in the reviewed literature that are based on regional levels are the education and life expectancy measures (Gheewala et al., 2011), which contribute to the Human Development Index. These indicators are based on observations of differences between national and regional levels where the project is placed. Although these metrics based on existing cases can provide information for new biorefinery developments, they rely on already existing data that is not always available, or is not transferable to new projects. That is to say, data from previous biorefineries is not necessarily applicable in future cases as these might be based on entirely new processes and raw materials.

Despite the fact that social indicators used in the design of biorefineries cover diverse topics in contrast to those in the environmental domain, their use is still uncommon (see Fig. 2.6). Furthermore, from the papers reviewed in this study, these indicators were only used in the same studies in which they were defined, with the exception of the energy self-sufficiency indicator in the study by Kempener et al. (2009), which was initially described in (Beck et al., 2008). Also, it is relevant to remark that social impacts might require the inclusion of actors relevant to the project, which is rarely addressed in the reviewed papers (further discussion is presented in section 2.4.2.4).

2.4.1.4. Multi-dimensionality

The previous sections covered different approaches to address separately the three dimensions of sustainability in the design of biorefineries. This section discusses approaches that have been developed by academics and professional organizations to address multiple dimensions of sustainability at once in engineering projects. An example of such approaches are the metrics from the Institution of Chemical Engineers (IChemE), which consider environmental indicators related to resource usage, emissions and other outflows; economic indicators like profit, tax and investments; and social indicators related to the workplace and society (IChemE, 2002). However, these metrics are meant to evaluate the performance of equipment, unit operations and processes, and some are exclusively of operational nature. For instance, IChemE's Society Metrics are based on performance, e.g., on the base of employees who have resigned or been made redundant, which are not easily transferred to ex-ante evaluations (IChemE, 2002). In this review it was found that although these IchemE sustainability metrics are sometimes incorporated in the design of biorefinery projects, the social indicators were in all cases excluded (Kasivisvanathan et al., 2012; Ng et al., 2013; Shabbir et al., 2012).

Other approaches that combine metrics related to different dimensions of sustainability are for instance those presented by Cheali et al. (2015) (metrics originally published by Posada et al. (2013)) and Sacramento-Rivero (2012). In the first publication, different economic, environmental and efficiency metrics like costs, GHG emissions and energy efficiency are combined with more detailed process metrics for sustainable process synthesis (Cheali et al., 2015). These metrics, embedded in a superstructure optimization framework, were used to obtain biorefinery designs for production of ethanol derivatives that outperform fossil based approaches (Cheali et al., 2015). By contrast, the framework proposed by Sacramento-Rivero (2012) is based on four categories related to feedstocks, processes, products, environment and corporate themes. The author defines these themes and their metrics to assess impacts on sustainability, covering the dimensionality and efficiency classifications, intended for both monitoring and design phases. Although these two frameworks do cover impact categories along the three dimensions of sustainability and efficiency metrics, they are still limited with regards to the analysis of impacts to society. In the sustainability index of Cheali et al. (2015), health and safety, a socio-environmental aspect (discussed below) is the only topic related to society. On the other hand, in the framework proposed by Sacramento-Rivero (2012), the corporate category with relevance to society is not applicable at the design stage, similarly to the IChemE society metrics mentioned above (IChemE, 2002; Sacramento-Rivero, 2012).

Some impacts can be considered to relate to more than one single dimension of sustainability (see Fig. 2.6 with an overview of multi-dimensional indicators used in the reviewed literature). This is the case of employment impacts, which have been used as part of the economic and social analysis of projects. For example, in the optimization studies by Cucek et al. (2014) and Kantas et al. (2015), labour costs are part of a single economic objective function to be minimized. In fact, labour requirements expressed as costs, are often accounted in the techno-economic analysis for estimating processing cost, and are thus considered an economic topic. Contrastingly, Santibanez-Aguilar et al. (2014) and You et al. (2012) use employment requirements (or jobs created) as a social objective function to be maximized as a benefit to society, illustrating them as opposed to the economic objectives (profit or costs) of their projects. Remarkably, in the work by Ayoub et al. (2009), a labour social objective function expressed as number of workers, is presented as objective function to be minimized or maximized depending on the project context, which in their case is in fact minimized according to discussed population issues in Japan. This labour requirement or job creation metric illustrates the importance of taking the context into consideration in sustainability analyses.

Impacts on human health are also found in relation to two dimensions of sustainability, the environment and society, which was briefly commented by Santibanez-Aguilar et al. (2014). In the reviewed papers, human health impacts are considered in widespread methods like EI99 and the WAR algorithm as environmental impacts, while these aspects are also accounted in the IChemE sustainability metrics as society impacts.

Health and safety indicators are also sometimes proposed in combination with (techno-) economic and environmental indices as measures of sustainability, thus inferring a correlation between health and safety impacts and society (Cheali et al., 2015; Ng et al., 2012). In general terms, it is observed that human health impacts, considered as environmental impacts, are typically analysed through measures of exposure to emissions as occupational health issues (like in the WAR algorithm) or as health effects related to global environmental phenomena (e.g. ozone depletion in EI99). In the cases where human health impacts are considered social impacts, besides accounting for occupational effects as mentioned above (like in (Cheali et al., 2015; Ng et al., 2012; Schaidle et al., 2011)) these impacts are in some cases measured through other indicators related to frequency of accidents (IChemE, 2002; Sacramento-Rivero, 2012), and the existence of occupational and environmental health and safety systems (Sacramento-Rivero, 2012). However, it is clear that the latter measures are not available at the early design stages of a project.

It is remarkable that some studies included a combination of indicators from different dimensions of sustainability, thus attaining multidimensional analyses. However, in some of these studies, this multi-dimensionality is only achieved through the use of limited aspects in these dimensions, particularly in relation to social sustainability as mentioned above. For instance, in the 3D works of You et al. (2012) and Golberg et al. (2014), employment creation is the only social sustainability impact considered, while in the works by Gebreslassie et al. (2013b) and Wang et al. (2013) it is health impacts that take this role. This is further illustrated in Fig. 2.7, where impact categories used in the reviewed literature are placed in a dimensionality scheme (circles as dimensions, and their overlap as multidimensional areas) and topics related to these categories are explicit. For instance, the Crop Sustainability metric (CSI) (Golberg et al., 2014), is an impact category composed of water efficiency, polluting chemical release and employment metrics that place it in the overlap of economic, environmental and social dimensions. However, social and economic dimensions are represented solely by the employment metric and thus allow a limited analysis of social and economic sustainability. However meritorious it is that engineering projects consider sustainability beyond the more common economic and environmental aspects only, there is clearly a need for improving the integration of social sustainability aspects for sustainable biorefineries.

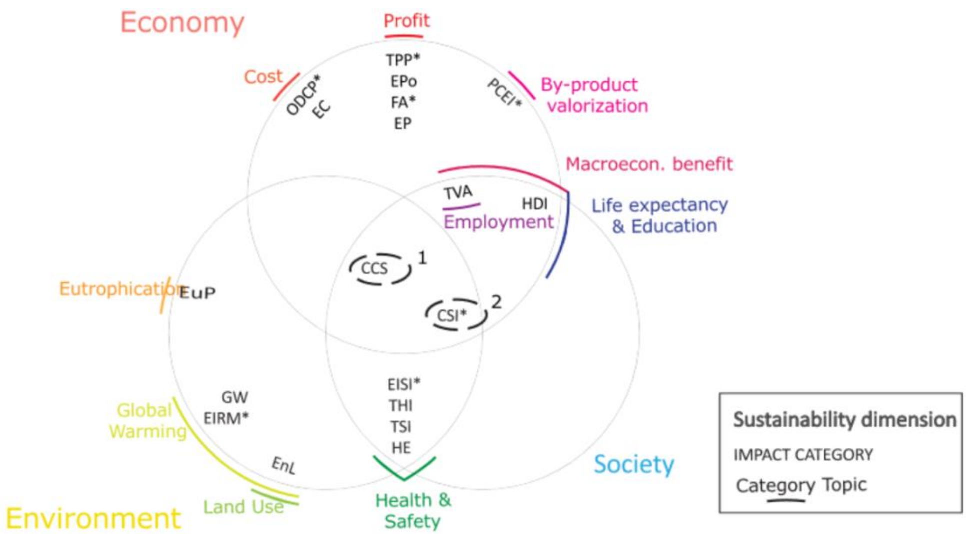

Fig. 2.7. Overview of impact categories in the reviewed literature, according to dimensionality (impact categories group multiple indicators, or are defined through specific mechanisms for their calculation, see section 2.4.1 for more details). In this figure, impact categories used in the reviewed literature are grouped according to common topics. For instance, GW, EIRM and EnL are impact categories based on environmental metrics that cover the climate change topic; EnL additionally addresses land use. 1: health, social investment; 2: pollutant emissions, employment. An asterisk (*) indicates that efficiency metrics are also part of the relevant impact category. No frequency is presented in this figure as almost all categories are used once; the outstanding exception is GWP potential referenced in 35 papers. See the Appendix I for the list of impact categories, their definition and authors that cite them.

In a recent study, Dale and Ong (2014) proposed a design framework considering a broader sustainability view based on objectives (related to economic, environmental and societal dimensions of sustainability) and not on particular sustainability indicators. Thus, by defining sustainability through objectives, the authors avoid limiting the concept to any particular set of metrics and leave it open to those of interest in a given context (although it can be discussed that by defining sustainability objectives the concept is already restrained at some level). Although some indicators are indeed suggested, the question remains if the same issues related to social IChemE metrics (discussed earlier in this section), would be faced following this approach, and how trade-offs in conflicting situations are to be dealt with.

2.4.1.5. Efficiency Metrics

Efficiency metrics indicators have been used to refer to the efficiency of the system with respect to mass and energy inputs and outputs. Efficiency indicators are often used in the process engineering domain, where they can be useful for identifying improvement opportunities in the design, for instance, through energy or mass integration at early stage design (Ruiz-Mercado et al., 2013). Furthermore, indicators in this category have also been useful to compare different systems beyond the production process, like the use of energy efficiencies when comparing different bioenergy system alternatives (Ayoub et al., 2009).

Energy efficiency indicators have been predominant in biorefinery projects, as illustrated in Fig. 2.2. These energy indicators provide information regarding the efficiency of energy resources use, sometimes considered indirectly related to environmental and economic sustainability, and also to socio-economic issues as mentioned in section 2.4.1.3. Also, given that most biorefinery products are energy products themselves, these metrics also provide information regarding the systems efficiency to convert raw materials into the target product without the need of a second indicator, like mass yields. Thus, energy efficiency indicators are often used to both compare and improve a production process based on the energy balance of a system. For instance, Caliandro et al. (2014); Tock and Marechal (2012) used the energy content of the product over energy inputs to assess the efficiency of process alternatives. This efficiency indicator, in combination with other economic and environmental metrics, was then used for heat and energy recovery as part of optimization frameworks used to improve the design.

Exergy, a measure of energy quality defined as the “maximum amount of work that can be extracted from a stream as it flows towards equilibrium” (Li et al., 2011), is also a common efficiency metric for biorefinery design, as shown in Fig. 2.2. Like energy metrics, exergy has been widely used to analyse and improve processes (Ng et al., 2012; Peralta et al., 2010). Furthermore, exergy indicators have been discussed to provide more relevant information for environmental and economic analyses than energy metrics, given that exergy is a measure of the usability of energy, not just quantity (Kalinci et al., 2013). For example, Cohce et al. (2011) used both exergy and energy measures to identify sub-processes and parameters that had a strong impact on the efficiency of a hydrogen production process. Although both metrics indicated similar efficiencies for the evaluated process, exergy analysis allowed to identify sub-processes where energy quality was lost, which is not possible with energy analysis only. Regardless of the broader scope that exergy analysis allows, in biorefinery project design this is not yet a common practice, which may be in part due to the historical place of energy balances in process engineering.

In addition to energy and exergy, other topics are also addressed through efficiency metrics, typically in reference to mass losses. For instance, water use is an indicator mostly used in relation to the efficiency of the conversion process (Bernical et al., 2013; Schaidle et al., 2011), although crop water use efficiency related to the evotranspiration phenomenon has also been applied for analysing biomass production configurations (Eranki et al., 2013). Also, efficiency metrics are used to analyse how much (potential) product is lost in the system through metrics like carbon efficiency (Bernical et al., 2013) or product losses (de Figueiredo and Mayerle, 2014). Clearly these metrics address topics of interest for each case, i.e. water efficiencies related to water availability concerns, carbon yield and product losses related to emissions or maximum use of raw material. Thus, their use depends on the project's context, and may add strength to a sustainability analysis.

2.4.2. Sustainability Incorporation in Design Activities

The sustainability methods and metrics discussed in the previous sections have been incorporated in design activities through assessment, optimization and design approaches. In this section, sustainability incorporation in these design activities is reviewed. Moreover, given the importance of stakeholder's perspective for sustainability in the biobased economy, an analysis of perspectives inclusion for biorefinery design during design activities is presented at the end of this chapter.

2.4.2.1. Assessment Approaches

In the design of engineering projects, design alternatives are typically evaluated or assessed based on performance indicators related to certain topics of interest. Thus, assessment methods are used as a tool when designs are already available, either for selection of most sustainable process alternatives or for their improvement. Furthermore, research for the design of biorefinery projects focused on performance assessment have been mostly related to the analysis of the conversion process or facility, with few studies related to the supply chain, like (Coleman et al., 2014; Eranki et al., 2013; Nguyen et al., 2014). For instance, Kalinci et al. (2013), present an assessment for the analysis of solar-assisted biomass gasification though GHG emissions, energy and exergy indicators. These metrics are used to compare the process performance under different conditions, like gasification temperature or feedstock type, in order to draw recommendations for future technology developments.

Assessments frameworks for sustainable biorefinery design are based on specific methods and metrics to evaluate certain aspects of sustainability. For instance, Li et al. (2011) present an explicit assessment framework that combines efficiency and economic metrics like exergy efficiency and NPV with methods for environmental and social analysis like the WAR algorithm, and the so-called EISI impact category (representing impacts on health and safety, referred to as impacts on society by the authors). Interestingly, this framework is based on a combination of process parameters and known chemical indices, like heat of main reaction and flammability, which are available at an early design stage. However, these metrics are limited to impacts directly related to the conversion process only, and do not cover upstream processes like raw material production or transport, which can be highly relevant in biobased conversions.

In contrast, the LCA methodology, with well-known methods like those discussed in previous sections, covers the entire life cycle of the products. However, LCA is limited to the environmental dimension of sustainability only. In the reviewed literature, few authors propose or apply integral assessment approaches, i.e. approaches that aim to integrate all dimensions of sustainability in a single analysis. Exceptions include the frameworks proposed by Li et al. (2011) and Sacramento-Rivero (2012), however, these lack a life cycle approach or consider limited topics regarding environmental and social sustainability, as discussed in depth in sections 2.4.1.2 and 2.4.1.4. In the recent years there have been developments towards life cycle sustainability assessments (LCSA), mainly through the combination of LCA with life cycle costing (LCC, a form of economic assessment like TEA) and social life cycle assessment (sLCA) (Kloepffer, 2008; Zamagni et al., 2013). Although this LCSA approach faces difficulties related the harmonization of different boundaries and units, and the adequacy and measurability of social indicators in sLCA (Schebek and Mrani, 2014), some authors have published practical approaches for this LCSA approach (Zamagni et al., 2013). However, according to the reviewed literature, LCSA is not yet applied for biorefinery design. Interestingly, the assessment framework recently published by Keller et al. (2015) extends on this LCSA concept for ex-ante evaluations of biorefineries, complementing it with sustainability and scenario analyses to face the methodological difficulties discussed above and analyse possible barriers to the projects.

Large data requirements are common difficulty to these assessments methods, particularly during early design stages. Therefore, shortcut assessment models are promising alternatives for this type of analysis. Karka et al. (2014) present a short-cut statistical model to assess environmental impacts of multiple product and process systems from knowledge on environmental impacts related to known products and production processes. The proposed statistical model relates molecular indicators and minimal process characteristics to potential environmental impacts and is suggested as a tool for selecting best alternatives for environmental sustainable design. However, given its limited accuracy, the model is proposed for high level estimations only, related to GWP and cumulative energy demand (Karka et al., 2014).

In some cases, assessment frameworks and methods include a normalization step, in which a reference value is used to harmonize results in a common scale. This normalization can be dependent or independent of the results of the analysis itself. For example, in the assessment framework by Li et al. (2011) the maximum and minimum values of each indicator are as limit values to further normalize them into a 0 to 1 scale. Hence, this type of normalization is only applicable when the assessment framework is used to compare multiple alternatives. Another type of normalization found is through the use of a value that is independent from the results obtained in the analysis itself. This type of normalization can be seen in the assessment framework proposed by Sacramento-Rivero (2012), where results are normalized based on “critical values” that represent the limit after which the considered system is no longer sustainable and is doomed to collapse. Given that this type of normalization is independent from the obtained results, it is also suitable for non-comparative assessments (e.g. to identify improvement opportunities in a design). However, the use of predefined “critical values” may subject the analysis to a normative perspective of what a sustainable state is.

Normalization is used to either ease the comparison of values or to allow aggregation of results by having the values in common units. However, this is an extra step that adds complexity to an assessment framework, and may also reduce the clearness of the analysis as real values are presented behind a normalized scale. In line with this reasoning, it is found that publications dealing with impacts related to one or two dimensions of sustainability do not normalize metrics to a common scale but rather present un-aggregated results in their absolute values. By contrast, all studies dealing with assessments that include the three dimensions of sustainability have a normalization step (Gebreslassie et al., 2013a; Gheewala et al., 2011; Golberg et al., 2014; Li et al., 2011;

Sacramento-Rivero, 2012; Schaidle et al., 2011; Wang et al., 2013; Ziolkowska, 2013) . In order words, these more complex assessments involving more numerous and diverse indicators, rely on normalized values to allow an easier analysis of results.

Besides normalization, weighting can also be part of an assessment framework in order to express the relative importance of various results or result categories. Studies related to the assessment of impacts on the three dimensions of sustainability often use weighting factors to emphasize the importance of these dimensions or impacts related to them. For instance, in the study by Schaidle et al. (2011), weighting factors are given to different metrics related to economic, environmental and social dimensions of sustainability. Moreover, given that these weighting factors are subjective representations of the decision maker's opinion, their influence on results can be further studied with a sensitivity analysis. For instance, Schaidle et al. (2011) arbitrarily gave equal values to the weighting factors, after which different "perspectives" were defined with higher importance given to either the economic, environmental or social metrics. This type of analysis allows comparing benefits and drawbacks of the evaluated alternatives, and in their case studies, identifying a compromise with a biorefinery alternative that scores best in 50% of the analysed perspectives. By contrast, weighting factors for different sustainability criteria can also be defined by a group of experts on the field, as in the work by Ziolkowska (2013). Although this expert approach allows for more educated insights on what can be considered as more relevant in the analysis, care should be taken in participant selection to avoid one sided inputs (see perspective inclusion in section 2.4.2.4).

2.4.2.2. Optimization Approaches

Optimization approaches have also been a common way for integrating sustainability concerns in the design of biorefinery projects, particularly related to sustainable supply chain optimization. For example, Giarola et al. (2011) present an optimization framework to find an optimal hybrid 1G+2G biorefinery and related supply chain, considering biomass production yields, demand centres and horizons, as well as technical, economic and market information. Optimization-based design has been also included process structure design in few cases. Tay et al. (2011b) present the optimization of the superstructure for an integrated biorefinery, based on raw material availability, processing technologies and related data on yields and economic performance. However, often in these optimization cases, the process stage, modelled with or without its supply chain, is reduced to only yields and black box models that are blind to, for instance, integration possibilities. From the reviewed literature, few studies use optimization approaches for process integration (Caliandro et al., 2014; Tock and Marechal, 2012), parameter optimization of already defined process structures (Vlysidis et al., 2011), or a combination of both (Ng et al., 2012).

Regardless of the main focus of the optimization approach, i.e. process or supply chain, sustainability issues are typically integrated through the use of indicators, mostly as objective functions. For example, a design can be optimized to meet the objective of the highest possible NPV or the lowest possible GWP. Therefore, optimization problems are mostly approached through mathematical programming modelling like linear and non-linear programming. An exception to this tendency is the use of evolutionary algorithms to find faster solutions of order-based combinatorial problems. However, the use of the latter approach is limited to a couple of papers (Ayoub et al., 2009; Caliandro et al., 2014), perhaps due to increased computational requirements that are commonly avoided with heuristics in classic optimization approaches.

Optimization of multiple objectives related to different sustainability dimensions can be done one at a time, where the model is optimized for one objective and subsequently for others, lie the optimization tests by Eranki et al. (2013) in relation to fuel, soil, water and emission category topics. Alternatively, non-economic impacts can be monetized or transformed into economic terms so that they can be added to economic metrics, and then the model can be optimized based on a single objective. This monetization is often based on expected CO2 or GHG emission penalty costs or savings (Ayoub et al., 2009; Cobuloglu and Bueyuektahtakin, 2014; Kantas et al., 2015; Sharma et al., 2011; Vlysidis et al., 2011), although other indicators (e.g. soil erosion prevention and water use) have also been monetized in some studies (Cobuloglu and Bueyuektahtakin, 2014; Kantas et al., 2015). These approaches are practical given that the multi-objective problem is simplified and units are harmonized. However, monetization is based on either volatile market values or on expected values and costs, which inherently add uncertainty to the analysis.

Multi-objective optimization approaches have been more frequently used to handle several objective functions related to diverse aspects of sustainability in the design of biorefinery projects. Most commonly, one of the conflicting objectives is defined as a constraint and the problem can be solved for a single objective. For example, Cucek et al. (2014) simplifies the profit-food security multi-objective problem already at the mathematical problem definition by setting a food security criterion as constraint for biomass conversion into energy. Subsequently the problem is treated as single-objective from this point on. The epsilon-constraint solution method for multi-objective optimization, which also relies on the re-definition of one of the objectives as inequality constraint, has also been widely used as a solution approach (Gebreslassie et al., 2013b; Giarola et al., 2011; Kempener et al., 2009; Santibanez-Aguilar et al., 2014; Wang et al., 2013; You et al., 2012; Yue and You, 2014a, b; Zhang et al., 2014). The results of the epsilon-constraint method can be further collected in Pareto curves where the trade-offs between both objectives can be analysed. For instance, You et al. (2012) compare the trade-offs between production cost vs. GHG emissions, and production cost vs. employment creation for cellulosic biofuel supply chains. On the other hand, to obtain a single result of optimization, fuzzy logic can be used to solve for multiple objectives by defining a degree of satisfaction or a value range for the objectives. Shabbir et al. (2012), define this degree of satisfaction by defining the fuzzy goals or limits for both objectives according to the optimal solution found for each objective individually. Another optimization approach through bi-level optimization, where a part of the problem is initially optimized to be used as input for the second part (Andiappan et al., 2015). All of these methods involve inherent limitations, either by not having a solution as a single result with the Pareto sets, by possible missing a global optimum or by having to define a compromise for two conflicting objectives.

Similarly to assessment approaches, optimization approaches often rely on normalization and weighting methods. Typically, these methods are used to combine different metrics related to a single sustainability dimension, which can be used to optimize multi-objective problems as discussed above. An exception is the optimization work by (Cheali et al., 2015), in which various metrics related to different sustainability dimensions are directly combined into a single objective through normalization and weighting factors. In the reviewed optimization studies, result-dependent normalization is a common practice. Also, the hierarchy, egalitarian and individualist modes of the EI99 used for environmental optimization, are in few cases also considered for normalization and weighting (Gebreslassie et al., 2013a; Santibanez-Aguilar et al., 2014).

2.4.2.3. Design Approaches

Sustainability aspects have been modestly incorporated in design of biorefinery projects (i.e. 10 out of the total 84) through design approaches that combine indicators, impact categories and methods. In these design approaches, sustainability can be considered as a guiding principle, like the study of Kolfschoten et al. (2014), where identified improvement opportunities for farming, processing and transport activities are used as guiding principles to design an integrated sugar and ethanol production value chain in The Netherlands. These opportunities included, for instance, the local processing of sugar beets to recycle nutrients and water to the soil, and avoid hampering transportation costs related to centralized plants. However, these types of approaches do not yield a design itself, but rather set constraints or criteria for further design. Then, the designing itself can follow for example knowledge-based approaches like in (Kolfschoten et al., 2014), or optimization approaches like those discussed above.

Most reported design approaches, however, present explicit frameworks for design that differ on the focus of design and on design methods included therein. For instance, de Figueiredo and Mayerle (2014) present a framework for designing anaerobic digestion supply networks that breaks down the design task into subsystems, i.e. planning of routing, logistics network design, and processing plant location. According to the authors, this breakdown approach allows for a better understanding of sustainability trade-offs, although the approach, in this case, is mostly focused on costs. Ng et al. (2015) present a design framework that integrates customer needs in a combined product and process design framework. Activities in their framework include product design through molecule prediction models, and process design through optimization models based on profits and efficiency metrics, which overall satisfy customer requirements. In general, design frameworks, regardless of their different emphasis, include a sequence of steps that lead to a “sustainable” design, often through optimization and assessment of defined sustainability criteria, like efficiency metrics.

Frameworks with a process design focus commonly combine process modelling with TEA, LCA and/or process integration tools, thus considering economic and environmental dimensions of sustainability, and efficiency metrics. Mayumi et al. (2010), present a design framework with a model of the process concept, which includes process routes and candidate products, to generate inventory information for an LCA. The assessment results are to be used as feedback for the improvement of the process concept. Jenkins and Alles (2011) includes an additional economic evaluation in their proposed framework, which is used for selecting promising process alternatives in combination with LCA results. PSE methods for process integration have been also used to provide additional insights for the design of biorefineries, by combining, for example, LCA results with process integration models (Chouinard-Dussault et al., 2011). Mansoornejad et al. (2014) further combined in a hierarchical design framework, market and techno-economic analysis with LCA and supply chain analysis. However, in most of the reported frameworks, the supply chain in which the process is to be embedded is not taken into account, missing a large part of the scope of biorefineries.

In contrast to the strongly process oriented frameworks, de Santoli et al. (2015) present a design framework that deepens on the analysis of the project context for developing a bioenergy production process and its related supply chain network. Interestingly, the context analysis is characterized as a territorial energy vocation that considers available resources, established socioeconomics and historical productions in the geographical area of the project. This territorial vocation, together with an analysis of energy needs, is used to develop scenarios for bioenergy production, and is further assessed through economic analysis. Sustainability considerations are integrated in this framework by defining the project constraints and basis of design related to the territorial vocation. This vocation, related to resource potential, waste exploitation and the recovery of traditions (through to the consideration of historical production), may be said to cover to some degree the economic, environmental and social dimensions of sustainability. However, in the framework, the evaluated alternatives are only evaluated through economic metrics.

2.4.2.4. Perspective Inclusion

Throughout this review of biorefinery design it can be observed that no single optimum sustainable biorefinery design, or method for attaining it, exists. That is, a sustainable design is not only context dependent but it also relies on the designer or decision maker's input on how to define, assess or select what sustainable is for each case, for example when a degree of satisfaction is defined as a compromise of opposing objectives. In the reviewed papers this understanding is in few occasions acknowledged, and often the "sustainable" biorefinery design is a product of mathematical, computational models based on hard data only.

In few works, the need for further input for finding a solution is addressed, particularly for the selection of weighting factors (Cobuloglu and Bueyuektahtakin, 2014; Xie and Huang, 2013), and the definition of fuzzy objectives for optimization (Andiappan et al., 2015; Tay et al., 2011b). Tong et al. (2014a) propose an alternative to balance these subjective choices by defining two measures for uncertain values in an optimization framework, which represent optimistic and pessimistic views. In the EI99 method, subjective inputs are presented through three idealized cultural perspectives, i.e. egalitarian, hierarchic and individualist (Goedkoop and Spriensma, 2001). Thus, from these cases it is clear that not only external knowledge is needed, but that the input also depends on subjective specific points of views. Thus, the worldviews of those involved in the design activity can have large impacts on global outcomes of the analysis.

Diverse stakeholders or perspectives have been considered in few cases. For example, Slade and Bauen (2013), consulted several experts to validate previous studies on microalgal systems and compare their energy use and environmental impacts. Through expert workshops, the authors discuss the validity of previous LCA studies for their meta-analysis, finding, for instance, that these are often outdated, superficial, or over optimistic. Similarly, Ziolkowska (2013) incorporates diverse stakeholder inputs into a framework to rank uncertain economic, environmental and social criteria. Thus, diversity in expert inputs is handled as uncertainty through fuzzy set theory, further analysed with a multi-criteria method. These two works are based in participatory approaches that acknowledge subjectivities and imprecisions in decision making, and although the latter is intended for design at the policy level, the approach could be applicable for design of biorefinery systems as covered in this review. A noteworthy study is that by Dale et al. (2015) in which a high level conceptual framework is presented for the selection and evaluation of indicators for bioenergy systems (thus no metric or indicator is directly proposed). Dale et al. (2015) bring this approach for sustainability assessment considering that the selection of indicators is related to stakeholder's objectives and values. Although not particularly presented for design, this framework brings forward relevant points for sustainable biorefinery design, such as the inclusion of all relevant stakeholders, articulation of their objectives, and trade-offs between conflicting goals. Furthermore, as the authors discuss, such an open procedure allows for transparency and legitimacy, which can have a positive effect on the support for such projects.

2.5. Challenges and Opportunities

Biorefinery design has passed the times when biomass was considered sustainable solely due to its renewability characteristic. Nowadays, published methods, models and databases are used for estimating possible impacts related to the three dimensions of sustainability, and shortcut models have been identified as an interesting approach to perform these analyses at the early-stage design. However, there is still the challenge to strengthen the incorporation of sustainability in the design of biorefinery projects, as discussed throughout this review.

Some authors, for example, have defined and applied a number of society related metrics for the design of biorefinery projects; however these are often limited to human health or employment metrics, as discussed in section 2.4.1. Although these bi-dimensional impacts are important aspects of sustainability, using these as only social sustainability metrics means that some relevant impacts to society might be completely by-passed. Thus, there is a need for a widespread application of social sustainability analysis in the designing of biorefinery projects that also considers the context of the project.

Environmental sustainability, on the other hand, is often taken into account for the design of biorefinery projects. However, it is often reduced to global warming related impacts only. Regardless of the significant global importance of this topic, it is by no means the only relevant environmental aspect for biorefinery projects. Some studies address other environmental impacts, like those related to soil and water quality, or include broad environmental methods and metrics, like the WAR algorithm and IChemE sustainability metrics, but these cases are few and the methods are not always fully incorporated for design. Furthermore, the latter approaches still face some shortcomings for biorefinery design, like geographical validity, uncertainty or the process-centred scope of the WAR algorithm and the IChemE metrics.

Sustainability analyses often consider the economy dimension. However, the analysis is generally focused on enterprise sustainability through metrics like NPV and production cost. Although relevant for assessing the feasibility and sustainability of a project from a microeconomic perspective, there is still a need to include macroeconomic views that reflect the impacts on the economy in which the project will be embedded.

Although some approaches that include a combination of metrics related to the dimensions of sustainability have been reported in the literature, they were found to have strong limitations like reduced applicability at the design stage, or at different contexts, or they have a narrow consideration of sustainability topics. Thus, there is a need for a holistic integration of broad and integral sustainability that is in-line with the context of given projects, and that is practical at the design stage when data availability is limiting.

Multi-objective optimization approaches and integral sustainability assessments have shown to be useful methodological tools to integrally incorporate sustainability aspects in the design of biorefinery projects through the combination of metrics related to the economy, environment and society dimensions. However, most of these approaches have been particularly limited by their disciplinary focus, designing processes that are blind to their supply chain, or by the contrary, designing supply chains that over-simplify the conversion process, and thus do not consider integration opportunities related to this supply chain stage. Thus, there is a challenge to overcome a discipline barrier to integrate supply chain and process knowledge for the design of sustainable biorefinery projects.

In this review it is observed that often process and supply chain research have a common mathematical programming approach, sometimes combined with, for instance, simulation and other tools. Thus, an obvious opportunity is the use of this mathematical approach to bridge disciplinary differences. Also, if different modelling approaches are used for supply chain and process design, a higher level design or assessment framework can be proposed to handle and harmonize these different approaches, as already practiced for product and process design.

Some approaches or concepts from other disciplines have already been used to enrich the sustainability incorporation in design practices. For instance, the inclusion of a territorial vocation as part of the context analysis of the project is regarded as an interesting option to incorporate context specific integral sustainability. Thus, multi- and transdisciplinary design approaches are identified as opportunities to successfully consolidate integral sustainability in biorefinery design practices, while also considering the broad scope of biorefinery projects, the process and its supply chain.

