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DEVELOPMENT OF A DECISION SUPPORT SYSTEM FOR COMPANIES IN THE ENERGY FROM BIOMASS AREA, APPLYING CIRCULAR ECONOMY PRINCIPLES WITH A LIFE CYCLE THINKING APPROACH

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PREFACE

The work described in this thesis has been conducted mainly at the Department of Engineering at the University of Palermo, partly at Eni s.p.a. Renewable Energy, Magnetic Fusion and Material Science Research Center (DE-R&D) (Novara, Italy), and partly at the Fundación IMDEA Energía, Madrid (Spain).

The project has been entirely financed by the Italian Ministry of Education, University and Research through the National Operational Program (PON) of the Ministry of Education, University and Research, entitled "For the School - skills and environments for learning", financed by the European Structural Funds contains the strategic priorities of the education sector and has a seven-year duration, from 2014 to 2020", dedicated to the universities located in Italian regions whose development is lagging. My thesis has been supervised by Professor Maurizio Cellura, an ordinary professor Expert in building physics and building energy systems and supported by Professor Sonia Longo, an associate professor expert in Life Cycle Assessment of energy systems and circular economy.

During my PhD project, I developed a new methodology framework for a decision support system aimed at identifying the best sustainability and circularity alternative for companies in the biomass supply chain according to different criteria through a life cycle thinking (LCT) approach. In more detail, I integrated the LCT approach and Multiple-criteria decision-making (MCDM) methods to identify the level of sustainability and circularity of the biomass supply chain. New software is also created as a variable tool of decision support systems (DSS) for companies.

This PhD research project aims to provide the scientific and technical international communities with a comprehensive methodology framework for DSS, as well as a flexible and helpful DSS tool for assessing and selecting the best sustainability and circularity alternative of the supply chain. The work consists of three main parts:

- background, review of the existing literature.
- presentation of sustainability and circularity indicator, the methodology framework of DSS and creation of DSS tool software.
- case studies on the application DSS tool for the biomass supply chain.

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I would like to thank PhD. Alessandra Bertoli, Prof. Enrico Benetto at ENI (Italy), Prof. Javier Dufour at IMDEA (Spain), and other colleagues at ENI and IMDEA for their support during my internship periods in the northern part of Italy and Spain. In these internships, I have been supported to learn about biomass supply chains, biomass process technologies, and chemical processes in biomass treatment and conversion. Activities for improving sustainability and circularity have also been analysed and discussed with tutors.

I am also thankful for the suggestions from the PhD. Tran Thi Tu Quynh on my scholarship application. I also thank my family and my friends for the support and encouragement they provided me throughout my entire life as well as during this up-and-down PhD period.

ABSTRACT

The biomass supply chain (BSC) for energy production has emerged as a promising alternative to traditional fossil fuels, playing a crucial role in mitigating climate change and promoting sustainable development. Biomass utilisation offers numerous environmental, economic, and social benefits, including reduced greenhouse gas (GHG) emissions, enhanced energy security, and job creation in rural areas, which are known as important aspects of sustainable development. Moreover, the use of waste, by-products, and residue in BSC is essential to improving the circular economy (CE) in agriculture, wood, and paper processing industries, as well as waste treatment and management. Therefore, to further harness the potential of biomass energy production in sustainability and transition to the CE context, it is significant for companies in the BSC to apply circular business models (CBM).

While the role of biomass in the CE has been confirmed, the gap still exists in evaluating the application of CE to the BSC. Up to the authors' knowledge, currently, there is no set of circularity and sustainability indicators as standard for the company in the BSC. The variety of CE approaches and indicators makes it difficult to convert linear business models into circular ones. In addition, the variety of biomass materials, differences in biomass processing technology and multiple end-products lead to transformation into a CE model in many alternatives with many stages and different technology processes. Furthermore, some indicators assessing aspects of sustainability and circularity of different alternatives are subject to conflict and trade-offs. A more sustainable solution might not necessarily be better in terms of circularity and similar trade-offs exist within the pillars of sustainability. Given the trade-offs between sustainability and circularity, decision support systems (DSS) based on life cycle thinking with a standard set of indicators are promising tools for evaluating and selecting the best alternative of sustainability and circularity BSC.

For what is above, this PhD research project was focused on developing a decision support system for a biomass company in the energy sector based on CE and sustainability models with a life cycle thinking approach. With the CE and sustainability model, a set of circularity and sustainability indicators is developed, and it is considered a criteria set to assess the circularity and sustainability of biomass companies and BSC. The life cycle thinking approach is employed to provide a comprehensive assessment for BSC. It is also basic to collect data from BSC and give value to indicators for assessing and ranking alternatives. The trade-off existing in alternatives is solved by using Multiple-criteria decision-making methods. That is integrated into the methodology framework of the decision support system.

The PhD research project is structured around two main objectives. First, from CE and sustainability models, a set of circularity and sustainability is development. Secondly, a DSS tool is created. The set of developed indicators considers various stages during the BSC, such as feedstock plantation, processing, transportation, energy conversion, and end-of-life management, being aligned with the United Nations Sustainable Development Goals (SDGs) and the EC's guidelines on the transition to CE. Meanwhile, the creation of a DSS includes

proposing a methodology framework for DSS, creating software in MATLAB GUI and Script as a new tool for DSS, and applying this tool to the rice straw supply chain as testing for the case study.

Regarding the case study, a rice straw supply chain for energy production in the Pavia region of Italy is selected. The data for the case study was collected during the internship period at the ENI company, such as parameters of the plant and process. The current of the rice straw supply chain is assessed by the DSS tool, and a re-edited version of this tool was taken. The alternatives of CE applications in the case study were performed through an external internship at the IMDEA Energy Institute (Spain). The data on alternatives is gathered based on the results of the simulation of the chemical process by Aspen plus@ at the IMDEA Energy Institute for suitable parameters of the current supply chain.

The sustainability and circularity indicators methodology framework and case study developed during this PhD research project have been published in international journals and conference proceedings. The results of the application and details of the decision support system are present in this thesis. The results of calculating indicators for all indicators show that global warming potential (GWP) is 1.21E+03 ton CO_2eq/yr to 55.7E+03 ton CO_2eq/yr. Meanwhile, rice straw's acidification potential (AP) in this study ranges from 9.66 tonnes of SO_2 eq/yr to 563 tonnes of SO_2 eq/yr. The internal rate of return (IRR) of the rice straw supply chain is from 5.92% to 11.3%. In addition, the net present value (NPV) of the case study ranges from 0.72 to 5.79 million euros. Furthermore, the rate of informal labour is from 71.9% to 82.10%, while the percentage of recycling rate out of all waste is from 96.61% to 99.2%, the circular material use is from 54.8% to 88.2%, and the proportion of material losses in primary material is from 14.61% to 15.5%. The ranking results indicate that the digestate pyrolysis option has the best sustainability and circularity points among the other options.

This PhD project research shows that the application of a comprehensive approach encompassing Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA) to identify sustainability indicators brings about significant advantages to the biomass supply chain. Existing research seldom integrates all three methodologies simultaneously. This integrated approach enhances the understanding of sustainability implications across the biomass supply chain, paving the way for a more holistic assessment.

Moreover, the utilization of the Life Cycle Thinking (LCT) tool and Material Flow Analysis (MFA) for circularity indicators introduces a novel dimension to the existing literature. The incorporation of these tools instills confidence in simulating both circularity and sustainability, a consideration often overlooked in previous studies. The resulting circularity and sustainability indicators offer a standardised set that serves as a step-by-step guide for achieving Sustainable Development Goals (SDGs) and transitioning to a circular economy, aligning with the European Commission's roadmap.

The development of a Decision Support System (DSS) methodology framework marks another crucial contribution, particularly by integrating circularity and sustainability within a unified framework for biomass companies in the supply chain. Unlike existing frameworks, this approach employs the PROMETHEE II and Entropy methods, leveraging life cycle results to enhance reliability and streamline calculations. Overcoming the limitations of PROMETHEE, this framework incorporates a multiple-criteria decision-making approach to address trade-offs in sustainability and circularity alternatives. This not only improves the robustness of the framework but also extends its applicability to general companies beyond the biomass sector.

Furthermore, the accompanying software in this study presents a more practical and potent DSS tool for ranking alternatives. Its flexibility, allowing the use of the DSS tool for calculating sustainability and circularity indicators for individual alternatives, provides users with a versatile platform. The ability to choose indicator groups and methods for weighting indicators enhances the adaptability of the framework, making it applicable in various scenarios for policymakers and researchers committed to advancing circular economy and sustainability initiatives. In summary, based on methods for application, methodology framework and useful software, the DSS tool developed in this thesis can be used to support companies in the biomass supply chain, managers, practitioners, policy-makers, and researchers in assessing and selecting alternatives for application of CBMs to transfer into CE.

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ABBREVIATIONS

AD	*Anaerobic digestion.*
ADP	*Abiotic Depletion Potential*
AHP	*Analytic Hierarchy Process.*
AI	*Artificial Intelligence.*
ANP	*Analytic network process.*
AP	*Acidification potential.*
BOCR	*Benefits, Opportunities, Costs and Risks.*
BSC	*Biomass supply chain.*
CBM	*Circular business models.*
CE	*Circular economy.*
CHP	*Combined Heat and Power.*
Cin	*Circular investment.*
Cl	*Child Labour.*
DALY	*Disability-adjusted life year.*
DEA	*Data Envelopment Analysis.*
DEMATEL	*Decision making trial and evaluation laboratory.*
DSS	*Decision support system.*
EC	*European Commission.*
Ecm	*Ecotoxicity, marine.*
ECfw	*Ecotoxicity, freshwater.*
Emc	*Employee participation in the circular model.*
Elo	*Local employment.*
EMY	*Effective mass yield*
E_{RD}	*Research and development expenditure as a proportion of revenue.*
EUf	*Eutrophication, freshwater).*
EUt	*Eutrophication, terrestrial.*
EUm	*Eutrophication, marine.*
FAHP	*Fuzzy Analytical Hierarchy Process.*
FBW	*Fuzzy best-worst.*
FGP	*Fuzzy goal programming.*
Fs	*Fair Salary.*
Fw	*Food waste.*
GDP	*Gross domestic product.*

GHG	*Greenhouse Gas.*
Gw	*Generation of waste.*
GWP	*Global warming potential.*
HUTno	*Human toxicity, non - cancer.*
HUTca	*Human toxicity, cancer.*
HMI_DSS	*Holistic Multi-Indicator Decision Support System.*
Hw	*Number of health workers in company.*
I_{fnf}	*Fatal and non-fatal occupational injuries.*
Inc	*Income generated by jobs.*
INVso	*Social investment.*
IO	*Input-Output.*
IORH	*Ionizing radiation human health.*
IORE	*Ionizing radiation ecosystem.*
IRR	*Internal rate of return.*
Jcre	*Job creation.*
LCA	*Life cycle assessment.*
LCC	*Life cycle costing.*
LCI	*Life cycle inventory.*
LCIA	*Life cycle impact assessment.*
LCSA	*Life Cycle Sustainability Assessment.*
LCT	*Life cycle thinking.*
Lfor	*Forced Labour.*
LU	*land use*
MAVT	*Multi-Attribute Value Theory.*
MCDA	*Multi-Criteria Decision Analysis.*
MCDM	*Multi-Criteria Decision Making.*
MFA	*Material Flow Analysis.*
MOPS-MPPH	*Multi-Objective Project Selection - Multi-Period Planning Horizon.*
NPV	*Net present value.*
OECD	*Organisation for Economic Co-operation and Development.*
OZD	*Ozone depletion.*
PAM	*Particulate matter.*
Pawre	*Percentage of recycling rate of all waste.*
PEC	*Primary energy consumption.*

PE_{edu}	*Proportion of employment with education and training out of total employment.*
PHOF	*Photochemical ozone formation.*
PI_{em}	*Proportion of informal employment out of total employment.*
Pmlo	*The proportion of material losses in primary material cycles.*
PRec	*Primary renewable energy consumption in primary energy consumption.*
Prep	*Percentage of recycling rate of plastic waste.*
PRISMA	*Preferred Reporting Items for Systematic Reviews and Meta-Analyse.*
PROMETHEE	*Preference Ranking Organization Method for Enrichment Evaluations.*
Pwrepp	*Percentage of recycling rate of paper and paperboard.*
PW_{em}	*Proportion of women in management positions out of total employment.*
R	*Revenue.*
Rcmu	*Circular material use rate.*
Rmp	*Reuse, manufacturing process.*
SDG	*Sustainable Development Goal.*
SE	*Steam explosion.*
SLCA	*Social life cycle assessment.*
SEU	*Subjective Expected Utility.*
SOx	*Sulphur oxides.*
Ssrm	*Self-sufficiency of raw materials.*
SUMP	*Sustainable Urban Mobility Plan.*
TC	*Total cost.*
TOPSIS	*Technique for Order Performance by Similarity to Ideal Solution.*
TS	*Total solids.*
Urm	*Use of raw materials for producing one unit of the main product.*
VIKOR	*Vise Kriterijumska Optimizacija I Kompromisno Resenje.*
Whou	*Working Hours.*
WTC	*Water consumption.*

CHAPTER I. INTRODUCTION

1.1. Motivation and research gaps

Transitioning to the circular economy (CE) plays a key role in sustainable development (Geissdoerfer et al., 2017). A recent study (European Commission, 2020) estimated that the application of CE principles throughout the EU economy has the potential to increase the Gross Domestic Product (GDP) of EU by 0.5% by 2030, creating around 700,000 new jobs. There is also a clear business opportunity for individual companies: since manufacturing companies in the EU spend, on average, around 40% of their budget on materials, the circular business models can increase their profits while at the same time protecting them from resource price fluctuations. It is estimated that eco-design and waste prevention could result in net savings for EU businesses of up to 600 billion Euros while reducing greenhouse gas emissions by 2-4 % (EC, 2014; Kalmykova et al., 2018). Furthermore, additional measures to increase resource efficiency by 30% by 2030 could boost the average GDP of the EU by almost 1% and create two million jobs (EC, 2014; Kalmykova et al., 2018).

Businesses are key actors in the transition to a CE (Tessitore et al., 2023; *Transitioning to a Circular Economy*, 2022). By incorporating CE principles, companies can transition from the traditional linear "take-make-dispose" paradigm to a more robust, sustainable, closed-loop system (European Commission, 2020; The Ellen MacArthur Foundation, 2013). This change requires designing products and processes for long-term use, remanufacturing, refurbishing, recycling, and repurposing, decreasing material consumption and reducing refuse production. Adopting a CE model can result in numerous business advantages, including cost savings through waste reduction, increased competitiveness, greater resilience against resource price volatility, a stronger brand image, and new revenue streams. The transition to a CE also inspires innovation, promotes collaboration among stakeholders, and contributes to the achievement of global sustainability goals such as the Sustainable Development Goals (SDGs) of the United Nations (Geissdoerfer et al., 2017; United Nations, 2015). To successfully transition to a CE, businesses must develop comprehensive strategies incorporating product design, supply chain management, business model innovation, and stakeholder engagement. In addition, ongoing adaptation, monitoring, and enhancement are required to maximise the prospective benefits of a circular approach and assure long-term success in this dynamic environment.

Meanwhile, circular business models (CBMs) play a pivotal role in an organization's transition to the CE (Smol et al., 2024). The application of CBMs focuses on using resources efficiently, reducing waste, and restoring natural systems, thereby benefiting the economy, the environment, and society. According to the Organisation for Economic Co-operation and Development (OECD), CBMs encompass a variety of production and consumption methodologies (OECD, 2019). Central to CBMs is the emphasis on prolonging product life cycles to retain their value, thereby minimising environmental footprints and delivering economic advantages to consumers (Salvador et al., 2021). There are different types of CBMs according to various classifications. The OECD categorises CBMs into circular supply models, resource recovery models, product life extension models, sharing models, and product service systems models (OECD, 2019). Moreover, Ludeke-Freund et al. outline six primary CBMs aligned with CE principles, comprising repair and maintenance, reuse and redistribution, refurbishment and remanufacturing, recycling, cascading and repurposing, and organic feedstock (Lüdeke-Freund et al., 2019).

In the energy sector, bioenergy and biofuels produced from biomass are considered sustainable renewable energy for replacing fossil fuels and reducing greenhouse gases (GHG) (Sherwood, 2020). Biomass energy production comprises different processes, such as harvesting, collection, transportation, pre-treatment, storage, and end-use, called the biomass supply chain (BSC) (Atashbar et al., 2016; Ooi et al., 2022). On the other hand, biomass is also significant in the CE regarding physical products and energy supply (Sherwood, 2020). A BSC with waste-free biorefineries utilises all the available biomass components to make products and energy, consistent with the fundamental objective of a CE (Kapoor et al., 2020; Kumar & Verma, 2021; Sherwood, 2020). Using waste, by-products, and residue in BSC is essential to improving the CE in agriculture, wood, and paper processing industries, as well as waste treatment and management. Although confirmation of biomass's role in the circular economy (CE) has been established (Ellen MacArthur Foundation, 2013), applying CE principles and CBMs to biomass companies within the BSC offers a promising avenue for enhancing their circularity and sustainability. This approach presents an anticipated alternative for transitioning these companies into the CE model, thereby maximising the potential of biomass energy production to contribute to sustainable development and the CE. However, this CE transition can be performed with multiple alternatives, which depend on the implementation of various CBMs. Meanwhile, the performance of implementing CBMs is variable depending on the types and sources of biomass, end products, and conversion technologies. As a result, the assessment and selection of CE transitioning alternatives for biomass companies within BSCs need to be fully clarified.

On the other hand, choosing the most suitable transitioning alternative by implementing CBMs to enhance a company's circularity and sustainability, also referred to as the circularity and sustainability alternative in this thesis, is challenging because circularity and sustainability can be measured by various indicators, including environmental, social, and economic impacts as well as levels of circularity. For example, Azevedo et al. (2017) suggested an index to evaluate manufacturing companies' sustainability and circularity, which is composed of seven social, three economic, four environmental, and four circularity indicators. This sustainable circular index is versatile and straightforward, making it possible to assess manufacturing companies' sustainability and circularity practices. However, this index is used for the individual company and cannot be used for the whole supply chain. Pollard et al. (2022) developed circularity indicators to measure the circular economy performance of electrical and electronic manufacturers' products. These circularity indicators were divided into 25 environmental, nine social, and six economic indicators. This study also considered the relationship between indicators and the life cycle product stage. De Pascale et al. (2021) provided a comprehensive overview of circular economy indicators: 61 indicators were considered, including 22 indicators at the micro-level, 15 indicators at the meso–level, and 14 indicators at the macro–level. In addition, circularity indicators were also published by the European Commission (EC) (Moraga et al., 2019) and the Ellen MacArthur Foundation (Goddin et al., 2019). Furthermore, up to the authors' knowledge, currently, there is no standard set of circularity and sustainability indicators for the company in the BSC.

Besides that, circularity and sustainability indicators are usually trade-offs between alternatives. Options that are beneficial for the environment tend to sacrifice economic criteria, whereas options that are beneficial for the economy tend to be less advantageous for the environment and society. The trade-off between a sustainable environment and cost-effective performance is mentioned by Gružauskas et al. (Gružauskas et al., 2018). which showed that the trade-off resulted in 18.4% lower transportation costs, but, unfortunately, increased CO_2 emission level by 43%. Zhang et al. demonstrated that different biomass energy production processes from algae have contrasting environmental and economic benefits (Zhang et al., 2013). Comparing the "closed-loop" approach to enhance circularity in algae-based oil production with the existing method, Kern et al. declared that a circularity alternative might be less cost-effective (Kern et al., 2017). For example, in circularity alternative has a global warming potential of 4953ton CO_2/year higher than the baseline at 1485tonCO_2/year, while resource use of the circularity alternative is at 205E+3 USD/year lower than 460E+3 USD/year of the baseline alternative.

In this context, decision support systems (DSS) based on the life cycle thinking (LCT) approach are becoming promising tools for the company within the supply chain to evaluate and select the circularity and sustainability alternative. De Luca et al. (2017) found three different ways to combine life cycle (LC) tools with Multi-Criteria Decision Analysis (MCDA) in agricultural sustainability assessments. Firstly, the MCDA methods were applied as part of an LC framework to complement the significance of evaluation results or to allow the combination and synthesis of different types of insights. In the second one, the life cycle results were used to provide information for MCDAs. In contrast, a third way considered the LC tools and MCDA methods on the same level and with the same importance, and therefore, they were fully merged. According to De Luca et al. (2018), life cycle tools (LCA, SCLA, and LCC) were integrated here using a multicriterial and participative method, the Analytic Hierarchy Process (AHP). LCA, SLCA, and LCC methods are used to calculate indicator values of environmental, social, and economic sustainability. After measuring indicators, the overall sustainability of the scenarios was assessed using the multi-criteria approach with the presented AHP approach. Ekener et al. (2018) developed a decision-making tool based on the Mult Attribute Value Theory (MAVT) method with the Life Cycle Sustainability Assessment approach for assessing the sustainability performance of products. This study used LC tools to calculate indicators (LCA values), and the MAVT was used to weigh and rank LCA values. Ren and Toniolo and Ren et al. employed LCA, LCC, and SLCA to obtain data on the alternative hydrogen production pathways concerning the environmental, economic, and social criteria, respectively (Ren et al., 2015; Ren & Toniolo, 2018). According to the results of LCA and LCC, the data on the alternative hydrogen production pathways concerning environmental and economic criteria was determined. SLCA was used to determine the data concerning the criteria in the social aspect. Subsequently, a decision-making matrix of various alternatives and criteria can be obtained. In this study, the Decision making trial and evaluation laboratory (DEMATEL) method was used to rank alternatives.

However, these existing decision-support tools have some limitations. These tools are subjective and challenging to use. For example, the tool developed by Ren et al. (2015) requires some quality indicators and compares pairs of indicators that must be based on expert judgements. Meanwhile, De Luca et al. (2018) employed 15 experts to express their subjective opinions in pairwise comparisons of criteria. Furthermore, to the author's knowledge, there is no DSS tool existing literature considering both sustainability and circularity indicators, most of them only focus on sustainability indicators, such as in De Luca et al. (2017), or Ekener et al. (2018). In addition, Ekener et al. focused on identifying environmental indicators, while social and economic indicators were sourced from the available literature, which might not exactly reflect the situation of the supply chain. To overcome the lack of a DSS tool for companies within the BSC considering both the sustainability and circularity indicators, solving conflict and trade-offs in sustainability and circularity aspects, as well as reducing decision-making dependence on experts, this thesis proposes and develop a comprehensive and helpful DSS tool for assessing circularity and sustainability of the company, as well as selecting the best alternative of sustainability and circularity. Research questions that need to be addressed include:

1. What indicators used in DSS measure sustainability and circularity, and how can the LCT approach be applied to determine these indicators?
2. Which decision-making methods/techniques (MCDM methods) are suitable for developing DSS that simultaneously assess circularity and sustainability for companies in the biomass supply chain?
3. How can a DSS methodology framework and software tool be developed by combining the LCT approach with decision-making methods, to objectively evaluate and integrate decision-makers' perspectives in choosing a transition alternative to a CE?

Additionally, the suitability of the tool for application to companies needs to be considered. Sustainability is an urgent objective that has attracted the attention of many organizations, policymakers, businesses, and governments worldwide. Thus, the developed DSS can also be used by managers, practitioners, policymakers, and researchers to guide enterprises in various supply chains in applying CE and sustainable models based on the LCT approach and achieving SDGs.