Finally, throughout this review it is observed that sustainable design is not only based on absolute values, but that it also relies on subjective input to approach sustainability. Although sustainability problems in the engineering field have been addressed as wicked problems (Azapagic and Perdan, 2014), social and sustainability science approaches can bring light on how to include diverse and relevant perspectives from different stakeholders. For instance, studies like those by Ziolkowska (2013), Slade and Bauen (2013) and the conceptual framework of Dale et al. (2015), illustrate the use of participatory methods to consider different perspectives for weighting or validation of criteria, and indicator selection. Even more, Dale et al. (2015) propose with their framework to consider the objectives and values of the stakeholders in the selection of evaluation metrics. This inclusion of different perspectives may simultaneously attain the integral incorporation of sustainability in design, while possibly shedding light on reconciliation strategies for conflicting objectives.

2.6. Conclusions

Sustainability has increasingly been incorporated in the design of biorefinery projects; however, some challenges have been identified in relation to this design practice. For example, social sustainability is generally omitted in design practices, while environmental sustainability is often reduced to the analysis of global warming impacts, and macroeconomic effects are hardly taken into account. Efforts have been made to develop integral sustainability analyses for biorefinery design, but these have often been limited by the scope mostly related to conversion processes or to supply chains, while being blind to contextual settings or stakeholder perspectives. Namely, it is found that sustainability incorporation for biorefinery project design faces the following challenges:

- Inclusion of an integral sustainability analysis that considers societal impacts and goes beyond the micro-economy and global warming issues.
- Applicability during early design stages when data availability is limited.
- Disciplinary boundaries that limit the scope of analysis.
- Sustainability subjectivity, typically disregarded through the use of normative approaches.

Based on the analysis of these shortcomings and challenges, some prospects for improvement have been discussed in this chapter. Overall, we identified the following opportunities towards the design of sustainable biorefineries:

- The analysis of the contextual setting for the project can be convenient to identify relevant sustainability issues related to the biorefinery projects.

• Common approaches and tools can be used to overcome disciplinary boundaries, like mathematical programming, simulation tools and databases.

• Incorporation of sustainability in design and assessment frameworks can allow the combination of different methodological approaches from different disciplines.

• Social and sustainability methods can be useful for considering sustainability subjectivities, particularly through the inclusion of stakeholder perspectives. Taking the phrase by Lou Reed (Reed, 1972) for emphasis, we encourage biorefinery researchers to "take a walk on the wild side" towards multi- and trans-disciplinary approaches by integrating social and sustainability sciences in their future developments.

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Results from the literature search are indicated with an asterisk (*) before the author's name.

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Chapter 3

Setting the design space of biorefineries through sustainability values, a practical approach

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3.1. Introduction

Emerging controversies over the impacts of biobased production (e.g. on land use, food, and energy security; Baka and Bailis 2014; Kline et al. 2016; Rosegrant and Msangi 2014) have made it clear that biorefineries cannot be assumed to be inherently sustainable or unsustainable. To promote sustainability in the early development of these systems, various biorefinery design methodologies have been published (e.g. based on assessment and optimization methods (Andiappan et al. 2015; Posada et al. 2016; Zhang et al. 2014). Although these types of studies can potentially contribute to sustainability (e.g. through impact minimization), they rely on a few aspects (mostly climate change and economics) that are often prioritized in closed processes that are blind to the context and the stakeholders' realities (Palmeros Parada et al. 2017). Given that the meaning of sustainability and its implementation depend on subjective beliefs and values, 8 there is a need for a different biorefinery design strategy that takes into account the context of the project and its stakeholders (Dale et al. 2015; Kline et al. 2016).

Design for Values approaches have been developed to consciously reflect on societal aspects related to emerging technologies (Hoven et al. 2015). As part of these approaches, value sensitive design (VSD) is grounded on the understanding that a technology's effect on society depends on its features, the context, and the stakeholders around it (Davis and Nathan 2015). In VSD, stakeholders are identified and their values (e.g. sustainability) are empirically elicited and actively incorporated in a product. In practice, this incorporation is done by enhancing technical features that positively relate to these values, and vice versa (e.g. through the value dams and flows approach of Miller et al. (2007). Furthermore, VSD has three characteristics that make it interesting for sustainable biorefinery design: 1) It does not prescribe a sustainability interpretation, 2) it is intended for a design outcome, and 3) it is embedded in engineering design practice. However, VSD has been mostly applied for the design of technological products from a well-established sector, namely IT, and in direct contact with end users (for a review refer to Davis and Nathan 2015). By contrast, biorefineries connect numerous stakeholders from diverse sectors, and yield many products. Furthermore, the transition to a biobased economy is still at an early stage, meaning that projects in this field evolve from conceptual to commercial stages while facing technical, economic, and institutional barriers (Bosman and Rotmans 2016).

The aim of the present study is to analyse and ascertain how sustainability, considering stakeholders' values in the context of a project, can be introduced into biorefinery design practice. From this analysis, we present a practical approach for incorporating sustainability in the early stages of design (Section 3.3.4). That is, in this work we focus on implementing sustainability to delimit a project's design space (typically defined by the variable's feasibility limits and the project requirements), concentrating on stakeholders' values with significance for sustainability. To do so, VSD is taken as a starting point by considering stakeholders and their values in the context of implementation. For developing the analysis, we took a conceptual biorefinery design case study for biojet fuel (BJF) production in Brazil.

3.2. Material and Methods

The methodology was built on VSD literature, but it was modified and further specified for the early phase of biorefinery design practice (prior to the generation of design alternatives). We therefore do not refer to typical VSD studies (i.e., conceptual, empirical, and technical). In section 3.3.4, we discuss the application of this methodology as an approach for early biorefinery design and give recommendations for its further application.

3.2.1. Case Study – Biojet Fuel in South-eastern Brazil

BJF is a biobased alternative to kerosene that in recent years has become prominent in research, development, and deployment projects, yet its total production is still limited in scale (Mawhood et al. 2016). The present case study was a conceptual design project for a BJF production chain at a commercial scale, and was part of a project to find promising sustainable production chain configurations for further research and piloting efforts. Therefore, it was an early stage project with a broad space for decision making. The main design variables for the project were feedstock, by-products, technology and conversion process, and supply chain.

Brazil, a country with considerable experience in biofuel production, was the target region for exploring possible BJF production chains. For practical purposes, this research was focused on Brazil's south-eastern states of Minas Gerais and Sao Paulo. These two states in particular have extensive experience with agricultural and biofuel production, and good access to some of the country's main cities, airports, and industries.

3.2.2. Stakeholder Identification

Stakeholders related to biofuel production chains are both numerous and diverse. Furthermore, in this case study their identification was difficult considering that specific production features had not been defined (e.g. location and participating companies). Therefore, we focused on identifying possible stakeholders as organizations likely to be active at any stage of a future BJF production chain in the target regions. The production chain presented in Fig. 3.1 was used to identify these stakeholder organizations from the private, research, and governmental sectors. Thus, specific organizations that are active or have experience in working with sugarcane and other agricultural products, biofuels, and jet fuel in the target regions were identified as possible stakeholders.

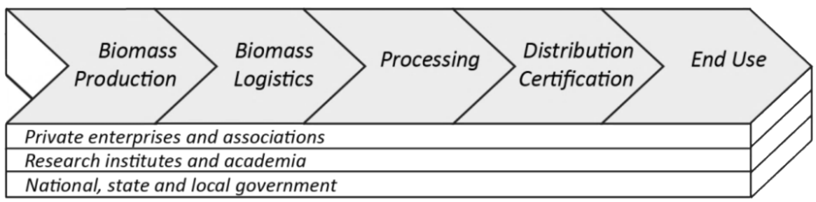

Fig. 3.1. Generic scheme of a biojet fuel production chain.

3.2.3. Sustainability Value Analysis

3.2.3.1. Value Elicitation

Actors from identified organizations were invited to an interview by email, and also through personal contact at an academic event in the University of Campinas (UNICAMP, in Sao Paulo state) in July 2016, which was also attended by governmental and industrial parties. In total, 16 semi-structured interviews were held with actors related to a possible BJF production chain in the target regions (see Table 3.1). Questions related to their experience and expectations of the biobased sector were asked to elicit values relevant for them and the organizations they represented (the interview guide can be found in Appendix II). The questions concerned their objectives, challenges, opportunities, harms, and sustainability itself, as they perceived them in relation to biobased developments. However, the interview questions and structure remained flexible, and a few respondents spoke with the help of slides and/or a technical assistant or co-worker. Interviews were held in English whenever possible; otherwise, a mix of Portuguese and Spanish was spoken.

Table 3.1. Respondents' organizations and their scope in relation to a possible future BJF chain

Respondent and organization type		Biomass production and supply	Processing	Distribution and certification	End use
Minas Gerais State					
03	State Secretary	x	x	x	
04	University		x	x	
05	State Secretary	x			
06	Technology company		x		
07*	Government enterprise	x			
08	Industry association	x	x		
13	Aviation company				x
15	Biobased company	x			
16	University	x			
Sao Paulo State					
01	Consultancy company	x			
02**	Industry association	x	x		
09	State institute***	x			
10	Technology company		x		
11	University		x		
12	State Secretary		x		
14	State Secretary	x			

* Respondent 07 is also a small-scale agro-producer; **Respondent 02 worked in the past for the respective association; ***the institute belongs to the organization of Respondent 14.

3.2.3.2. Value Analysis

First, a qualitative analysis of the interview material was conducted to identify stakeholders' situated values, that is, values of importance to the stakeholders in relation to biorefinery or BJF projects. Specifically, normative interview statements were iteratively coded and categorized, allowing a continuous comparison of categories that represented the stakeholders' situated values. MAXQDA 12 was used during the analysis, which allowed coding and retrieving statements while visualizing the interview context.

To analyse situated values in relation to sustainability, use was made of van de Poel's interpretation of the Brundtland Commission's definition of sustainability (van de Poel 2017; World Commission On Environment and Development 1987). Thus, sustainability was considered as an overarching value composed of at least intergenerational and distributive justice, and care for nature. This interpretation served as a framework for sustainability while leaving space open for values elicited from the interviews. In practice, all situated values from the interviews with all stakeholders were compared to the sustainability constitutive values to determine whether and, if so, how they related to sustainability.

During the analysis, we considered distributive and intergenerational justice as the fair distribution of goods, services, opportunities, and rewards in the socioeconomic sphere between different groups of people now and in the future. As care for nature, we took issues of importance to the stakeholders in relation to the sustenance of nature, both as instrumental for the sustenance of human wellbeing and for the sake of nature itself. Although it could be argued that environmental obligations are also an issue of distributive justice (e.g. ensuring that groups of people have access to natural resources), we took justice as related to implications between human beings only, and care for nature for those between humans and nature (van de Poel 2017).

3.2.4. Design Space Analysis

Design propositions were derived from the value analysis. In practice, the researchers systematically asked themselves what could be done in relation to the biorefinery project (BRP) and its variables, for the sake of a given value, in the BRP context, and according to the respondent's statements. This was done for all values related to sustainability, derived from all stakeholders.

Finally, for setting the design space of the project, we analysed three aspects related to the design propositions: i) how do the different propositions relate to each other in the context of the BRP and its main variables; ii) which design propositions benefited each other, and iii) which ones conflicted with each other. Based on this analysis, we proposed flexible design space boundaries and discussed design implications for the BRP context. These results were discussed with the project coordinator to ensure that the propositions were in line with the project.

3.3. Results and Discussion

3.3.1. Sustainability and Stakeholders' Values

Care for nature and distributive and intergenerational justice served as a framework for analysing stakeholders' situated values and sustainability for the BRP. In the following subsections, we discuss how stakeholders' situated values related to sustainability constitutive values in line with their responses (Fig. 3.2). Although the discussion is structured in three sub-sections for each sustainability constitutive value, it is acknowledged that some of the situated values could conceptually relate to more than one. In these cases we took the respondents' statements to discern to which constitutive value they were referring to, as discussed in the following sections.

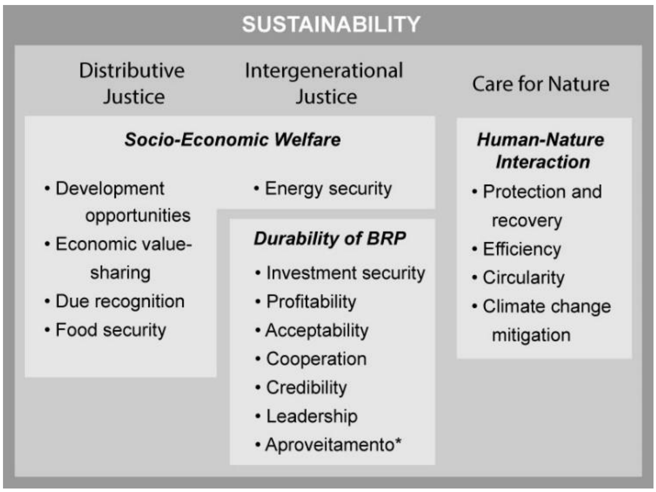

Fig. 3.2. Scheme presenting stakeholders' situated values (bulleted) in relation to sustainability and its constitutive values: distributive and intergenerational justice, and care for nature. Situated values are grouped according to the common themes discussed throughout the section on Sustainability and stakeholders' values. The Portuguese word aproveitamento is discussed in the section on Intergenerational justice.

3.3.1.1. Distributive Justice

Situated values for distributive justice represent what stakeholders considered desirable, important, and fair from a BRP. Overall, these situated values were related to a fair socioeconomic welfare, although they varied in their focus. *Development opportunities* were one situated value addressed by most respondents. A few responses focused on opportunities that a BRP should bring to their country or region, pointing to an identity loyalty. For example, Respondent 09 said*: "So, I think this [biobased economy] is a big opportunity in Brazil and for this region because Brazil [now only] exports grains, and things of low added value. So, if we can extend these production chains into more high value products this would be very good for our economy, generate jobs in companies, taxes, opportunities for people."* Others focused on the need to create development opportunities for the poor and the rural sector, and how biobased projects should be favourable to them. Some respondents further emphasized the importance of creating opportunities by speaking of farmers' migration to cities, and the often negative outcome of this (i.e., the new urban poor, their social segregation in favelas, and the socioeconomic burden on cities). A few respondents also specifically spoke about giving opportunities to alternative actors by including them in biobased developments through technology transfer, use, or ownership. For example, Respondent 10 stated that: *"[Through] diversification of technologies we would not depend on specific technologies developed by big companies. [Instead] we would include a small player, a medium player that has his own patents. [Then, the project] would not depend on international patents… because this is a real issue here in Brazil."* This respondent also questioned the current path of biobased developments in Brazil, which are based on political and economic structures that, in the respondent's view, leave little or no opportunities for the majority. Overall, respondents from all sectors valued fair development opportunities that a BRP should bring to Brazilian society and its economy.

Economic value sharing along production chains was also mentioned as being desirable for the socioeconomic benefit of those involved in it. Particularly, Respondent 11 said: *"I was very surprised when I went to Argentina and saw the wine producers. The grape producer earns nothing, a kilo of grapes is cheaper than 1 $R, they don't earn anything. If you look at the condition of the person, it's bad, same with sugarcane […] but he who transforms the product into products of more value, he will earn the money. I am not saying this so the person opens [gives away] his or her profit, but a part of his or her profit."* More in the context of biobased production, the CONSECANA system was brought up by Respondent 02. Through this system, the distribution of revenue from bioethanol and sugar sales is managed by both sugarcane producers and processors (Chaddad 2015). That is, through CONSECANA, economic value is distributed in proportion to the production costs at each processing stage. In sum, these respondents valued a fair distribution of economic value for all actors along the production chain, particularly when some remain in low economic value-adding activities, or when they have unequal bargaining power.

Due recognition emerged during the interviews when respondents referred to a fair acknowledgement that should be given to those who put effort for sustainability. For instance, Respondent 02 mentioned in relation to certification efforts that: *"The concern from the start was, 'Great, we're going to have standards. I'm prepared to change a few things, make it better if that's what you want'; we found it reasonable [...] And then what? What about the guy that doesn't do it? Who's going to tell him, 'What are you going do, buddy? Are you just going watch while I just spend money, and I make better sugar than you, and then that gets no recognition from the buyer?'"* This response was echoed by Respondent 08, who spoke of market recognition as a price premium deserved by those who invest in sustainability. For these industry respondents, it is desirable that recognition, in the form of preference for their products or some kind of acknowledgement, is given to those who improve their production process. Thus, for these respondents, it is only fair that they receive due recognition for their investments.

Food security was discussed on several occasions during the interviews; however, the majority of respondents referred to it in terms of acceptability or as a debate that is not relevant for Brazil (further discussed in section 3.3.1.2). Yet, Respondent 03 considered food security a relevant issue when speaking about the use of a specific feedstock for production: *"This can be like a new source of raw material, without competing with [the] food sector, because we know this big problem in the whole world, making fuel from produce that could be feeding people."* Although generally addressing food security, this statement seems to indicate the respondent's fundamental difficulty in consenting to the use of food crops for fuel when hunger still exists. For the respondents, it is a matter of distributive justice that food crops are first used to meet nutritional needs, particularly of those in a hunger condition, before diverting food resources for the production of fuels.

3.3.1.2. Intergenerational Justice

Intergenerational justice relates to a fair distribution across generations, either forward or backward looking. In this case, the respondents' statements focused mostly on forward-looking aspects, namely about current and future times, and not about historical distributions. Respondent 11 spoke of intergenerational justice when addressing development: *"For example, a kid born in a poor family has to have opportunities, it is not* *possible to think of a future in which people will be born without opportunities. That is not correct."* However, most times, situated values were related to intergenerational justice through discussions about the feasibility of a biobased or BJF project, now and in the future (i.e., durability). This durability is for the sake of intergenerational justice when considering that the BRP supports the values of distributive justice, as discussed in section 3.3.1.1, while allowing access to aviation services without needing limited fossil fuels.

Investment security and *profitability* were spoken of as desirable qualities that are necessary for making the BRP feasible. This means that these qualities are not only an economic requirement for a BJF biorefinery in the future (none currently exists in the target region), but also aspects of importance for inducing its realization and durability. Profitability, including price competitiveness, was mentioned by most respondents. For instance, Respondent 13 spoke of price competitiveness as a pressing issue for airlines, and they transfer to BJF developers as a maximum price they would be willing to pay for BJF. In relation to investment security, respondents from government, academia, and the technology sector spoke of the need to convince investors and agro-producers to participate in the development of biobased production, as the latter perceive non-traditional or unproven technologies as risky. For example, Respondent 03 described a typical reply from producers when trying to involve them in the development of a BRP: *"… the farmer says: 'How can I trust? I will plant, I will invest money and in the future [...] things will happen. How do we know how much money that [the investment in biobased projects] can give me back? I don't know, or if the government will give support. I don't know if the company will buy the products' […]."* Besides pointing to trust issues of agro-producers, this statement indicates the importance that farmers attach to securing their investments and the feasibility of BRP in the longer term. That is, in order to actually invest and take part in such projects, agro-producers and investors need to have a certain security for their investments and understand the risk they would be taking.

Other situated values were identified as instrumental for the durability of a BRP, although no longer as preconditions for it. For instance, *acceptability* emerged in discussions related to the introduction of new products that have to overcome the cultural barrier separating them from the public and industry actors. Respondents related this rejection of new products in the aviation industry to perceptions of safety held by their clients, consumers, and co-workers, and they did not consider it related to the facts or beliefs that they themselves held (i.e., they did not think safety was an issue on test flights fuelled with certified BJF). Along the same lines, food security issues were addressed by some respondents in terms of acceptability, while considering the food debate itself as an overstatement that did not relate to the Brazilian situation. For example, Respondent 09 stated that: *“You shouldn’t apply it here [the food vs. food debate], but of course, this is a big discussion. If you produce jet biofuel out of soybean oil, probably the jetliners of European companies wouldn’t be pleased because of local restrictions… people there would [say] ‘Well, you are fuelling your aircraft there in Brazil with soybean oil, this is no…’ [Respondent trailed off]”.* Thus, to have a functional BRP, respondents gave importance to understanding the conditions under which their products would be accepted by consumers, the government, and other actors in the production chain, regardless of their own understandings.

Respondents also valued *cooperation* between actors both within and across sectors. For example, Respondent 09 stated: *“So, then you have to bring the others [besides agro-actors], engineering people, and then sustainability […]. So, it’s a complex issue, and then there are the issues of logistics and distribution, and trade. So, it becomes more and more complex. […]. You now have to bring people that are working on computer science, engineering, images…”* Others indirectly referred to it by pointing to problems they had observed. Thus, while Respondents 01 and 12 had a critical opinion of governments and industries that work on BRPs without planning for biomass supply, Respondent 16 spoke of agro-producers who were in trouble because they cultivated without commercial agreements with the industry. Furthermore, respondents considered that the credibility of actors in the production chain played a prominent role in the realization of BRP projects. Credibility was considered important for getting or assigning commercial contracts and partnerships within the scope of a BRP, and also for convincing farmers and investors to participate (as discussed for investment security). This was especially the case for small agro-producers in Minas Gerais, where negative past experiences with vegetable oils and biofuel projects cast a shadow on the credibility of new biobased project proposals, according to respondents and as discussed in the literature (C. A. Castellanelli 2016; Watanabe and Zylbersztajn 2013).

Leadership was also mentioned by some respondents as a value that plays an important role for BRP development. For instance, Respondent 13 alluded to leadership as part of the company’s *“DNA”*, by describing how the company environment supports or provides space for looking for new paths toward sustainability and renewable biofuels. Some government and academic respondents referred to leadership as the desire to make their region a leader in the green economy, or to consolidate their region as a knowledge or production centre. Others indicated the value they give to it by referring to the perceived lack of political leadership (Respondent 07), or by contrasting new entrepreneurial actors who are developing biobased production chains, with traditional ethanol producers who are not developing any further (Respondent 01). Overall, having a leading position (i.e., exploring and bringing actors together to set out on new paths) was strongly appreciated by some respondents as a way to successfully develop BRPs in the target regions.

Stakeholders also spoke about *aproveitamento* (Portuguese word related to making the most of something, and grasping the opportunity to do something. This word shares some meaning with efficiency, enjoying, harnessing, and valorisation) for the development of BRPs. Aproveitamento was mostly discussed with a focus on economic value, or in relation to the use of available, non-natural resources. For instance, Respondents 01 and 08 spoke of ethanol mills that buy extra raw materials to produce more ethanol when sugarcane is out of season, and thus make the most of their installed capacity. Respondents also spoke of using old industrial sites (Respondent 15), upgrading a laboratory for road fuels certification to also certify aviation fuels (Respondent 03), using abandoned buildings for urban food production (Respondent 14), and using existing milk logistics for biomass (Respondent 13). Finally, several respondents focused on the aproveitamento of sloppy and degraded lands that are not easily exploited, and even promoted the use and recovery of some protected lands through extractivism. Thus, overall, aproveitamento was mentioned as something that can make BRPs more feasible, and also as something desirable on its own, for the sake of grasping certain opportunities.

Energy security was also spoken of in terms of intergenerational justice; however, its focus was not related only to the durability of BRP, but more globally to the welfare of society and its economy. Whereas government respondents spoke of ensuring future energy access, reliability, and self-sufficiency, industry respondents remained focused on the perceived benefits of or constraints on biomass use for energy self-sufficiency in potential projects (their energy needs are typically covered by biomass co-generation). Therefore, although energy security relates to socioeconomic welfare and can be regarded as a matter of distributive justice, the respondents' statements show that they are mostly focused on future outlooks. That is, respondents spoke about avoiding future energy crises in government policies and strategies, and on renewability and sufficiency for energy generation in the development of future BRPs.

3.3.1.3. Care for Nature

Care for nature is the constitutive value of sustainability with reference to our relationship as humans with nature. In this sense, we found environmental values that can be considered instrumental, both for human wellbeing and for the sake of nature itself. The *protection and recovery of nature*, or its resources, often emerged during the interviews with stakeholders. Some respondents referred in general terms to, for example, minimizing pollution and environmental damage, like deforestation (Respondents 03, 09, and 12). Others specifically referred to recovering degraded land, protecting soil and water quality, and associated issues like better practices for vinasse and fertilizer use (Respondents 01, 03, 05, 06, 09, 13, and 14). A few respondents also mentioned plantations as monocultures, and associated them with environmental and/or investment risk. For example, Respondent 09 spoke about the risk associated with new monoculture systems: *"So, when we do agriculture we try to organize things in our favour to make it easy to produce and reduce cost. So, we put all the plants together. [However] we also make it easy for other organisms that feed into [from] those plants. So we are breaking the ecological equilibrium. That's why we have an outbreak of pests and diseases in agriculture [...]. So, for all the crops that are not domesticated or are grown in small batches, we really don't know the challenges when they become an agricultural crop in extensive areas, all together. So, whenever we expand areas, we have chances of outbreaks of diseases."* Respondent 06 went further by mentioning the risk, not only for commercial plantations, but also for environmental areas around them. Agro-forestry or integrated practices of agriculture, forestry, and/or livestock were mentioned by a few respondents as desirable production systems for minimizing the risks mentioned above, and as a way of taking care of soil and recovering degraded lands. For example, Respondent 14 said that: *"…if you have good agricultural practices, you have a way to improve production. Then, there is no need to expand [...]. The forest, agriculture, and livestock integration is a form of intercrop production. This is a possibility to promote care in relation to the soil and the question of saving water."*

Respondents spoke about *efficiency*, related to care for nature through the reduced utilization of natural resources, and to the durability of BRP projects by using fewer economic resources for processing them. Closely linked to efficiency is aproveitamento, which was discussed in the previous sub-section. However, the former is based on a target output, while aproveitamento is based on the use of what is already available. Also, contrary to aproveitamento, efficiency was mostly discussed by respondents in relation to natural resources like land, biomass, and energy; we therefore present it in this analysis as closer in meaning to care for nature in relation to sustainability. For instance, Respondent 09 said: *"… if we use just a part, one third, of this pasture land, we can double the land for agriculture production, for producing crops, without felling any forest. […] if we look at the Brazilian statistics, […] we've been experiencing a huge increase in productivity with the same amount of land, so this opened up the space to add other crops."* This and other respondents valued efficiency gains for reducing the damages to nature and the degradation of resources.

Resource *circularity* was also outspoken as important to some of the respondents. Like efficiency, this value can be considered related to the durability of the project (e.g. through resource and transportation cost), but respondents mostly discussed it in relation to nature and its resources, or as a desirable trait for the local environment. For instance, Respondent 10 said: *"For me this is related to sustainability, to recycle materials and to recycle energy. So, if we do this we will stop to consume any other materials, we are going to recycle in the field, recycle in the city in a closed loop. This is good; I believe that this is an opportunity to increase the sustainability…"*, where the increase in sustainability referred to the opening of opportunities for local development (closely related to development opportunities addressed in section 3.3.1.1; post-interview clarification). By affecting the use given to natural resources, this respondent also spoke of circularity as a potential way towards socio-economic welfare. Overall, respondents discussed resource circularity for directly reducing the use of natural resources or its impacts, while potentially benefiting other aspects of sustainability.

Finally, *climate change mitigation* was indirectly brought up by respondents who spoke of their objectives or desires to reduce their personal or organizational emissions, carbon footprints, and fossil resource use. For instance, Respondent 13 said: *"…it's my desire [that] this approach [using renewable BJF for aviation], in two or three years, it should be an industry policy [...]. Renewable fuel, reducing the footprint... I am reducing my footprint, and they are reducing their footprint. It's not a competition between airlines."* So, although climate change is also a distributive issue between different groups now and in the future, respondents mostly focused on their actions for avoiding or mitigating this environmental effect, and not on societal consequences or responsibilities.

3.3.2. Biojet Fuel Design Propositions

Twenty design propositions for the project’s variables (i.e., feedstock, products, technology and processing, supply chain) were derived from the values discussed in the previous section (see Table 3.2). These propositions are normative but suggestive, that is, not prescriptive. If their implementation is not possible or desirable, they at least promote an active reflection during design decision-making. Additionally, some propositions concerning the development of a BRP business case were also derived from the value analysis (propositions 16–20 in Table 3.2). Although the business case is not typically a variable in biorefinery design, these propositions are nonetheless useful given the broad space for evaluating business case alternatives in such an early stage project (i.e. the project was at a conceptual level, and no investments and contracts had been fixed).

The identified propositions are presented in Table 3.2, where the related design variables are indicated. We also identified possible beneficial and conflicting relations between these design propositions, and indicated them in the right-hand columns. For conflicting propositions, we do not suggest or give any preferences; we only indicate the identified conflict so that it can be considered when designing. It is clear that other beneficial and conflicting relations between propositions may arise when continuing with the design activity, and in turn, some of these relationships may be avoided through new designs. Therefore, we discuss only those conflicts and benefits that seem most likely to play a role during the design activity.

Table 3.2. Design propositions derived from the value analysis

	Design proposition	Related design variable	Related value(s)	Possible benefit	Possible conflict
1	Avoid the use of food crops or assure relevant parties that food security is unaffected or promoted by synergies with the project.	Feedstock	Distributive justice: food security; intergenerational justice: acceptability.	5	
2	Traditional or proven crops and technologies are preferred.	Feedstock & technology	Intergenerational justice: credibility and investment security		9
3	Feedstocks that can provide continuous and profitable revenue to family farmers are preferred.	Feedstock	Distributive justice: development opportunities	16	
4	Feedstock from robust agronomic systems (*e.g.* with low fertilizer input, that maintain or recover soil carbon, and that minimize erosion and pest risks) is preferred.	Feedstock	Intergenerational justice: investment security; care for nature: climate change mitigation, protection		
5	Biomass from currently unproductive areas or produced in coordination with the agriculture and livestock producers are preferred.	Feedstock	Care for nature: climate change mitigation, protection, recovery; Intergenerational justice: aproveitamento	1	
6	Drop-in bio-based products are preferred for highly regulated markets, or with direct contact with the public.	Products	Intergenerational justice: acceptability		
7	Energy products from distributed processing units are desirable.	Products	Intergenerational justice: energy security	10	11
8	The BRP should be flexible to process various feedstocks, and produce alternative products.	Technology and processing	Intergenerational justice: Investment security	15	
9	Innovative technology and designs are preferred.	Technology and processing	Intergenerational justice: leadership		2
10	The project should be at least energy self-sufficient.	Technology and processing	Intergenerational justice: aproveitamento, energy security;	7	11

11	Aproveitamento for energy and material resources: use, reuse, recycle, and valorize as much as possible while minimizing emissions.	Technology and processing	Intergenerational justice: aproveitamento, energy security; care for nature: efficiency, circularity, climate change mitigation		7, 11
12	Technologies that are locally owned/produced (*e.g.* in Brazil or countries in the region) by alternative actors are preferable.	Technology and processing	Distributive justice: development opportunities		
13	The BRP should process locally and be based on short transportation distances.	Supply chain	Intergenerational justice: profitability; care for nature: climate change mitigation, efficiency.		
14	Availability or lack of infrastructure and land should be taken into account when designing.	Supply chain	Intergenerational justice: aproveitamento, profitability, nature protection.		
15	Back-up biomass sources should be secured close to the BRP region.	Supply chain	Intergenerational justice: investment security	8	
16	The BRP should create jobs and opportunities for everyone, particularly for those regions and people who need it most.	Business case development	Distributive justice: development opportunities	3, 17, 18	
17	A pricing policy and other mechanisms that ensure fair value sharing along the chain are desirable.	Business case development	Distributive justice: development opportunities, due recognition, economic value sharing	16	
18	BRP development and implementation should be developed gradually, and be open to participation by various stakeholders	Business case development	Intergenerational justice: cooperation, investment security, profitability.	16	
19	The BJF should be price competitive with alternatives in the market.	Business case development	Intergenerational justice: profitability		
20	BRP business cases should only consider stable beneficial government policies with adequate risk assessments.	Business case development	Intergenerational justice: Investment security	19	

3.3.3. Flexible Design Space Boundaries

The propositions presented in the previous section form indicative design space boundaries for the project variables. These boundaries suggest limits or constraints on the variables for the specific project. In this section we discuss how they relate to the design variables and form a design space. (In Appendix II the background rationale for each of the propositions is presented) As mentioned in section 3.3.2, some design propositions do not directly relate to these design variables, but rather indicate at a higher level how the business case for the BRP should be. We discuss the latter at the end of this section.

3.3.3.1. Feedstocks

Propositions 1 and 2 specifically limit the range of feedstock types that should be considered for the BRP, and do not necessarily conflict with each other; whereas one excludes food crops, the other excludes undeveloped or undomesticated crops in the project context. That means that food crops like sunflower and soybean, and crops that have not yet been adapted for Sao Paulo or Minas Gerais, are not a priori desirable for the project (excluding food crop by-products, such as straw and other residues). However, these propositions remain indicative, and if the use of a food crop for jet fuel has a demonstrable synergy with food security in the target regions, the use of this crop could become acceptable for the project, in line with the discussion by Kline et al. (2016). In the case of undeveloped crops, the flexibility of the boundaries is dependent on time. That is, when a BRP project is for a longer term, the proof of concept and development of a crop can be included in the project scope.

Propositions 3, 4, and 5 relate to the agricultural system setup and the land required for it. However, the extent of the BRP’s influence on the agricultural stage depends on the engagement of agricultural producers during the project development. Proposition 3 limits the feedstock selection to crops that can be grown in agricultural systems that provide continuous revenue. For the BRP this means, for example, that perennial systems with an initial unproductive phase should be designed to yield continuous revenue in the initial years (e.g. gradual cropping of the perennials combined with a cash crop). This proposition therefore has the potential to also have a beneficial relationship with proposition 16, by opening development opportunities suitable for family farmers. Proposition 4 indicates that agricultural practices and systems that benefit the soil quality should be considered in the feedstock selection. This can be related to, for instance, the amount of agricultural residues that can be taken for processing, or whether and, if so, how much biomass residues should be returned to the soil. These propositions also suggest that systems other than extensive monocultures should be preferred for the sake of environmental and investment risk minimization. Lastly, proposition 5 relates to land use for biomass production, where unproductive or underutilized land is currently preferred (e.g. through coordination with agriculture and livestock producers to capture liberated land from their sector, or in integrated systems, such as the sugarcane–dairy system proposed by Egeskog et al. (2011). Thus, this proposition has the potential to facilitate the implementation of proposition 18 in close association with the participation of diverse actors in the development of a BJF production chain in the target region. This is further discussed below.

3.3.3.2. Products

Two propositions directly relate to the BRP products: One specifies the main product requirements (6), the other suggests a BRP by-product (7). Proposition 6 is actually a common condition in BJF studies, where the main product is restricted to having the same functionality as the fossil alternative, and to being compatible with existing infrastructure (see, for example, the works by Alves et al. 2017, de Jong et al. 2015, and Karatzos et al. 2014). In practical terms, this proposition implies certification by ASTM for a short-term project and certification in progress for a longer term project, given that certification can take up to six years (Mawhood et al. 2016). Importantly, certification is specific not only to a generic BJF product, but to the whole production pathway. Therefore, this proposition also has implications for the technology and process selection. Proposition 7, by contrast, focuses on energy as a by-product supplied to the grid. Thus, as biomass processing units generate energy, they have the potential to decrease dependency on imports. Furthermore, when producing energy for the grid, the BRP becomes an alternative to centralized hydropower stations, thus reducing the region’s vulnerability to hydric crises (Volpi et al. 2006).

3.3.3.3. Technology and Processes

Propositions 8-11 relate to qualities of the process: flexible, innovative, energy self-sufficient, and circular, respectively. Flexibility in proposition 8 is the capacity to adapt the biorefinery to changes in biomass feedstocks, which is relevant with seasonal crops or when facing biomass availability problems. In these cases, specification for biomass processing flexibility can be anticipated when, for instance, two crops are planned as raw material for a year-long production, or there is knowledge of accessible biomass markets that could be an alternative feedstock supply. Flexibility also refers to the adaptability to market disturbances that could otherwise put the BRP investment at risk. Thus, the BRP process should be able to produce a variety of products or product qualities without the need to replace the process at large, for example, through modular technology additions.

Proposition 9 suggests a preference for innovative technologies and processes for the BRP. That is, novel technologies and designs are preferred for gaining a competitive advantage in, for example, productivity, while putting the BRP in a leading position. As Köhler et al. (2014) point out, in a BJF production chain it is technology development for the biofuel processing plant that can bring potential for a lead market. However, this proposition appears to be in direct conflict with propositions 2 and 6, which suggest the use of known and proven technologies, processes, and products. In reality, this will depend on the level of novelty in relation to the timeframe of the project: For long-term projects, novel technologies can be conceived, developed, and proved under the project time-line, whereas for shorter term projects, technologies that have already been demonstrated but remain novel in the large-scale context could also be considered in line with propositions 8, 10, and 14.

Proposition 10 indicates that the process should be as energy self-sufficient as possible. In the biorefinery context, this mainly refers to the industrial stage, when processes generate their own power and energy. Common examples are sugarcane and palm oil mills, where sugarcane bagasse and mill residues are typically used to meet their energy requirements. Thus, in combination with proposition 7, this proposition indicates that the biomass processing unit should generate its own energy and sell the excess to the grid, as is currently the case with some biomass mills. Proposition 11 goes further, indicating that all resources should be exploited, reused, recycled, and valorised. Circularity and cascading are two concepts that touch on these points and could be convenient for the generation of BRP concepts. A circular system focuses on the reduction of flows and the reuse and recycling of materials, while cascading refers to using as much of the biomass as possible, giving priority to biomass uses with the highest possible valorisation potential before energy purposes (Geldermann et al. 2016; Morone and Cottoni 2016). In the biorefinery context, these efforts have been focused on the processing stage with the development of integrated biorefineries (Ghisellini et al. 2016). These approaches could be further put into practice considering whole production chains, allowing for favourable stream integration across production stages and supply chains (Budzianowski and Postawa 2016). Favouring these strategies can also yield a diverse product portfolio, with the co-production of, for example, feed and value added chemicals. However, propositions 10 and 7 also restrict, to some extent, a cascading strategy by limiting the allocation of biomass for higher value products, to ensure energy self-sufficiency or export it.

Proposition 12 relates to the origin of the technology, stating that technology developed or produced in the project's region is desirable. Although countries like the USA and Germany lead in technology ownership in relation to biofuels, Brazil has a relatively large number of patents on biomass processing (prominently for second-generation technology), and is a leading country in the development, demonstration, and production of first- and second-generation technology (Köhler et al. 2014; Miller and Viscidi 2016; Schlittler et al. 2012). Furthermore, Brazil has been an active player in international technology research and development, suggesting an international approach to biofuel developments (Köhler et al. 2014). All of these aspects indicate that technology that is developed/co-developed or produced in Brazil can be available and would be preferable for a BRP.

3.3.3.4. Supply Chain

Proposition 13 refers to transportation distances and locality to keep emissions and costs low, and to allow for stream integration across production chain stages. Much has been studied in this regard, including optimization approaches and design principles for determining transportation distances and scale (e.g. Pantaleo et al. 2013, and Kolfschoten et al. 2014) and the consideration of peripheral pre-processing facilities (e.g. Kim and Dale 2015, and Yue and You 2014). For BJF production, similar approaches could be considered with target airport location and possible biomass production sites as input. Also, as part of proposition 14, the availability of pipelines, waterways, railways, or highways should be considered when establishing feasible transportation distances in the specific region. Proposition 14 further suggests the aproveitamento of available land and industrial sites, like ethanol and biodiesel plants, that could be upgraded for BJF production.

Proposition 15 relates to access to secondary biomass sources as back-up in the case of availability problems. This can be achieved by ensuring access to spot markets, through ports and inland distribution hubs. In addition, alternative biomass feedstock can be produced in coordination with agro-producers, cultivating more than a single crop to minimize availability risks. This risk minimization relates to having crops that a single pest or disease cannot destroy, and increasing the overall system's reliance to weather events through poly-cropping or agroecology systems (Altieri et al. 2012; Martinez and Maier 2014). If available back-up biomass differ in structure and composition, proposition 8 is fundamental for processing these alternative feedstock types. Then, stochastic supply chain approaches that include biomass availability can be used to analyse risks in the BRP context and support decision making (e.g. Correll et al. 2014, and Tong et al. 2014).

3.3.3.5. Business Case Development

Propositions 16–18 relate to the distribution of opportunities and rewards to everyone affected by the BRP. This distribution can be integrated in the BRP business case by considering partnering opportunities with local actors. In practice, this implies including local small and medium-sized enterprises, research institutes, and government bodies during project development, benefitting them also with the transfer of knowledge, skills, and technology. In addition, small producers should be encouraged to integrate into cooperatives or other organizational forms that facilitate technical and commercial support, and give them more power in the face of larger actors in the BRP (Dijk et al. 2012). This type of horizontal integration is proposed as a better alternative to contract farming and vertical integration of the BRP, which limit the value-sharing capacity toward small farmers, and have been proven ineffective for including them in biodiesel projects in Brazil (Chaddad 2015; Stattman and Mol 2014). Furthermore, pricing policies and other mechanisms for the distribution of rewards and risk between different actors across the production chain, like CONSECANA, should be considered for the BRP business development.

Proposition 19 states that the fuel product should be competitive in the market, particularly with low crude oil prices. Furthermore, price competition for intermediate products should be analysed when exploring BRP business cases, especially considering vegetable oil prices, which have been higher than fuel prices in Brazil. 43 Uncertainties in market prices and unfavourable scenarios also have to be considered when building a business case. Governmental policies like penalties and subsidies, which are often considered when exploring cases for biofuel production (e.g. in the work by Cobuloglu and Bueyuektahtakin 2014, and Kantas et al. 2015), could also be used to build feasible business cases. However, given the perceived discontinuity of Brazilian governmental policies and the consequent distrust by industry respondents, it is proposed that the BRP should not rely on government policies unless they are secured for the long term (proposition 20). Furthermore, uncertainties and risks related to these policies should be assessed. In this way, BRPs can still benefit from favourable, stable policies while minimizing vulnerability to political changes.

3.3.4. Sustainability in the Design Space of Biorefineries

By following the presented case study, an approach was developed to implement sustainability as relevant to the project context, its stakeholders, and in line with the technical particularities of the project (through the design propositions), see Fig. 3.3. The approach is intended to be part of the biorefinery design methodology, as a complementary step to the problem definition where design objectives and variables are identified. Once the approach has been followed, it's proposed as a starting point for the synthesis of design alternatives that will proactively support sustainability in line with the project context and its stakeholders.

The identification of stakeholders is supported by considering the whole production chain related to the design project. By investigating who are and could be involved, and who can be affected by the operation of each step of the production chain, a diverse list of stakeholders can be identified (i.e. the focus is widened beyond the conversion step and can include groups like farmers, local companies and institutes). Stakeholders that are not visible in a generic production chain can be further identified on the field by the snowballing technique, through which stakeholders themselves identify other stakeholders of relevance. In design projects at conceptual level, like the presented case study, stakeholders that are directly involved can be few. In these cases, we suggest the identification of stakeholders through the use of a generic BRP production chain, which can be brought into the specific context by considering stakeholder organizations from related sectors, as discussed in section 3.2. In this way, possible stakeholders to a future biorefinery can be considered at conceptual stage of project development too. Then, as the project gets more defined and more stakeholders get involved, this approach could be used again to analyse their values and further specify the BRP.

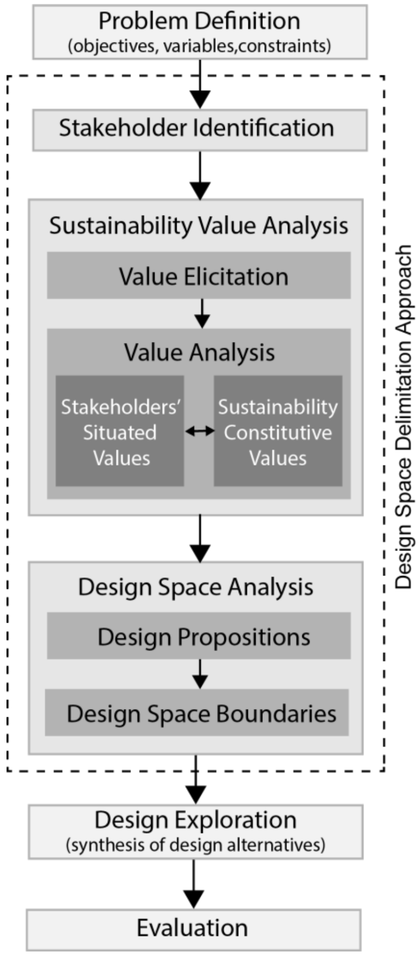

Fig. 3.3. Schematic representation of the developed approach in the context of typical biorefinery design steps.

The sustainability value analysis is composed of an empirical value elicitation and a subsequent value analysis step. Various value elicitation methods can be used at this stage, like photo-elicitation techniques (for example, with the use of production chain schemes), or surveys that orient the elicitation to pre-identified value conflicts or issues. In this case study, semi-structured interviews were used for elicitation, which was convenient given the project's explorative nature (i.e., when not much had been defined yet and closed questions would not have been possible, section 3.2.3). Also, given the diversity of stakeholders, interviews are suitable for adapting questions according to the respondent's knowledge of and scope of involvement in biobased developments. However, interviews are time consuming and difficult to implement when dealing with different cultures. Thus, for later stages of biorefinery design along the project development, we suggest the use of targeted value elicitation methods to facilitate the process (e.g. surveys, Miller et al. 2007). Furthermore, for this study, the sustainability constitutive values served as the framework for the value analysis. However, if targeted value elicitation approaches are to be followed, such a framework could be used for the design of the elicitation instrument, simplifying the value analysis. This is a balance between practicality and openness that is up to the user of the presented approach.

During the design space analysis, stakeholders' sustainability values are used to create normative design propositions for the project variables, as presented in section 3.2.4. As these propositions set boundaries on the design space, the project scope is narrowed down and focused on design alternatives that proactively accommodate these sustainability values. Furthermore, in this approach no ranking or choice of values is intended; all values related to sustainability are considered. This means that during further design activities, the designers are encouraged to find design solutions that support all values. In some cases, the design team may have to cross some of the design boundaries formed by the design propositions to make the design feasible. As mentioned in section 3.3.2, the boundaries are indicative, and when they are crossed, they are expected to at least prompt an active reflection on their implications. Thus, the proposition's contribution to sustainable biorefinery design is related not only to their implementation, but also to the reflection on how design decisions can and will affect the project's context and stakeholders.

3.4. Conclusions

We have presented an approach to effectively introduce sustainability into early phase biorefinery design through the setting of the design space, ex ante the generation of design alternatives. Thus, by narrowing the space for designing, this approach is suggested as a practical way toward sustainable biorefinery design. A key part of the approach is the inclusion of different stakeholders who put forward their own views on what is of importance in their context. This is based on an empirical analysis of stakeholders' sustainability values, brought into engineering practice through design propositions. In this way, contextual and societal aspects around biobased systems, which have been identified as crucial for further advances in the sector (Dale 2017, 2016; Mabee 2017), form part of their development. Then, by being open to these project-specific issues, this approach embraces the subjectivity and interpretative flexibility of sustainability, in line with recent calls for context-aware analyses of biobased systems (Efroymson et al. 2013; Kline et al. 2016; Souza et al. 2017).

Furthermore, sustainability is promoted in the design process by inviting the design team and the stakeholders to reflect on the interaction between the biorefinery project and their context. This means that the scope of the approach is at both the biorefinery project level – by affecting its evolution and configuration – and the individual level, by engaging designers and stakeholders in an active reflection for sustainability. Although the developed case study was carried out at a conceptual level, its use in such an explorative manner can nonetheless contribute to incorporating sustainability for further decision making. Thus, this approach could also be used to analyse the values of stakeholders identified later in the project, or to further specify the BRP in more detail. Therefore, the presented approach can potentially be applied at any biorefinery development stage, from conceptual to detailed design, making it a promising starting point for considering an inclusive and context-aware sustainability in biorefinery design.

Finally, it should be noted that this case study, like any BRP, has an institutional setting that is beyond the scope of the presented approach. In this case, this institutional setting emerged through respondents' statements about barriers to the development of BRPs, such as governmental and economic instability, financial commitments to fossil resources, and power relationships between actors. These factors can strongly affect the project feasibility and implicitly lead the decision-making process. Although there is no clear way to resolve these issues from the design engineer's desk, we suggest considering this institutional setting as openly and explicitly as possible for decision making in biorefinery design.

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Chapter 4

Integrating value considerations in the decision making for the design of biorefineries

This chapter has been submitted as:

Palmeros Parada, M., Asveld, L., Osseweijer, P., Posada, J.A. Integrating value considerations in the decision making for the design of biorefineries.

4.1. Introduction

It is now more than a decade since controversies over the sustainability of biofuels began to surface (Rosegrant and Msangi 2014). These controversies called attention to societal concerns, value tensions and uncertainties that had not been considered during the development of biobased production. For example, once biofuel production started to increase in the 2000s, its association with food production and land use change started to be debated (Rosegrant and Msangi 2014). As consequence, tensions emerged between these sustainability aspects and the emission reduction objectives that drove biofuel production in the first place. While these concerns do not necessarily relate to all biobased products, they do illustrate some of the complexities that can arise around this production approach.

Biorefineries are the processes and systems for the production of fuels, materials and chemicals from biobased resources (Bauer et al. 2017). During the design of biorefineries, the various alternatives that can define them are explored, including feedstock types, technological platforms, and by-products. Therefore, addressing stakeholder concerns about sustainability and acknowledging value tensions during the design of these systems can contribute to the development of more sustainable and acceptable biobased production. Several methods have been developed to consider sustainability during the design of biorefineries. However, these methods are typically closed to stakeholder participation and are often limited to issues that already drive biobased production, such as energy efficiency and the reduction of carbon emissions (Palmeros Parada et al. 2017; Pfau et al. 2014). This means that existing biorefinery design approaches rarely address societal concerns, value tensions and uncertainties related to the sustainability of biobased production.

Value Sensitive Design (VSD) is a design approach to proactively consider and design in support of stakeholders' values (Friedman et al. 2008). However, there has been limited work done on the application of VSD for technological systems such as biorefineries, where diverse stakeholders across various geographies and sectors play a role. Additionally, at early stages of development of the biorefinery, there is limited availability of information, and involvement of stakeholders is difficult; at later stages the capacity to change the project is limited once investments have been made. An explorative VSD research on the investigation of stakeholders' values and the generation of project specific principles for the early-stage design biorefineries has been published recently (Palmeros

Parada et al. 2018). In their analysis, the authors suggest that these principles could guide subsequent design activities for obtaining a value sensitive biorefinery concept. However, there was no empirical work on the use of this analysis to derive a design concept (i.e. a biorefinery), and how to implement it as part of a design project.

In this work we investigate the development of an early-stage biorefinery design project by a design team. Specifically, the aim of this work is to investigate how considerations of stakeholders' values can be integrated to the decision making processes that lead to a biorefinery concept. Taking as starting point the work by Palmeros Parada and colleagues (2018), the hypothesis is that this integration can be achieved by promoting reflection during the design activities. To put this into practice, an approach to promoting the consideration of societal aspects during research and development (R&D) activities called Midstream Modulation (MM) (Fisher et al. 2006) is adapted to encourage a design team to reflect on identified stakeholders' values. Therefore, while we argue that this work contributes to the application of VSD by bringing considerations of stakeholders' values during the design of complex systems like biorefineries, the focus here is on the design process itself and not so much on the outcome (the biorefinery concept).

4.2. Background

Prior to describing the methodology, the theories and concepts that serve as a basis for this work will be introduced in the following paragraphs.

4.2.1. Biorefinery Design

Biorefineries are defined as the processes, facilities, and production systems for obtaining biobased products. In the broadest sense, biorefineries can be spread across various locations and include different stages of a product value chain (Bauer et al. 2017), such as the processing of agricultural residues and the conversion steps for obtaining specialty products. To specify the technical features of a biorefinery, design decisions are made along various development stages. At early-stages of development, the design space is broad and decisions involve high level design *variables*. As the biorefinery becomes more defined thorough pilot and demonstration testing, the design space gets narrower and the decision making involves more detailed variables. For example, for an early-stage design, a decision might concern the conversion process (e.g. fermentation as one alternative and thermochemical conversion as another), whereas in later stages of development the decision may be about conversion parameters for the chosen alternative (e.g. temperature, aeration rate). Decisions over a variable are made along iterative processes that include the generation and exploration of alternatives (e.g. calculations, simulations, experiments), and a final decision.

In biorefinery design practice, sustainability has mostly been approached from an engineering perspective. As part of assessment, integration, and optimization methods, sustainability is typically defined through metrics that indicate impacts on global warming and energy efficiency (Palmeros Parada et al. 2017). In this way, sustainability has been reduced to a few indicators that fit engineering methods but do little to address the complexity of the concept, as discussed above. To design for sustainability there is a need to open up to different methodologies and fields of knowledge (Azapagic and Perdan 2014) in order to address the contextual implications of biobased projects and the values of stakeholders on which different sustainability judgements are based (Asveld and Stemerding 2018). Value Sensitive Design (VSD), an approach to design with consideration of stakeholder values in the context of a particular technology, is therefore a promising approach to the development of more sustainable biorefinery concepts.

4.2.2. Value Sensitive Design

VSD is an approach to the design of technologies that proactively seeks to consider human values during the design process (Friedman et al. 2008). With a focus on design projects, VSD is grounded on the understanding that the influence of a technology on society depends on its technical features, the context of its implementation, and its stakeholders (Davis and Nathan 2015). VSD is applied through three investigations: a) a *conceptual investigation* to identify stakeholders and their values in relation to a technology, b) an *empirical investigation* to recognize understandings and contexts concerning stakeholders' values and the technology, and c) a *technical investigation* that leads to the accommodation of investigated values in a design outcome (Friedman et al. 2008). Iterations between these investigations, which are not necessarily independent, can serve to validate or gain more insight into how stakeholders' values can be better supported by the technology.

Until now, VSD has mostly been applied for the design of artefacts and software, and its application for technological systems, such as biorefineries, is not easily deduced from previous experiences. This is largely because the development of biorefineries is a long process that requires the involvement of diverse stakeholders and large investments that cannot be reallocated once they have been made. This brings biorefineries into a complex socio-technical domain. Facing equally complex situations, VSD has been applied for the early stages of development of an urban simulation system (Borning et al. 2005; Friedman et al. 2008), and to approach the energy transition in Finland (Mok and Hyysalo 2018). However, these cases greatly differ from that of biorefineries as they address already existing systems or specific parts of them (i.e. a city, a building), with clearly identifiable stakeholders and locations, and for which the design of the system itself was not in focus. Therefore, it is not possible to take a similar approach to the design of biorefineries. In biorefinery design there is no pre-existing system. Involving stakeholders can be problematic when they come from a variety of sectors and geographies, especially in the early stages of development when different products or feedstocks are still under evaluation. Even when revamping an existing industry, designing a biorefinery implies creating a system with new stakeholders related to, for example, new biobased products. This means that stakeholders' roles and interests in a biorefinery can be very uncertain or tenuous, and involving them may require commitments that are not easily made at the early stages of a project.

The application of VSD for delimiting the design space of biorefineries in early stages of development has been explored recently (Palmeros Parada et al. 2018). As result, design propositions were derived as project specific design principles, and the authors suggest that reflecting about these propositions can support the integration of values in the subsequent design of biorefineries. In a similar line, Yoo and colleagues (2013) show that promoting reflection in a co-design space results in the identification of new technical features for the design of a value sensitive device. However, there is no experience on this type of work to derive a value sensitive technical concept, especially for a complex system like a biorefinery, and integrated to a design project. This leads to the observation that while various methods for value elicitation and empirical data analysis have been used in VSD (e.g. Czeskis et al. 2010; Dantec et al. 2009; Miller et al. 2007; Pommeranz et al. 2011), not much has been elaborated about the design process itself. There is some empirical work on the translation of values into design principles and desired technical features, and the works by Miller and colleagues (2007), and Xu and colleagues (2012) are particularly insightful. But no systematic investigation has been elaborated on the consideration of values during the technical design process, when alternatives are generated, explored, and decided over. This is not only a crucial point when defining technical features in support of stakeholders' values, but such an analysis could also serve as a reference for future developments, as suggested by Oosterlaken (2015). Therefore, this work focuses on the generation and exploration of design alternatives, and how decisions about design variables are made in support of stakeholders' values.

4.2.3. Midstream Modulation

To bring reflection into biorefinery design practice, we looked at MM, a method that focuses on the practices of researchers and their decision making. MM is applied to broaden R&D practice to include considerations of societal aspects (Fisher and Schuurbiers 2013). MM is typically applied as a series of interventions that promote reflection and can result in the modulation of R&D decision making. When R&D participants improve their performance within the bounds of theories and values common in their field, it can be said that they are involved in a normal or *de facto modulation* of their practice (Fisher and Schuurbiers 2013). Then, as engagement takes place with an MM researcher, R&D participants are prompted to reflect upon their decisions and their potential impact, while becoming aware of themselves as agents in their own practice and of the de facto modulations. This *reflective*[1] *modulation* has the potential to incite the envisioning of alternative paths in the participant's practice (Fisher and Schuurbiers 2013; Schuurbiers 2011). Lastly, *deliberate modulation* has been recognized as a consequence of gained reflective awareness (Fisher and Schuurbiers 2013; Schuurbiers 2011), expressed as its deliberate use for the direction of decision making in R&D activities with consideration for societal aspects (Flipse et al. 2013).

Therefore, in contrast to VSD, MM does not explicitly aim to direct the outcomes of R&D activities towards a specific target, i.e. to integrate the values of stakeholders within the design concept, or support a central value such as safety. As Fisher and Schuurbiers (2013) put it, MM encourages reflection not to "shape the process" but rather to "stir" it. Nonetheless, MM has been shown to successfully raise levels of reflection and to result in a deliberate change of practices in R&D decision making, with considerations beyond those typical to R&D in both academic and industrial environments (Flipse et al. 2013;

[1] In this work the word *reflection* is used in reference to both *reflection* and/or *reflexivity* to avoid unnecessary complexity.

Schuurbiers 2011). Therefore, MM could also be applied to promote reflection about stakeholders' values in a design context. Particularly, identified stakeholders' values and design propositions, as derived for biorefinery design by Palmeros Parada and colleagues (2018), can be brought forward through MM interventions along the design process. Bringing forward these elements to a design group could promote reflection and support the identification of new technical features, as shown by Yoo and colleagues (2013) with stakeholder prompts. Then, by promoting reflection with MM during a design project, value considerations could be integrated into the biorefinery design process.

4.3. Methodology

In this work, the consideration stakeholders' values during the design of a biorefinery for bioplastics production was investigated. For this, MM was adapted to promote reflection about stakeholders' values during the decision making processes over design variables. These values were identified following the work by Palmeros Parada and colleagues (2018), through a design space investigation. In the next paragraphs the case study and the followed methodology are presented in more detail.

4.3.1. Case Study

4.3.1.1. Design Project

The development of a design project carried out from January to June 2017 was investigated. The project was developed by a design group participating in an international business competition for biobased production. This competition was organized by actors in the biobased sector, and was targeted towards graduate students with the aim of stimulating entrepreneurship and innovation in the biotechnology and bioengineering field. For the competition, the group had to develop a business plan for their own biorefinery concept; thus, they had to design not only a biorefinery, but also a plan of how to implement it as a business. The evaluation criteria for the competition were: design quality, business plan viability and originality, sustainability[2] performance, and presentation of the business plan. However, no further detail was given with respect to

[2] Sustainability was stated as an important criterion in the competition, however no specific list of aspects to consider was given beyond stating its economic, environmental and social dimensions.

these criteria. The prize of the competition was a grant to continue the research and development of their idea.

4.3.1.2. Design Group

The starting point for the design project was ongoing research at TU Delft on microbial platforms to produce a biodegradable biobased polymer (BBP), which is an alternative to fossil-based plastics. Because of the early stage of development of this technology, the design was at a conceptual level, where all available information was theoretical or experimental at lab scale only. The group was composed of two Process Design PDEng[3] trainees (Designers 1 and 2, D1 - D2) who had no previous connection to the research project, and a PhD candidate and two master students who worked on the larger research project in the university (Designers 3, 4 and 5, D3 - D5). Most of the designers worked on the project as an additional activity to their regular work. Additionally, a group mentor with experience on biotechnology research supported the group during the project development. A sustainability team, composed of D1 and D4 was defined at the beginning of the project. The word team is used to refer to this subgroup in contrast to the whole group including all the designers.

4.3.1.3. Researcher Stance

The authors of this article are academic researchers focused on understanding societal and sustainability aspects of biotechnologies, and the use of this understanding in support of responsible innovation practices and communication processes. All authors work in the same research group and have experience with biorefinery design, life cycle and technology assessments, and midstream modulation. Although the authors work at the same university as the designers, they had not collaborated previously. The collaboration for this work started after the suggestion of the design group mentor, who was aware of the authors' field of research. The first author, also referred to as the researcher throughout this paper, was in charge of the field work and had all contact with the design group. The first author is currently doing a doctoral dissertation and has research interests on how technological innovations in the fields of biotechnology and renewable energy can be developed responsibly and in support of sustainability.

[3] PDEng: Professional doctorate in engineering is a title given to graduate engineers who work on design projects in industry and academia partnerships for two years. ("PDEng programmes" n.d.).

4.3.2. Interventions

During the development of the case study different interventions took place along four project phases as schematized in Fig. 4.1. Throughout these phases, the researcher conducted 10 interventions with the design group as described in Table 4.1.

Table 4.1. Overview of interventions along the project development

Phase	Intervention	Time (weeks[c])	Intervention Type	Designers Present
A. Start	1	0	Individual interviews	D1 - D5
	2	1	Group meeting observation	D1 - D5, mentor
B. Design space workshops[a]	3	2	Workshop with sustainability team	D1, D4
	4	3	Workshop with sustainability team	D1, D4
	5	5	Workshop with sustainability team	D1, D4
C. Investigation of the design decisions	6[b]	7	i. Interview with sustainability team; ii. Group meeting observation	i. D1, D4; ii. D1, D3 -D5, mentor
	7	10	Interview with sustainability team	D1, D4
	8	12	Interview with sustainability team	D1[d]
	9[b]	15	i. Group meeting observation; ii. Interview with sustainability team	i. D1, D2, D4, D5; ii. D1, D4
D. End	10	17	Individual interviews	D1-D4[e]

[a] After each intervention in this phase, the designers investigated identified stakeholders (Table 4.3).
[b] Roman numerals indicate different parts of the same intervention; [c] In weeks from the first intervention; [d] D4 was not available to participate in intervention 8; [e] D5 was not available for a post-interview.

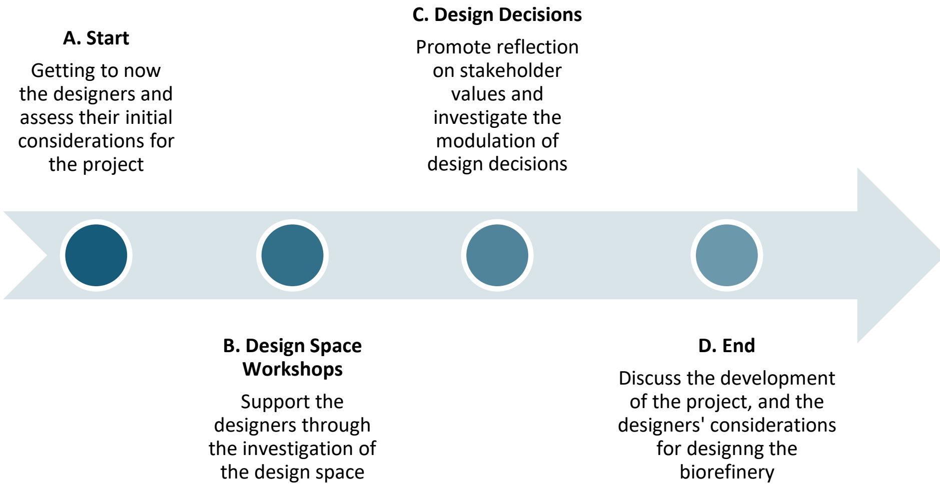

Fig. 4.1 Schematic representation of the four different phases of this research

4.3.2.1. Start and End Phases

Interviews at the start and end of the project were held with all group members, D1 - D5. These interviews were prepared to identify changes in the value considerations before and after the interventions, as complement to the data gathered along the development of the project. These interviews also served to start identifying the main design variables in the project, and to investigate the expectations of the designers with this research. An interview guide was prepared (available in Appendix III) but the interviews were flexible, leaving room to explore emerging topics. Additionally, the information from the interviews was complemented with observation data from the first group meeting, where all group members discussed their ideas about the project (Table 4.1, intervention 2).

4.3.2.2. Design Space Workshops

These interventions were intended to support the designers through the design space investigation as proposed by Palmeros Parada and colleagues (2018). The objective of this investigation was to identify potential stakeholders and their values, and to derive design propositions to guide later design activities. For this, three 2-hour sessions were scheduled with the sustainability team, and during these workshops the researcher asked questions and guided the sustainability team through a discussion about stakeholders, their values, and the relationship between the project and the identified values. Available notes and board photographs from these sessions, and documents exchanged with the team were used for subsequent analysis (see Appendix III).

During the first design space workshop (intervention 3), the sustainability team together with the researcher started to identify stakeholders who were relevant to the project. For this, a generic biobased production chain was taken as a starting point. The sustainability team and the researcher discussed the various production chain activities (i.e. if there was anything missing or specific about bioplastics), and subsequently identified stakeholder groups that could be directly and indirectly affected by these activities and their development. All of these potential stakeholders to the future biorefinery are generically referred to as stakeholders, with no distinction between direct and indirect stakeholders as typically done in VSD, because they are all equally distant to this project or their role is uncertain in this early-stage of development. When necessary, however, ‘project stakeholders’ are specifically mentioned given that they are a clearly identifiable group of direct stakeholders at this stage of development (see section 4.4.2).