1.2. Methods

This thesis illustrates the proposal of a methodological framework and a software tool for a DSS to guide the enterprises involved within the “supply chain of biomasses used for energy purposes” in the application of CE and sustainable models with a LCT approach. This DSS tool was conceived to be as generic as possible and apply to all enterprises in every point of the supply chain for selecting the best sustainability and circularity alternative based on applying CE principles and CBMs in alignment with the achievement of the SDGs and EC guidelines for the transition to a CE. In addition, this methodology framework and DSS tool allow companies to measure their level of sustainability, circularity, and energy efficiency in the current situation.

In more detail, the research project presented in this thesis is focused on two objects. First, construct the sustainability and circularity indicators to evaluate the circularity and sustainability of the company in the BSC. Second, how to select the best changes for the company to transition to a CE model and promote sustainability based on the indicators. The design of the structure of the decision-making process begins with the identification of procedural steps, methodological tools, analysis to be carried out, indicators to be used, decision variables and constraints, and any other element that can play an active role in the decision-making process, with particular attention to the indications of the latest national and European communications and regulations on the CE, sustainable development, and the LCT.

The process of developing the DSS tool for this research project includes some steps, as shown in Figure 1.1. In this figure, from step 1 to step 3, the sustainability and circularity indicators are collected, selected, and classified, as well as defined based on the LCT approach and MFA. The remaining steps focus on developing the methodology framework of DSS, creating software for DSS tool, and performing test DSS tool with a case study.

To select CE and sustainability indicators, firstly, the CE and sustainability indicators were collected from United Nations and literature databases, including SDGs, environment, economy, and social. Subsequently, they are selected based on some included and excluded criteria such as out-of-level, potential of collecting data, overlap content, and suitability with biomass supply chain. The selected indicators were also redescribed and divided into four groups due to the application potential of the LCT approach and MFA to define their values. The formulas for each indicator were identified.

For weighting criteria (indicator) and ranking alternatives, the entropy and PROMETHEE II methods have been selected. According to these methods, a new framework decision support has been developed for a company in the supply chain. In this framework, the LCT approach and MFA are applied to determine the criteria data in sustainability (environmental, economic, and social aspects) and circularity aspects. Subsequently, a decision-making matrix of various alternatives and criteria can be obtained, that is used to weight indicators and rank alternatives by MCDM methods. The MCDM method - PROMETHEE II is used to rank the sustainable performance and circular efficiency of the alternatives, while for weighting criteria, multiple weighting methods are used, such as the entropy method or user/decision-maker definition.

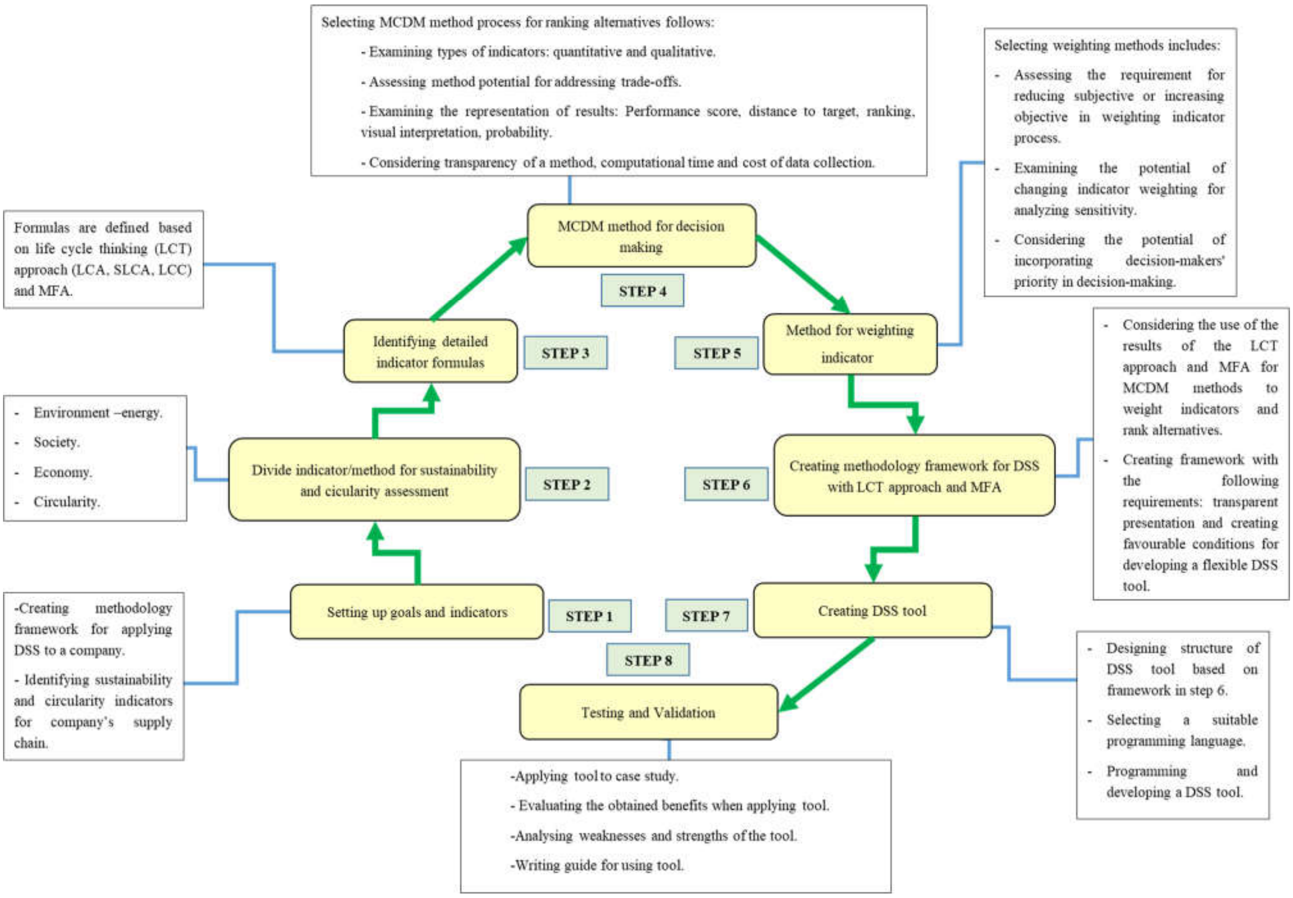

Figure 1.1. Methodology framework of developing HMI_DSS tool based on circular economy and sustainability model for company in supply chain with LCT approach.

Programming the software for the decision support tool was done in MATLAB. The structure of DSS software includes a Human interface, a Main – program and Sub-programs. The main program has two functions, such as calculating indicators for the present situation and ranking alternatives. Sub-programs for calculating each type of indicator and relevant to weighing alternatives. The tool is created by MATLAB GUI and Script. GUI has been used to design Human interfaces. The script is programmed for the main and subprograms. After programming, the software was created. This software can run on computers that have been installed MATLAB runtime.

The case studies included in this thesis are mainly aimed at proving the effectiveness of the methodology developed for the present project. The rice straw supply chain for energy production was selected as a case study. The data collected includes the input and output of the supply chain and the specific impacts on sustainability and circularity corresponding to each input and output. The collecting process has been taken from plant owners, the ENI and

IMDEA database, and literature for situational alternatives. They were used to examine the sustainability and circularity of the supply chain. The set of alternatives was generated and represented by energy-environmental, social, and economic performance improvement solutions and circular economy business models. The evaluation and selection of alternatives were carried out through the estimation of the benefits related to their implementation and their potential contribution to the achievement of the SDGs. The data collection phase was performed in different ways and with a different level of accuracy for the case study, thus affecting the reliability of the results. For this reason, the outcomes of the case study should not be considered as a reference or guidelines for selecting the best circular business model for the supply chain, although they comply with common design practices.

The development of the methodology deriving from this PhD research project and corporate activity at companies (ENI and IMDEA) of the research activities that are focused on the assessment and selection of circular business models for the biomass supply chain. In more detail, there are activities for selecting the case study and collecting data for it at ENI and the definition of alternatives at IMDEA. Moreover, the method and case study were described in papers published in international journals and peer-reviewed conference proceedings.

1.3. Contribution

The present PhD project aims to develop a methodology framework and software tool of a DSS to support the companies involved in the "supply chain of biomasses used for energy purposes" transition to a circular economy model for sustainable development. The goal of this framework is to rank the alternatives of circular business models for the supply chain for the selection of the best application business model. Besides that, this framework also allows users to evaluate the sustainability and circularity of the supply chain in the present situation and define the holistic of the supply chain. They are the evidence for identifying the alternatives of applying circular business models to improve sustainability and circularity in the supply chain.

According to the developing methodology framework, the thesis has presented a new DSS tool. It was programmed in MATLAB. This tool was the result of integrating the LCT approach (LCA, SLCA, LCC) and MFA with MCDM methods. The LCT approach was used to calculate the value of sustainability and circularity alternative indicators. After that, the MCDM method was employed to rank alternatives. From the methodological approach point of view (LCA, LCC, SLCA approach) and material flow (MFA approach), this tool can assess comprehensively the alternatives in sustainability and circularity and improve the accurate selection of the best alternative. Furthermore, the sustainability and circularity indicators in this thesis were taken in general so that this tool can be applied to all companies in different fields. Otherwise, these indicators are quarterly, and they can be easy to collect data in companies and literature, so this tool is more feasible and friendly to use.

The results of the application for case studies in this thesis showed that the decision-support tool is flexible in selection evaluation. The tool allows users to select multiple indicator groups (environmental, social, economic and circularity catalogues) for calculating and ranking. The tool also allows users to rank alternatives as user-oriented and non-user-oriented by selecting the indicator weighting method. If users want to rank alternatives as user-oriented, they can select weighting by experts. In contracts, the user can use the Entropy method for indicator weighting. This method weights indicators based on the quantity value, so the weighting results are independent with user-oriented.

1.4. Thesis structure

This thesis is organised as follows: Chapter 2 presents the context and background for the research developed in this thesis, providing an overview of the various areas of knowledge that were combined in this study, namely the life cycle thinking approach and MCDM methods. Chapter 3 illustrates a review of literature studies about applying life cycle thinking and circular economy principles to the biomass supply chain and decision support systems in a sustainability context. This chapter is necessary to identify a general framework for the existing studies, detect existing research gaps, and develop the methodology for the present research project. Chapter 4 presents the development of sustainability and circularity indicators to assess the level of sustainability and circularity for companies in the supply chain. The application of the LCT approach to defining these indicators is also shown in this chapter. Chapter 5 presents the development of the new methodology framework of the decision support system, describing the programming decision support tool for companies in the biomass supply chain, introducing how to use it, as well as discussing the strengths and weaknesses of this tool. One case study was chosen to show that the method works and to make a decision-making tool that is easy to use and friendly. It is shown in Chapter 6 and is about evaluating the situation of rice straw supply chains and ranking rice straw supply chain alternatives for circular business model applications. The main conclusions of the thesis are outlined in Chapter 7, together with recommendations for future research.

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CHAPTER II. BACKGROUND

2.1. Circular economy

2.1.1. Concept of circular economy and linear economy

1. Linear economy

A linear economy is a concept that implies the traditional economy follows the "take-make-dispose" step-by-step plan. In a linear economy, raw materials are collected and subsequently transformed into used products until they are discarded as waste (figure 2.1). The primary mechanism for value creation in this economic system is rooted in the prolific production and extensive commercialization of products. This leads to wasteful use and deployment of resources.

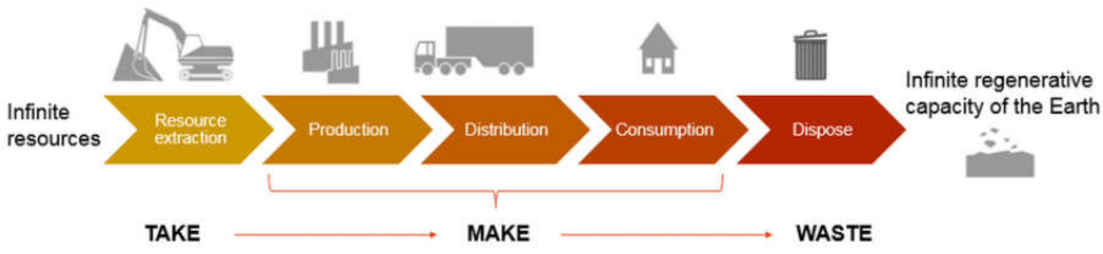


Figure 2.1. Linear economy

2. Circular economy (CE)

CE was first introduced officially in 1990 by Pearce and Turner (Pearce & Turner, 1991; Su et al., 2013). CE refers to a new economic model based on the basic principle of "everything is an input to another," which is entirely different from the view of the traditional linear economy. The European Commission (2015), in its Action Plan on the CE, has defined: "In a CE, the value of products and raw materials is maintained for as long as possible; waste and resource use are minimised, and resources are kept in the economy when a product has reached the end of its life cycle, to be used to continue to create even more value" (European Commission, 2015) (figure 2.2).