In between the design space workshops, the designers gathered information about the identified stakeholders. These investigations were based on public media and reports, academic literature, and, when possible, through direct contact with representatives from the identified organizations. Additionally, as part of the competition the team had the opportunity to contact business professionals and academic researchers in the scope of the project or with experience in biobased production. The aim of these stakeholder investigations was to gather data to support the identification of stakeholders’ values, focusing on information about the expectations, hopes and concerns of stakeholders by looking, for example, at the mission and vision of the identified organizations, their statements in relation to bioplastics and biobased production, and past actions or ongoing projects in the field. Where possible, the designers directly asked stakeholders, for example, if and why they would be interested in participating in the development or implementation of the project, what benefits or disadvantages they would face with its implementation, what actions they had previously taken in relation to biobased production, and why these were considered to be important.

The collected information about the stakeholders was discussed by the sustainability team and the researcher during the second and third design space workshops (interventions 4 and 5). During the second workshop, their initial findings about the stakeholders were discussed in the context of the project to identify where further research was needed. During the third workshop all the gathered information about the stakeholders was analysed to identify values of relevance for the project. Once a value was identified, it was put into contrast with care for nature, intergenerational justice and distributive justice, as constitutive values of sustainability (Palmeros Parada et al. 2018). In this way, values from all stakeholders that related to sustainability in the context of this case were identified. Additionally, during the third workshop, the sustainability team and the researcher conducted a preliminary examination of how the identified values were related to the technical aspects of the project. For this, the team made a block scheme of their project and marked the aspects that they considered to be related to a given value (e.g. a feedstock, a processing step). Based on this exercise and following the third workshop, the sustainability team developed a set of design propositions that suggested boundaries to the design space.

4.3.2.3. Investigation of the Design Decisions

The investigation of the design decision took place along four interviews with the design team. During these interviews the researcher asked the team to discuss the *alternatives* they were exploring for the *design variables*, the *considerations* involved in their decision making, and the *outcomes* they anticipated. This inquiry was based on previous MM literature, with two adaptations: (1) *research opportunities* investigated in MM were substituted by *design variables* to bring MM to the design context, considering that both imply potential paths for action that designers and researchers decide over; and (2) decisions were discussed in relation to the values and design propositions from the design space workshops, in contrast to the generic social and economic perspectives of previous studies (Fisher et al. 2006; Fisher 2007; Flipse et al. 2013; Schuurbiers and Fisher 2009). The researcher asked the designers about these aspects directly and indirectly, and prompted them to explain their assumptions, for example by pointing to extreme alternatives. Although interviews were focused on the design variables being explored at the time, they remained flexible. If not mentioned by the team members themselves, questions about how their decisions related to the design propositions and the identified values, especially the workshop values, were asked.

Additionally, the researcher took part in two group meetings attended by most of the group members and the mentor (interventions 6ii and 9i in Table 4.1). These meetings were set up by the group, to share their results, discuss difficulties, and agree on subsequent activities. The researcher observed the discussions and, if time was available, asked questions about the group's design decisions, considerations, and expected outcomes.

4.3.3. Data Analysis

The gathered data was coded and analysed by the researcher to identify emerging values. Values identified from the start phase data were contrasted with the values from the design space workshop data, the decision making investigation, and from the group's final report for the competition. This made it possible to analyse if and how the value considerations and reflections changed as the project progressed. For this, audio files, pictures, and intervention notes were analysed with the use of MAXQDA 12.

The identified values during the start phase (project values) and the design space workshops (workshop values) are presented in sections 4.4.1 and 4.4.2 respectively. The consideration of all of these values during the design of a biorefinery was investigated by analysing the decisions about each project variable, and is presented in section 4.4.3. This analysis centred on the various decision making processes in which alternatives were being explored for defining the design variables. The identification of different modulation levels (i.e. de facto, reflective and deliberate) allowed to recognize the emergence of reflection concerning specific issues of relevance to the project. Feedback on this analysis was received from several designers (D1, D3, D4) by email, or discussed in person.

4.4. Results

4.4.1. Start Phase

During the start phase, the design group defined their project by agreeing on the microbial platform and the main feedstock of the process. Sugarcane was decided upon as feedstock because of its high sucrose content (input for the microbial conversion). Brazil, as a leading country in the production of both sugarcane and biofuels, was selected as the target country for the project. Therefore, the definition of the feedstock type fixed the location of the design project: the sugarcane producing areas of Brazil. Once these aspects were agreed upon, four main design variables were discussed by the group: (i) Feedstock streams, (ii) Products, (iii) Processing and technologies, and (iv) Business plan. These variables and the main alternatives considered during the decision making process are described in Table 4.2.

Table 4.2. Description of the four main design variables

Design Variable	Description
Feedstock streams	This variable relates to the main input material for the biological conversion for obtaining BBP. From the beginning of the project the considered feedstock was sugarcane. Therefore, rather than addressing the feedstock crop, the group discussed whether to consider sugarcane juice only or whole sugarcane, as harvested. This choice relates to the first steps of sugarcane processing, which leads to two primary fractions: a sugarcane juice that contains most of the sucrose, and a bagasse fraction mostly composed of fibres
Products	Different product forms and by-products considered as alternatives. Decisions over this variable ran parallel to some of the decisions about the process because certain products can only be obtained with certain technologies or process configurations. Also, the decision to consider the whole sugarcane as feedstock meant that sugarcane bagasse was available for processing. The main product alternatives were to produce pure BBP or a co-polymer of BBP with other compounds. Energy as a by-product from bagasse was also considered, as well as using bagasse for the production of compounds to co-polymerize with BBP (second generation or 2G copolymer compounds), and BBP itself (2G BBP) [4].
Process	Different alternatives were explored in relation to the unitary operations of the process, the process structure, and operation mode. The alternatives for the recovery of the product from the microorganism and its purification were widely discussed, i.e. whether it should be a mechanical, enzymatic or chemical process, or a combination. Also, when co-polymer products were being considered as alternatives, polymerization processes were included in the discussion
Business plan	The business plan was explored in relation to what the team considered to be their value proposition (e.g. lower production cost, biodegradability), their target clients (e.g. plastic producers, companies specialized in biodegradable plastic), and most significantly, the business model. Alternatives to the business model were related to the option of integrating the process and/or business with an existing sugarcane mill, running it as a partnership or licensing the design.

Project values were identified at the start phase as the aspects that the group considered relevant for the project itself and for the competition (brief descriptions of all

[4] *Generations* are used to refer to the type of feedstock used for production: first generation refers to sugar or oil-rich process crops, while second generation refers to more recalcitrant lignocellulosic materials. Very often, first-generation crops are food crops and second-generation crops are considered residues or ‘energy crops’.

values are presented in Table 4.4). The majority are values typically associated with the science and engineering domains, such as process simplicity, scientific focus and technical feasibility. Achievement and designing feasibility appear to be more related to the competition context presented in the methodology section: The designers found it important to do what was needed to try to win the competition, taking their expertise and the available resources (e.g. time, data, and software) into consideration. Also, each of the designers mentioned sustainability as an important part of their project. Specifically, they spoke about the biodegradability of the target product as a means to prevent the pollution and harm to the environment that is typically associated with conventional plastics. Furthermore, they discussed that their project was about proposing an alternative to fossil resources, BBP being renewable and potentially associated with fewer CO2 emissions than conventional plastics. In other words, the designers discussed their project as a potentially more sustainable alternative.

4.4.2. Design Space Workshops

In the first two workshops the team raised questions and discussed the implications of bioplastics production and use, the related stakeholders, and potential locations where production could take place. Starting from a generic production chain for biobased products, the sustainability team initially added two extra steps: the application production process (i.e. from bulk plastic to end-use products) and the waste management process. In this way, the designers made a distinction between the scope of the project for the production of a biobased plastic polymer, and its use as raw material for the production of end-use products such as packaging. Also, they observed that some stakeholders would vary according to the end-user's location (e.g. would the plastic product be exported worldwide or would it be sold locally?). Another topic that was raised related to the food and sugarcane-ethanol industries. These industries were discussed as affected parties or even as potential participants in the production process. Once they had discussed the parties affected by the operation of the production chain, the discussion turned to stakeholders who could be affected or be involved during development, notably the public, NGOs, government and academia. For example, government bodies were discussed as the parties who set the rules and enter into commitments that could potentially open up a space, or could incentivize or discourage this type of technology. Table 4.3 summarizes the stakeholder groups that were identified and specifically investigated by the team.

Several values were identified as a result of the design space workshops and the investigation of stakeholders by the design team, and are presented in Table 4.4. From this table it can be seen that, from the beginning, the design group as a whole was already familiar with many of the sustainability issues that were relevant to the project. Part of this awareness may be due to some of the designers' academic experience with bioplastics (D3 – D5), having had opportunities to face discussions about the sustainability of these materials. However, the design space workshops and related investigations were not redundant, as they served to understand these values more specifically for their case and considering the stakeholders (see table 4.3).

Table 4.3. List of stakeholders investigated during the project

Stakeholder	Relation to biobased production or this project[a]
Biobased end-product manufacturers and industrial associations	They use bioplastic as feedstocks for the production of goods that reach final users (e.g. food-packages, eating utensils). (DC)
Bioplastic producers	They produce plastic materials from biomass resources, such as corn-based PET. (DC)
Biotechnology business experts	They manage capital investments and businesses in the field of biotechnology. (DC*)
Project stakeholders	This group includes the design group, researchers associated with the BBP research project, and the competition organizers. (DC)
Waste and recycling companies	They process waste streams to a desired quality, or to obtain new products. (DC*)
Bioethanol companies, logistics and industrial associations	They produce, distribute and/or purchase sugarcane, and produce bioethanol
Conventional plastic end-product manufacturers	They produce manufactured plastic goods from fossil resources, which reach a final user
Conventional plastic manufacturers	They use fossil resources for the production and/or transformation of plastics
Non-governmental organizations	They are related to the preservation and recovery of natural resources, and educational activities about bioplastics, their consumption, and environmental laws.
Regional government	This group includes regional government branches in charge of developing plans and actions related to agricultural and industrial production

[a] DC stands for direct communication with representatives of the related stakeholder group, which includes face to face interviews and multi-media calls with the designers. An asterisk (*) indicates that the direct communication took place after the design space workshops.

Table 4.4. Values identified from the start phase and the design space workshops

Values	Start Phase	Design Space Workshops[a]	Related Stakeholders[b]
Achievement	The group's ambition to win the competition	N/A	Project stakeholders
Biodegradation and environmental safety	Importance of cleanliness and prevention of harm to life (human and non-human), related to the persistence of waste, including plastic, the pollutants released, and chemicals used during production of biobased alternatives. Biodegradability as a desirable trait of the product. Since the material degrades over time, it is expected to be less harmful to the environment than "conventional plastics"	The same, and the actual biodegradation of the plastic, considering the conditions under which the material degrade (dependent on its composition), and the extra processing and infrastructure required for it	Biobased end-product manufacturers, bioplastic producers, waste and recycling companies, NGOs, and project stakeholders
Cooperation	N/A	Cooperation in the sense of building partnerships with various organizations to ensure the success and long-lasting durability of the initiative	Bioplastic producers, bioethanol companies
Designing feasibility	Related to the group's capacity to design a biorefinery and the business case with the available resources for the competition, especially time and data	N/A	Project stakeholders
Entrepreneurship	The need to design a cheaper process for bioplastics that can compete with conventional plastics in the market	The same, and also about expanding the design and business idea to other applications and locations	Biotechnology business experts, biobased end-product manufacturers, bioplastic producers, bioethanol companies, conventional plastic producers, NGOs and project stakeholders
Food security	Using food crops for non-food applications is not desirable as it may affect food access for a section of		Biobased end-product

	the population. Awareness that that all crops, edible or not, use land and may affect food price or availability. Preference for second generation (2G) feedstock		manufacturers, NGOs and project stakeholders
Leadership	Developing a product and/or process that is inventive and that will contribute to companies' market leadership		Bioplastic producers and project stakeholders
Process simplicity	Minimum operational needs, such as lower maintenance requirements, or fewer conversion steps	N/A	Project stakeholders
Product quality	Generically related to a given quality or trait that is desirable in the product. At this point, it is vaguely related to ease of use, irrespective of the user	The same, but further specified in the context of end-product applications, and considering the reliability of the design	Biotechnology business experts, biobased end-product manufacturers, conventional end-product manufacturers and project stakeholders
Renewability	The substitution of fossil-based resources with a renewable material, the importance of reducing CO_2 emissions		Biobased end-product manufacturers, bioplastic producers, bioethanol producers, NGOs, and project stakeholders
Resource efficiency	Minimum use of resources per unit of product. Focused on conversion yields, such as amount of substrate needed for the product	The same, and broadened to using less of all resources (e.g. water, energy) in the production process	Biotechnology business experts, bioethanol companies, waste and recycling companies, NGOs and project stakeholders
Scientific focus	Related to the interest of the project stakeholders in investigating the "real-world" feasibility of the research being conducted in the university	N/A	Project stakeholders
Technical feasibility	Related to the design of an applicable process, one that works in practice	N/A	Project stakeholders

[a] Merged columns in some rows indicate that there was no change in the specification of the value from the start phase to the design space workshops. [b]Input from biobased business experts and waste and recycling companies is included although the team was only able to talk with them

after the design space workshops. N/A: the value was not discussed in the corresponding project phase.

During the workshops the designers had the opportunity to think more deeply about many of the stakeholders they identified and investigated, as well as the emerging sustainability aspects in the context of the project. This was particularly evident on the subject of biodegradation. While the group had already expressed the importance of biodegradability during the pre-interviews, it became clear during the design space workshops that ensuring the actual degradation of the material was also important. This originated primarily from the investigation of non-governmental organizations who were critical about bioplastics, and who noted that while bioplastics were often advertised as more sustainable, little effort was done to ensure that they were biodegraded. This made the team recognize that some biodegradable plastics, depending on their composition, required specific conditions for their biodegradation, otherwise they could remain in the environment for a long period (see, for example, Emadian et al. 2017).

In the last session of the design space workshops the team reflected on the relationship between the identified values and the design variables. This occurred as the team derived design propositions to delimit the space for decision making. However, these propositions remained very generic. For example, in relation to environmental safety and resource efficiency the team proposed that the project should "*ensure waste minimization by ensuring maximum utilization of raw materials and proper design selection*". This activity invited the team to think of the design project and their prospects for decision making in relation to all identified values and sustainability. While the contribution of the design propositions may initially appear negligible, in the next sections it will be presented how the results from the design space workshops served as modulators of the designing process.

4.4.3. Investigation of the Design Decisions

The design group developed the project by making design decisions regarding four main variables (Table 4.2). The decisions for these variables were analysed to see if and how the workshop values were being considered. Overall, six different decision making processes going through de facto, reflective and deliberate modulations were identified. To illustrate these decision making processes, an account of two of them is presented in this section, one about the main product of the project, and the second about the business model. In Table 4.5 these two processes are summarized with reference to the different modulations and considered values; all six decision making processes can be found in Appendix III.

Products. Pure BBP, the main biorefinery product, was the starting point for the products variable. Additionally, after deciding to process the whole sugarcane, bagasse (i.e. a sugarcane processing residue) was recognized by the group as an available material that could be used in the biorefinery to produce electricity. So, energy became their ***de facto*** alternative as a by-product. However, by the time of the 5th intervention, the assumption that the product would be pure BBP granules and that bagasse would only serve for energy generation was questioned. During this time, the sustainability team ***reflected*** over different possibilities they identified for the main product. Particularly, they spoke about a co-polymer as a main product (i.e. the product could be composed of two types of compounds, the original BBP and a second co-polymer compound). The group argued that a co-polymer product would have better properties and consequently a higher market price. When speaking about one of the possible compounds for the co-polymerization, the team recognized that they had the option to use bagasse to produce it. Using bagasse for producing a co-polymer compound was expected to appease concerns over food security and first-generation production (i.e. a part of the plastic product would be produced from a non-food raw material). This discussion resulted in the exploration of using bagasse for producing a co-polymer compound and also for producing 2G BBP from a different metabolic route.

However, during intervention 6, after enquiring again about the utilization of bagasse, the sustainability team explained that they had decided, after exploring other alternatives, to design for energy generation. In this case, the team ***deliberately*** changed their original idea: they explored and researched alternatives based on considerations that reflected the workshop values. However, due to their concerns over their own expertise and the feasibility of designing for the 2G alternatives, as well as the impact it would have for the competition, they decided to keep to their de facto idea (i.e. production of BBP granules and bagasse for energy). Nevertheless, the sustainability team stated that the explored alternatives would be integrated in the final report as an alternative to consider for future research, writing in the groups' final report: *"Another interesting solution would be the simultaneous studies of using the sugarcane bagasse for the production of PHB... This will ensure we are not dependent on sugarcane juice alone and will also reduce the* *competition with sugarcane used as a food source, which is part of our sustainability design proposition."*

Business model: The business model discussion was started later than the other variables. It was first observed during intervention 6 when the group was already investigating the production process as integrated with an existing sugarcane mill. Their ***de facto*** idea about the business model was then related to this decision only: the business model had to be able to accommodate the integration of the process. The initial alternative of the group was to have two separate companies with integrated streams. This integration would take place by means of a type of partnership that would allow to buy and sell each other raw materials and utilities. However, later in the same intervention, they ***reflected*** about other possibilities for developing the integration idea. By the end of the discussion, the alternatives to the partnership model were to merge their business into a milling company, and a licensing model in which they would not sell the BBP product, but rather license the technology.

The group discussed these options while reflecting on their implications during the interventions 6, 7 and 8. They concluded that the partnership model would benefit their project by increasing resource efficiency, while providing engagement for cooperation and business growth. Regarding the merging model, they also anticipated a positive effect on resource efficiency, and flexibility for the product portfolio. As for the third alternative, they thought that the licensing model would allow them to cooperate with multiple companies and to generate opportunities for expanding the business idea. Additionally, they discussed the idea that licensing agreements might offer the option of pushing for a biodegradation deal with licensee companies.

However, by intervention 9 the team ***deliberately*** focused on the partnership model, and discarded the license idea due to its undesirable implications for their project. Aiming for a licensing model in the long term seemed to the team to be too risky when considering the high competition in the bioplastics market. More crucial to the discussion, however, seemed to be the realization that a licensing path conflicted with the scientific openness endorsed by the project stakeholders. Also, the sustainability team discussed how the merging model would imply a loss of ownership of the production process and the project. In this way, ownership of the project and scientific openness were discovered to be project values that had not been recognized before, either by the group or the researcher.

Having an increased awareness of the values at play, the group deliberated over the alternatives and the values that they did or did not support. As a final decision for the business case, the group decided to favour the alternative that better suited the scientific pursuits related to the project and the feasibility of starting it up as a business. However, having disregarded the option that could support biodegradation, the team explained they would support the value in another part of the project, i.e. through the targeting of clients (see Appendix III for more details on this decision process). Specifically, D1 stated during intervention 9: *"We need to focus on companies that are looking for this kind of sustainable solutions or biodegradable plastic, and then target them as customers to make sure that it actually goes where it has to end up",* referring to the plastic biodegradation.

Table 4.5. Identified modulations in the two decision making processes discussed in this section. Final decisions refer to what was discussed as their design concept by the end of the project

Modulation	Alternatives and decisions[a]	Considered values
Decision making process I – Products		
De facto	Bagasse as feedstock for energy production (2)	Achievement, process simplicity, resource efficiency, technical feasibility
	Pure BBP (2)	Scientific focus
Reflective	Bagasse as 2G feedstock (5)	Achievement, entrepreneurship, food security, resource efficiency
	Co-polymers as main product (5)	Achievement, entrepreneurship, product quality, resource efficiency
Deliberate	Investigate alternative uses for bagasse: 2G BBP production, and co-polymer compound alternatives and their production (5)	Achievement, entrepreneurship, food security, product quality, resource efficiency
Final decision	Model energy generation from bagasse and the production of pure BBP granules. The sustainability team suggested to include a proposal in the business plan to research 2G and wastewater BBP production	All of the above
Decision making process II - Business Model		
De facto	The model accommodates the integration of the process with an existing sugarcane mill: a partnership with an existing sugarcane mill was the group's initial idea to achieve this (6)	Achievement, cooperation, entrepreneurship, resource efficiency

Reflective	The integrated process can be supported by other business models: BBP production as part of the same sugarcane company (merge model), or by licensing the patented technology to the mill companies (licensing model) (6)	Cooperation, entrepreneurship, resource efficiency, growth, leadership
	If the business is integrated, there is an option to vary the production of any of the products as desired (7)	Entrepreneurship
	A licensing model implies confidentiality until a patent application is made (8)	Scientific openness
	A licensing model can be combined with a biodegradation step (8)	Biodegradation
	The merge model means losing ownership of the project (9)	Ownership
Deliberate	Discard the licensing alternative and investigate further into the stand-alone and partnership business models (9)	Entrepreneurship, scientific openness
Final decision	Partnership model for the business	All of the above

[a] Intervention of first observation in parenthesis; all interventions are described in Table 4.1

4.5. Discussion

In this section the integration of stakeholders' values as part of the design project is discussed. Firstly, we discuss if stakeholders' values, as identified, were considered during the design process. We also discuss the role of MM in this integration, and how bringing forth the investigated values and design proposition during the MM interventions supported it. Subsequently, we discuss this work in the context of VSD, suggesting that the present work is form of technical investigation in VSD. We argue that bringing elements of VSD into biorefinery design practice with flexibility, considering what is possible in the project, can serve to bring value considerations during their development. Next, the role of the researcher in this work is discussed in contrast to typical MM and VSD literature. Lastly, some implications and limitations of the presented work and recommendations for future studies are presented.

4.5.1. Reflection and Value Integration in the Design Process

Value considerations changed along the development of the project. Through the interventions at the start phase, it was possible to see that the group was generally aware of most of the values found to be relevant to the project. The understanding of these values, however, became richer during the design space workshops when the team gained awareness of how different stakeholders cared about different aspects of the project, most prominently in the case of biodegradation. Already at this point the team started to reflect somewhat about the relationship between the values and their design project, however this understanding was still vaguely specified for their project as shown with the design propositions (see Section 4.2). It was during the investigation of the design decisions, as the team advanced in their project, that this relationship was put into focus.

MM interventions during the investigation of the design decisions were planned with the aim to encourage reflection and support the integration of values in the design decisions. It was found that the interventions stimulated the team to reflect upon the ongoing design decisions and their relation to identified stakeholders and values. Although the design propositions themselves were not directly followed or considered to the letter for raising reflection (i.e. they were mostly too broad or not applicable), asking the team about them, and the identified stakeholders and values, stimulated them to envision new design alternatives. For example, while discussing the decision to implement an integrated process with an existing sugarcane mill, the group identified different alternatives for their business model that could support this integration, as well as how these alternatives related to the investigated values (e.g. licensing the technology and merging with a sugarcane mill). Furthermore, it was found that encouraging reflection during design decision making meant that the team remained open to the discovery of previously overlooked values that were relevant for the project. Scientific openness and ownership of the project are two examples, as elaborated in section 4.4.3.

In occasions, value tensions emerged when the designers had to make decisions over design alternatives. As the team was prompted to talk about their decisions, they reflected on how the alternatives to a variable supported or opposed values in the context of the project. As result, the team became aware of emerging tensions, when choosing one alternative for a variable supported a given value but could undermine or negate the support to another value. Then, with a close understanding of the design space, the team had the opportunity to generate new alternatives and find solutions according to the specific decision at hand. For example, for the product recovery process, the values of efficiency, environmental safety, profitability, and quality were in tension. When looking at the emerging tension and the alternatives at hand, the team saw it was possible to combine two seemingly opposing alternatives: with the use of mild solvents in minimum quantities and in combination with a secondary processing, they would maintain a relatively low environmental risk and prevent large losses in efficiency, quality, and profitability. In this way, it seems the group intuitively followed the maximin principle (i.e. a decision rule based on the selection of the alternative that is best when looking at the least supported values of all alternatives (Van de Poel 2014)).

However, it was not always possible to find new alternatives that eased value tensions. Particularly, when there was tension between project and workshop values, and there was no effective alternative, the final decision would tend to favour project values (especially regarding technical feasibility). When this was the case, it was observed that the team nevertheless sought to integrate the workshop values in other parts of the project. For example, once it became impossible to support biodegradation with their decision on the business model, the team proposed to target specific clients for their business case (see section 4.4.3). They decided to focus on industries that would not only be interested in using biobased plastics, but that could also have an interest in their biodegradation (such as single-use plastic users who could accommodate industrial biodegradation within their business). Another example is related to using bagasse for 2G production. Although 2G production was perceived as having less risk for food security than 1G, the group found its feasibility questionable under the project circumstances. As a result, the group chose to focus on 1G production for their design, while 2G feedstocks were suggested for consideration in later research. These examples show that although project values were favoured by the team for specific decisions, they still tried to accommodate the workshop values within the project. These values also seemed to have become a part of the project even in a context that was not specifically supportive, as indicated in the comment by D1 (intervention 7): *"In the competition they said 'why do you care? You're producing the [bioplastic] granules and if people are ready to pay, then you give it and you don't worry about where it ends up.' But [...] we want to make sure that [...] [the granules] end in the right places and the plastic actually degrades".*

Through the MM interventions value considerations were then brought to the design desk. In this way the team was encouraged to find creative ways to integrate values in the design, not only for specific variables, but in the context of the whole project. This real-time response in the design process was possible as the designers had the capacity to find new alternatives and flexibility to deal with value tensions in accordance with each decision, instead of choosing values a priori or relying on a single solution strategy (e.g. cost-benefit or multi-criteria analyses) that can result in undesirable or unfeasible solutions (Van de Poel 2014). Even more, it could be argued that facing value tensions without a predefined decision making strategy opened up a path for innovation, as suggested elsewhere in the literature (Van den Hoven et al. 2012). Overall, a reflective design decision making, with openness to discover new values and technical features, and a flexible approach to value tensions is suggested as a good practice for integrating values in the design decision making processes.

4.5.2. Contribution to Value Sensitive Design

This work is focused on the integration of values in the design decisions to obtain a biorefinery concept. By focusing on how design alternatives support or hinder the identified values, and on the integration of these values in the design decisions, the investigation of the decision making with MM can be described as the technical investigation of VSD (see Friedman et al. 2008). Additionally, applying MM allowed to make a systematic analysis of the design decisions, having a record of the alternatives that were considered, and the reasons on why they were or were not taken for the project (see the identified decision making processes in Appendix III). As discussed by Oosterlanken (2015), such a record can be part of a ´design library´ that inspires or informs the development of other biorefineries or technologies, and thus facilitates the integration of values in design. Additionally, this record could serve as self-reference for the researchers and developers of the same technologies, to look back to their decisions when evaluating and improving the technology in more advanced stages.

Furthermore, the present work shows an example of how elements of VSD (e.g. the identification of stakeholders and values, and their translation to technical features) can be put to practice for the early stages of development of complex systems like biorefineries. Particularly, as previous VSD experiences in the literature were found unsuitable for the current biorefinery project (see section 4.2), in this work some elements of the VSD investigations were integrated into common biorefinery design practice. This integration was done from the definition of the design space, with the design space workshops aiming for the identification of stakeholders and relevant values to the project, to the investigation of the decision making, with the analysis of how values relate to project variables and their consideration for producing a design concept (see Fig.4.1).

It is acknowledged, however, that there are limitations on how these VSD elements were brought into this biorefinery design project. Particularly, while a design space investigation could serve to address aspects of the conceptual and empirical investigations of VSD (Palmeros Parada et al. 2018), in this work it was only possible to do so to very limited degree. That is, there was no dedicated value elicitation method, and engagement with all identified stakeholders was not possible. This is a large contrast to VSD literature, where close engagements with stakeholders are a main aspect of applying VSD, allowing to, for instance, elicit values, identify desirable technical features, and address value tensions (e.g. Miller et al. 2007; Yoo et al. 2013). In this design project, for instance, the variables to the project were too broad to ask specific questions as in a survey, and the amount of reachable stakeholders would have been too limited to take their responses as a rule for choosing between alternatives. Additionally, in this work, there was not a clear difference between direct stakeholders and indirect stakeholders to the biorefinery. This is because, besides the project stakeholder, all other stakeholders were distant and uncertain in their potential role with a biorefinery at such early-stage of development (see section 4.3.2.2). Therefore, the investigations along the design space workshops provided only an indication of the stakeholders and values relevant to the biorefinery.

Nevertheless, some stakeholders to the biorefinery project were identified, and values were explicitly discussed in relation to the project and the main variables. Particularly, it is significant that at such an early-stage of development, a reflection was started on identified stakeholders, their values, and the broader socio-technical context of the project. As a consequence, bioethanol organizations, for instance, were identified as potential stakeholders with whom to enter into a cooperative relationship. Also, the investigation into non-governmental organizations led the team to question their initial assumption about the positive impacts of biodegradable plastics. They realized that it was not only about designing for biodegradability, but also about ensuring the effective biodegradation of the material. Furthermore, they recognized themselves and other actors (e.g. end-product manufacturers, users, waste and recycling companies and the government) as parties that had a role in encouraging such biodegradation.

Therefore, bringing elements of VSD into biorefinery design practice with flexibility, considering what is possible in the project, can serve to bring value considerations to the design of a biorefineries along their development. Although bringing VSD elements to early-stage biorefinery design may face some limitations as presented in this case, opening a discussion about stakeholders and values can already contribute to the development of biorefineries that are more responsive to emerging societal concerns. This achievement would be significant for biorefineries specifically, considering the ongoing debates around biobased production, as discussed in section 4.1. Also, while in this case there was limited engagement with stakeholders, the integration of VSD elements to biorefinery design practices, as structured here, leaves room for conducting dedicated empirical investigations with stakeholders (as in the work by Palmeros Parada et al. (2018), or in-between design space workshops). This could be applied for more developed projects, with more defined features (e.g. with a specific location or product application) that allow to recognize and engage stakeholders. In this way, VSD could be brought to the design of biorefineries with flexibility, depending on the design context as recently suggested elsewhere (Friedman et al. 2017), and considering the development stage of the project.

4.5.3. The Role of the Researcher and the Designers

A point of discussion in this work is the role of the researcher, considering that this work is grounded on two different approaches. MM researchers are in the field, they have frequent contact with participants but typically act from a position independent to the ongoing research from which they promote reflection (e.g. as embedded humanist in a research laboratory, Fisher et al. 2015). The role of the VSD researcher ranges from that of a researcher investigating the specific value implications of a technology for its design (e.g. Czeskis et al. 2010; van Wynsberghe 2013), to that of a designer or participant within a design group that investigates and takes these implications into account to design it (e.g. Miller et al. 2007; Xu et al. 2012). Therefore, in MM, the researcher has no aim to change a technology or research in a particular direction, nor the capacity to do so directly; in VSD the researcher has the aim to change the technology in consideration of stakeholders' values, and can influence it directly (as a designer or part of a design group) or indirectly (e.g. by suggesting principles, guidelines, etc.).

In this work, MM was applied to promote reflection on stakeholders and the investigated values, to seek its integration in a design concept. Therefore, from the conception of this work, the role of the researcher was more similar to VSD, seeking to integrate stakeholders' values in the design decisions for a biorefinery concept. However, the researcher remained somewhat external to the group, as in MM, not participating in calculations or making design decisions, for example. Additionally, although the researcher supported the team in the identification of stakeholders and on the analysis of how values related to the technology, the contact with stakeholders and the gathering of information was performed exclusively by the designers. Therefore, although the first part of this project (i.e. investigation of the design space) is closer to VSD in content and aim, the researcher acted from a more distant position to the design project than commonly for a VSD researcher.

As result, the designers had a more active role in the discovery of values and their translation into technical features than the researcher. This is a result of how the design project was set-up, with the designers as the registered participants of the competition, and the researcher with limited availability for participation. It was observed that this active involvement by the designers contributed to the reflective process, even in the early parts of the project, as mentioned in section 4.4.2. However, in this case, not having the time or space for action resulted in limited capacity on the part of the researcher to investigate in depth the relationships between values and design decisions in areas where the designers had no expertise. This is particularly the case with complex issues such as food security, which remained a difficult aspect to deal with within the project. Therefore, having a dedicated VSD researcher with capacity to investigate value considerations and their translation into design features, as in the VSD cases of Miller and colleagues (2007), and Xu and colleagues (2012), together with a design group that is actively involved in the conceptual and empirical investigations of VSD and is encouraged to reflect upon the ongoing design decisions, as shown here with MM, is suggested for future work.

4.5.4. Other implications, Limitations, and Recommendations

By promoting a reflective design practice, the present work not only had an impact on the resulting biorefinery concept, as typically aimed with VSD (Doorn et al. 2013), but also brought a potential influence on the research trajectory related to the technology in question (microbial platforms). The discussions about feedstocks and products are an illustration of this, when alternatives that better supported the workshop values but that were considered unfeasible for this present project were still reported as aspects to consider in future developments. Although the extent of this influence is not known and cannot be proven in this work, it shows that reflective design exercises as presented here could be applied to open on-going research to societal concerns when researchers seek to explore the potential applicability of their work. Even more, applying such a reflective design approach in industrial environments could contribute to overcome the challenge of aligning responsible innovation and industrial practices (Dreyer et al. 2017).

However, having integrated stakeholders' values in the development and design of a biorefinery does not mean that the outcome will be acceptable in societal terms. This limitation is related to the scope and forward-looking nature of the present work, and VSD too when applied in the context of biorefineries with long development times. Firstly, a technology can always be used differently than intended or anticipated by designers (Ihde 2008), and the farther in time a design is from the ultimate application, the more limited the capacity for anticipation will be. Secondly, even if all stakeholders had their values reflected in a design, there are other factors beyond the scope of a biorefinery design project that can shape its development, and thus its relation to stakeholders (e.g. governmental programs and policies, Bosman and Rotmans 2016). To illustrate these two points, we refer to the early phases of the biodiesel case in Brazil in the early 2000s: Biodiesel biorefineries and a diesel program were set-up to promote social development, but their initial result was a large participation from large-scale soybean oil producers and little inclusion of small-scale family farmers (Castellanelli, 2016). Biorefinery operators mostly bought soybean oil (unanticipated), while the biodiesel program was not sufficient to incentivize the entry of family farmers to the fuel market (institutional scope beyond the biorefinery). In addition to the two previous points, the social, moral, and institutional context surrounding a technology can change with time and render a design with value considerations inadequate, as discussed by Kiran in the scope of Responsible Innovation (2012). A broad example is the case of biofuels, which were initially regarded as sustainable because they are produced from renewable sources. Nowadays it is not enough that biofuels are renewable; other aspects like biodiversity and food security are recognized as important too (see section 4.1).

Continuous learning about stakeholders and the context of a system or technology, like biorefineries, throughout its development and implementation can be an appropriate measure as suggested by Asveld and Stemerding (2018). In this way, the work presented here, seeking to contribute to the integration of stakeholders' values during biorefinery design, can be applied as part of a continuous learning process about the societal implications of a technological innovation. Such a process could be applied, for example, as a broader iterative VSD practice, from early-stage conceptual design to more detailed stages. Also, in later stages when applications and stakeholders are more certain and easily involved, stakeholders could be involved by means of participatory evaluations (Borning and Muller 2012), or the selection of indicators (Dale et al. 2015), for example.

Finally, the applicability of this type of work in the industry may be put into question given the time, expertise, and commitment required to include it in the development of design projects. In this case, it helped to be embedded in a university environment, considering that some of the designers were involved in the research about the microbial platform and had an interest in learning more about their technology. An option to facilitate its industrial application could be the development of a framework that aligns VSD elements, not only with an overarching design approach, but also with common biorefinery design methods. However, such a framework would need to compatible with the industrial sector where specific conditions may pose a challenge to its application (e.g. confidentiality). Another avenue is to investigate whether recurrent VSD exercises can lead to knowledge about stakeholders and their values related to specific technologies and application contexts. This knowledge could serve to create a “design library” as mentioned before, and potentially simplify its application.

4.6. Conclusions

In this paper the integration of values into the decisions of a design project to obtain a biorefinery concept is presented. This integration was achieved by promoting reflection during the design decision making with MM. Particularly, MM interventions allowed to bring reflection over the variables of the project, and how design alternatives related to the identified values. This reflection allowed to generate new design alternatives, and to recognize and respond to emerging value tensions. In this way, we show a novel approach to a systematic technical investigation of VSD, especially in the context of biorefineries.

Additionally, based on this work we conclude that, not only reflection, but also flexibility and openness are important for bringing VSD to the context of biorefinery design. MM was proven useful to put this into practice, showing that an open and reflective decision making, with the capacity to adapt the design, gave opportunities to integrate values in design decisions and face emerging value tensions. For a value sensitive design of biorefineries we suggest to apply VSD with flexibility, in alignment to design practices in the field and considering the development stage of the project. Also, by looking at the role of the researcher in this work, we suggest that VSD should be applied by dedicated VSD researchers that are part of a design group, where all designers actively involved in the conceptual and empirical investigations of VSD and are encouraged to reflect upon their ongoing design decisions.

The presented work allowed to recognize and discuss emerging value tensions and contextual implications that are not usually part of the design process of biorefineries. While it is acknowledged that not all moral and societal issues can be solved, we suggest that this type of activity can be intended as part of a continuous learning process during the development of technologies and technological systems like biorefineries. However, there are some issues to be resolved regarding the applicability of such an approach in an industrial context, where confidentiality, for instance, could be detrimental to its objectives. Overall, by opening the design process to considerations of stakeholder values and societal concerns, the authors hope to contribute to the development of more sustainable biorefineries.

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Chapter 5

Sustainability tensions and opportunities for biojet fuel production in Brazil

This chapter has been submitted as:

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5.1. Introduction

Biobased production has been promoted as a sustainable alternative to fossil-based production in order to mitigate climate change (Pfau et al. 2014). Prominent targets for biobased production are compounds for which there are limited alternatives, such as biojet fuels (Tsiropoulos et al. 2018). Biomass is the only current alternative for obtaining these products, however, due to high production costs and limited availability of sustainable feedstocks, their production remains a challenge (Mawhood et al. 2016). Nevertheless, the CORSIA agreement by the United Nations' aviation agency enforces an international commitment for carbon neutral growth in the aviation sector (relative to 2020), and biobased and other sustainable aviation fuels are critical to achieve this (ICAO United Nations 2019).

Concerns over the sustainability of biofuels have been raised since the production growth in the 2000s (Rosegrant and Msangi 2014). They include effects on food security from the use of edible feedstocks, effects of land use changes on emissions, and negative impacts on the livelihood of local communities (Aha and Ayitey 2017; Bouzarovski et al. 2017; Rosegrant and Msangi 2014). While not necessarily related to all biofuels, those examples indicate that there are downsides of biobased production as well, and that tensions may emerge between sustainability measures, like emission reduction targets and food security impacts. As these tensions depend on local contexts (Efroymson et al. 2013), there is a need for comprehensive sustainability analyses, taking into consideration the context-dependence of biofuel production.

With the growing interest in biojet fuels, various production alternatives have been assessed, indicating that biojet fuels have the potential to reduce emissions when compared to fossil-based kerosene (Capaz and Seabra 2016). However, existing approaches for the design and ex-ante assessment of biofuel production tend to focus on techno-economic feasibility, climate change, and energy efficiency, and rarely address societal aspects and the local context of the intended production chains (Palmeros Parada et al. 2017). Recently, Cavalett and Cheribuni (2018) investigated the impacts of biojet fuels from forest residues in relation to the UNs Sustainable Development Goals. Although their study addresses some societal implications of biojet fuels, the analysis was based on the assessment of environmental impacts only.

Here, we present a novel context-dependent ex-ante sustainability analysis of biojet fuel production in the Southeast region of Brazil that includes economic, environmental, and societal aspects. Based on inputs from local stakeholders and sustainability literature (Palmeros Parada et al. 2018; Pashaei Kamali et al. 2018), eight aspects of sustainability were considered: climate change, commercial acceptability, efficiency, energy security, investment security, profitability, social development, and soil sustainability. For the analysis, we integrate and contrast estimates of the performance of production alternatives with regard to these aspects, which were estimated separately as part of the same research project (Alves et al. 2017; Brinkman et al. 2017; Capaz et al. 2018; Cornelio da Silva 2016; Santos et al. 2018; Pashaei Kamali et al. 2018; Palmeros Parada et al. 2018; Wang et al. 2019; Vyhmeister et al. 2018). Based on this contrast, sustainability tensions for the production of biojet fuel in Southeast Brazil are discussed, and some opportunities for reconciling them in future developments are presented. In view of these findings, we provide conclusions related to the case study and the followed methodology for an enhancement of sustainable biobased production.

5.2. Biojet fuel Production

Based on previous studies on feedstock availability and technical feasibility in Southeast Brazil (Alves et al. 2017; Cornelio da Silva 2016; Santos et al. 2018), we identified production alternatives regarding feedstocks and technologies. Considered feedstocks are sugarcane, eucalypt residues, and macauba (*Acrocomia aculeata*); conversion technologies are the ethanol to jet route (ETJ) for the conversion of sugars, the hydro-treated esters and fatty acids process (HEFA) for oils, and fast pyrolysis (FP) and hydrothermal liquefaction (HTL) for the conversion of lignocellulosic residues. We considered the conversion technologies as part of a production chain depending on the biomass type, with eucalypt residues as a lignocellulosic feedstock, macauba with oil and lignocellulosic residue fractions, and sugarcane with a sugar-rich fraction (juice) and a lignocellulosic residue fraction (bagasse). As an exception, Gasification Fischer-Tropsch (GFT) is the technology considered for eucalypt conversion when evaluated for social development (see Section 5.6, Methods, for details).

Thus, the considered production chains were: sugarcane processed with ETJ and FP, eucalypt residues processed with FP, eucalypt residues processed with HTL, macauba processed with HEFA and FP, and macauba processed with HEFA and HTL. Derived from the combination of feedstocks and conversion technologies, by-products included energy products like diesel and naphtha, and excess power to be sold to the grid. Additionally, because sugarcane-based production is negatively affected by the seasonality of sugarcane (low annual productivity due to idle installed capacity during off-season, Alves et al. 2017), two improvement scenarios were considered: 1) the purchase of sweet sorghum, which has similar structure and processing requirements to sugarcane, to process during off-season; 2) the dedication of a fraction of the sugarcane juice for the production of biobased chemicals, with succinic acid as a characteristic higher-value chemical.

5.3. Sustainability Performance of Production Alternatives

The sustainability framework for this analysis includes various aspects that were qualitatively and quantitatively estimated as indicated in Table 5.1; for details see section 5.6, Methods. These aspects were identified from engagements with local stakeholders, including representatives of the regional government and biomass producers, and a review of the literature.

Table 5.1. Sustainability framework for the ex-ante analysis of biojet fuel production in Southeast Brazil.

Sustainability Aspects		Description	Indicators	Methods	Main Ref.[a]
Qualitative	Commercial acceptability	Analysed in relation to ensuring safety and a good performance of biojet fuel	ASTM approval	Literature review and stakeholder interviews	1-3
	Energy security	Related to energy supply reliability and self-sufficiency	Potential for power generation and NREU	Literature review and stakeholder interviews	2, 4, 5
	Investment security	Related to the readiness level of new crops and technologies, and previous experience with potential crops	FRL and crop development status	Literature review and stakeholder interviews	2, 6, 7
	Soil sustainability	Regarding the protection and recovery of the soil in relation to biomass production.	Residue harvest	Literature review	8-11

Quantitative	Climate change	Analysed as the GHG emissions derived from the biomass production and distribution stages, and the biojet fuel production process	GHG emissions	Life cycle assessment	4, 5, 12
	Efficiency	Primarily evaluated in terms of non-renewable energy use and other mass and energy efficiency indicators related to the process	NREU	Process modelling	4, 5
	Profitability	Analysed in terms of the minimum selling price of biojet fuel required to payback production expenses, including capital and operational expenses	MSP	Techno-economic analysis	4, 5
	Social development	Analysed in relation to impacts on national employment, gross domestic product and trade balance	Direct and indirect jobs, GDP contribution and trade balance	Input-Output analysis	13

[a] Main references: 1: ASTM International (2019); 2: Palmeros Parada et al. (2018); 3: US DOE (2017); 4: Cornelio da Silva (2016); 5: Santos et al. (2018); 6: Altman (2012); 7: Mawhood et al.(2016); 8: Brinkman et al. (2017); 9: Carvalho et al. (2017); 10: Rocha et al. (2016); 11: Rosim et al. (2016); 12: Capaz et al. (2018); 13: Wang et al. (2019); ASTM: American Society for Testing and Materials; FRL: Fuel readiness level; GDP: Gross domestic product; GHG: Greenhouse gases; MSP: Minimum selling price; NREU: Non-renewable energy use.

5.3.1. Quantitative aspects

Climate change. Biojet fuel produced from macauba oil and residues is estimated to be the least emitting alternative, with about 90% lower GHG emissions when compared to conventional kerosene; eucalypt alternatives are second best with emission savings of 75-90% (Fig. 5.1 a). For eucalypt, higher GHG emissions were estimated with HTL than FP due to greater natural gas requirements for producing H_2 (Cornelio da Silva 2016). Sugarcane-based production results in about 60 – 70% lower GHG emissions than fossil-based production depending on the process configuration (Santos et al. 2018). In-house power generation and hydrogen production improve the performance on environmental indicators, while a cracking step that increases the production yield has a small impact (Vyhmeister et al. 2018). A consequential life cycle analysis (LCA), which also takes into account indirect effects such as land use changes and product replacement, indicates that

ETJ biojet fuel from sugarcane juice has a potential for negative emissions of about -40 g CO_2/MJ when assuming the replacement of natural gas power from the grid (Capaz et al. 2018). While this number does not mean that CO_2 is absorbed, it indicates a potential for fewer emissions in a context beyond biojet fuel (i.e. considering power generation for the grid). However, the effects of by-products, such as the actual provisioning of bioenergy to the regional energy system, need to be investigated in more detail.

Energy efficiency. All production chains require lower non-renewable energy use (NREU, an indicator of efficiency) per amount of biojet fuel than conventional kerosene. The processing of macauba and eucalypt residues with HEFA and FP is more energy efficient than alternatives with HTL and sugarcane (Fig. 5.1 b). The lower efficiency of HTL compared to FP is due to higher energy requirements for H_2 production (Cornelio da Silva 2016). The lower efficiency of sugarcane alternatives is derived from the biomass growth stage, considering that all the energy use from this stage is accounted for the sugarcane feedstock, while for eucalypt it is allocated between by-products (e.g. wood and residues, Cornelio da Silva 2016; Santos et al. 2018). Regarding process options, in-house power and hydrogen production in thermochemical routes improve the process efficiency, but are economically unfavourable (Vyhmeister et al. 2018).

Profitability. Production based on eucalypt residues and macauba shows a lower minimum selling price (MSP, the lowest price at which biofuel can be sold to cover production expenses), indicating a higher profitability potential than with sugarcane (Cornelio da Silva 2016; Santos et al. 2018). As expected, all alternatives perform worse than conventional kerosene (Fig. 5.1 c). Biojet fuel MSP from the processing of eucalypt and macauba is in the range of 850 - 1100 $/ton. For processing lignocellulosic residues, HTL shows a lower MSP than FP, although the difference is small when compared to sugarcane ETJ conversion (1720 – 2390 $/ton). The low profitability potential of sugarcane ETJ is a result of lower conversion yields and the high capital expenses related to the seasonality of sugarcane. In the improvement scenarios, sugarcane ETJ MSP can be reduced by 3-28% by processing sweet sorghum during sugarcane off-season and by producing higher-value chemicals (Santos et al. 2018). However the estimated MSP for these alternatives remains higher than production based on eucalypt and macauba (Fig. 5.1 c).

Social development. Macauba-based production shows 17% more employment generation than the other crops, while the difference between alternatives is less than 5%

in terms of gross domestic product (GDP) contributions (Fig. 5.1 d, e). For both employment and GDP, direct effects are largely due to feedstock production as expected, and indirect effects are primarily related to the trade sector (Wang et al. 2019). When considering that biojet fuel may displace part of the production of conventional kerosene, an input-out analysis reveals that overall net jobs and added value (i.e. GDP) can be generated by the transition to biojet fuel (Wang et al. 2019). Regarding trade balance impacts, eucalypt- and macauba-based production resulted in about 34% less imports than with sugarcane (Fig. 5.1 f). However, based on the existing economic structure in Brazil, it is estimated that more imported goods, such as industrial chemicals, would be required for the production of biojet fuel than for conventional kerosene (Wang et al. 2019). A possibility to avoid this import increase would be to stimulate the national production of (bio-)chemicals together with the development of biojet fuel. Lastly, these comparisons are made with available data, with macauba production still under development (Cardoso et al. 2017). It can be expected that as macauba production matures, production costs will drop as has already happened with other mature crops, e.g. sugarcane (van den Wall Bake et al. 2009). This possibility needs to be further investigated as macauba-based production could result in lower direct effects on employment and GDP, and trigger different indirect effects than those presented here.

5.3.2. Qualitative aspects

Commercial acceptability. From the considered alternatives, only HEFA and ETJ biojet fuels have been approved for commercial use by the American Society for Testing and Materials (ASTM, in alignment with the Brazilian National Agency of Petroleum, Natural Gas and Biofuels, 2016), indicating that these technologies are more commercially acceptable than the other alternatives. FP fuel is in queue for certification, and HTL is the farthest behind (US DOE 2017). Because certification assures that a fuel has the same safety and performance, and can be distributed and used with the same infrastructure as conventional kerosene (Cortez et al. 2015), the commercial acceptability of HTL biofuel is considered the lowest when compared to the other technology alternatives (Fig. 5.2). To get ASTM approval, HTL developers, like others have done already, have to directly invest in certification, which takes 3-5 years and costs 10 to 15 million dollars on average (US DOE 2017), and they have to obtain sufficient volumes for testing. Therefore, certification implies investing time and resources to scale-up the technology (US DOE 2017), which will constrain start-up ventures.

Energy security. Brazilian biojet fuel production can reduce the need for kerosene imports, with about 20% of kerosene being imported in Brazil (1.3 million m^3 imported in 2016, Agencia Nacional de Petroleo, Gas Natural and Biofuels 2017). Hence, more significant contributions can be expected from conversion alternatives with higher efficiency, i.e. FP and HEFA (Fig. 5.2). Significant to the case is the potential to benefit regional power reliability through co-generation from biomass or process residues, considering stakeholders' concerns regarding energy security (i.e. related to past drought-driven power shortages, Palmeros Parada et al. 2018). Energy balances suggest that process energy self-sufficiency and power surplus for the grid can be achieved through co-generation from sugarcane residues (Santos et al. 2018), which is already the case in many sugarcane mills in Brazil (Nogueira and Capaz 2015). In the case of eucalypt and macauba, a dedicated fraction of the biomass for co-generation would be required to reach energy self-sufficiency, implying a lower biojet fuel production per amount of processed feedstock (Cornelio da Silva 2016). Therefore, sugarcane alternatives are considered as having a relative positive impact when compared to the other feedstocks (Fig. 5.2).

Investment security. Investment security was explored in terms of technologies and feedstocks. With regards to technologies, HEFA biojet fuel is the alternative that implies less investment risk with a fuel readiness level (FRL) of up to 8, indicating that HEFA biofuels are certified and commercially available (Mawhood et al. 2016). ETJ fuels recently received ASTM approval, bringing them to an FRL of 7 (ASTM International 2019), and slightly behind some HEFA fuels. For FP, there are some ventures in the process of ASTM certification (Borislava 2017; Mawhood et al. 2016), indicating a FRL of 6. However, HTL for biojet fuel production has only been tested at lab scale (Biller and Roth 2018), and it is therefore considered to imply more investment risk at an FRL of 4. For feedstocks, investment security was explored in terms of supply certainty and the familiarity of farmers with the crops (Palmeros Parada et al. 2018). Sugarcane and eucalypt, despite not being originally from Brazil, are well established crops in the region, covering developed markets such as sugar, ethanol, charcoal, and wood (McMahon and Jackson 2019; Sant'Anna et al. 2016), and implying a relatively high investment security. Macauba, although native to Brazil, has not been studied or developed at the same level. Currently there are a few macauba demonstration plantations being started in Minas Gerais, however there is still a need for research to develop a production chain (e.g., develop new varieties and plantation management practices, Cardoso et al. 2017; Colombo et al. 2018). Therefore, investing in macauba in the short term would imply a relatively higher risk for biorefinery operators related to supply uncertainty, as well as for farmers who have neither experience nor access to management practices for production.

Soil sustainability. Soil sustainability was reviewed regarding the effect of residue harvest for biobased production, although there is limited information about macauba (most is known about sugarcane followed by eucalypt). In a recent review where effects of yield, nutrient recycling, soil carbon stocks, GHG emissions, and soil erosion were considered, it was concluded that leaving 7 ton/ha of sugarcane straw is recommendable in order to sustain soil properties (Carvalho et al. 2017). Usually, sugarcane straw yields can vary, as much as 8-30 ton/ha, so it is not simply a matter of leaving half the straw in the field (Carvalho et al. 2017). Remaining straw also comes at a cost, as it may increase certain pests and weeds, and nutrient addition is required as only some 31% of N and 23% of P in the straw will become released for use by plants (Carvalho et al. 2017). Eucalypt trees, as macauba and other trees, consist of stems, bark, branches, and leaves. The eucalypt wood is 77 % of the total tree biomass, but it contains 39% of the nutrients when considering wood and harvest residues together (Hernández et al. 2016). When stands age, the proportion of wood to total biomass increases, and more nutrients get removed when harvesting, although there are differences among species (Harrison et al. 2000; Zaia and Gama-Rodrigues 2004, p.) and selection lines (Rosim et al. 2016). Also, the type of residue management in a replanted eucalypt plantation has effects on productivity. For example, eight years after planting, biomass production was 88% when harvest residues were removed compared to when harvest residues were retained (Rocha et al. 2016) and even decreased to 63% when also the litter was removed (Gonçalves et al. 2007; Rocha et al. 2016). Therefore, residue management in tree plantations, such as eucalypt and macauba, appears to be crucial for sustainability. Keeping harvest residues on the fields will be an effective way to maintain soil organic matter (SOM) levels for all crops. However, in contrast to sugarcane, little information is available on amounts of residues that need to be left behind for eucalypt, and effects depend on the age of the stands when harvested. Recommendations for forests with long rotation cycles range from 20 to 50% of residues and are merely based on expert judgement (de Jong, Akselsson, et al. 2017; Lamers et al. 2013; Titus et al. 2009). Therefore, in all cases of biomass production, soil sustainability will depend on leaving behind harvest residues, and further integral studies need to establish rotation lengths and other management practices in order to enhance sustainability impacts.

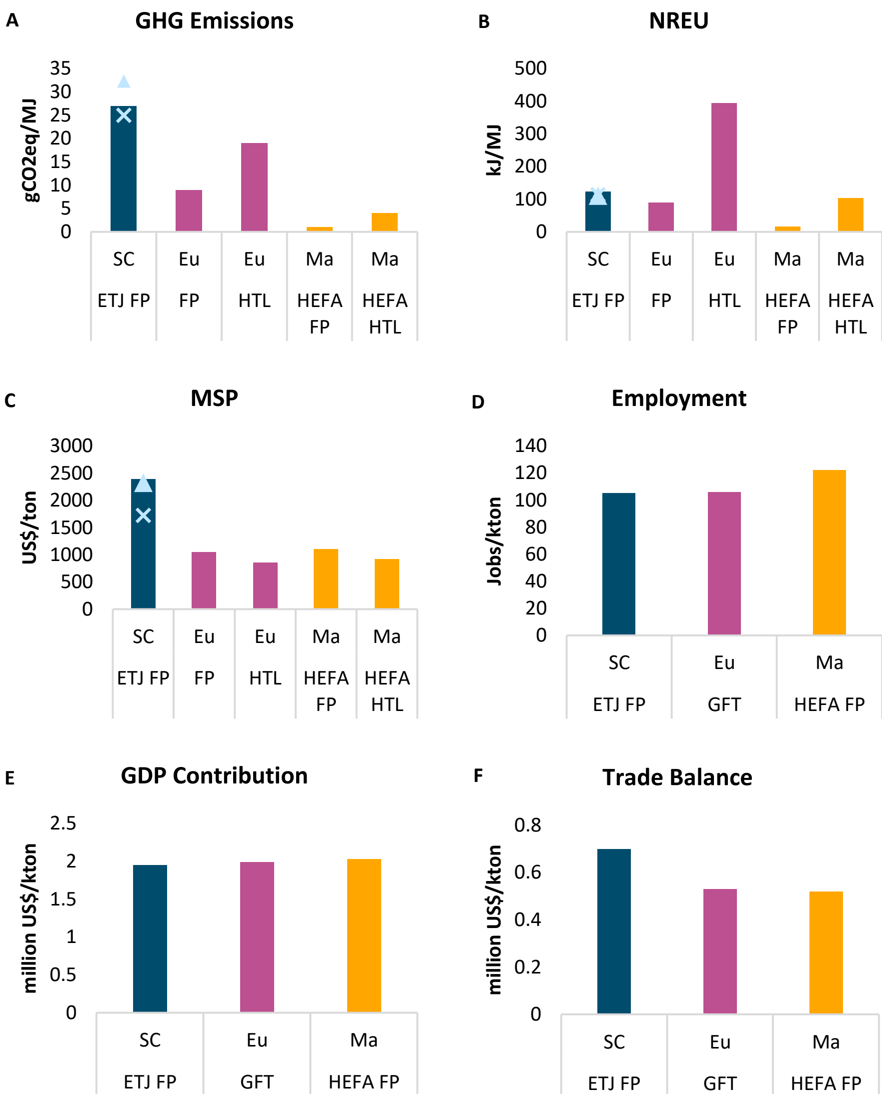

Fig. 5.1. Performance of potential production chains with regard to GHG emissions (A) as indicator of climate change, with GHG emissions from fossil kerosene at 87.5 gCO2/MJ (de Jong, Antonissen, et al. 2017); NREU (B) as indicator of efficiency, with 1200kJ/MJ of NREU required for fossil kerosene production; MSP (C) as indicator of profitability, with conventional kerosene price in the range of 311 - 722 $/ton the past three years (IndexMundi 2019); and employment (D), GDP contribution (E), and trade balance (F) as indicators of social development. In A, B, and C a triangle marker (▲) indicates the improvement scenarios with sweet sorghum during sugarcane off-season; a cross (x) indicates the scenario with a fraction of the sugar for succinic acid production. ETJ: Ethanol to Jet; Eu: Eucalyptus; FP: Fast pyrolysis; GFT: Gasification Fischer-Tropsch (see section 5.6, Methods); HEFA: Hydro-processed esters and fatty acids; HTL: Hydrothermal liquefaction; Ma: Macauba; SC: Sugarcane.

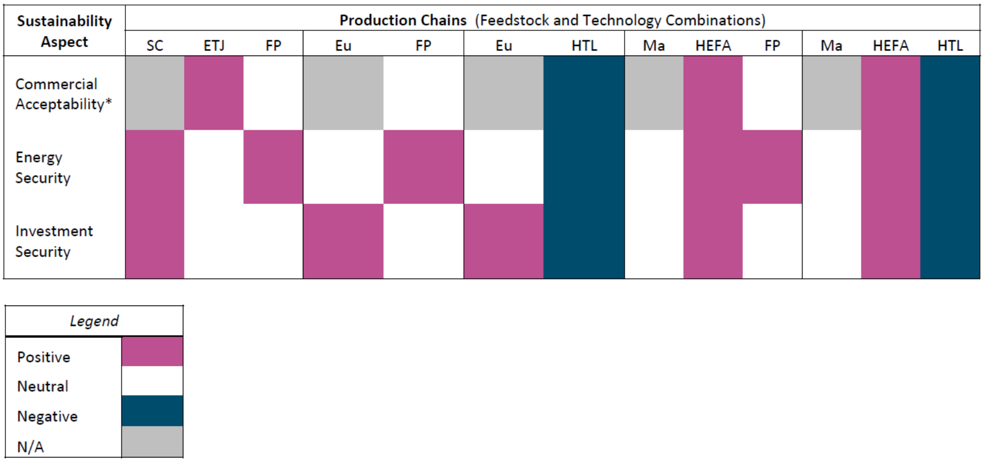

Fig 5.2. Qualitative comparison of the performance of the biojet fuel production alternatives presented per production chain. Production chains (five in total) are evaluated in terms of commercial acceptability, energy security, and investment risk, considering the combination of a feedstock and one or two technologies (3x2 or 3x3 cells respectively). The sustainability aspects were analysed in relative terms, and commercial acceptability was only evaluated for technology alternatives (see Section 5.6). ETJ: Ethanol to Jet; Eu: Eucalypt; FP: Fast pyrolysis; HEFA: Hydro-processed esters and fatty acids; HTL: Hydrothermal liquefaction; Ma: Macauba; N/A: Not available; SC: Sugarcane.

5.4. Sustainability tensions and opportunities

Tensions emerge with regard to different sustainability aspects. Prominently, all options yield much lower emissions than fossil-based kerosene but all are more costly (over $300/ton more than the average kerosene price of the past 3 years (IndexMundi 2019)). Analysing the other sustainability aspects reveals other tensions as well. In this section these tensions and some opportunities for further developments on biojet fuels in the region are discussed. We discuss tensions related to the technical alternatives for production, to the implementation of production itself, and to the ex-ante analysis of sustainability (Fig. 5.3).

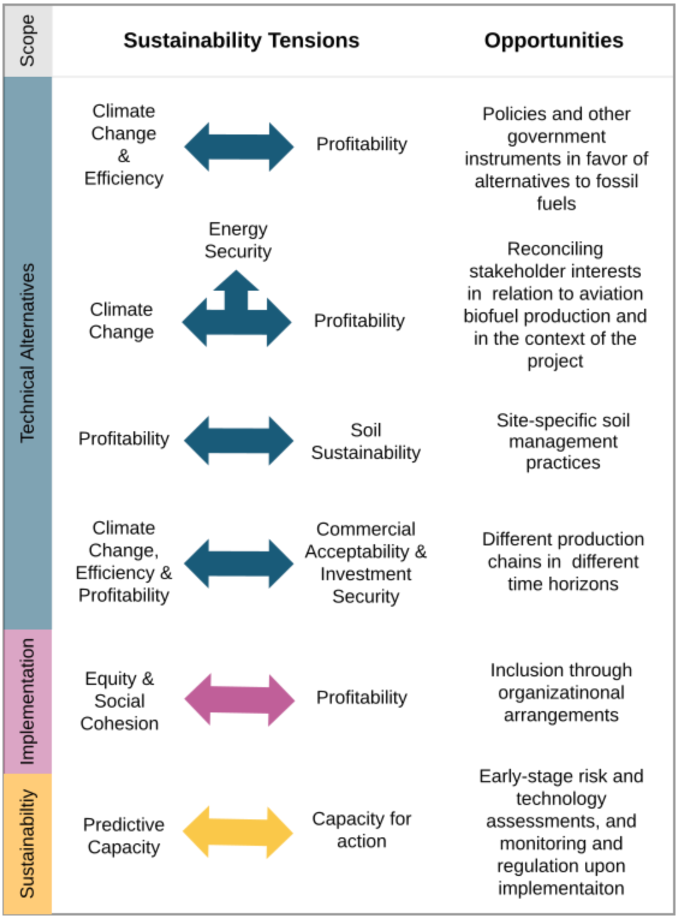

Fig. 5.3. Identified sustainability tensions and opportunities for production in the context of Brazilian biojet fuel production. Sustainability aspects on opposite sides of arrows are in tension in the context of biojet fuel production. The coloured column in the left indicates the scope in which the tension emerges: technical aspects in blue, production implementation in magenta, and sustainability analysis in yellow.

Technology alternatives: Looking at policy contexts. All studied options lead to lower emissions and less NREU than conventional kerosene, however at higher expenses. When looking at technology alternatives to process lignocellulosic residues and produce in-house power and hydrogen, the most favourable alternative in economic terms (HTL) is the least favourable with respect to climate change and energy efficiency. An opportunity for resolving this tension is to explore alternative approaches for the generation of hydrogen. Steam methane reforming considered in the present study is the most common and economic option but it is one of the main contributors of NREU and emissions in the case of HTL (Cornelio da Silva 2016). Interesting alternatives that can be further explored are, for example, the thermochemical conversion of a fraction of the biomass for producing H_2, or even the electrolysis and photolysis of water run on renewable energy (Nikolaidis and Poullikkas 2017).

Furthermore, the presented profitability estimations did not account for GHG emission costs, which have become more relevant since the 2015 Paris Agreement (European Commission 2016). Prominently, Brazil recently passed the National Biofuel Policy (RenovaBio) to promote the reduction of GHG emissions by the country's fuel sector (Agencia Nacional de Petroleo, Gas Natural and Biofuels 2018). As part of this policy, a market for certificates representing GHG emissions savings (relative to fossil fuel emissions) is being launched. Certificates are to be issued by biofuel producers and bought by distributors who have to meet decarbonisation targets (Ministerio de Minas e Energia 2018). As result, GHG emission savings related will yield a profit for biofuel producers. Mechanisms like this can therefore open opportunities for biojet fuels by making them financially more competitive (Alves et al. 2017; Santos et al. 2018), especially those biofuels that yield lower emissions (i.e. from macauba with HEFA and FP, and eucalypt with FP).