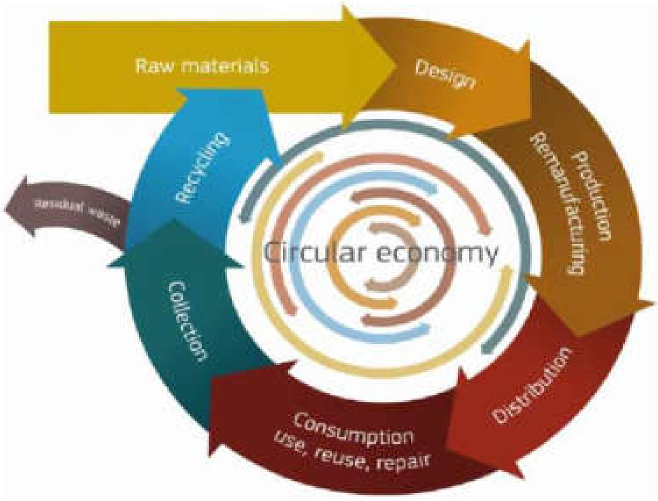


Figure 2.2. Circular economy

Currently, the concept of CE is widely accepted as that of the Ellen MacArthur Foundation (The Ellen MacArthur Foundation, 2013). According to this concept, a CE is "a system that is restorative and renewable through proactive planning and design. It replaces the concept of "end of life" of materials with the concept of recovery, shifting towards using renewable energy, not using harmful chemicals that harm reuse, and reducing waste reduction through the design of materials, products, engineering systems, and business models within that system". The purpose of the CE is to prolong the useful life of products and increase the productivity of resources. All "waste" of one manufacturing process is considered raw material for other manufacturing processes. The CE development strategy focuses on the efficient use of resources, minimizing waste, reusing materials, and improving the ecosystem through business activities. According to Kumar et al., there are some concepts of CE from other authors are shown in Table 2.1 (Kumar et al., 2023).

Table 2.1. Some other CE concepts from the literature

Author's	CE concept
Ghisellini, Ripa and Ulgiati	"Circular economy (CE) as a new model of economic development promotes the maximum reuse/recycling of materials, goods, and components in order to decrease waste generation to the largest possible extent. It aims to innovate the entire chain of production, consumption, distribution and recovery of materials and energy according to a cradle-to-cradle vision".
Geissdoerfer et al. (2017)	"A regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can

	be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling ".
Kirchherr et al., 2017	"An economic system that replaces the ‘end-of-life’ concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible Consumers".
Korhonen, Honkasalo and Seppälä	“Circular economy is an economy constructed from societal production consumption systems that maximizes the service produced from the linear nature-society nature material and energy throughput flow. This is done by using cyclical materials flows, renewable energy sources and cascading1-type energy flows. Successful circular economy contributes to all three dimensions of sustainable development. Circular economy limits the throughput flow to a level that nature tolerates and utilises ecosystem cycles in economic cycles by respecting their natural reproduction rates”
Ellen MacArthur Foundation	“A circular economy is based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems".

3. Strongness of the Circular economy

Compared with linear economy, CE has some strength like that:

- CE can be applied to many different scales, from micro to macro, as well as to individual households (In Vietnam, the CE has been used in rural family models to reduce hunger and poverty: model garden pond and barn)
- The CE helps to take advantage of used materials instead of consuming processing costs, minimises the exploitation of natural resources, makes the most of the value of resources, and reduces waste and emissions into the environment.
- CE helps reduce social costs in management, environmental protection and response to climate change; creates new markets and job opportunities, and improves people's health.

- CE contributes to reducing the risk of overproduction and resource scarcity crisis; creates motivation to invest, innovate technology, reduce production costs, and increase the supply chain.

4. The weaknesses of circular economy:

Although, CE has some strengths, it also has some weaknesses follows:

- The CE's purpose harmonises the purposes from production to product consumption, so the economic goal is lowered compared to the linear economy, inadvertently creating an opposing view—pole for investors. Not everyone can afford to understand its importance and urgency.
- The CE is in the development stage, so there are many different views and application forms, leading to difficulties communicating about the circular economy to adopters and product users. Products.
- CE tends to isolate the self-sufficient model, thus reducing the openness of mutual exchange.
- The application of the CE is associated with technological changes, especially in waste recycling technology. This change requires human resources and investment capital, which is difficult to change with existing production paths.
- The adoption of a CE leads to a significant change in the old business model, the results of which may have to be built from scratch, which is a substantial obstacle for businesses that already follow an existing error. This change is not easy and takes a long time.
- Applying a CE requires synchronous participation of partners; everyone's understanding of the circular economy is not the same, causing asynchronous partner participation.
- The CE has just developed, so supporting policies have not been designed accordingly.

5. Aspects of transition from a linear economy to the circular economy

Numerous persuasive justifications support the shift from a linear to a CE. To begin with, a key impetus behind this transition is the objective of diminishing the need for basic materials, particularly non-renewable resources such as minerals, which are progressively depleting. The European Commission's 2020 report emphasised the alarming forecast that worldwide material consumption, including that of minerals, biomass, fossil fuels, and metals, will more than double by 2050 (European Commission, 2020). Concurrent with this upsurge in consumption, it is anticipated that annual refuse production will increase by 70% by 2050. In other words, the resources required to manage the expanding waste generation and meet this increased demand would be equivalent to those of three planets. This renders the circular economy an intriguing strategy.

Furthermore, it is anticipated that the CE will lessen the substantial reliance of one nation on another, particularly with regard to natural materials. This type of dependence has the potential to disrupt the progress of individual nations. For example, the European Union's dependence on Russia for natural gas supplies and the reliance of various countries on China for rare earth resources both highlight the inherent vulnerability of such dependencies.

Finally, the CE exhibits the potential to mitigate significant worldwide challenges. Considered a viable approach to address the challenges posed by climate change and attain sustainable energy generation and utilisation. In addition to these critical environmental considerations, the adoption of a CE may generate employment and economic prospects. This transition is anticipated to stimulate creativity, innovation, design, and recycling, which will generate measurable economic benefits. The adoption of the CE model is anticipated to generate approximately 700,000 new jobs and increase GDP by 0.5% in the European Union by 2030 (European Commission, 2020). Comparable favourable outcomes, including significant economic investments and the generation of employment opportunities, have been observed in nations such as the United Kingdom (50,000 new jobs) and the Netherlands (54,000 new jobs), thereby underscoring the extensive advantages of the CE (Kalmykova et al., 2018).

2.1.2. Principles of circular economy

The core principles of the CE are widely recognized as reduce, reuse, recycle and recover (Han et al., 2020; Kirchherr et al., 2017; Rovanto & Bask, 2021). Besides that, repair, refuse, rethink, refurbish, remanufacture, and repurpose are also considered CE principles.

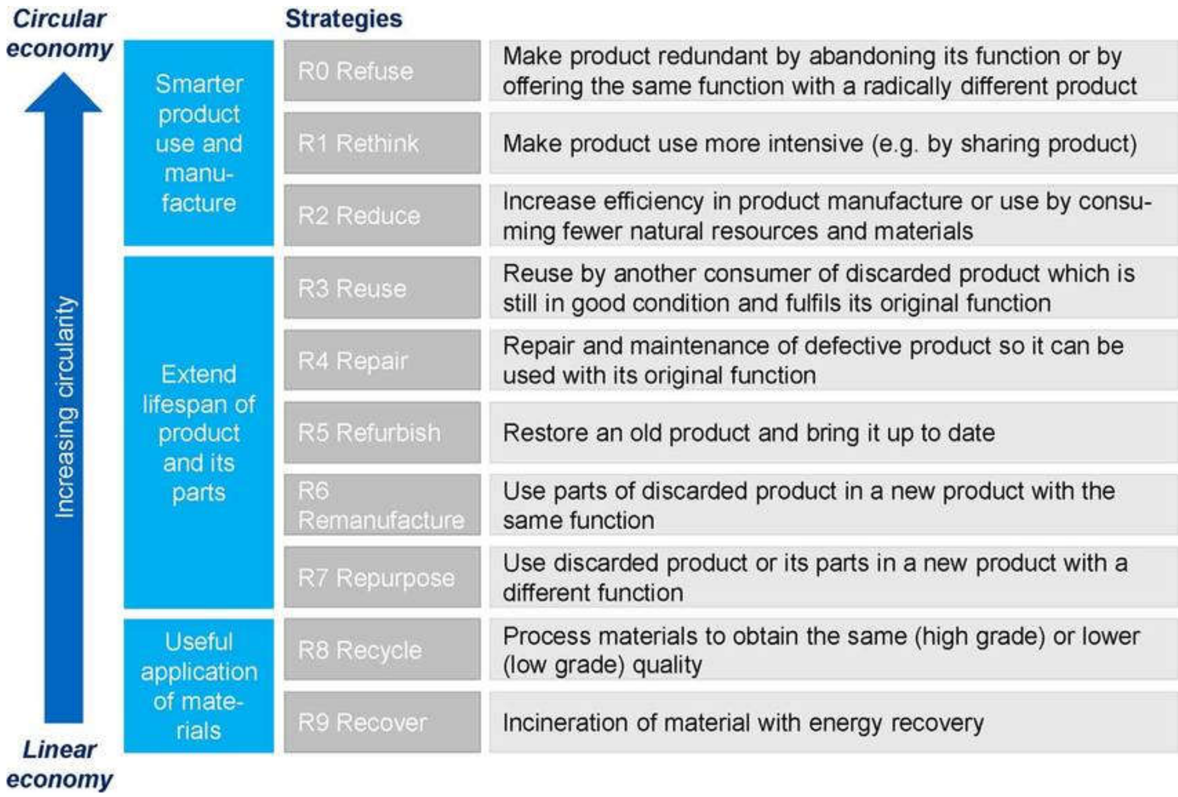


Figure 2.3. The 9R Framework. (Kirchherr et al., 2017)

However, according to Ellen Macarthur Foundations, CE has three principles, including regenerating ecosystems (natural systems), designing out waste and pollution, and keeping products and materials in use longer. The relevance between the 10R framework and

Ellen Macarthur Foundation's CE principle is presented in Figure 2 (Esther Goodwin Brown et al., 2021).

CIRCLE ECONOMY'S CORE ELEMENTS	STRATEGIES FOR RESOURCE CYCLING[13]	10R FRAMEWORK	5R FRAMEWORK	ELLEN MACARTHUR FOUNDATION
Prioritise Regenerative Resources	Regenerate flows			Regenerate ecosystems
	Narrow flows	Refuse		Design out waste
		Reduce	Reduce	
		Rethink		
Stretch the Lifetime	Slow flows	Reuse	Reuse	Keep products in use for longer
		Repair	Repair	
		Refurbish	Refurbish	
		Remanufacture		
Use Waste as a Resource	Close flows	Repurpose		Design out waste
		Recycle	Recycle	
		Recover		

Figure 2.4. Key elements framework (Esther Goodwin Brown et al., 2021).