Technology alternatives: Reconciling stakeholders' interests. A tension emerges between different product alternatives as each favour the interests of different stakeholders: Higher-value products like succinic acid can be produced from a dedicated part of the feedstock stream, resulting in more profitability for investors. However, this option comes at the cost of biojet fuel production capacity per amount of processed feedstock, requiring more feedstock to meet the emission reduction targets of the aviation sector. Alternatively, power generation can be favoured over higher-value products or biojet fuel by dedicating a fraction or all of lignocellulosic residues for co-generation. Bioenergy can thus be part of distributed power generation in the region for the sake of energy security, as it is in the interest of the regional government. These interests represent sustainability aspects favoured by different stakeholders depending on the values and beliefs of the group they represent (Asveld and Stemerding 2018). Therefore, a sustainability analysis on its own cannot indicate which alternative is the best or the worst. Instead, a sustainability analysis that explicitly identifies sustainability tensions, as presented in this work, can contribute to a negotiation process with all stakeholders to define acceptable conditions (e.g. a minimum contribution to the regional power supply per production plant), or even a common objective for developing a production chain. Such openness and inclusion of stakeholders, with e.g. social learning and responsible innovation tools, could reduce the ambiguity associated to diverging values of stakeholders (Asveld and Stemerding 2018), and strengthen the stakeholder network for the development of more sustainable and responsible biobased production (Hellsmark et al. 2016; Mossberg et al. 2018).

Technology alternatives: Site-specific soil management practices. A clear tension exists between soil sustainability and harvesting as much biomass as possible for increasing productivity, and thus profitability (Brinkman et al. 2017; Carvalho et al. 2017). Defining an optimal amount of residues to leave on the field, as well as other improved practices regarding rotation length, can contribute to solve this tension while also accounting negative consequences of leaving harvest residues in the field (i.e. pest and weed management, Carvalho et al. 2017). Also, fertilization is needed as in all cases nutrients are removed when harvesting, and not all the nutrients from leftover residues become available to the next crop (Carvalho et al. 2017). However, nitrogen fertilizer is costly in terms of GHG emissions and energy efficiency (Han et al. 2013). Therefore, planning of biomass crop plantations for biofuels requires site-specific recommendations accounting for, e.g., soil type, land surface steepness, climate, length of the rotation, and how these factors influence residue retention and its effect on soil quality and soil functioning, as well as on pest and weed management.

Technology alternatives: Explicit time horizons. Biojet fuel production based on macauba and eucalypt residues results in more potential benefits in terms of climate change, profitability, and social development. However, they imply a lower investment security than other alternatives. Macauba implies a high investment risk in the short term as production is still under development, and harvest only starts after more than 6 years from planting (César et al. 2015). Eucalypt, although widely available in the region, implies processing technologies (i.e. FP and HTL) that are still under development, resulting in a lower commercial acceptability and higher investment risks than sugarcane processing technologies.

An opportunity to deal with the tension between climate change, profitability and social development on one hand, and commercial acceptability and investment risk on the other, is to consider the time horizon of projects, bearing in mind that a single crop-and-technology combination does not need to supply all biojet fuel demand in the region at once. In this way, production based on macauba, with HEFA for processing oil and FP or HTL for residues, could be considered as an alternative in the long term. Sugarcane ETJ and eucalypt FP biojet fuels could be considered for meeting emission reduction targets in a shorter term. In the case of biojet fuel from sugarcane juice, the total capital investments could be lower if ethanol mills are already in place, requiring extra capital expenses for ETJ only. This would make sugarcane an easier option. Additionally, the improvement scenarios presented for sugarcane (i.e. production of higher-value products and second crop during off-season) and optimized plantation management options (related to, e.g., nutrient recycling and carbon storage in the soil, as well as net production of greenhouse gases from the fields) could be explored in more detail to improve the system performance on climate change, profitability, and also soil sustainability. Nevertheless, stimulating the development of biojet fuel production implies encouraging producers to switch from their usual crop or product. For example, in the case of sugarcane biojet fuel, introducing feed-in tariffs in combination with a gasoline tax can encourage its large scale production and use (Moncada et al. 2019).

Implementation: Organizational arrangements. Although impacts on equality and social cohesion were not evaluated with regard to the different alternatives (see section 5.6, Methods), a tension between these aspects and profitability was identified. In the emergence of production chains for commodity products, like biojet fuel, economies of scale tend to favour land concentration and vertical integration models (i.e. where the production plant owner also (co-)owns other stages of the production chain, like biomass production, Chaddad 2015). These production models are in tension with equity and social cohesion aspects since they could lead to the exclusion of smallholders (e.g. family farmers, small-scale local companies) from the production chain (Kaup 2015; Latorre et al. 2015; Levidow 2015). An opportunity however, are the business models of non-traditional mill owners, or new entrants, who base their production on arrangements with feedstock producers, as reported for sugarcane expansion areas like Goiás (Marques Postal 2014). While new entrants favour these partnership models due to the lower capital requirements for production (i.e. no need to acquire land, Kaup 2015), these models also open the possibility for the inclusion of smallholder farmers, reconciling aspects of equality and social cohesion with entrepreneurship concerns. To encourage partnership models, there is a need to support organizational arrangements among producers (e.g. cooperatives and farmers associations), and the development of contracts that give revenue certainty to farmers and feedstock security to biorefinery operators (Marques Postal 2014; Watanabe and Zylbersztajn 2013). Partnership models with organizational arrangements could then result in benefits for rural smallholders with respect to income and stability opportunities, and also support the preservation of local knowledge and culture, which would be a major advantage when compared with fossil fuels.

Sustainability analysis: Knowledge and capacity for action. There is an intrinsic tension between the capacity for action and the available knowledge when analysing the sustainability impacts of a technology. In early stages of development there is more space for changing an innovation (e.g. a technology or a crop) in support of sustainability when learning about its performance. This is more difficult at later stages of development, as by then investments are already in place as, e.g., pilot or demonstration facilities. However, ex-ante analyses as presented here imply inherent uncertainties related to limited data and knowledge about the performance and consequences of production. For example, in this study there are uncertainties related to production yields and GHG emissions at commercial scale, indirect land use changes, the effect of bagasse power on the Brazilian energy supply, and long-term consequences for the sustainability of soils. This quandary is an instance of the famous Collingridge dilemma, which states that at early development stages of a technology there is limited knowledge about its impacts, but later when it is implemented there is limited capacity to change it (Collingridge 1980).

A straight forward solution to this dilemma is increasing the predictive capacity of ex-ante analyses, for example by incorporating risk analyses to support decision making, as done in the case of safety risks of nanomaterials (Fadeel et al. 2018; van Wezel et al. 2018). In the case of biojet fuels, there are already a few studies looking at the uncertainties associated to biojet fuels production, mostly focused on economic and technological uncertainties (Alves et al. 2017; Connelly et al. 2015). These type of analyses could be further extended to other relevant aspects of a specific biofuel production chain. However, knowledge gaps will remain because of limited predictive capacity, and unexpected events that are always a possibility. A way to deal with these limitations is to develop the capacity to monitor consequences and change the course of a technology, or production chain as in this case, if no longer desirable (Asveld and Stemerding 2018; Liebert and Schmidt 2010). Overall, combining strategies for increasing knowledge and capacity for action is a way to deal with the limitations of ex-ante sustainability analyses.

5.5. Conclusions

We presented a novel ex-ante analysis of the sustainability of biojet fuel that includes a discussion of sustainability tensions and opportunities for its production in Southeast Brazil. Our analysis shows that macauba-based production with HEFA, followed by thermochemical conversion of lignocellulosic residues, performs better than sugarcane alternatives in terms of climate change, efficiency, profitability and social development. However, choosing the macauba-based alternative over others implies facing a relatively low commercial acceptability and high investment risks. Therefore, we conclude that sugarcane is the most opportune feedstock for the production of biojet fuel in the short term, while eucalypt processing with FP and macauba processing with HEFA and HTL seem as better alternatives in the longer term. To improve the profitability of sugarcane, the production of higher-value products and the processing of a second crop in order to complement off-season production dips will be beneficial. These improvements could be combined with plantation management practices (e.g. optimized nutrient recycling) to ameliorate sugarcane production effects on soil sustainability and GHG emissions, which is applicable to all feedstocks. Additionally, to improve the efficiency and climate change performance of thermochemical alternatives, hydrogen generation options based on renewable energy should be explored. As different by-product alternatives can be in the interests of different stakeholders (e.g. improving the economic performance of the production chain or contributing to the energy security of the region), the decision over by-products should be open to participation of relevant stakeholders. With regard to the implementation of production, it was found that producer–operator partnerships can open opportunities for the inclusion of smallholders in the region. Promoting these partnerships and strengthening the role of smallholders through, e.g. organizational arrangements, can serve to bring equality and social cohesion into the development of the production chain. Lastly, we conclude that emerging fuel and carbon policies may provide opportunities for the development of biofuel production.

The presented approach allowed to integrate considerations of the local context and stakeholders for an ex-ante sustainability analysis. Engagements with stakeholders allowed to identify relevant sustainability aspects for the case study, and to specify them with regard to the local context. While it was not possible to evaluate all identified sustainability aspects, the recognition of these issues allowed to understand sustainability tensions related to the considered production alternatives, and to identify opportunities for further developments. This understanding will provide a first step towards reducing the ambiguity associated to diverging values of stakeholders, and support the strengthening of a stakeholder network for the development of more sustainable biobased production. For achieving this, social learning and responsible innovation tools can be useful. Overall, the presented approach may be also applicable to other regions and other production chains in support of a more sustainable transition away from fossil resources.

5.6. Methods

5.6.1. Production Alternatives for Biojet fuel

Possible production alternatives for the case study were based on a previous study taking into account expected economic potential (the difference between sale revenues from all products and feedstock costs), production yields and feedstock availability in Southeast Brazil (Alves et al. 2017). Feedstocks initially in consideration were macauba jatropha, camelina, soybean, sugarcane, sweet sorghum, and the lignocellulosic residues of sugarcane, sweet sorghum, eucalypt, pine, coffee, and rice. These feedstocks were selected based on oil/sugar content, land productivity, availability in Brazil, resistance to lack of water or nutrients, production and harvesting cost and potential expansion, amongst others (Alves et al. 2017). By-products in consideration include secondary fuel products derived from the process (such as naphtha and diesel). Higher-value bio-chemicals as by-product alternatives obtained from a dedicated fraction of feedstock stream were evaluated, and included intermediates for bioplastics such as ethylene, lactic acid, and succinic acid. The economic potential results from Alves et al. (2017) were then used to narrow the range of feedstocks to eucalypt, macauba and sugarcane, and higher-value products to succinic acid only. Economic potential results are summarized in Appendix IV, more details can be found from Alves et al. (2017).

The preliminary techno-economic analyses from Cornelio da Silva (2016) and Santos et al. (2018) were used as a basis to define specific combinations of feedstock and technologies for the case study, based on a production scale of 210 kton/year of biojet fuel. Evaluated conversion technologies in these studies were DF and ETJ for sugar streams, HEFA was considered for oil streams, and HTL and GFT for lignocellulosic streams (Cornelio da Silva 2016; Santos et al. 2018). Pre-treatment alternatives were also evaluated for lignocellulosic residues where lignin was considered for biojet fuel production through FP and GFT, or for power co-generation. Fermentable sugars from pre-treatment alternatives were considered for the production of higher-value chemicals, or for 2G ETJ biojet fuel in the case of bagasse. Bare equipment costs were estimated from literature data for similar technologies (mainly from Dias et al. 2011; Hamelinck et al. 2005; Humbird et al. 2011; Kautto et al. 2013; Kumar and Murthy 2011) and taking into account economies of scale. Variable costs were determined from mass and energy balances, using the list of prices in Appendix IV. Total capital and operational expenses were estimated based on economic factors in Process Design literature (Warren D. Seider et al. 2008), which include a capital charge for the processing technologies considering a plant life of 15 years. Based on the results of the preliminary techno-economic analysis (Appendix IV, for more details see Cornelio da Silva 2016; Santos et al. 2018), the considered production chains were: sugarcane processed with ETJ in combination with FP for bagasse, eucalypt residues processed with either FP or HTL, and macauba processed with HEFA in combination with HTL or FP for macauba residues. As an exception, Gasification Fischer-Tropsch (GFT) is the technology considered for eucalypt conversion when evaluated for social development. While GFT scenarios showed a poorer techno-economic performance than FP and HTL (Cornelio da Silva 2016), GFT was considered for the social development evaluation because the availability of data and development stage of the technology were considered crucial for the analysis (see below the section on social development).

5.6.1. Sustainability Analysis

The performance of promising production chains was evaluated considering the sustainability framework in Table 5.1. The sustainability aspects that conform the framework were identified from previous work in the target region (Palmeros Parada et al. 2018; Pashaei Kamali et al. 2018), which includes interviews with stakeholders related to the potential production of biojet fuel (such as representatives of government bodies and biomass producing organizations), a survey with experts on biofuel production, and a sustainability literature review. The sustainability aspects in this study take as benchmark the definitions in the work by Pashaei Kamali et al. (2018), which are based on the Sustainability Reporting Guidelines of the Global Reporting Initiative and the FAO Sustainability Assessment of Food and Agriculture systems (Food and Agriculture Organization of the United Nations 2014; Global Reporting Initiative 2015).

From the total of identified sustainability aspects, four were analysed through quantitative indicators (i.e. climate change, efficiency, profitability, social development), and four were qualitatively explored based on literature data (i.e. commercial acceptability, energy security, investment security and soil sustainability). Due to the scope of this work and the availability of data, some aspects identified by Palmeros Parada et al. (2018) and Pashaei Kamali et al. (2018) were left out of the framework (i.e. accountability, cooperation and leadership, cultural diversity, equity and social cohesion, human health and safety, labour rights, property rights, participation, rule of law, standard of living, training and education, and working conditions). These aspects are mostly related to the implementation of production and are beyond the scope of design choices, or for their analysis they require monitoring data that was not available (especially for macauba for which there is no commercial full scale production). Additionally, food security, often discussed in relation to the sustainability of biofuels, was not evaluated given that stakeholders did not consider it a prominent issue in the region (according to Palmeros Parada et al. 2018), possibly related to reported food production surplus and land availability in Brazil (Woods et al. 2015)). Perceptions of food security impacts, particularly from international stakeholders related to the aviation sector, did emerge from the interviews and could be analysed as an aspect of commercial acceptability (Palmeros Parada et al. 2018). However, food security perceptions as part of commercial acceptability were not further investigated given that none of the considered feedstock alternatives are food crops.

Profitability, climate change, and efficiency impacts were estimated with MSP, GHG emissions, and NREU as indicators. The quantitative results presented in this work are based on the detailed estimations in Cornelio da Silva (2016) for production with eucalypt and macauba using FP, HEFA and HTL technologies; and in Santos et al. (2018) for sugarcane using ETJ and FP. Additionally, two improvement scenarios for sugarcane based on the processing of sweet sorghum during sugarcane off-season and the co-production of succinic acid from fermentable sugars are also presented in this work (Santos et al. 2018). The estimations of MSP, GHG emissions and NREU in the referenced studies consider the stages of biomass production and transportation, and the conversion and upgrading to bio-kerosene. Since the carbon emitted during combustion is biogenic carbon (i.e. captured during plant growth – photosynthesis, Jeswani 2017), CO_2 emissions from combustion were considered as neutral in the analysis. Considering that the evaluated alternatives are multi-product systems where most products are energy products (e.g. biojet fuel, diesel), the allocation method for GHG emissions and NREU between products was based on energy content (economic allocation was avoided due to fluctuating market prices in the energy sector). Additionally, Santos et al. (2018) show that different allocation methods for sugarcane-based production, which includes non-energy products (i.e. succinic acid), lead to the same conclusions, with figures differing in no more than 5%. Emissions from the agricultural stage are an exception, and were allocated based on the economic value of by-products generated at this stage because energy allocation would neglect differences in wood and wood residue products that have similar energy contents but very different uses and economic value. A system expansion approach was followed for bioenergy as a product of the production chain, assuming it replaces the generation of power from the Brazilian grid under national mix conditions. With regard to process alternatives, the in-house production of H_2 through steam methane reforming, the heat and power generation from solid residues, and the optional cracking step were considered based on the estimations from Vyhmeister et al. (2018). However, here we don't refer to specific results from Vyhmeister et al. (2018) as they are based on different indicators (i.e. the GREENSCOPE assessment framework). We do, however, refer to their conclusions regarding the inclusion of process options given that their analysis is based on similar scenarios than the ones considered in this report.

Social development impacts were estimated in terms of employment, GDP and trade balance contributions based on the macroeconomic Input-Output analysis from Want et al. (2019). Effects with regards to these indicators are estimated for the overall economic structure of Brazil as described by the most recent national Input-Output tables (Brazilian Institute of Geography and Statistics 2017), and include effects directly related to the production of biojet fuel, and indirect effects that relate to intermediate inputs and activities that support production. The effects on employment, GDP, and trade balance are presented for three potential production chains as described in Want et al. (2019): (i) sugarcane based production with ETJ conversion for sugarcane juice and FP conversion of bagasse; (ii) eucalypt based production with GFT conversion; and (iii) macauba based production with HEFA conversion for macauba oil and FP for residues. GFT is the considered technology because the Input-Output analysis was based on policy and technology development scenarios for which technologies got discarded based on data availability and development stage. It is expected that the difference between GFT considered in the social development analysis, and FP and HTL for the rest of the indicators, does not strongly affect the overall comparison considering the large effect of the feedstock production stage on social development impacts, such as employment creation (Diaz-Chavez et al. 2015). In Want et al. (2019) two different estimations are available for the three production chains, differing only on the projected biojet fuel demand (i.e. 360 kton and 540 kton). In this work we present the average of these two estimations per kton of biojet fuel (the difference between estimations is less than 3%).

Commercial acceptability, energy security, investment risks and soil sustainability were aspects explored qualitatively based on recent literature reports for the considered feedstock and technology alternatives, as seen in Table 5.1. **Commercial acceptability** was explored as an aspect of the sustainability of biojet fuel production, and considering the concerns of stakeholders in the aviation sector regarding regulations and safety perceptions (Palmeros Parada et al. 2018). This aspect was explored in terms of the approval status by the ASTM, in alignment with the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (Agencia Nacional de Petroleo, Gas Natural and Biofuels 2016). ASTM sets quality standards for “drop-in” biojet fuels, and certification is granted to a specific biojet fuel depending on the production processes to obtain it. Certification thus assures that the fuel has the same safety and performance, and can use the same infrastructure as conventional kerosene (Cortez et al. 2015). To put the results from the exploration of commercial acceptability in a visual form (Fig. 5.2), alternatives that imply ASTM approved conversion technologies were considered as having a positive score, a neutral qualification was given to alternatives with technologies in queue for approval, while a negative performance on this aspect was considered for technologies that are not yet in consideration for ASTM approval.

Energy security was explored in terms of contribution to energy reliability and self-sufficiency considering the concerns of government and biofuel stakeholders about these aspects, and who referred to energy supply problems in the past (Palmeros Parada et al. 2018). Therefore, to analyse energy security, the estimations of energy efficiency were used as a relative indication of the performance of conversion technologies on this aspect (i.e. a negative score for the alternative with highest NREU and a positive score for the alternative with lowest NREU). The potential of the different alternatives for power generation (expected to contribute to energy reliability Palmeros Parada et al. 2018) was taken as an indicator of energy security performance related to each feedstock. A positive qualification was given when a feedstock alternative implied the availability of residues for co-generation regardless of the process configuration, while a neutral effect was considered when availability depended on the process configuration (there was no alternative with a negative effect on this aspect).

Investment security was explored depending on the readiness level of a conversion technology and feedstock. This aspect was considered according to the responses of stakeholders from the government, technology companies, and research institutes, and referencing farmers, who perceived risk in unproven technologies (including feedstocks), especially those for which they had no relatable experience (Palmeros Parada et al. 2018). For technology alternatives the fuel readiness level scale (FRL, 1-9) was used as a reference, which is a risk management approach to specifically track the research and development stage of alternative fuels, considering the technology to produce it, manufacturing capacity, and compatibility with existing infrastructure (Altman 2012). The analysis takes as reference the conclusions from a previous study (Mawhood et al. 2016), and it is complemented with more recent information about the considered technologies (ASTM International 2019; Biller and Roth 2018; Borislava 2017). For feedstocks, the FRL scale from the Commercial Aviation Alternative Fuels Initiative was used as a benchmark (Hileman et al. 2009), taking recent literature on the considered feedstocks (Cardoso et al. 2017; Colombo et al. 2018; McMahon and Jackson 2019; Sant'Anna et al. 2016). Then, a positive effect was considered for feedstocks that already reached a full-scale commercial deployment, a neutral effect for feedstocks in pre-commercial testing, and a negative one for feedstocks at the preliminary evaluation stage.

Soil sustainability was considered based on stakeholders' concerns regarding the protection and recovery of natural resources, especially with regard to deforestation and the degradation of land (Palmeros Parada et al. 2018). Most interviewed stakeholders showed concern about this aspect, including respondents from the government, aviation and technology companies, and research institutes (Palmeros Parada et al. 2018). Soil sustainability was studied through a review of the literature. For sugarcane, a recent and extensive review on the agronomic and environmental implications of residue removal in Brazil was used as main reference for our analysis (Carvalho et al. 2017). For eucalypt, different studies in the context of Brazil were consulted (Cook et al. 2016; Fialho and Zinn 2014; Gonçalves et al. 2007; Harrison et al. 2000; Rocha et al. 2016; Rosim et al. 2016; Zaia and Gama-Rodrigues 2004), as well as other studies regarding forests in other contexts (de Jong, Akselsson, et al. 2017; Hernández et al. 2016; Lamers et al. 2013; Titus et al. 2009). Extensive budgets were made for biomass and nutrients present in the various components of the trees (wood, bark, branches, leafs) depending on stand age, geographic region, and tree species and cultivars (Brinkman et al. 2017). All these factors were of influence on the conclusions on harvest residues, but as for sugarcane, there were no studies that provide an integral assessment of all components of soil sustainability.

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Chapter 6

Conclusions

In this thesis, the consideration of stakeholder values and the context of production into biorefinery design for sustainability has been investigated through case studies at different stages of the design process, i.e. the definition of the design space, the design space exploration, and the evaluation of alternatives. In this chapter the overall conclusions from these studies will be presented as answers to the three sub research questions stated in Chapter 1 (RQ 1-3). From this discussion I will conclude on the main research question of this work: **how can the perspectives of stakeholders and the local context where production would take place be investigated and integrated to the early-stage design biorefineries?** I will then discuss the main limitations of this work and some opportunities for future work. Derived from this discussion I will present an approach for early stage biorefinery design that considers stakeholders perspectives and the local context with regards to sustainability.

6.1. RQ 1: Stakeholder and context considerations in the definition of the design space

The design of biorefineries starts with the definition of the design space, when the objectives of a project are recognized and used to define the project requirements, variables, and constraints. In Chapter 3 of this thesis I have explored how considerations of stakeholders' values and the context of production can be integrated into this definition of the design space when designing for sustainability **(sub research question 1**, Chapter 1). For this, VSD and the concept of value hierarchy (van de Poel 2013) served as starting points. Particularly, the identification of stakeholders and values of relevance to the project, and the awareness of how technical features relate to these values served to derive design propositions as norms to guide the design. These propositions set limits or constraints to the project variables for the sake of the identified values. For example, a design proposition can suggest or reject certain by-products to be obtained from a biorefinery, such as bioenergy for a regional grid for the sake of energy security. In this way the design propositions narrowed down the design space of a biorefinery in support of the identified values. Therefore, after identifying relevant stakeholders and their values, it is possible to proactively investigate how they relate to the project variables in consideration and integrate them in the definition of the design space.

For a case study on biojet fuel production in Southeast Brazil, a generic biofuel production chain served as starting point to identify regional stakeholders. A broad range of values were recognised from the investigations with some of the identified stakeholders. Some of these values were related to the durability of the project (investment security, profitability) and care for nature (e.g. climate change mitigation, efficiency, protection and recovery of nature), which are relatively common in the scope of biofuels. Besides these, other values that are no often considered in the field of biorefinery design emerged too, particularly in relation to socio-economic welfare, such as development opportunities and economic value sharing. Furthermore, based on the interviews with stakeholders it was possible to specify the identified values in the context of the project. For example, it was found that investment security, which is sometimes considered in techno-economic assessments of industrial production, is also an important aspect for farmers in the region. A change of crop and production practices to supply biomass for a biorefinery implies risk to farmers, especially in the case of regional smallholders who may be in a difficult position to manage risk, and who have had negative experiences with crops for biodiesel production in the past. Another example is the case of economic value-sharing across the production chain when some stakeholders spoke of a fair distribution of economic value for all actors along the production chain, particularly considering that some actors remain in low economic value-adding activities, or they have unequal bargaining power (i.e. small-scale farmers).

Design propositions were defined as a way to integrate the investigated stakeholders and values in the definition of the design space. That is, these propositions narrowed the design space of the specific project while proactively intending to accommodate the investigated values. All main variables of the project were subject to design propositions, being related to the feedstocks, conversion technologies, by-products and supply chain. Additionally, design propositions were derived with regards to the business case or the implementation of the biorefinery as some of the investigated values were more relevant to these aspects of the development of biorefineries than to technical variables. While the design scope is centred on variables, design concepts are usually evaluated in the scope of a business case, and thus having propositions for it can influence how a biorefinery concept is developed or assessed.

For developing the design propositions, all identified values from all investigated stakeholders were considered with the intention to encourage the designers to find technical features of the biorefinery that support all values. Thus, no assumption about the priority of some values over others was made. However, it can be expected that in occasions the design space may be too narrow and make the project over constrained if taken strictly. Therefore, these propositions are suggested as flexible design boundaries. More than being formulated as strict requirements, the design propositions are intended as guiding principles to prompt reflection about the consequences of defining a variable with regards to stakeholder values.

6.2. RQ2: Stakeholder and context considerations in design decisions

During the design process to create a biorefinery concept, design decisions are made on project variables when a design alternative is selected as a technical feature for a biorefinery. Design decisions are made as different alternatives are envisaged and explored through calculations, experiments, simulations, etc. In Chapter 4 the consideration of stakeholders' values and the context of production during this decision making was investigated to answer the **sub research question 2**. Particularly, design propositions and stakeholders' values were brought forward during Midstream Modulation (MM) interventions on the design process to encourage reflection, and thus promote their consideration during the design decision making. The hypothesis was that by following or trying to follow the design propositions during the designing process, value considerations would be made in to the design decision making.

As a result it was found that while the design propositions contributed to the generation of design alternatives in support of the investigated values, they did not serve to prompt reflection directly. That is, in the case study in Chapter 4, the derived design propositions were too broad or ambiguous with regards to the project variables, and following them as design guides did not necessarily constraint the project, nor encouraged the designers to reflect on their decisions. That is, it was not possible to derive more detailed design propositions due to the early-stage of the project, when only the main technological platform was known but the rest remained open during the design space definition phase, i.e. main product and application. However, by asking the designers about the propositions and values of stakeholders during the MM interventions, the design propositions and the identified values served as prompts for reflection about the variables and the consequences of their decisions with regards to the stakeholders and the context of production. As a result, new alternatives for the project variables were envisaged and considered during the design decision making; see, for example, the different downstream processing steps for the sake of profitability, product quality and environmental safety discussed in Chapter 4.

However, not all alternatives that supported the investigated values were ultimately selected for the final biorefinery concepts. It was found that tensions emerged when a design decision implied choosing one value over another. For example, a tension emerged when a value was supported by one design alternative for a design variable, but the same alternative opposed another value; or when an alternative supported one value, and another alternative for the same variable supported a different value. When a tension emerged between project values (values related to the development and implementation of the project such as technical feasibility), and the values identified from the investigation of stakeholders, the designers' decisions leaned towards project values. This observation is a reasonable outcome, as the main objective of the designers was the development of the project to obtain a feasible biorefinery concept. Nonetheless, it was found that the designers sought to integrate the investigated values in different parts of the project: In cases where a value could not be supported through a given alternative for a project variable, they sought its integration in another variable or even suggested alternatives for future research activities, beyond the scope of the design project, as in the case of feedstock alternatives discussed in more detail in Chapter 4. Therefore, investigated values were not only considered or integrated in the design decision making, they were also integrated into the broader design project. Overall, with MM interventions considerations of stakeholders' values and the context of production were brought into a design project, not as an afterthought during an evaluation when design concepts had already been created, but during the design process itself when there is still space for envisaging new alternatives.

6.3. RQ3: Stakeholder and context considerations in the evaluation of biorefinery alternatives

To support the evaluation of biorefinery alternatives, a sustainability framework was defined based on an understanding of stakeholders and the context of production, as presented in Chapter 5. For this, sustainability aspects and indicators considered for the evaluation of alternatives were identified from engagements with stakeholders and sustainability literature. Continuing with the case study for biojet fuel production in Southeast Brazil from Chapter 3, the situated knowledge about the project context allowed to focus on relevant sustainability aspects besides those typically addressed in biorefinery design literature, or to specify them according to the local stakeholders concerns. For example, investment security was explored through the readiness level of conversion technologies and feedstocks. While the readiness level of technologies has been to a certain degree considered in previous biojet fuel studies (Alves et al. 2017), in Chapter 5 feedstocks were also explored in terms of investment security through the readiness level of their production in the region. Investment security for both feedstocks and technologies was identified as important from the engagements with regional stakeholders in Chapter 3. Particularly, through the interviews with stakeholders it was clear that investment security was a prominent aspect for biomass producers when they have to change their production practices and crops for producing biomass for a biorefinery. Another example is social development, rarely addressed in biorefinery design, as discussed in Chapter 2. Social development was identified from the concerns of stakeholders about the generation of opportunities that a biorefinery should bring to their country or region (see Chapter 3), and it was integrated in the sustainability framework with socio-economic indicators for the evaluation of production alternatives.

The developed sustainability framework in Chapter 5 included global drivers for biobased production, e.g. climate change mitigation, and also sustainability aspects relevant for the case study such as commercial acceptability of biojet fuels and investment security of technologies and feedstocks. Additionally, having situated knowledge about the project allowed to specify sustainability aspects to the local context. For example, energy security was explored with regards to its contribution to both national energy availability and the regional energy supply. While the first point is relatively common in sustainability analyses of bioenergy, the second point is specific to the Brazilian case given their dependency on hydropower and the water shortages experiences in the past years, as mentioned in Chapters 3 and 5.

For the interpretation of results, the estimations for each sustainability aspect were contrasted to each other, allowing to identify sustainability tensions between different aspects and production alternatives. This way to interpret results is major contrast to some approaches in the biorefinery design literature and sustainability frameworks that rely on normalization, aggregation, and ranking methods (e.g. Li et al. 2011; Ng et al. 2013). While these approaches are intended to facilitate the interpretation of results, they can hide relevant data and carry methodological biases, restricting the analysis (see Chapter 1). As result, in this study no alternative was singled out as the most sustainable option, but rather promising opportunities for further research were identified within the scope of the case study.

Also from this analysis, tensions between different sustainability aspects for the evaluated production alternatives were identified, and opportunities for further developments in the region were suggested. For example, in-house production of hydrogen with renewable energy was suggested to reconcile profitability, decarbonisation targets, and efficiency. Also, producer–operator partnerships with the promotion of organizational arrangements for farmers and opening the decision making to stakeholder participation are suggested for stimulating social cohesion, and reconciling diverging interests in biobased production. Contextualizing results also served to deepen the exploration of the production alternatives as indicators only provide a limited view on sustainability impacts. For example, while employment generation, national GDP contribution and trade balance are practical indicators for comparing alternatives, they only provide a view of social development at the macro-economic level and do not say much about impacts on regional stakeholders. In Chapter 5, the discussion of the identified sustainability tensions in the context of the project allowed to address other aspects that were not necessarily part of the framework but that were also relevant for the case study, like equality and social cohesion, and thus enriched the interpretation of results.

As result of this study, it is concluded that a sustainability evaluation on its own cannot indicate which alternative is the best or the worst in terms of sustainability. Instead, a sustainability analysis that explicitly identifies emerging tensions in the context of the project can contribute to discussions about what is desirable for different stakeholders, and thus support the decision making process for the development of a biorefinery.

6.4. Sustainability in biorefinery design

This research aimed to identify how considerations of stakeholders' values and the context of production can be integrated into biorefinery design for sustainability. In this section I will briefly discuss how stakeholders' values on the one hand, and the project context on the other, were integrated in the design cases discussed in this thesis. Based on the findings of this thesis, I will discuss how the different parts of this thesis can be aligned into a single design approach as an answer to the main research question.

6.4.1. Integrating stakeholders' values and the context of production into biorefinery design for sustainability

From the discussion in sections 6.1 through 6.3 of this Chapter, it can be concluded that stakeholder values were integrated into biorefinery design practice in three ways: First, values were integrated into the definition of the design space when deriving design propositions as boundaries to the design space. Secondly, values were integrated to the evaluation of alternatives when they served as basis for defining the sustainability framework. And thirdly, values were integrated into the design process when they, together with the design propositions, served as prompts for reflection during the design decision making.

Additionally, the project context played a role in the specification and consideration of stakeholders' values and the aspects that defined the sustainability framework. That is, values and sustainability aspects were not considered in a vacuum as the context around production supported their analysis and interpretation with regards to the design case studies. The specification of energy security mentioned above is one example of how the context was integrated in the analysis. Knowledge about the context enriched the discussion of the sustainability tensions between different production alternatives and supported the identification of opportunities for future developments in the region, as presented in Chapter 5. Additionally, considerations of the production context were made during the exploration of the design space when the designers in Chapter 4 reflected over their design decisions. As shown in the discussion in Chapter 4, the consideration of the context supported the identification of new alternatives for a project, and the recognition of uncertainties that could impact the project ultimate implementation and its impacts on society. For example, by recognizing the importance of bioplastics degradation, the team sought alternatives to support it in the short term in a context of uncertain bioplastics policies and regulations, as discussed in Chapter 4.

6.4.2. Limitations and opportunities for research

There are four main limitations to the present work on the integration of stakeholder and context considerations in the design of biorefineries. In this section I will discuss these limitations and opportunities for future research. Three of the presented limitations are related to the early stage of development of the biorefinery cases presented in this thesis. The fourth limitation is related to the scope of design projects when seeking to design sustainable complex systems like biorefineries.

(1) During early stages of biorefinery design, projects are broadly specified when various feedstocks or products are typically under consideration. As a consequence, at these stages of development, stakeholders' interests and roles with a biorefinery are uncertain or tenuous. This means that identifying relevant stakeholders can be complex, and involving them for a value elicitation may not be feasible in some cases. In the developed case studies, it was not possible to contact or engage all stakeholders. Particularly, it was not possible to contact or engage with farmers nor with sugarcane worker unions in Chapters 3 and 4, both relevant to the sustainability analysis of the presented case studies. Also, for some stakeholders presented in Chapter 4 it was impossible to contact them directly, and thus the value investigation could only be done through public reports and media, and academic literature. Therefore, the stakeholder and value investigations in this thesis provided only an indication of the stakeholders and values relevant to the biorefinery. In future cases where stakeholders are more defined and approachable, dedicated value elicitation methods could be applied based on surveys, scenarios, and sketches as those described by Friedman et al. 2017. Nevertheless, even with the mentioned stakeholder engagement limitation, the presented work gives an indication of what is relevant to some or most of stakeholders, and thus sharps the view of the overall sociotechnical context around the biorefinery in early-stages of development.

(2) In the present work, the context was brought into consideration taking as reference the investigation of stakeholders, and what they themselves expressed through interviews. In this way, the context was considered form the perspective of investigated stakeholders. While this approach allows to initiate the consideration of stakeholders in the early stages of a project, it also means that relevant elements of the context could have been missed. A way to enhance the analysis as presented in this work, is to have a structured context analysis taking as reference innovation and transition theories. For example, the Multi-Level Perspective (MLP) describes innovations as changes in regimes

(i.e. the Brazilian ethanol regime) that can be driven through the emergence of smaller technological niches (i.e. biojet fuel, bioenergy) and/or through pressure from the broader landscape around the regime (i.e. long term governmental schemes, international commitments). In this way, the technological context is structured around the elements that define these regimes, niches and landscapes. Technology Innovation Systems (TIS), by contrast, is a theoretical framework centred on the technological innovations themselves (biojet fuel technologies) and, to analyse the innovation process, the innovation system is studied as composed by actors, networks, and institutions that can support their development. Complementing the stakeholder value analysis with a TIS or a MLP analysis could result in a broader and deeper understanding of the context to the development of biorefineries, and show insights on the interaction between the biorefineries to be designed and the socio-technical context around them.

(3) Additionally, being at early-stages of development means that there is a more limited view on how implementation of a biorefinery occurs, in contrast to later stages. This means that the intended biorefinery can evolve and be implemented differently than intended or anticipated by designers at early-stages. Therefore, it must be acknowledged that early-stage stakeholder and context considerations for sustainability does not necessarily set the path for a sustainable biorefinery. Also, during long development times, and during the life cycle of a technology or a product, it is possible that the social, moral, and institutional context changes and render a design for sustainability ineffective or undesirable, as mentioned in Chapter 4 and discussed elsewhere (Ihde 2002; van de Poel 2018). To overcome these limitations, continuous learning about stakeholders and the context of a biorefinery along its development and implementation can be an appropriate measure, as discussed in Chapter 4. In this way, the work presented here for obtaining a biorefinery concept can be applied as part of a continuous learning process about the sociotechnical implications of a technological innovation.

(4) Even if all stakeholders could be perfectly represented, and had their values identified and reflected in a design, there are factors beyond the scope of a biorefinery design project that can shape its development, and thus its impacts on society (e.g. governmental programs and regulations, and industrial networks, as shown in the analysis by Bosman and Rotmans (2016). This is a limitation of a design project. That is to say, some issues cannot be readily fixed with design alternatives, but rather require dedicated attention and investigation. This was the case of, for instance, food security in Chapter 4, where addressing the impacts on food security was clearly beyond the capacity for action

in the design project. Hence, questions worth asking are: *at what point could having a researcher investigating an issue such as food security be part of a biorefinery design project? Is it the role of the biorefinery developers to investigate these aspects in depth?* Perhaps, for early stage projects, opening the design to identify these aspects is sufficient, with the condition that if such a trajectory is to be continued, they should be independently and thoroughly investigated.

6.5. An approach to the design of biorefineries for sustainability

Based on the findings from this work, the following design approach is suggested for the integration of stakeholders' values and the context of production in the early-stage design of biorefineries. This approach is broader than typical design approaches in the literature, as it aims to produce (1) a normative design for sustainability, i.e. with consideration of stakeholders' values, and (2) the identification of main uncertainties, challenges and opportunities for sustainability upon its implementation. The approach is presented broadly, giving it flexibility to be adapted to the specific conditions of a given design project for biorefineries, and potentially other complex socio-technical systems such as photo-voltaic or wind turbine parks.

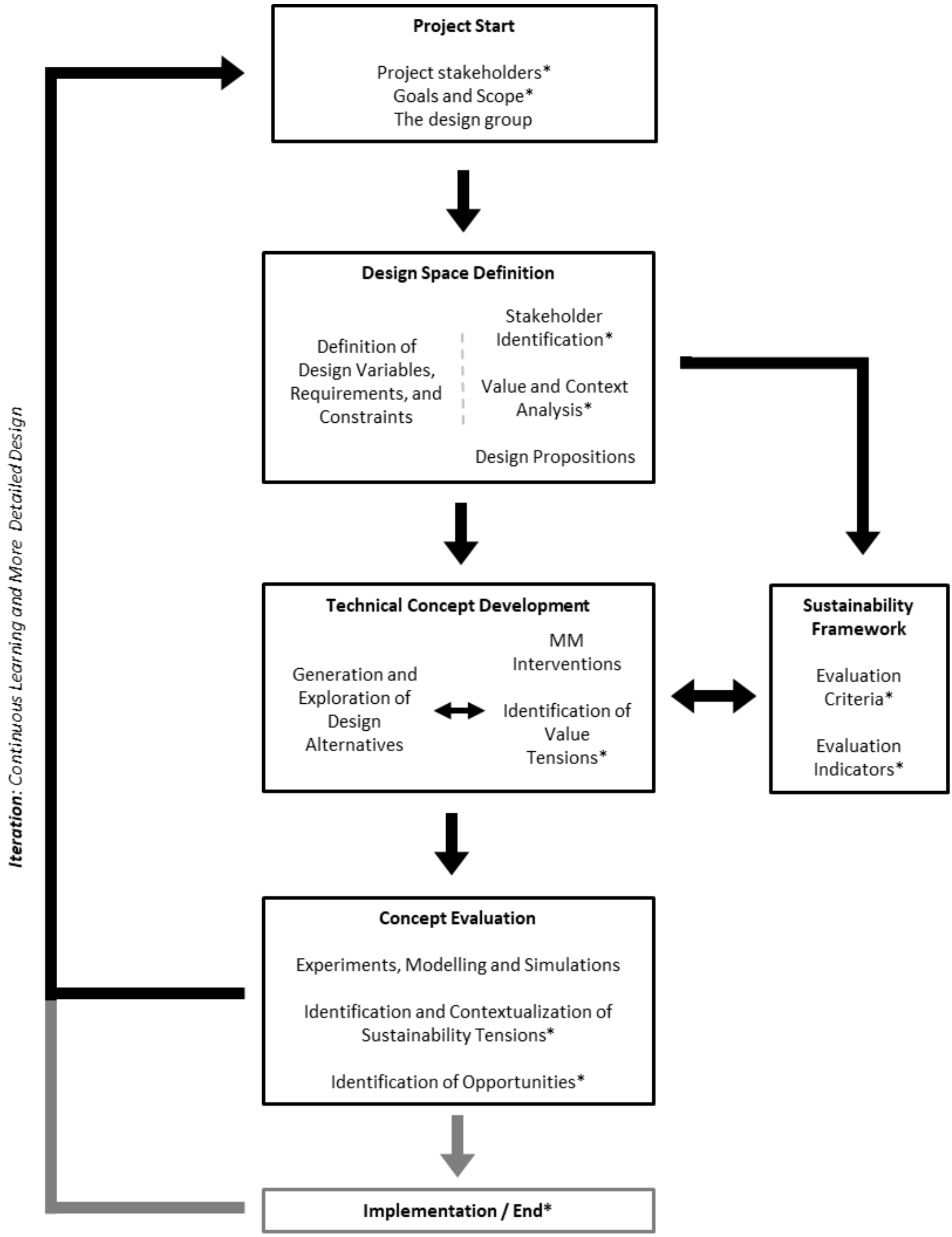

Fig. 6.1. Approach to the design of biorefineries for sustainability and continuous learning. For continuous improvement, the approach is iterative along the development of biorefineries, from conceptual to detailed design and its implementation or termination. An asterisk (*) indicates a recommendation to open the step to the participation of stakeholders. Double sided arrows indicate continuous feedback, upstream arrows indicate an iteration after a cycle is complete.

- ***Project Start:*** As with a regular project, in the start of the project the participant stakeholders, the goals and scope of the design project, and the design group are to be defined. For this, it is suggested that this step is open to the involvement of other stakeholders recognized as relevant to the project, and for the definition of the goals and scope. For the design group, it is recommended to have a dedicated sustainability researcher(s) with the capacity to investigate value considerations and their translation into design features. However, all participants of the design group should be actively involved in the investigation of stakeholders and values, and the derivation of design propositions (see Chapter 4 for a discussion on the role of the design group).
- ***Design Space Definition:*** Parallel to the typical definition of variables, requirements and constraints for any design project, in the design space definition stakeholders relevant to the project are identified and invited for participation. Analysis of stakeholders' values and the context of production are performed to derive design propositions for the specific case study, and with regards to the different project variables. For this, the identification of stakeholders and the value and context analysis are preferably open to the participation of stakeholders; the suggestions in Chapter 3 and section 6.4.2 in this Chapter can support this step.
- ***Technical Concept Development:*** MM interventions take place along the design engineering activities (Double sided arrow inside the Technical Concept Development block in Fig. 6.1). For this, the identified values and design propositions are used as prompts for reflection over project variables. Value tensions are identified and explored with the design team to find new design alternatives that could solve them. These steps are largely based on the findings from Chapter 4. Before deciding on biorefinery concepts to take to the concept evaluation step, it is suggested to discuss alternatives and value tensions with stakeholders to the project.
- ***Sustainability Framework:*** A sustainability framework is defined by sustainability aspects and indicators for the evaluation of biorefinery concepts. Insights from the analysis of stakeholders, their values and the context are used for the selection of the elements of the sustainability framework, as presented in Chapter 5. If possible, the selection can be validated by identified stakeholders, or be open for their participation. Communication between the group members working on the sustainability framework and the technical concept development is to be held to discuss the selection of indicators (double sided arrow between the Technical Concept Development and the Sustainability Framework blocks in Fig. 6.1). In this way, the sustainability framework will be composed of indicators that can be used to

evaluate concepts (i.e. in terms of measurement feasibility, data availability and reliability, and relevance to the design alternatives), and the designers can plan or gather data for the evaluation.

- ***Concept Evaluation:*** The evaluation of biorefinery concepts is based on data from experiments, modelling and simulations, and based on the sustainability framework. The results are contrasted with regards to the different sustainability aspects of the framework. Sustainability tensions are identified and contextualized to identify improvement opportunities, and strategies for further research as discussed in Chapter 5. If possible, the concepts and the evaluation results are brought for discussion with stakeholders for feedback, potentially providing new insights for their contextualization or the identification of new opportunities, and to deliberate on the sustainability tensions and possibilities for future action.
- ***Implementation/End:*** This is the end of one iteration or cycle of the design approach, which is intended to take place along a similar time frame of a typical design approach. Based on the concept evaluation results, decisions are made over promising biorefinery concepts based on the findings from the previous stages. A decision can be to continue with the implementation of the findings from this design cycle, as experiments, pilot or demonstration activities, or to iterate for a more detailed design of one or more biorefinery concepts. As the project goes through one more iteration cycle, the project is more defined, bringing more opportunities to identify stakeholders and open the project for their participation. Iterations are intended for a continuous learning about the project impacts on sustainability from conceptual design to detailed design and implementation. Alternatively, a final decision of the design cycle can be to end the project and not continue with any of the proposed concepts. Again, to the extent possible, the findings of the project are brought for discussion with stakeholders.

Although the work that serves as basis to the presented approach is to a large extent applied in an academic context (particularly Chapters 4 and 5), it is expected that opening the design practice to considerations of stakeholders and the sociotechnical context around biobased innovations is also the interest of the industry. This is related to the fact that, in spite of the numerous technologies and potential applications, the uptake of biobased production has been slower than anticipated (Mossberg et al. 2018). First, the implementation of biorefineries at commercial scale faces various socio-technical barriers that hinder their uptake, like feedstock supply uncertainty and limited coordination amongst actors involved with biobased production (Bosman and Rotmans 2016; Breukers et al. 2014; Hellsmark and Söderholm 2017; Kedron and Bagchi-Sen 2017). Second, some disagreements about the impacts of biobased production on sustainability put its social acceptability into question and highlight the uncertainty that surrounds this production approach (Asveld and Stemerding 2018; Tempels and Van den Belt 2016). Additionally, the industry is facing increasing pressure to decarbonize its production paradigm, while at the same time it has to respond to Corporate Social Responsibility and Sustainability demands. By bringing context considerations to early stage design and encouraging the involvement of stakeholders, the presented approach can potentially contribute to form a stakeholder network and the anticipation of some socio-technical barriers, with the expectation to result in the advancement of more socially acceptable and sustainable biorefinery innovation.

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Appendices

Appendix I

Table A1.1 Stand-alone indicators used in the reviewed literature.

Name(s)	Description	Unit Dimensions	Sources
Economic			
Actual Sequestration Cost	Cost minus revenues of sequestration and utilization of CO2	Money/ Time	(Gong and You, 2014a, b)
Capital Costs (Capital Expenditures, Investment Cost)	Sum of capital costs, depending on the case, it may include installation and start-up costs.	Money	(Caliandro et al., 2014; Coleman et al., 2014; Kalnes et al., 2007; Tock and Marechal, 2012)
Operating Costs (Operational Expenditure)	Sum of operating cost.	Money/ Time	(Coleman et al., 2014)
Production Cost (Cost of Production, Least Expected Cost, Total System Cost, Total Supply Chain Cost)	Sum of capital and operating costs, when applicable biomass and product transportation costs, import penalty costs and credits are considered.	Money/ Time	(Akgul et al., 2012; Baliban et al., 2013; Bernical et al., 2013; Coleman et al., 2014; Correll et al., 2014; Gong and You, 2014c; Huang et al., 2010; Iakovou et al., 2012; Michels and Wagemann, 2010; Sadhukhan and Ng, 2011; Slade and Bauen, 2013; Tong et al., 2014a; Tong et al., 2014b; Tong et al., 2014c; Xie and Huang, 2013; You et al., 2012; Yue et al., 2013; Yue and You, 2014b; Ziolkowska, 2013)
Transport Cost	Cost of transportation of biomass and/or product	Money/ Product Unit	(de Figueiredo and Mayerle, 2014)
Total Savings	The sum of utilities/mass savings and emission credits minus implementation cost	Money	(Chouinard-Dussault et al., 2011)
Gross Operating Margin (Financial Return)	Sales minus cost of raw material and utilities	Money/ Time	(Field et al., 2013; Martinez-Hernandez et al., 2012, 2013; Rizwan et al., 2015; Tay et al., 2011a)
Credited Gross Operating Margin (Bioenergy Cost)	Sales and credits minus cost of raw material, utilities and penalties if applicable.	Money/ Time	(Ayoub et al., 2009; Kantas et al., 2015)
Gross Profit (Annualized	Sales minus operating and capital cost (excludes	Money/ Time	(Andiappan et al., 2015; Cheali et al., 2015; Cucek et

Expected Profit, Overall Profit, Total Profit, Earnings Before Interest, Depreciation, Taxes and Amortization)	taxes but may include overhead), when applicable biomass and product transportation costs, import penalty cost and credits		al., 2014; Ng et al., 2015; Osmani and Zhang, 2014; Sammons et al., 2008; Santibanez-Aguilar et al., 2014; Shabbir et al., 2012; Shastri et al., 2011)
Internal Rate of Return	Calculated (interest) rate at which the NPV of the project equals zero	%	(de Santoli et al., 2015; Laser et al., 2009; Li et al., 2011)
Minimum Selling Price	Minimum Selling Price of the Product to fulfill profitability requirements	Money/ Product Unit	(Biddy et al., 2016; Dutta et al., 2012; Laser et al., 2009; Sen et al., 2012; Tan et al., 2016; Zhu et al., 2013)
Net Present Value	Sum of discounted revenues and costs in the life-time of a project	Money	(Gebreslassie et al., 2013a; Gebreslassie et al., 2013b; Giarola et al., 2011; Karschin and Geldermann, 2015; Kempener et al., 2009; Li et al., 2011; Vlysidis et al., 2011; Wang et al., 2013; Zamboni et al., 2011; Zhang et al., 2014)
Payback Time	Expected time in which the investment cost is payback from the projects cash flows.	Time	(de Santoli et al., 2015)
Return on Investment	Net profit over investment costs	%	(Schaidle et al., 2011; Sen et al., 2012)
Stakeholder Value	Weighted sum of future cash flows and terminal value of the enterprise minus the overall debt	Money	(Sharma et al., 2011)
Total Economic Value	Sum of revenues plus monetized (GHG and soil erosion) environmental impacts	Money/ Time	(Cobuloglu and Bueyuektahtakin, 2014)
Environmental			
Greenhouse Gases Emissions	Sum of emissions as CO2 equivalents per unit of product.	Mass/ Product Unit	(Barnes et al., 2011; Bernical et al., 2013; Iakovou et al., 2012; Kalinci et al., 2013; Kempener et al., 2009; Sharma et al., 2011; Shastri et al., 2011)
Nitrogen Oxides Emissions	Sum of nitrogen oxides emissions over the system boundary.	Mass/ Product Unit	(Schaidle et al., 2011)

Sulfur Oxides Emissions	Sum of sulfur oxides emissions over the system boundary.	Mass/ Product Unit	(Schaidle et al., 2011)
Mitigation of GHG	The mitigation value is estimated from the half-life of the product in soil in a 100 year time horizon.	Mass/ Mass	(Field et al., 2013; Laser et al., 2009)
Net GHG emissions reduction	Difference between total CO2eq emissions displaced and total CO2eq emissions form the feedstock, transport and processing systems of the proposed design	Mass/ Product Unit	(Eranki et al., 2013)
Change in Soil Organic Carbon	Total change in solid carbon after growing feedstock	ns	(Eranki et al., 2013)
Erosion	Average soil eroded over the watershed land area	ns	(Eranki et al., 2013)
Nitrogen Losses	Total mass amount of nitrogen losses over the system boundary.	Mass/ Product Unit	(Eranki et al., 2013)
Phosphorus Losses	Total mass amount of phosphorus losses over the system boundary.	Mass/ Product Unit	(Eranki et al., 2013)
Oil Displacement	Petroleum use displacement.	Energy/ Mass	(Laser et al., 2009)
Social			
Energy Self-Sufficiency	Energy generated relative to estimated demand in the region	-	(Kempener et al., 2009)
Food Price Increase	Semi-quantitative potential for increasing food prices in **relation to feedstock type**, and a measure of food security	%	(Schaidle et al., 2011)
Sustainability Factor	Sustainability factor that represents the fraction of biomass production that can be used for biofuel production, to ensure food security, based on a defined set aside land	-	(Akgul et al., 2012)
Socio-environmental			
Human Exposure Risk	Semiquantitative risk for human exposure to polluting emissions in relation to feedstock type	%	(Schaidle et al., 2011)

Socio-economic			
Employment Creation	Employment Creation	Created jobs	(Santibanez-Aguilar et al., 2014; Schaidle et al., 2011; You et al., 2012)
Labor requirement	Employee time of labor requirements	Employee time	(Ayoub et al., 2009)
Efficiency and Process			
Bioenergy Efficiency (Cold Gas Efficiency)	Energy in the product over energy in biomass	-	(Cohce et al., 2011; Kalinci et al., 2013; Tock and Marechal, 2012)
Energy Efficiency (Bioenergy yield, Net Energy Balance (NEB), Fossil Energy Consumption)	Energy in product(s) over energy inputs	-	(Bernical et al., 2013; Cohce et al., 2011; De Meyer et al., 2015; Eranki et al., 2013; Golberg et al., 2014; Jenkins and Alles, 2011; Kalinci et al., 2013; Kalnes et al., 2007; Li et al., 2011; Ojeda et al., 2011; Schaidle et al., 2011)
Net Bioenergy Efficiency	Energy output (product minus process requirements) over energy in biomass	-	(Caliandro et al., 2014)
Energy Use	Total energy use	Energy/ Time	(Ayoub et al., 2009; Shastri et al., 2011)
Specific Total Energy Use (Cumulative energy demand)	Total energy use per amount of product	Energy/ Product Unit	(Kalnes et al., 2007; Karka et al., 2014; Tan et al., 2016)
Specific Fossil Energy Use	Total fossil energy use per amount of product	Energy/ Product Unit	(Kalnes et al., 2007)
Heat of reaction (Biorefinery Energy Consumption)	Sum of enthalpy of reactions, or main reaction	Energy/ Time	(Andiappan et al., 2015)
Net Energy Ratio	Used energy over energy in biomass product	-	(Slade and Bauen, 2013)
Exergy Efficiency	One minus the ratio of exergy losses and exergy inputs; exergy in product over exergy inputs	%	(Cohce et al., 2011; Kalinci et al., 2013; Li et al., 2011; Ojeda et al., 2011; Peralta et al., 2010)
Exergy Losses	Exergy Balance	Exergy	(Peralta et al., 2010)
Carbon Efficiency (Carbon utilization)	Carbon in product streams over carbon in biomass	-	(Bernical et al., 2013; Tan et al., 2016)
Crop Water Use Efficiency	Ratio of biomass yield to evapotranspiration	-	(Eranki et al., 2013)

	resulting from a particular feedstock		
Water Efficiency	Mass or volume water requirements over mass, volume or energy amount of product	-	(Bernical et al., 2013; Laser et al., 2009; Schaidle et al., 2011; Ziolkowska, 2013)
Mass Losses (Methane Loss)	Mass losses that reduce the production yield	ns	(de Figueiredo and Mayerle, 2014)
Production Rate (Ethanol Production)	Production rate as a function of process parameters like conversion yield and biomass inflow.	Mass/ Time	(Eranki et al., 2013; Ng et al., 2015; Ziolkowska, 2013)
Biofuel Yield	Product outflow over biomass feedstock inflow	Product Unit/ Mass	(Rizwan et al., 2015; Tan et al., 2016)

ns – not specified in reference(s).

Table A1.2 Impact categories used in the reviewed literature.

Category Name	Category References
Economic Constraint	(Cheali et al., 2015)
Environmental Impact of Raw Materials	
Process Cost and Environmental Impact	
Global Warming	(Andiappan et al., 2015; Ayoub et al., 2009; Baliban et al., 2013; Chouinard-Dussault et al., 2011; Cucek et al., 2014; Eranki et al., 2013; Gebreslassie et al., 2013a; Gebreslassie et al., 2013b; Gheewala et al., 2011; Giarola et al., 2011; Gong and You, 2014a, b, c; Jenkins and Alles, 2011; Kalnes et al., 2007; Karka et al., 2014; Martinez-Hernandez et al., 2012, 2013; Mayumi et al., 2010; Michels and Wagemann, 2010; Nguyen et al., 2014; Sadhukhan and Ng, 2011; Schaidle et al., 2011; Tan et al., 2016; Tock and Marechal, 2012; Vlysidis et al., 2011; Wang et al., 2013; Xie and Huang, 2013; You et al., 2012; Yue et al., 2013; Yue and You, 2014a, b; Zamboni et al., 2011; Zhang et al., 2014; Ziolkowska, 2013)
Human Development Index	(Gheewala et al., 2011)
Total Value Added	
Crop Sustainability	(Golberg et al., 2014)
Enhanced Inherent Safety Index	(Li et al., 2011)
Economic Potential	(Kasivisvanathan et al., 2012; Ng et al., 2013; Tay et al., 2011b)
Economic Performance	(Ng et al., 2013)
Total Safety Impact	
Total Health Impact	
Feedstock Adequacy	(Sacramento-Rivero, 2012)
Transformation-process Performance	
Oil-displacement Capacity of Products	
Environmental Load	
Corporate Commitment to Sustainability	
Eutrophication Potential	(Schaidle et al., 2011)
Health Effects	

Appendix II

This Appendix contains additional information to Chapter 3 on two main points: the topic guide for the interviews (1.2.1) and the rationale behind the generation of the design propositions (1.2.1).

Interview Guide

- Getting to know the stakeholder and respondent
    - Intro to the organization, to confirm background info.
    - Respondent position within the organization & activities
- Background info on participation with a bio(jet) project (if the organization is part of a biojet/biorefinery project already)
    - Confirm participation on the given project
    - Background info on the project
    - Role in the project
    - Are they involved in other biojet/biobased projects?
- Goals, challeges, expected benefits and harms with an operating biorefinery in the region
    - Identify their foreseen role in the value chain and elaborate
    - Benefits for the organization with an operating biorefinery
        - Objective for participating in developing a biorefinery production chain (examples: diversify operations, ensure supply of biofuel, ensure the use of renewable material, find another market for products, secure a regional supplier). If sustainability is referred to, enquire.
        - Why important to them?
    - Challenges?
    - Need of partner organizations to reach objective (examples: For finance, technology)
    - From the organization’s perspective (in rel. to their objectives) what harms could there be with the biorefinery?
        - Strategies to cope
- In relation to a main decision variables
    - Inquire about preference/opinion on the use of specific: region-biomass, feedstock, technology, logistics.
        - Is there any interest for or against a given biomass, feedstock, etc.?
        - What key aspects necessary for the development of that topic?
        - What can interfere with it?
- Sustainability by the organization, benefits and harms of a biorefinery
    - Past projects implemented for sustainability in the organization

        - Regional context
        - Their Importance
        - Present and/or expected challenges and outcomes
            - Current and/or past conflicts regarding sustainability:
- Conflicting sides, strategies to cope, sustainability criteria taken into account, measures used, certifications, schemes.
- How did the conflict evolve, get resolved?
- Was it the organization's initiative or was it externally originated?
    - Benefits regarding sustainability with a jet fuel refinery project
        - How to achieve them, who should do it?
    - Weaknesses/threats in relation to sustainability
        - How, who?
- Extra input
    - Do you personally consider other issues relevant to the project that have not been considered up to now?
- Closing
    - Summarize and ask if there is nothing more to say
    - Follow-up contact
    - Confirm agreements with records, publication

Background Rationale to Design Propositions

- *Feedstock*

1. <u>Avoid the use of food crops or ensure and assure relevant parties that food security is unaffected or promoted by synergies with the project.</u> Food crops for biofuels are a sensitive issue mainly in relation to food prices (Rosegrant and Msangi 2014). Although some studies point out that in Brazil sugarcane ethanol expansion did not have negative food security impacts, and actually state possible social development benefits of biobased production (Kline et al. 2016; Koizumi 2015), respondents still identified this issue as problematic in the terms of acceptability. This proposition suggests that food crops should either be avoided for biojet fuel production given the importance of acceptability by industry and public actors, as spoken by the respondents, or that they should be used with a synergistic benefit for food security according to the local context in line with Kline et al. (2016).

2. <u>Traditional or proven crops are preferred.</u> The selection of well-known crops is for the sake of giving investment security to the producers; to make it easier for them to invest and produce feedstock for a biorefinery, and make biojet fuel available for current and future generations. This proposition relates to respondents observations that producers perceive risk with non-traditional crops for which they have no experience. This risk perception means that producers will be reluctant to adopt new crops, technologies and production systems that have not been proven to them.

3. Feedstock types that can provide continuous and profitable revenue to family farmers are preferred. The raw material for biojet fuel is the product of agro-producers, and a main product for family farmers if they are to be included in the BRP. Given that family farmers often depend on their produce for their livelihood, certain crops may be not suitable for their livelihoods. That is, investing on crops and cropping systems that start giving revenue after several years, or for which margins are low per hectare, may not be feasible for family farmers without other support, and may thus not be adopted by them (see for example (Leite et al. 2015)). Thus, this proposition is for the sake of giving opportunities to family farmers, as a distributive justice that considers the difference of people in more vulnerable positions.

4. Feedstock from robust agronomic systems (e.g. low fertilizer input, that maintain or recover soil carbon, and that minimize erosion and pest risks) is preferred. Respondents identified monocultures (systems where the same plant is produced extensively in area and time) as risks to nature and to their investments. That is, respondents spoke of monocultures as detrimental to soil quality due to erosion and nutrient depletion, which besides negative environmental impacts, are unfavorable for their investments in the long term. Also, monocultures were spoken as increasing the risks for pests and diseases. According to respondents in government, industry, and academia, new crops in monoculture systems are particularly perceived as risky, given the lack of knowledge and management strategies for dealing with pests problems. Crop rotation, integrated systems and agroecology were promoted by some respondents as promising alternatives in the Brazilian context (see also Altieri et al. (2012) and Chaddad (2016) for academic discussions, and Martinez and Maier (2014) in the biorefinery context). Therefore, we propose the use of feedstock from these systems for further consideration as alternative to conventional monocultures, for the sake of investment security and care for nature.

5. Biomass from currently unproductive areas or produced in coordination with the agriculture and livestock producers are favored. For the sake of aproveitamento, efficient land use, and at the same time, nature protection, biomass feedstock are preferred when sourced from land that has been liberated from efficiency gains, or through integration with other production systems. However, there should be coordination with agriculture and livestock producers and associations to ensure that there is really no subsequent land expansion, e.g. that their activities are not displaced to other areas. Alternatively, biomass production suitable for marginal lands that show low yields with conventional crops, are considered favorable in terms of land recovery, aproveitameto, efficiency and nature protection by avoiding land use changes.

- *Products*

6. Drop-in products are preferable. In the case of biojet fuel, respondents spoke about acceptability issues related to engine adaptations, safety perception, regulations and other “cultural barriers”. For this reason, it is proposed to target the production of drop-in biofuels to minimize the need for engine modifications or long-testing for regulations, which affect the acceptability of the biojet fuel products.

7. Energy products from distributed processing units are desirable. Energy import dependence and power generation unreliability was outspoken by government respondents. This issues are echoed in academic and public media, pointing out that despite being an important producer, Brazil is a net energy importer due to the low refining capacity for its heavy crude resources, and the rising demand for energy in the country (Almeida Prado Jr. et al. 2016; U.S. Energy Information Administration (EIA) 2015; World Bank 2016). Also, overreliance on renewable hydropower has been discussed as problematic due to hydric crises (Almeida Prado Jr. et al. 2016; Caroline Stauffer 2016; Joe Leahy 2015; Nobre et al. 2016; Volpi et al. 2006), and further expansion remains questionable for some (Almeida Prado Jr. et al. 2016). Thus, by having energy by-products from processing units part of a BRP, energy availability and reliability through decentralization from large scale hydropower plants can be benefited.

- *Technology and process*

8. The BRP should be flexible to process various feedstocks, and produce alternative products to reduce vulnerability to market and biomass availability problems. These values relate to intergenerational justice by promoting a long-lasting biojet fuel business, and for care for nature by ensuring a year-long biojet fuel availability from the same resources. This proposition in particular relates to of maximizing the use of infrastructure throughout the year, reducing risk of production halt due to feedstock availability problems, and reducing investment risks related to the product and market uncertainties, which have all been topics brought up by various respondents, and have been addressed in the biorefinery literature (see, for example, Mansoornejad et al. (2011) and Martinez and Maier (2014)).

9. Innovative technology and designs are preferred. This proposition is for the sake of ensuring the durability of the BRF project by seeking a competitive advantage through innovative technology to the project owners. That is, through innovation, productivity can be increased, but also more valued can be added to the biomass raw materials. This is particularly relevant given the market characteristics of fuels, with high volume demand but low value.

10. The project should be, at least, energy self-sufficient. This self-sufficiency for the BRP is for the sake of energy security of the mill or processor. Also, if extra energy is supplied to the grid, the BRP can contribute to the national or regional energy security by participating in a decentralized, and more reliable, energy production. Also, self-sufficiency is seen as a positive characteristic by some of the respondents, pointing out that the use of non-renewable resources is minimized.