2.1.3. Circular business model

The transition to more circular production and consumption systems affects businesses and forces them to redesign their business strategies and models (Reim et al., 2019; Rovanto & Bask, 2021). These business models are considered circular business models (CBMs). According to the OECD (2018), "CBMs represent fundamentally different ways of producing and consuming goods and services. They have the potential to drive the transition towards a more resource-efficient and circular economy and, in doing so, significantly reduce the environmental pressure resulting from economic activity" (OECD, 2019). Rovanto & Bask stated that "A circular business model is the company-level application of a CE (Rovanto & Bask, 2021). It is the logic of slowing and/or closing material loops by which an organization creates, delivers, and captures value with long-term environmental, economic, and social implications systemically on the micro, meso, and macro levels to accomplish sustainable development". Unlike the traditional business model, the CBM focuses on extending the product's life cycles to maintain the economic value of the product for as long as possible, reducing the impact environment and bringing a great deal to customers. CBMs are considered the core role in building a sustainable economy (Sherwood, 2020) (Rovanto & Bask, 2021).

There are various types of CBMs according to different classifications. Some authors categorized circular business models into circularity design, optimal use, and value recovery (OECD, 2019). Others categorize CBMs according to material flows, including short loop, long loop, rearrangement, and pure loop (Geissdoerfer et al., 2018; Lüdeke-Freund et al., 2019).

OECD (2019) reclassifies circular business models into five categories, including:

(1) circular supply models.

(2) resource recovery models.

(3) product life extension models.

(4) sharing models.

(5) product service systems models.

Ludeke-Freund et al. proposed six main CBMs (Lüdeke-Freund et al., 2019):

(1) repair and maintenance.

(2) reuse and redistribution.

(3) refurbishment and remanufacturing.

(4) recycling.

(5) cascading and repurposing.

(6) organic feedstock.

The CBM has the following critically essential roles. Firstly, CBM plays a core role in building a sustainable economy (green economy, circular economy). The CBM will help quickly reduce the growing amount of waste from human consumption today. Besides, the CBM also helps to reduce the overexploitation of resources. CBM helps to prolong the product life, thereby decreasing costumers' costs ought activities such as renewing/refurbishing, remanufacturing, etc. CBM, although still taking profit as the first condition, the focus of this model is to restructure economic activities based on natural processes, to make them renewable and not generate waste, not just for profit. Encourage companies to introduce disruptive technologies and new business models, especially techno waste reuse and recycling technologies edition, the model shifts from ownership to consumption based on a pay-per-use approach. CBM helps change and shape consumer behavior and identifies critical behaviors needed for working CBMs.

2.1.4. development of circular economy in the world

The development of the CE has gained significant momentum worldwide in recent years, with various governments, businesses, and organizations recognizing its potential to promote sustainable growth, resource efficiency, and waste reduction. The CE aims to design out waste and pollution, keep products and materials in use, and regenerate natural systems. Several key initiatives and milestones have contributed to the development of the CE at a global level:

1. **European Union**: The EU has been a frontrunner in promoting the circular economy through policy and regulations. In 2015, the European Commission adopted the Circular Economy Action Plan, which included measures to strengthen product durability, recycling, and waste management (European Commission, 2015). In 2020, a new Circular Economy Action Plan was introduced as part of the European Green Deal to further advance circularity across industries (European Commission, 2020).
2. **China**: China's government has recognized the importance of the circular economy in its national strategy. The country has implemented policies like the Circular Economy Promotion Law (2008) and incorporated CE principles into its five-year plans to reduce waste, increase recycling rates, and improve resource efficiency (China's National Development and Reform Commission, 2008).
3. **Ellen MacArthur Foundation**: Established in 2010, this UK-based foundation has played a pivotal role in raising awareness about the CE and developing frameworks for its implementation. They collaborate with governments, businesses, and academia to accelerate the transition to a circular economy.
4. **Global corporations**: Many leading companies, such as Philips, Google, Unilever, and IKEA, have embraced CE strategies by creating innovative business models, designing products for longevity and recyclability, and collaborating within their supply chains to minimize waste and resource consumption.
5. **Plastic waste initiatives**: The issue of plastic pollution has driven many efforts to develop circular solutions for plastics. For instance, the New Plastics Economy Global Commitment, led by the Ellen MacArthur Foundation and the UN Environment Programme, unites businesses, governments, and NGOs in a commitment to eliminate plastic waste and pollution at its source (The New Plastics Economy Global Commitment, 2022).
6. **Circular Cities**: Cities around the world are adopting CE principles to address challenges related to waste management, energy, water, and transportation. Examples include Amsterdam, San Francisco, and London, which have

developed action plans and specific targets to implement circular strategies at the local level (Calisto Friant et al., 2022).

7. **International cooperation:** Multilateral organizations, such as the United Nations, World Bank, and Organization for Economic Cooperation and Development (OECD), have recognized the potential of the CE for achieving the Sustainable Development Goals (SDGs) and addressing global environmental challenges.

These initiatives and milestones demonstrate the growing recognition of the CE as a viable pathway toward sustainable development. As the concept continues to gain traction, more countries, cities, and businesses are expected to adopt circular strategies and contribute to a global transformation.

2.2. Sustainability

2.2.1. Sustainable development

In 1980, in the "World Conservation Strategy" published by the International Union for Conservation of Nature and Natural Resources (IUCN), the goal of sustainable development was “Achieving sustainable development by protecting biological resources” and the term sustainable development is mentioned here with a narrow content, emphasizing the sustainability of development in terms of ecology. It was called for the conservation of biological resources (IUCN et al., 1980). Until 2002, at the World Summit on Sustainable Development held in Johannesburg (Republic of South Africa) "Sustainable development" was a development process with a close, reasonable and harmonious combination of the three aspects of development, including economic development (economic growth), social development (implementation of social progress and justice; poverty alleviation and job creation), and environmental protection (treatment and remediation of pollution, restoration, and improvement of environmental quality; prevention of fire and deforestation; rational exploitation and economical use of natural resources) (United Nations, 2002). In 2015, the 2030 Agenda for Sustainable Development, adopted by all United Nations Member States, set forth a common plan for peace and prosperity for people and the planet, currently and in the future (United Nations, 2015). At its heart are the 17 Sustainable Development Goals (SDGs), which are an urgent call to action by all countries - developed and developing - in a global partnership .

The concept of sustainable development is gradually formed from the reality of social life and is inevitable. In principle, sustainable development is the process of operating at the same time three development aspects: sustainable economic growth, prosperous society, equity, stability, diverse culture, and a healthy environment. resources are maintained sustainably. Therefore, the complete system of ethical principles for sustainable development includes principles of sustainable development in all "three pillars" of economy, society, and environment. Economically sustainable development is fast, safe, and quality development.

Socially sustainable development is assessed by criteria such as the Human Development Index (HDI), income equality coefficient, indicators on education, health, social welfare of society, and enjoying the culture. Environmentally sustainable development includes the following basic contents. Firstly, to effectively use natural resources, especially non-renewable resources. Second, development does not exceed the load-bearing threshold of the ecosystem. Third, to protect biodiversity, protect the ozone layer. Fourth, control and reduce greenhouse gas emissions. Fifth, closely protect sensitive ecosystems. Finally, reduce discharge, overcome pollution (water, gas, soil, food), and improve and restore the environment of polluted areas.

2.2.2. 17 goals of SDG

The SDGs are a set of 17 interconnected global goals adopted by the United Nations General Assembly in 2015 as part of the 2030 Agenda for Sustainable Development (United Nations, 2015). The main objective of the SDGs is to promote sustainable development by addressing various interrelated challenges, including poverty, inequality, environmental degradation, climate change, and social injustices.

Each SDG has specific targets aimed at achieving the broader ambitions outlined by the goal. The SDGs encompass 169 targets in total, which provide measurable outcomes and indicators to track progress towards the goals.

Figure 2.5. 17 sustainable development goals

17 SDGs include:

1. No Poverty: End poverty in all its forms everywhere.

2. Zero Hunger: End hunger, achieve food security and improved nutrition, and promote sustainable agriculture.
3. Good Health and Well-being: Ensure healthy lives and promote well-being for all at all ages.
4. Quality Education: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
5. Gender Equality: Achieve gender equality and empower all women and girls.
6. Clean Water and Sanitation: Ensure availability and sustainable management of water and sanitation for all.
7. Affordable and Clean Energy: Ensure access to affordable, reliable, sustainable, and modern energy for all.
8. Decent Work and Economic Growth: Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all.
9. Industry, Innovation, and Infrastructure: Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.
10. Reduced Inequalities: Reduce income inequality within and among countries.
11. Sustainable Cities and Communities: Make cities and human settlements inclusive, safe, resilient, and sustainable.
12. Responsible Consumption and Production: Ensure sustainable consumption and production patterns.
13. Climate Action: Take urgent action to combat climate change and its impacts.
14. Life Below Water: Conserve and sustainably use the oceans, seas, and marine resources for sustainable development.
15. Life on Land: Protect, restore, and promote sustainable use of terrestrial ecosystems, manage forests sustainably, combat desertification, halt and reverse land degradation, and halt biodiversity loss.
16. Peace, Justice, and Strong Institutions: Promote peaceful and inclusive societies for sustainable development, provide access to justice for all, and build effective, accountable, and inclusive institutions at all levels.
17. Partnerships for the Goals: Strengthen the means of implementation and revitalize the global partnership for sustainable development.

These goals and targets are designed to be universal, integrated, and indivisible, meaning they apply to all nations and require collaborative efforts to create a better, more sustainable future for everyone.

2.3. Background of Life Cycle Thinking and MFA

"Life cycle thinking" is a comprehensive approach that evaluates the ecological impact of a product (for example, biodiesel), throughout its complete life cycle, comprising the stages of raw material extraction and final disposal. This approach commences with the extraction of natural resources and culminates in the transformation of said resources into the ultimate product through the process of design and development, which is customised to fulfil its designated function (European Commission, 2010). Then, these goods are disseminated to their respective destinations, such as residential areas for electricity or petrol stations for biofuel. Upon reaching the end of their useful life or following maintenance, physical products are subject to meticulous management before disposal. This may involve categorising to identify opportunities for possible reuse. Some materials can be recovered, and certain components can be recycled for use in production. Into landfills goes anything that cannot be reused, recycled, or recovered.

There may be a variety of emissions and pollution at each stage of this product's life cycle, which contribute to environmental impacts from beginning to end. LCT, as illustrated in Figure 2.6, places significant emphasis on the recovery, reuse, and recycling of basic materials derived from natural resources before their disposal in landfills or incinerators. Through the implementation of this methodology, individuals can acquire a deeper understanding of possible emissions as well as the possibilities for recovering, reusing, and recycling components. By adopting this methodology, adverse effects can be mitigated, and advantages can be maximised, all while aiming to reduce ecological repercussions. In the end, sustainable strategies for a given product or system are produced (UNEP, 2012).

LCT takes a comprehensive view of a product's environmental impacts by considering its entire life cycle. This includes production, consumption, reuse/recycling, and disposal of the product (e.g., biofuel). The approach helps develop sustainable strategies for products or systems by understanding their potential emissions, recovery, reuse, and recycling possibilities while minimizing negative impacts.

Below is the description of the life cycle approach, as illustrated in Figure 2.6:

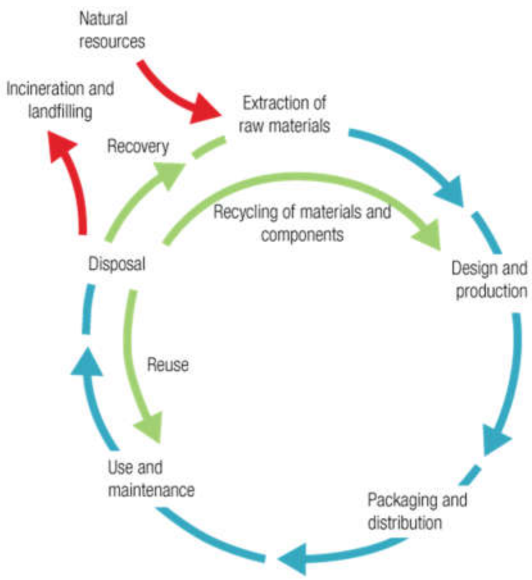


Figure 2.6. Life cycle approach

1. Raw materials extraction: Raw materials are obtained from the natural environment.
2. Design and development: Materials are converted into useful products according to end-user requirements.
3. Distribution: Products are transported to their intended locations (e.g., gas pumps for biofuel, homes for electricity).
4. Use and maintenance: Products are utilized and might undergo maintenance if necessary.
5. Disposal:

- Reusing: Some components may be repurposed for other uses, mainly in the case of physical products.
- Recycling: Some parts of the disposed product could be recycled for use in the production process.
- Recovery: Some materials may be recovered from the product.
- Landfill or incineration: Components with no possibility for reuse, recycling, or recovery are forwarded to landfill or incinerated.