11. Aproveitamento for energy and material resources: use, reuse, recycle, and valorize as much as possible while minimizing emissions. Aproveitamento, efficiency and circularity have been discussed in relationship to sustainability, as contributing to the sustenance of resources and reduction of emissions that contribute to climate change, as care for nature. Also, these values have also been discussed as beneficial for profitability by keeping variable costs low by reducing the need for purchasing external materials. For example, vinasse is an processing residue that could be *aproveitado* for nutrients and energy, while minimizing emissions. Second generation production from residues and use of marginal, sloppy or liberated land from pastures are possible efficient uses of available resources. In the literature, this and other alternatives have been studied for different contexts of biomass use, and some propose biomass cascading as an efficient, environmental and socially desirable strategy for biomass use (Ghisellini et al. 2016; Liguori and Faraco 2016).

12. Technologies that are locally owned/produced (e.g. in Brazil o countries in the region) by alternative actors are preferable. The preference for these technologies is for the sake of giving fair opportunities for everyone, while acknowledging differences in the technology development sector, in which large and foreign companies predominate leaving no space for small and medium enterprises. Furthermore, the use of locally developed or produced technologies means that they can be better suited for the local context than imported ones. This suitability issues with technology was brought forward by industry and government respondents, pointing out that they are forced to double invest, first on importing a technology and then on adapting it to their system (or even adapting their system to it). Furthermore, by developing and acquiring technology, or "producing in rather than extracting wealth" (Dijk et al. 2012) from these smaller players, the BRP actively engages in strengthening and giving opportunities to these smaller actors.

- *Supply Chain*

13. The BRP should process locally, based on short transportation distances. Transportation distance is one of the commonly studied aspects of biorefinery design (see, for instance, Searcy and Flynn (2009), and Wright and Brown (2007)). Given that biomass has low density as compared to other materials, transportation distances are the obvious counter-force to economies of scale when looking at production cost and profitability. Additionally, short transportation distances are desirable for the sake of minimizing GHG emissions, which together with transportation cost, was a recurrent topic brought up by the respondents.

14. Availability or lack of infrastructure and land should be taken into account when designing. This proposition relates to the availability of infrastructure for logistics, as railways, roads and waterways, which have an impact on the profitability and practicality of the BRP, and GHG emissions. For instance, some of the respondents identified a lack of infrastructure for mobilizing biomass and products, and should be thus taken into account. Also, in some cases, abandoned or underutilized infrastructure, as old refineries, were identified by some respondents as promising starting points for BRPs. In this case, a revamp of existing facilities might prove beneficial for the biorefinery business case, while making use of already available processing infrastructure. Importantly, all production routes for biojet fuel end up with a fuel upgrading step to bring it to satisfactory qualities for flight. Fossil based refining facilities have similar processes, and therefore the revamping of such facilities for biojet fuel production might save considerable capital.

15. Back-up biomass source close to the BRP region is desirable. Although some forms of biomass are being traded (see, for instance, Goh et al. (2014) on biomass trade to the Netherlands) biomass is not perceived as a real commodity available upon request by some respondents. That means that if there are problems in the production of a given crop, it is not certain that there will be availability of another crop of similar characteristics in the same region or at a similar price. Therefore, for the sake of investment security it is desirable that back-up biomass sources are available in close-by markets.

- *Business case*

16. The BRP should create jobs and opportunities for everyone, particularly for those regions and people who need it most (9). The opening of opportunities for the Brazilian region, and for population groups in most need, was one of the most referred benefits of BRPs by the respondents. Therefore, as part of the business case, the distribution of opportunities and benefits of BRP developments should take into account the most vulnerable, while bringing business and development opportunities for local communities. Some authors address this fair distribution in value chains as part of sustainable business creation, achieved through partnering of smaller local enterprises with larger international companies, and the empowerment of local producers through transfer of skills, technology and quality, amongst others (Dijk et al. 2012). These and other sustainable business approaches for fair distribution of opportunities and benefits should be further researched for the BRP development.

17. A pricing policy and other mechanisms that ensure fair value sharing along the chain is desirable. Pricing policies or other mechanisms for fair distribution of rewards to all actors involved in the production chain of BRP are proposed for the sake of distributive justice in BRPs. This is particularly relevant given that value creating processes are often downstream of the agricultural process, often at industrial chain stages run by foreign actors with higher power and investment capacity (Clancy 2013; Dijk et al. 2012). That means that small agro producers have the lowest margin, which is regarded as unfair by respondents because it is them who are in most need, or because their work is not rewarded as it deserts. Therefore, we suggest that mechanisms for value sharing, like CONSECANA or contracts between processors and agro producers that consider the needs of the agro producers, should be pursued during the development of BRPs.

18. The BRP development and implementation should be done gradually, and be open to participation by various stakeholders. The BRP should be developed with time to engage different actors and integrate learning into the project, improving productivity and profitability. Implementation should also be done in a step-by-step manner to distribute capital expenditures in several years and integrate learning while minimizing risks. Also, this proposition relates to the cooperation value brought forward by different stakeholders as instrumental for a successful BRP. Therefore, cooperation for developing a suitable business case for the whole biorefinery project, considering all relevant actors for strategic decision making is proposed. This cooperation is particularly relevant for biojet fuel production, given the strict regulations and infrastructure implications related to distribution, blending and certification of jet fuels.

19. The BRP should be price competitive with alternatives in the market. Although this might be considered an obvious requirement, given the prominence of competitiveness and profitability spoke by respondents, we bring it forward in this proposition. Mostly, respondents addressed price competition with fossil resources and related products. This competition is not only affected by market prices, but also by corporate policies with the semi-public Petrobras oil company and taxes related to different governmental levels in Brazil, and they should always be evaluated when developing a business case in Brazil. Also, respondents spoke of competition with high value vegetable oils that make some oil-based biofuel production unfeasible; i.e. when vegetable oil raw materials for a biorefinery are equally or more valued than the fuel product itself. Furthermore, respondents in some occasions spoke about feasibility and competition regarding land. This relates to the highly saturated and competitive market in Sao Paulo state and the perceived productive land potential from extractivism and land liberation in both states. Clearly, both the competition and the extractivism situation are relevant for the sake of the feasibility of the BRP, and in the second case, it is closely related to the management of natural resources in protected areas.

20. BRP business cases should only consider stable beneficial government policies with adequate risk assessments. Governmental uncertainty was spoken by various respondents while describing government policies and projects being suddenly stopped or changed for political reasons. This uncertainty phenomenon in the Brazilian political context was discussed as severely detrimental for project development and deployment. Therefore, for the sake of investment security, we propose that the BRP should not rely on government policies unless they are secured for the long term. Furthermore, governmental policies and risks should be adequately assessed. In this way, BRPs can still benefit from favorable, stable policies at all levels of government while minimizing vulnerability to political changes.

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Appendix III

Pre- and post-interview guide

This interview guide was used for the interviews at the beginning and at the end of the design project (see Table 1, discussed in section 3.2 in the main text).

About the project

1. Please tell me more about your project. What are the project goals?
2. Could you tell me about the origin of this thesis/competition project, where does it fit with the institution that organizes it?
3. Is this project part of another project? How is the larger project/competition funded? Is there cooperation with other universities, industry?
4. Are there any specific sustainability goals linked to your project?

Scientific/technical significance

5. What are currently the most important scientific/technical challenges of your project?
6. How does the project contribute to progress in your field of science and engineering?

Project Progress

7. How is the research reviewed during the research process? Who is involved?
8. Regarding decisions on research progress: who decides the direction of research? Subsequent steps? What is your role in this process?
9. What kinds of considerations play a role in these progress decisions?
10. What are the criteria for determining the success of your specific project?

Expertise and roles

11. What is your background? What is the background of others in the development of this project?
12. Do you think there should be more people with different expertise, which and why?

Project stakeholders and their values

13. When (in time) do you expect your research to offer a concrete industrial application?
14. Who will have a role and be affected by this research/design project and its industrial application?
15. What do you think is important for them with this project, what do they/could they value from your project? Nature, society & the economy, the future?

The designer's view on this project and sustainability.

16. Do you think "biobased R&D" benefits sustainability? Nature, society & the economy, future generations? How?
17. Do you think "biobased R&D" should benefit them? (Nature, society, future generations?)
18. Do you think this project benefits, or will contribute to benefit them? (Nature, society, future generations?)
19. Do you consider there is any specific challenge for your work/research with this project?

The designer perspective with sustainability in technical design

20. How have you been confronted in your work with sustainability aspects during the past 12 months, prior to this project?
    a. If yes, could you elaborate on the role of these aspects in your daily work?
    b. If not, what is your motivation for choosing this project over others? / participating on the competition?
21. Does your own personal opinion on sustainability issues play in determining the future direction of your work/research? How?
22. Would it be ''good'' for the quality of "bio-based" R&D to increase attention on sustainability issues, implications? How?
23. Do you think it would be beneficial for society if "bio-based" R&D would take into account sustainability issues? How?

Expectations

24. What are your expectations for the next months with this project and these sessions? What do you expect from my participation?
25. Do you consider these sessions part of your project, necessary, or as something extra to your work?
26. Do you have any further questions, or are there issues that have not been addressed?

Design Space Workshops

As supplementary material from the design space workshops, we include two photographs of the white boards used during the first and third workshops (Figure A3.1 and A3.2 respectively). These board images contain some of the topics discussed during these sessions and how they were being discussed at the moment: Figure SI-1 is related to the production chain and life cycle of bioplastics, and different stakeholders involved; Figure SI-2 lists some of the sustainability aspects identified from the different investigations about, and with, the identified stakeholders.

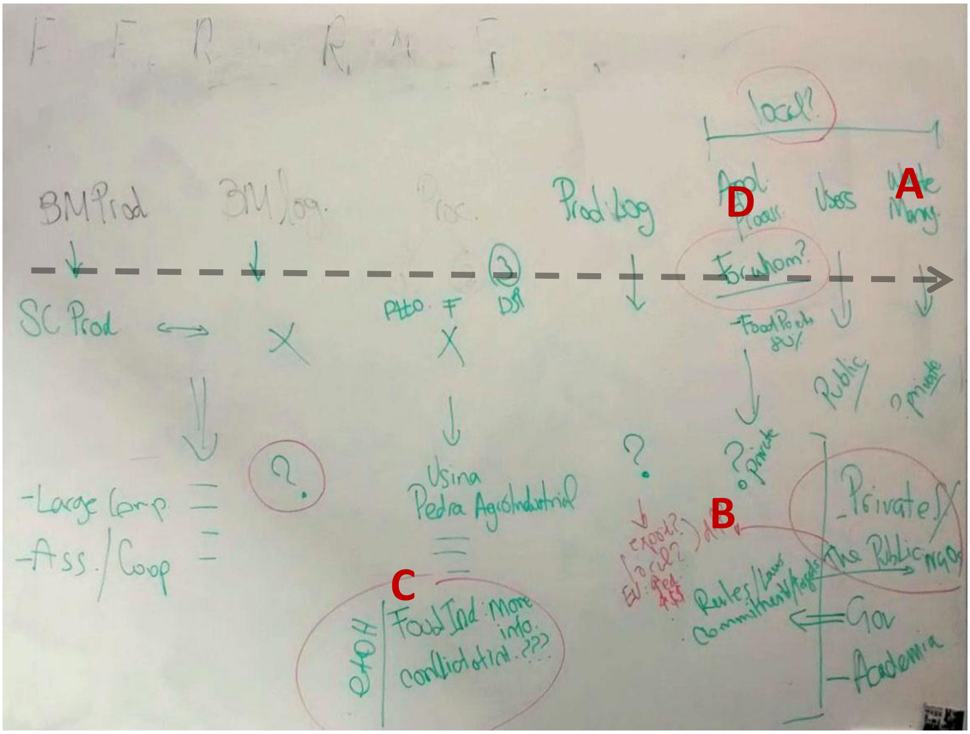

Figure A3.1. Photo of the board during the first workshop (intervention 3). Words above the dashed line (drawn on the photograph) indicate the generic production and life cycle stages of bioplastics, below it are different points discussed in relation to these stages. Letters A through D indicate these discussion points. A: extra activities in the production chain added by the team and related to the end-product application, product use, and waste management; B: location of users; C: role of biomass producers, and ethanol industries; D: application alternatives, prominently food packaging.

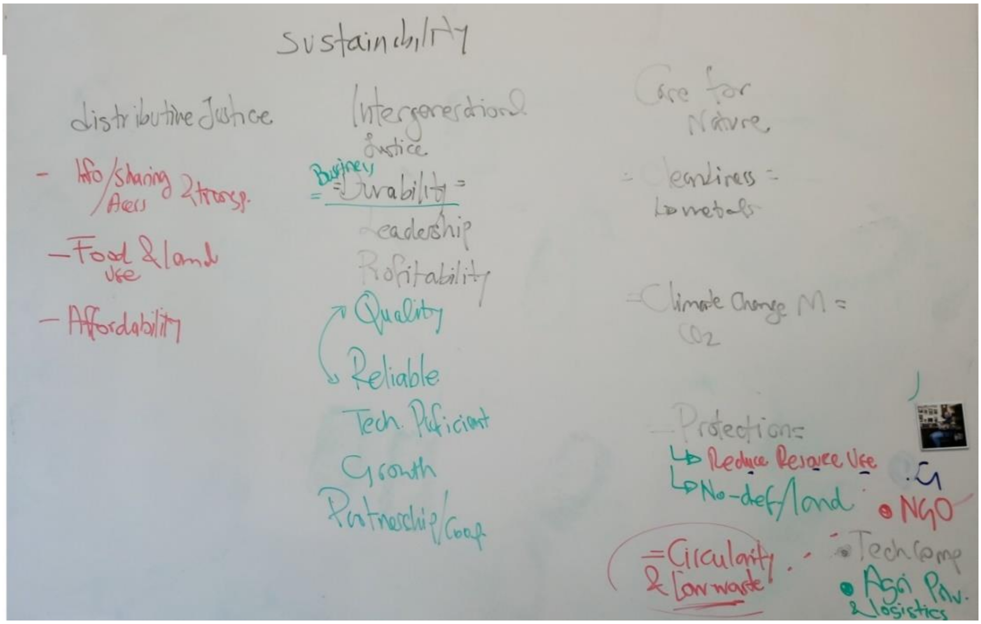

Figure A3.2. Photo of the board during the third workshop (intervention 5). In the bottom right corner are the stakeholder groups that were part of the discussion at that point: government (G), non-governmental organizations (NGO), technology companies (Tech Comp), and agricultural producers and biomass transportation stakeholders (Agri. Prdu. & logistics).

Identified decision making processes

Table 3.1. Summary of the different decision making processes identified along the development of the project with respect to the project variables: feedstock, products, process and business model.

Modulation	Alternatives and decisions	Values
<u>**Feedstock**</u> - ***Sucrose input***		
De facto	Sugarcane juice	Designing feasibility
Reflective	The whole sugarcane can be processed and bagasse could be used in the process	Achievement, designing feasibility, entrepreneurship, food security, resource efficiency, process simplicity
Deliberate	Model the process parts for processing the whole crop as black boxes and add to the main conversion process	
Final decision	Idem	

Products - ***Bagasse use and PHB form***		
De facto	Bagasse as feedstock for energy production	Achievement, process simplicity, resource efficiency, technical feasibility
	Pure BBP	Scientific focus
Reflective	Bagasse as 2G feedstock	Achievement, entrepreneurship, food security, resource efficiency
	Co-polymers as main product	Achievement, entrepreneurship, product quality, resource efficiency
Deliberate	Investigate alternative uses for bagasse: 2G BBP production	Achievement, entrepreneurship, food security, product quality, resource efficiency
	Investigate co-polymer compound alternatives and their production	
Final decision	Model energy generation from bagasse and the production of pure BBP granules. The sustainability team suggested to include in the business plan a proposal to invest in researching 2G and wastewater BBP production	All of the above
Process - ***Downstream Processing***		
De facto	The use of solvents for PHB recovery is not desirable	Environmental safety
Reflective	There are other chemical, mechanical and enzymatic alternatives but they all carry disadvantage. The most common alternative is, however, based on solvents	Designing feasibility, entrepreneurship, environmental safety, product quality, technical feasibility
Deliberate	Model the process with an uncommon alternative that has low environmental impact. Use assumptions to cover missing data and estimate economic performance	
Final decision	Idem.	
De facto	Stand-alone plant that buys the sucrose feedstock	
Process – ***Integration***		
Reflective	The production of PHB can be integrated to an existing sugarcane mill. It would imply diverting some of the sugarcane juice for PHB production. In this way, streams can be integrated to recover energy/materials	Cooperation, entrepreneurship, resource efficiency
Deliberate	Model and compare the production process as integrated (with sugar and ethanol production as black boxes) with as an independent process	Achievement, cooperation, entrepreneurship, resource efficiency, designing feasibility, process simplicity
Final decision	Idem.	

<u>Business Plan</u> - *Business model*		
De facto	The model has to be able to accommodate the integration of their process to an existing sugarcane mill, and a partnership with an existing sugarcane mill was the group's initial idea for supporting this	Achievement, cooperation, entrepreneurship, resource efficiency
Reflective	The integrated process can be supported by other business models: BBP production as part of the same sugarcane company (merge model), or by licensing their patented technology to the mill companies (licensing model)	Cooperation, entrepreneurship, resource efficiency, leadership
	If the business is integrated, there is the possibility to vary the production of any of the products as desired	Entrepreneurship
	A licensing model implies confidentiality until a patent application is made	Scientific openness
	A licensing model can be combined with a biodegradation step	Biodegradation
	The merge model means losing ownership of the project	Ownership
Deliberate	Discard the licensing alternative and investigate further about the stand alone and partnership business models	Entrepreneurship, scientific openness
Final decision	Partnership model for the business	All of the above
<u>Business Plan</u> - *Target clients*		
De facto	Clients are based on application and location.	Entrepreneurship
Reflective	The end user can have a prominent position to make sure the material gets degraded	Biodegradation
	Biodegradability does not mean biodegradation	Biodegradation
	There is a need for information about the biodegradability of the final product	Biodegradation
	Clients that cannot or do not recycle plastic are potential clients for biodegradable plastics, others might just be as interested	Biodegradation, environmental safety
	By targeting such clients the mixing of recyclable plastics with biodegradable plastics can be avoided	Biodegradation, environmental safety, renewability
	Targeting a limited amount of clients can limit the business	Entrepreneurship.
Deliberate	Focus on clients that are interested or that could make sure the material is biodegraded	Biodegradation
Final decision	The business plan is focused on possible clients that can process the bioplastic	Biodegradation

Appendix IV

Supplementary information for the economic evaluation of alternatives

Table A4.1. Economic Potential (US$/kg feedstock) of various production chain alternatives, depending on feedstock type and by-product based on the results in Ref.1. Ranges express the minimum and maximum economic potential obtained considering the conversion yields with different technology alternatives.

HVC	Macauba		Jatropha		Camelina		Soybean		Sugarcane		Sweet sorghum	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
SA	0.19	0.29	-0.04	0.03	0.15	0.32	0.11	0.28	0.23	0.39	0.21	0.38
ET	0.06	0.15	-0.12	-0.06	0.03	0.20	0.00	0.16	0.06	0.24	0.06	0.23
EtOH	0.00	0.09	-0.16	-0.10	-0.03	0.15	-0.05	0.11	0.00	0.17	0.00	0.16
LA	0.13	0.22	-0.08	-0.02	0.09	0.26	0.06	0.22	0.14	0.32	0.14	0.30
1-BUT	0.02	0.12	-0.14	-0.08	0.00	0.17	-0.03	0.14	0.02	0.20	0.02	0.19
IsoPRO	0.00	0.09	-0.16	-0.10	0.00	0.17	-0.06	0.11	0.00	0.17	0.00	0.16
3-HPA	0.05	0.14	-0.13	-0.07	0.02	0.19	-0.01	0.15	0.05	0.23	0.05	0.22
2,5-FDCA	0.04	0.13	-0.14	-0.07	0.01	0.18	-0.02	0.15	0.04	0.21	0.04	0.20
1,3-PDO	0.06	0.15	-0.12	-0.06	0.03	0.20	0.00	0.17	0.07	0.24	0.06	0.23
1,4-BDO	0.05	0.14	-0.13	-0.06	0.02	0.19	-0.01	0.16	0.05	0.23	0.05	0.22

HVC	Sugarcane residues		Sweet sorghum residues		Eucalyptus residues		Pine residues		Coffee residues		Rice residues	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
SA	0.21	0.37	0.18	0.32	0.21	0.34	0.18	0.31	0.19	0.33	0.19	0.33
ET	0.08	0.23	0.04	0.19	0.08	0.22	0.06	0.19	0.06	0.20	0.06	0.20
EtOH	0.02	0.17	-0.01	0.13	0.03	0.16	0.01	0.14	0.00	0.14	0.01	0.15
LA	0.15	0.30	0.11	0.25	0.15	0.28	0.12	0.25	0.13	0.27	0.13	0.27
I-BUT	0.04	0.19	0.01	0.15	0.05	0.19	0.03	0.16	0.02	0.16	0.03	0.17
IsoPRO	0.01	0.17	-0.01	0.13	0.03	0.16	0.00	0.13	0.00	0.14	0.01	0.14
3-HPA	0.06	0.22	0.03	0.18	0.07	0.21	0.05	0.18	0.05	0.19	0.05	0.19
2,5-FDCA	0.05	0.21	0.02	0.17	0.07	0.20	0.04	0.17	0.04	0.18	0.04	0.18
1,3-PDO	0.08	0.23	0.05	0.19	0.09	0.22	0.06	0.19	0.06	0.20	0.07	0.20
1,4-BDO	0.07	0.30	0.04	0.25	0.08	0.28	0.05	0.25	0.05	0.26	0.06	0.26

1-BUT: 1-butanol; **1,3-PDO**: 1,3 propanediol; **1,4 BDO**: 1,4-butanediol; **2,5-FDCA**: ET: ethylene; **3-HPA**: 3-hydroxypropionic acid; **HVC**: High-value chemical; **EtOH**: ethanol; **IsoPRO**: Isopropanol; **LA**: lactic acid; **SA**: succinic acid

Table A4.2. List of prices used for the techno-economic estimations, adapted from Ref.2, with prices updated to 2015, in US$/ton, and based on the Brazil market, considering crude oil barrel price 64 US$/bbl.

Compound	Price (US $.ton^{-1})	Specifications[a]	Reference
Sugarcane	22.3		[3]
Transportation of sugarcane	6.2	10 km with 40 ton truck, bundles density – 400 kg.m^{-3}	[4]
Sugarcane trash	16.9		
Transportation of sugarcane trash	9.8	10 km with 40 ton truck, bundles density – 175 kg.m^{-3}	[4]
Sweet sorghum	27.0		[1]
Transportation of sweet sorghum	10.4	22 km 40 ton truck, bundles density – 350 kg.m^{-3}	[4]
Sweet sorghum grains	78.4		[5]
LPG	234.8	Prices of May, 2015	[6]
Naphtha	598.1		
Jet fuel	605.2		
Transportation of jet fuel – Sao Paulo	14.8	150 km with train	[4]
Transportation of jet fuel – Rio de Janeiro	26.6	570 km with train	[4]
Diesel		Price of May, 2015	[6]
Acetic acid	672.6		[7]
Furfural	957.5		[8]
S sulfur	151.1		[9]
Lignin [b]	400		estimated[2]
Sugarcane juice [c]	631.8		estimated[2]
Transportation of juice (65°Brix)	6.5	20 km with 35 ton tank-truck	[4]
Enzyme for biomass hydrolysis	156.6	Price per ton of ethanol	[10]
Cooling water	0.1		[11]
Chilled water	0.5		[12]
Natural gas	104.7	LHV of CH_4 considered 40.7 MJ.kg^{-1}	[13]
Process water	0.25		estimated[2]
Solids disposal in landfill	0.84		[14]
Operators salary	10.9	US$/h	[15]

Catalysts	Price (US $.ton^{-1})	WSHV (h^{-1}) w/w	Life-time (years)	Type	Reference
Ethanol dehydration	411905	5 [16]	3	[17]	[18]
Ethylene condensation and oligomerization	252934	2	5	[17]	[18]
Olefins hydrogenation	245723	3	5	[17]	[18]
Farnesene hydrocracking	39354	2	5 [19]	[20]	[19]
PSA packing	5079	0.685	3	[14]	[14]

Hydrotreating catalyst	39354	1st- 1.5; 2nd- 0.5	2	[21]	[22]
H2 SMR	38084	1.4	3	[14]	[14]
Water gas shift	20315	0.07	3	[23]	[14]
Fischer-Tropsch	15760	2.22	3	[23]	[23]

[a] Distances are estimated once location of plant is established in Campinas, Sao Paulo. Feedstock transportation distance is estimated with land productivity and average feedstock annual capacity of all scenarios. Transportation method and cost methodology follows from Ref.[4].

[b] maximum selling price of lignin, considering that it will be sold for a polyurethane manufacturer with a project payback time of 10 years, IRR at 12% and polyurethanes sold at market price

[c] maximum selling price of juice, considering that it will be sold to a succinic acid (SA) manufacturer with an annual capacity of 42.3 kton SA.yr^{-1},with a project payback time of 10 years, IRR at 12% and succinic acid sold at 2356 US$.ton^{-1}. Process yields, OPEX and CAPEX methodology follow from *Efe et al.*, [24].

Table A4.3. Minimum Selling Price (MSP) estimations from the preliminary techno-economic analyses of Ref.2

Main conversion	PTT	Lignin fate	MSP (US$/t)	Main conversion	PTT	Lignin fate	MSP (US$/t)
Sugarcane							
ETJ	DA	FP	3410	ETJ	O-GAC	GFT	4343
ETJ	DA	GFT	3796	ETJ	O-GAC	co-gen	4135
ETJ	DA	co-gen	3577	DFJ	O-GAC	FP	8467
DFJ	DA	FP	7013	DFJ	O-GAC	GFT	9220
DFJ	DA	GFT	7864	DFJ	O-GAC	co-gen	9134
DFJ	DA	co-gen	7603	ETJ	WO	FP	3623
ETJ	DA-A	FP	3829	ETJ	WO	GFT	3772
ETJ	DA-A	GFT	4021	ETJ	WO	co-gen	3587
ETJ	DA-A	co-gen	3769	DFJ	WO	FP	7112
DFJ	DA-A	FP	7870	DFJ	WO	GFT	7602
DFJ	DA-A	GFT	8567	DFJ	WO	co-gen	7691
DFJ	DA-A	co-gen	8037	ETJ	LHW	FP	3583
ETJ	SE	FP	3435	ETJ	LHW	GFT	3909
ETJ	SE	GFT	3739	ETJ	LHW	co-gen	3607
ETJ	SE	co-gen	3409	DFJ	LHW	FP	7016
DFJ	SE	FP	6718	DFJ	LHW	GFT	8036
DFJ	SE	GFT	7666	DFJ	LHW	co-gen	7608
DFJ	SE	co-gen	7197	ETJ	LHW-A	FP	3874
ETJ	SE-A	FP	3737	ETJ	LHW-A	GFT	4091
ETJ	SE-A	GFT	3935	ETJ	LHW-A	co-gen	3815
ETJ	SE-A	co-gen	3675	DFJ	LHW-A	FP	8004
DFJ	SE-A	FP	7714	DFJ	LHW-A	GFT	8561
DFJ	SE-A	GFT	8375	DFJ	LHW-A	co-gen	8212
DFJ	SE-A	co-gen	7871	ETJ	none	FP-bag	2393
ETJ	O-GAC	FP	4164				

Main conversion	PTT	Sugar destinatio n	Lignin fate	MSP (US$/t)
Eucalyptus				
HTL	N/A	N/A	N/A	617
FP	N/A	N/A	N/A	726
FP	DA	HVC	Co-gen	1143
HTL	DAP	HVC	Co-gen	1059
HTL	SE	HVC	Co-gen	992
HTL	O	HVC	Co-gen	1089
N/A	DA	DF	GFT	4507
N/A	DA	ETJ	GFT	4659
N/A	DA	DF	FP	3527
N/A	DA	ETJ	FP	3745
N/A	SE	DF	GFT	3848
N/A	SE	ETJ	GFT	4005
N/A	SE	DF	FP	3025
N/A	SE	ETJ	FP	3509
N/A	O	DF	GFT	5766
N/A	O	ETJ	GFT	5893
N/A	O	DF	FP	5028
N/A	O	ETJ	FP	4864
Coffee residues				
HTL	N/A	N/A	N/A	1664
HTL	DA	HVC	Co-gen	2039
HTL	O	HVC	Co-gen	2178
Macauba, HEFA +				
GFT	N/A	N/A	N/A	1367
FP	N/A	N/A	N/A	496
HTL	N/A	N/A	N/A	315
N/A	O	DF	Co-gen	883
N/A	O	ETJ	Co-gen	1234

Co-gen: Heat and power co-generation; **DA**: Dilute acid; **DA-A:** Dilute acid plus alkaline treatment; **DF**: Direct fermentation; ***ETJ**: Ethanol to Jet; **Eu**: Eucalyptus; **FP**: Fast pyrolysis; **GFT**: Gasification Fischer-Tropsch; **HEFA**: Hydro-processed esters and fatty acids; **HTL**: Hydrothermal liquefaction; **Ma**: Macauba; N/A: not-applicable;* **PTT**: pretreatment; **SE**: steam explosion; **SE-A**: steam explosion with alkaline treatment; ***SC**: Sugarcane.*

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List of Publications

Journal Articles

- Palmeros Parada, M., Asveld, L., Osseweijer, P., and Posada Duque, J.A. (2018). Setting the Design Space of Biorefineries through Sustainability Values, a Practical Approach. *Biofuels, Bioproducts and Biorefining* 12, no. 1: 29–44.
- Palmeros Parada, M., Osseweijer, P., and Posada Duque, J.A. (2017). Sustainable Biorefineries, an Analysis of Practices for Incorporating Sustainability in Biorefinery Design. *Industrial Crops and Products* 106: 105–23.
- Palmeros Parada, M., Asveld, L., Osseweijer, P., Posada, J.A. (*submitted*) Integrating value considerations in the decision making for the design of biorefineries.
- Palmeros Parada, M., van der Putten, W.H., van der Wielen L.A.M., Osseweijer, P., van Loosdrecht, M., Pashaei Kamali, F., Posada, J.A. (*submitted*) Sustainability tensions and opportunities for biojet fuel production in Brazil.

Oral Presentations

- Palmeros Parada, M. (2019). Sustainability in the design of biorefineries, empirical explorations with Value Sensitive Design. Netherlands Biotechnology Conference, 22 May, Ede, the Netherlands.
- Palmeros Parada, M. (2018). Aligning responsible research and innovation with conceptual design in the biotechnology industry. UK Synthetic Biology Social Sciences/Humanities Satellite Event, 19 November, Bristol, United Kingdom.
- Palmeros Parada, M., Asveld, L., Osseweijer, P., and Posada Duque, J.A. (2018). Towards sustainable biorefineries, empirical explorations with value sensitive design. 4-CIAB: Iberoamerican Congress on Biorefineries, 24 – 26 October, Jaen, Spain.
- Palmeros Parada, M., Asveld, L., Osseweijer, P., and Posada Duque, J.A. (2018). Biorefinery design for sustainability, an early stage responsible innovation activity. 10th Annual Meeting of the Society for the Study of New and Emerging Technologies (S.NET), 25 – 27 June, Maastricht, the Netherlands.
- Palmeros Parada, M., Asveld, L., Osseweijer, P., and Posada Duque, J.A. (2017). An Approach for Incorporating Sustainability in Early Stages of Biorefinery Design. 25th European Biomass Conference and Exhibition, 12-15 June, Stockholm, Sweden.

Curriulum vitae

María del Mar Palmeros Parada was born on the 19th of January, 1985 in Veracruz, Mexico. In 2003 she completed her high school diploma with a clinic laboratory specialization at the CBTis 78 in Poza Rica (Mexico), having coursed the 11th year as an exchange student at the Kecoughtan High School in Hampton (U.S.A.). In 2007 she received her Engineering Degree on Biotechnology Engineering from the Instituto Politécnico Nacional in Mexico City. After a brief period of teaching English in her hometown, she decided to start a master programme on Biotechnology at Lund University (Sweden). In 2010 she received her master's degree having completed her thesis and an internship on biogas production from solid industrial residues.

In 2011 she started a Professional Doctorate in BioProcess Engineering at Delft University of Technology in the Netherlands. As part of this programme, she worked on the design of biorefineries for the production of intermediate chemicals from palm oil solid residues in Malaysia. In 2013 she joined Photanol B.V. as a BioProcess Development Engineer, where she developed techno-economic models and evaluated Photanol technology for different applications. In 2014 she joined the Biotechnology and Society Group in the Department of Biotechnology of the Delft University of Technology as a PhD student with Prof. dr. P. Osseweijer as promotor. Since then, she has worked on the research presented in this thesis.

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