Throughout each stage of the product life cycle, there can be potential waste and emissions. LCT focuses on maximizing resources and energy recovery, reuse, and recycling before disposing of them in landfills or through incineration. By adopting this perspective, practitioners can minimize environmental impacts and create more sustainable products or systems (UNEP, 2012).

In the last years, three main "dimensions" of LCT have been developed, according to the three dimensions of sustainable development:

- Environmental dimension: Life Cycle Assessment.
- Economic dimension: Life Cycle Costing (LCC).
- Social dimension: Social Life Cycle Assessment.

Besides that material flow analysis (MFA) is considered a helpful method to measure environmental impact and the level of CE (Moraga et al., 2019).

2.3.1. LCA

An objective method for assessing the environmental impacts of a product, process, or activity, the LCA identifies the energy and materials consumed, as well as the wastes discharged into the environment. Its purpose is to identify potential avenues for environmental improvement and facilitate their implementation (Finkbeiner et al., 2006). LCA is a methodology utilized to quantitatively assess and evaluate the environmental impacts linked to the complete life cycle of a product (Rebitzer et al., 2004). These consequences may include but are not limited to the following: eutrophication, acidification, depletion of resources, water and land use, noise pollution, and stratospheric ozone depletion and creation (smog)—Rebitzer et al. (2004) list.

Typically, the design/development phase is omitted from LCAs on the assumption that its contribution is negligible. However, it should be noted that the environmental impacts of the subsequent life cycle stages are significantly impacted by the decisions made during the design and development phase. The behaviour of a product in subsequent phases is significantly influenced by its design. For instance, the fuel consumption and emissions per kilometre driven by an automobile during its use phase are essentially determined by its design. Furthermore, the feasible recycling options at the end-of-life stage are also substantially impacted by this design. The assessment covers the full life cycle of the product, process, or activity, which includes the extraction and processing of raw materials, manufacturing, transportation, and distribution, as well as use, reuse, and maintenance. Additionally, it considers recycling and final disposal, adhering to the 'cradle-to-grave' concept.

According to the ISO 14040 and 14044 standards (Finkbeiner et al., 2006; Rebitzer et al., 2004), a LCA is carried out in four phases: goal and scope definition, inventory analysis, impact assessment; and interpretation (figure 2.7).

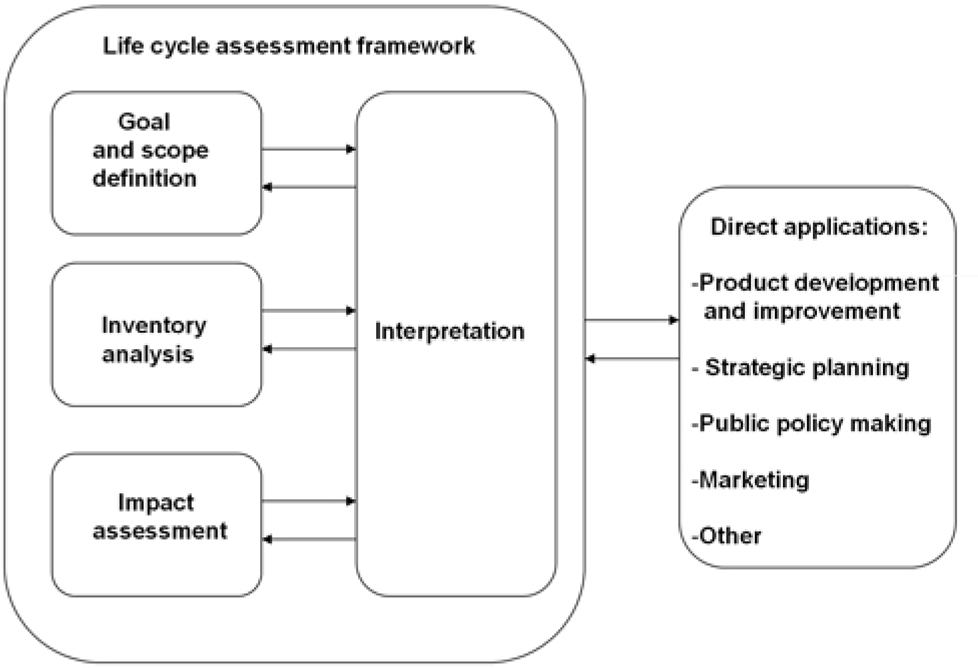


Figure 2.7. The framework of life cycle assessment (source: ISO 14040)

The scope, boundary, and level of detail of an LCA are determined by the objectives and intended applications of the study (Finkbeiner et al., 2006). Despite variations in the depth and breadth of details included in different analyses, the fundamental framework remains consistent. In the initial stage, the analyst's task is to define the functional unit, which precisely delineates the product or process under investigation. The functional unit typically extends beyond a mere quantity of material. For instance, it might encompass various packaging options based on 1 m^3 of the packed and delivered product. All process flows that take in information and send it out are linked to this functional unit (Rebitzer et al., 2004). This unit must be clearly defined so that it is easy to compare different studies that use the same data.

A life cycle inventory (LCI) is a methodical procedure used to estimate the levels of resource consumption, waste production, and emissions that are either directly or indirectly linked to the life cycle of a specific product (Rebitzer et al., 2004). As a proportion of the total emissions, the quantity of resources consumed and waste or emissions produced are likely to fluctuate at any given site (for instance, the proportion required to supply a specific functional unit or the distribution of related and unrelated byproducts in a facility such as a refinery); at various times (for instance, during operation versus disposal of a vehicle); and over various periods (for instance, multiple periods). It is feasible to develop models that illustrate the product system's interactions with and impacts on the natural environment via the material and energy fluxes and processes of the life cycle. The results of this procedure are a product system model and a catalogue of environmental exchanges linked to the functional unit.

Life cycle impact assessment (LCIA) (Rebitzer et al., 2004) provides the foundation for analysing the potential contributions of resource extractions and wastes/emissions in an inventory to a variety of potential impacts through the use of indicators and metrics. The LCIA yields a functional unit-based evaluation of a product's life cycle concerning a variety of impact categories (e.g., land use, toxicological stress, climate change, noise, etc.) and, in certain instances, an aggregated evaluation (e.g., years of human life lost as a result of noise, carcinogenic effects, climate change, etc.).

Based on Rebitzer et al., the interpretation of the life cycle is indispensable at each phase of a LCA (Rebitzer et al., 2004). In situations where there are two product options and one of them uses more materials and resources than the other, the Life Cycle Inventory (LCI) can be very insightful when used alone. However, there are instances in which comparing the environmental impacts of various product types may be useful. Examples include situations in which trade-offs exist between various product types or when specific concerns must take precedence in a life cycle study. For example, carbon dioxide emissions from one life cycle may have a greater effect on the climate change indicator than emissions from another life cycle, but the latter may require more pesticide use and have more unfavourable outcomes. In these situations, stakeholders might need more details to determine which distinction requires more focus.

2.3.2. LCC

LCC (Life cycle costing) is an economic analysis method employed to assess the comprehensive expenses linked to a given engineering project, product, or asset throughout its complete life cycle (Yang et al., 2020). LCC facilitates effective decision-making for stakeholders concerning investment plans, maintenance strategies, and overall cost efficiency by taking into account all expenses accrued throughout the asset's existence. The methodology takes into account initial capital outlays, prospective further capital outlays, yearly recurring expenses, and the asset's potential salvage value upon its useful lifespan (Woodward, 1997) (Miah et al., 2017).

The fundamental aims of life cycle costing are as follows:

1. Facilitating informed decision-making: furnishing decision-makers with exhaustive cost data to enable them to evaluate and contrast different designs, products, or projects in terms of their enduring financial consequences.

2. Cost optimisation entails the identification of opportunities to decrease expenses throughout the entire life cycle. This may involve instituting energy-efficient solutions, optimising maintenance strategies, or enhancing design.

3. Risk management: For more precise financial planning, anticipating potential risks and variables throughout the asset's useful existence and developing strategies to mitigate these risks.

4. Sustainability encompasses the optimisation of resource utilisation, waste reduction, and mitigation of adverse environmental effects through the incorporation of long-term economic ramifications into the design and execution of products or projects.

LCC is an influential factor in numerous sectors, such as energy management, construction, manufacturing, and transportation. Incorporating LCC analysis into the decision-making process can help organisations achieve greater long-term return on investment, enhanced sustainability, and improved cost management.

LCC is a process that can be implemented across multiple domains of organisational decision-making. A few examples consist of the following: LCC assists in the computation of present value net cash flows, total cost of ownership, and expected return on investment (ROI), all of which contribute to the formulation of well-informed capital budgeting decisions concerning asset acquisition. Through an analysis of the total cost of ownership, procurement personnel are able to choose products that incur the least amount of combined expenses for installation, operation, maintenance, and disposal. This ultimately results in financial savings. LCC guides the development of products that incur minimal expenses for consumers throughout their lifecycle, thereby informing the engineering and production processes of design and manufacturing. Life cycle costing aids in the reduction of warranty, replacement, and field service work for customers by identifying products that have diminished long-term servicing needs.

Businesses that prioritise strategic foresight are more inclined to implement life cycle costing methodologies, thereby guaranteeing optimal returns on their investments spanning multiple years. On the contrary, organisations that place a higher emphasis on immediate cost reductions might fail to consider LCC, which could ultimately lead to increased servicing expenses and a decrease in profits. Organisations can foster sustainable practices and improve their long-term financial performance by incorporating life cycle costs into their decision-making processes.

According to different classification criteria, there are three methods to classify LCC, which are content dependence, time dependence, and cost dependence (Yang et al., 2020).

Based on content, the LCC could be divided into four categories, which are operation cost, utility cost, and investment cost (figure 2.8).

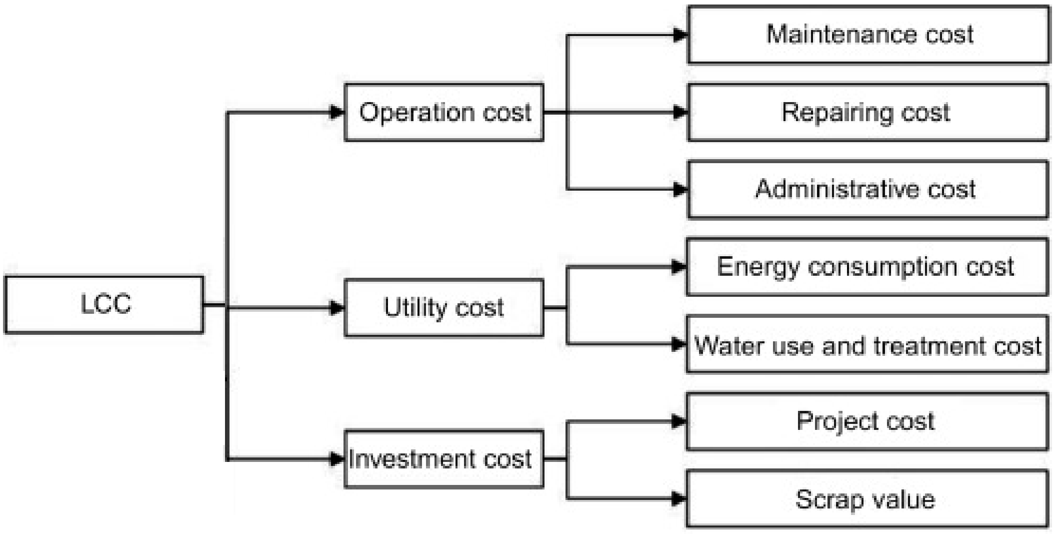


Figure 2.8. Costs of LCC based on content (Yang et al., 2020)

In the context of time dependence, the LCC classifies costs into two distinct categories: initial cost and future cost as shown in Figure 2.9 (Yang et al., 2020). Initial cost represents the sum of all expenses incurred before the equipment's use, whereas future cost encompasses the expenses incurred from the time the equipment is placed into operation until it is discarded. The prospective cost is composed primarily of one-time and recurring expenses. Nonrecurring costs, also known as nonannual costs, comprise the total amount of expenditures required to maintain the apparatus in optimal condition once it begins operation. The accumulated cost devoted every year to ensure the apparatus operates efficiently, including maintenance, operating, administrative, and repair expenses, is the repetitive cost (annual cost).

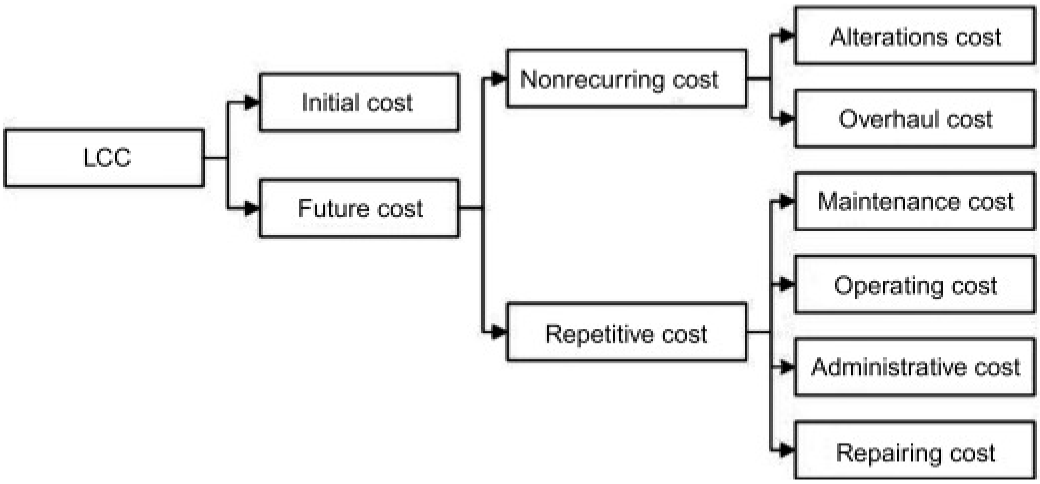


Figure 2.9. Costs of LCC based on time dependence (Yang et al., 2020)

An LCC could be subdivided into the following three categories: operation and maintenance cost, alternative cost, and construction cost, taking into account cost dependence. In order to define the cost function, this classification also encompasses certain subclasses. To facilitate observation and cost analysis, each expense can be represented by a tree diagram, wherein distinct equipment comprises unique costs.

2.3.3. S-LCA

The S-LCA (Social Life Cycle Assessment) is a method employed to assess the social and environmental aspects of products, considering their present and potential positive and negative impacts throughout their life cycle, as discussed by Yang et al. in 2020 (Yang et al., 2020). This assessment covers the entire product life cycle, encompassing stages such as extraction and processing, manufacturing, distribution, use, reuse, maintenance, recycling, and ultimate disposal. In addition to the Environmental Life Cycle Assessment (E-LCA) and LCC, S-LCA utilises both generic and site-specific data and can be of a quantitative, semi-quantitative, or qualitative nature. It may be implemented independently or in conjunction with the remaining methodologies.

Although S-LCAs do not provide definitive answers regarding the necessity of manufacturing a product, they provide valuable information for contemplation that can assist in the decision-making process. While S-LCAs adhere to a structured framework, specific elements exhibit variability, greater prominence, or increased significance during each phase of the investigation. The United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) introduced a methodology in 2009 for developing life cycle inventories (UNEP/SETAC, 2009). This method encompasses the creation of an indicator-based life cycle inventory, incorporating impact categories such as local employment and utilising indicators like the number of jobs generated. These impact categories are associated with five primary stakeholder groups: (1) workers, (2) consumers, (3) local communities, (4) society, and (5) participants in the value chain.

Table 2.2. Stakeholder categories and subcategories (UNEP/SETAC, 2009)

Stakeholder categories	Subcategories
Stakeholder "worker"	Freedom of Association and Collective Bargaining Child Labour Fair Salary Working Hours Forced Labour Equal opportunities/Discrimination Health and Safety Social Benefits/Social Security
Stakeholder "consumer"	Health & Safety Feedback Mechanism Consumer Privacy Transparency End of life responsibility
Stakeholder "local community"	Access to material resources Access to immaterial resources Delocalization and Migration Cultural Heritage Safe & healthy living conditions Respect for indigenous rights Community engagement Local employment Secure living conditions
Stakeholder "society"	Public commitments to sustainability issues Contribution to economic development Prevention & mitigation of armed conflicts Technology development Corruption
Value chain actors not including consumers	Fair competition Promoting social responsibility Supplier relationships Respect for intellectual property rights

2.3.4. MFA

MFA is an evaluation method which assesses the efficiency of the use of materials using information from material flow accounting. MFA is a systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner & Rechberger, 2004) (Nakem et al., 2016). MFA is instrumental in uncovering the wastage of natural resources and other materials within the economy, often escaping detection by conventional economic monitoring systems.

The core principle of MFA is the conservation of mass, enabling the application of mass balance to any process and stock within the system (Barkhausen et al., 2023). This is achieved by meticulously tracking the inflows and imports and contrasting them with the outflows and exports, ensuring that materials are accounted for throughout the entire system. MFA studies encompass a broad spectrum of goals and objectives, spanning from the micro-level to the macro-level. An MFA system serves as a model for an industrial plant, an industrial sector, or a specific region of interest. The degree of intricacy in the system model is determined based on the study's intended purpose.

An MFA system always consists of the system boundary, one or more, material flows between processes, and stocks of materials within processes (Seyhan & Brunner, 2018). The physical exchange between the system and its environment happens via flows that cross the system boundary. Contrary to the preconceived notion that a system represents a specific industrial installation, systems and processes in MFA can represent much larger and more abstract entities as long as they are well-defined. The explicit system definition helps the practitioner locate the available quantitative information in the system, either as stocks within certain processes or as flows between processes. A description of an MFA system can be enhanced by breaking down processes into more detailed components (disaggregation) or streamlined by combining processes into broader categories (aggregation).

2.4. Decision support system

2.4.1. Defining decision support system

The principles associated with DSS were initially formulated in the early 1970s by Michael S. Scott Morton, referred to as "management decision systems" (Sprague, 1980). Several companies and scholars initiated the development and research of Decision Support Systems (DSS), which evolved into systems characterized as interactive, computer-based tools designed to assist decision-makers in utilizing data and models to address unstructured problems. The unique contribution of DSS resulted from these keywords. That definition proved restrictive enough that few actual systems completely satisfied it. Some authors recently extended the definition of DSS to include any system that makes some contribution to decision-making; in this way, the term can be applied to all but transaction processing. A significant challenge in defining DSS is that the terms possess a degree of "intuitive validity." Essentially, any system that aids in making decisions, regardless of how it does so, may be categorized as a "Decision Support System."

The concept of DSS is extremely broad and its definition varies:

“Interactive computer-based systems intended to help decision makers use data, documents, knowledge and models to identify and solve problems and make decisions.” (Power, 2002)

“A system used to support managerial decisions. Usually, DSS involves the analysis of many units of data in a heuristic fashion. As a rule, DSS processing does not involve the update of data.” (Inmon, 2002)

“Commonly known as DSS databases, these support decisions, generally more management-level and even executive-level decision-type of objectives.” (Powell, 2006)

“A decision support system (DSS) is a computer-based system that combines data and decision logic as a tool for assisting a human decision-maker.” (Crossland, 2008)

“A branch of the broadly defined management information system (MIS). It is an information system that provides answers to problems and that integrates the decision maker into the system as a component. The system utilizes such quantitative techniques as regression and financial planning modelling. DSS software furnishes support to the accountant in the decision — making process.” (Shim & Siegel, 2009)

“A DSS is an interactive computer-based system or subsystem intended to help decision makers use communications technologies, data, documents, knowledge, or models to identify and solve problems, complete decision process tasks, and make decisions.” (Daniel J. Power & Ciara Heavin, 2017)

“A computer-based information system that supports individual or team decision making. Five primary types: communications-driven, data-driven, document-driven, knowledge-driven, and data-driven DSS.” (Power, Daniel & Heavin, Ciara, 2018).

“A decision support system (DSS) is a scientific tool to assist decision-making in a specific form. It provides decision-makers with a working environment that combines knowledge, initiative, creativity, and information processing ability and combines qualitative and quantitative methods through human–computer dialogue. It helps decision-makers analyze problems, explore decision-making methods, and conduct evaluation, prediction, and optimization.” (Hou et al., 2023)

2.4.2. Decision support system benefits and components

DSSs play a crucial role in error reduction and workflow efficiency enhancement. They expedite important decision-making processes, resulting in a more productive work shift by reducing the time required for crucial decisions. Furthermore, these systems assist professionals in making decisions by providing predictions and data, which contribute to minimizing errors and unfavourable outcomes, thus further enhancing workflow. Additionally, decision support systems contribute to improved planning and higher management effectiveness. Many of these systems offer precise plans based on data, facilitating error correction and the initiation of new processes, thereby lightening the managerial load. Furthermore, these systems enable professionals to gauge the potential impact of their decisions. By analyzing historical data and current trends, they can offer informed predictions regarding the effects of a decision on the organization or its clients. This understanding of potential outcomes empowers professionals to select the most optimal course of action.

These are the three main components in DSSs (Güvenç et al., 2015; Power, 2002; Xambre et al., 2016):

Database: Every DSS incorporates a database, with some categories having more extensive databases or relying more heavily on them. The database serves as a foundational element of the DSS, enabling the system to swiftly analyze large volumes of data when assisting in decision-making. The database's content varies based on the system's category and the industry it caters to. Some databases may contain statistical data, while others may be more document-oriented.

Models: DSS systems also generate models to support professionals in making decisions that positively influence their situation. These models, established within the DSS, represent predictions or projected outcomes that the program deems plausible. They provide professionals with insights into how their decisions can impact their situation, clients, or organization. The DSS relies on the database to create accurate models, which can represent variables related to the organization's business plan, competitors' actions, or professional relationships.

User Interface: The user interface serves as the point of access for individuals utilizing the DSS. Effective DSS systems feature flexible and intuitive user interfaces, allowing professionals to access necessary information and operate the system without requiring extensive technical expertise. For instance, a financial expert's user interface may provide clear guidance on running projections and requesting models from the system.

2.4.2. The process of developing a DSS

According to Bui, the process of developing a DSS often revolves around five building blocks (Bui, 2002):

1. Information resource management.

In software engineering terms, input data are required for decision analysis and resolution; output data are generated and presented to decision-makers for policymaking. Effective management of these data constitutes the first major task of any decision support tool.

2. Model management.

A model serves as a conceptual representation of reality designed to assist decision-makers in directing their attention towards the principal components of a given problem. Multiple objective optimizations under constraints is a classic modelling approach in management science. Alternate approaches for decision formulation include qualitative reasoning, expert heuristics, and data mining methodologies. Given a decision problem, the challenge of DSS is to find the best decision method(s) able to suggest a satisfying solution to policymakers.

3. Interactive problem solving.

Direct interaction between the DSS and its user allows for a more responsive and user-centred view of the problem. A good DSS provides the right information to the right person at the right time with full transparency. Decision-making frequently entails the involvement of multiple decision-makers, and the provision of support for communication and coordination represents a crucial dimension of Decision Support Systems (DSS).

4. Communications and teamwork support.

Decision-making frequently involves multiple decision-makers, and effective support for communication and coordination stands as a crucial dimension within the framework of DSS. Support for information exchange, federated organizational memory, group decision and negotiation is an integral component of organizational decision support.

5. DSS as non-human co-workers.

In a tightly connected networked world, we postulate a working scenario in which humans will team up with computers as coworkers to optimize the execution of business decisions (Negroponte 1995). We envision a new social structure that emerges from the interaction of individuals— both humans and non-humans — operating in a goal-oriented environment under rules that place only bounded demands on each individual's information and computational capacity (Bui 1999). In the multi-dimensional context of sustainable development, various DSS, such as those reported in this book, could serve as task-specific aids to policymakers.

The immediate benefit of employing these five building blocks is to enhance the decision outcomes for users of DSS. To fulfil its support mission, a DSS should assist its users by emphasizing the importance of high-quality input data. Enhanced data quality is anticipated to contribute to a more comprehensive assessment of the problem situation and a more diverse array of decision alternatives. The utilization of more sophisticated decision algorithms is anticipated to empower decision-makers in uncovering solutions that might have otherwise remained elusive. Expansive real-time trade-off analyses and interactive simulations are expected to provide decision-makers with further insights. Communication and group decision support is expected to increase the chance of finding a shared vision and socially equitable solution. Ultimately, a computerized coordinated DSS workflow should seamlessly augment the integration of sustainable development on a national or global scale.

2.4.3. Trade-offs and Unexpected Consequences of decision making relevant to CE, LCT and sustainability development

It has been demonstrated that when unanticipated consequences ensue, decisions made with a limited perspective on a problem can be counterproductive and, in extreme circumstances, steer society in the incorrect direction (UNEP/SETAC, 2012). While trade-offs are an intrinsic aspect of the decision-making process, adopting a life cycle perspective provides a more comprehensive understanding of the matter at hand. An analysis of the complete value chain can facilitate the identification of acceptable and intolerable trade-offs, as well as reveal unforeseen repercussions that may arise at different points along the chain, influencing other facets of sustainability, foreign societies, and beyond. Life cycle assessment, owing to its comprehensive, methodical, and systemic characteristics, is an indispensable instrument for generating insights and enhancing our knowledge of the potential and actual consequences that may occur throughout a product's lifetime. Consequently, this raises the possibility of augmenting the overall sustainability of the product.

Potential trade-offs may be classified into the following categories (UNEP/SETAC, 2012):

a) Trade-offs among phases of the product value chain

A product and its constituents may travel thousands of kilometers and pass through the hands of hundreds or thousands of individuals prior to their ultimate disposal phase, beginning as a raw material extracted from the Earth. Each component of the product value chain may be impacted by decisions such as which primary material to utilise. As an illustration, contemplate a vehicle constructed from lightweight composite materials as opposed to conventional steel. Although the fuel efficiency of a lighter vehicle can be advantageous, it is critical to evaluate the environmental impact of composite material production, disposal, and recycling in comparison to conventional steel. This assessment is imperative in order to ascertain the alternative that yields greater societal and environmental benefits.

b) Trade-offs between categories of environmental impact

Land, water, and oxygen are essential components in both the product life cycle and the human life cycle. Inadvertently endangering another of these environmental aspects, decisions intended to safeguard one may have far-reaching consequences for human health. MTBE (Methyl Tertiary Butyl Ether), which is commonly added to petrol to increase octane and enhance combustion, thereby reducing emissions, is a classic example. MTBE in gasoline can reduce ozone precursors by 15%, benzene emissions by 50%, and CO emissions by 11%. Although MTBE aids in the reduction of air pollution, incomplete combustion can render it toxic. Numerous states in the United States have enacted bans on MTBE (UNEP/SETAC, 2012), predominantly on the grounds that its presence in reservoirs, lakes, and groundwater endangers potable water supplies.

c) Balanced trade-offs among sustainability pillars—environmental, social, and economic

When envisioning a circular economy where the ultimate purpose of products and services is to benefit society and the environment throughout its life cycle, it is crucial to account for the comprehensive expenses associated with environmental protection and equitable labour practises. Alternatively stated, the manufacturing process of a product ought to be devoid of any detrimental effects on the environment or the individuals engaged in the value chain. The global textile and electronics industries, for instance, have faced scrutiny due to their production of affordable clothing and electronic equipment, which brings economic benefits to various global enterprises and their consumers, while using inappropriate labour practices that are socially detrimental to the people working in the production of these items (UNEP/SETAC, 2012). In a divergent scenario, organic farming not only exhibits lesser environmental impact compared to conventional farming methods, particularly in terms of chemical usage but also has the potential to enhance farmers' working conditions and contribute to overall health benefits for society.

d) Trade-offs between societies/regions

Within the context of a globalised economy, product value chains are dispersed throughout various nations. Thus, decisions implemented to tackle a problem in one region may have unanticipated repercussions in other global areas. As an illustration, "one person's waste is another person's gold" could be applied to electronic waste (e-waste), given that electronics comprise numerous recyclable and valuable materials (e.g., copper). The exponential growth of electronic product innovation and the escalating demand for electronic goods over the last twenty years have contributed to the generation of progressively larger quantities of electronic refuse that necessitate recycling. In certain developing nations, however, the process of recovering the "gold" from e-waste recycling has incurred significant environmental and social consequences. Certain developed nations implemented regulations regarding the recovery and recycling of electronic waste (e-waste). As a result, substantial quantities of e-waste were recycled illicitly in developing countries, where the hazardous waste releases contained toxic substances and harmed both the environment and the individuals engaged in the recycling activities. EU-approved directives from 2012 have bolstered prohibitions on the exportation of electronic refuse (UNEP/SETAC, 2012).

e) Generational trade-offs

Sustainable development entails present-day decision-making that safeguards the capacity of future generations to fulfil their own requirements. The Native American Ojibwe tribe acknowledged this and, as a guiding principle, incorporated the well-being of seven generations of children into their decision-making process (UNEP/SETAC, 2012). On the contrary, the contemporary globalised economy, which is predominantly accountable for the current environmental crisis, generally regards time as a considerably shortened duration.

Long-term business decisions are typically formulated with a maximal time horizon of 10-20 years, which is shorter than one generation. The current climate change debate and the fluctuating international commitment to reduce greenhouse gas emissions are prime examples of this. Whether for better or worse, decisions taken now will have a profound effect on future generations and the long-term stability of the climate. In a contrasting instance, the positive consequence of incorporating future generations' interests into decisions regarding ozone layer depletion is evident. The consequence of eliminating ozone-depleting substances from consumer and industrial use following the Montreal Protocol (UNEP/SETAC, 2012).

2.5. Background of biomass supply chain for energy

2.5.1. Biomass types and biomass supply chain

According to Sherwood (2020), Biomass is considered the alternative organic feedstock to crude oil and natural gas and biomass is a general term applicable to all plant and animal-derived materials (Sherwood, 2020). Besides that, the European Commission (EC) considered that biomass is derived from organic materials such as trees, plants, and agricultural and urban waste. It can be used for heating, electricity generation, and transport fuels.

Biomass sources for energy comprise:

- Firewood, wood pellets, wood chips, sawdust and waste from lumber and furniture mills, as well as from pulp and paper mills.
- Agricultural crops and waste materials, including corn, soybeans, sugar cane, switchgrass, woody plants, algae, and residues from crop and food processing.
- Biogenic materials found in paper, cotton, wool products, as well as in food, yard, and wood wastes.
- Animal manure and human sewage.

These biomasses are very different in their chemical-physical characteristics, which depend on the main product from which they originate, and their availability is linked to agricultural production. For the transformation of biomass, it is not enough to know its availability, but other aspects must be considered, such as:

• collection from places of origin

• transformation into products useful for energy enhancement

• the transfer to the place of final use.

The transformation process of biomass considers the association of material between the initial source and the end-user. It is typically comprised of some distinct processes called biomass supply chain (BSC) (Toka et al., 2010), including harvesting, collection, transportation, pretreatment, storage and end use. These processes are crucial for success of bioenergy production (Laínez-Aguirre et al., 2015; Yadav & Yadav, 2016).

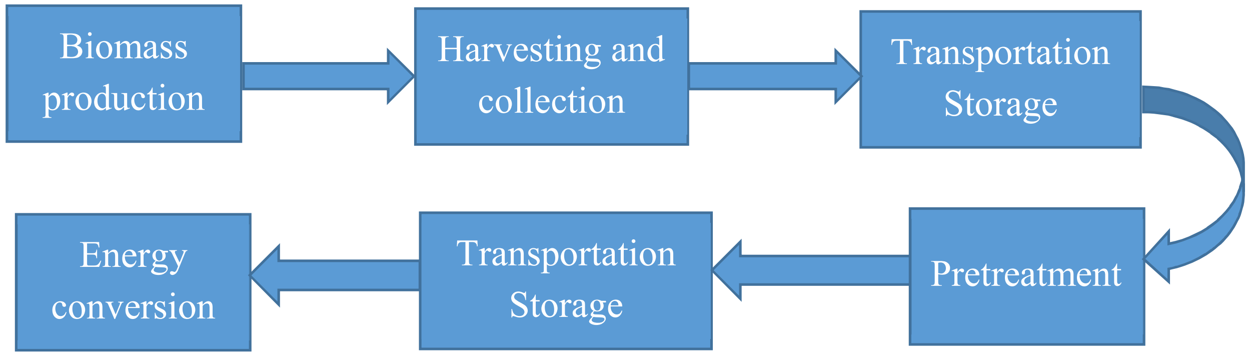


Figure 2.10. Stages of biomass supply chain

All these phases of the supply chain involve costs and sometimes technical difficulties, such as making accurate preliminary assessments necessary (Rapone et al., 2022). For example, transporting biomass to the energy conversion plant poses critical issues for containing procurement costs and fossil CO_2 emissions into the atmosphere. The influence is, however, negligible if the distances travelled are short or if any large distances are travelled by transporting large quantities of biomass (transport on ships). It has been calculated that road transport, even if prolonged (for articulated lorries and trucks of 27t, up to 1,000 km), negatively affects the CO_2 balance by no more than 10%; from the point of view of the environmental costs of transport, a CO_2 production of 0.22 kg/km is estimated for each ton of biomass transported (Rapone et al., 2022).

Among the biomasses destined for energy use, the most significant availability is represented by the residues of some specific agricultural food crops. These biomasses consist of all those parts of the plant that are not for food use. The residues originate from the operations carried out at the end of the crop cycle. The details used for energy transformation can be collected directly in the field, such as the stems of cereals (wheat, corn, rice, etc.). Industrial crops (sunflower, tobacco) or the branches and trunks derived from pruning and explants at the end crop cycle of fruit plants, or they can be recovered from product processing processes (grape stalks, bracts, rice husks, glumes, and glutes). The quantities of recoverable crop residues depend on many factors, including cultivated areas, crop productivity, and harvesting methods. In addition, the seasonality of the harvest and the possibility of storing the by-product also affect availability. The crop residues have intrinsic characteristics that differentiate them from the top products from which they derive and from any co-products. The main differences concern: the composition of the dry matter, water content at the time of collection, apparent density, lower calorific value (PCI) and content of ash and other minerals.

2.5.2. Energy biomass conversion technology

Biomass is converted to energy through various processes (Gupta & Agarwal, 2023; MacQueen, 2011; McKendry, 2002), including:

- Direct combustion (burning) to produce heat.
- Thermochemical conversion to produce solid, gaseous, and liquid fuels.

- Chemical conversion to produce liquid fuels.
- Biological conversion to produce liquid and gaseous fuels.

Direct combustion is the most common method for converting biomass to useful energy. All biomasses can be burned directly for heating buildings and water, for industrial process heat, and for generating electricity in steam turbines.

Thermochemical conversion of biomass includes pyrolysis and gasification (Tezer et al., 2022). Both are thermal decomposition processes in which biomass feedstock materials are heated in closed, pressurised vessels called gassifiers at high temperatures. They mainly differ in the process temperatures and amount of oxygen present during the conversion process.

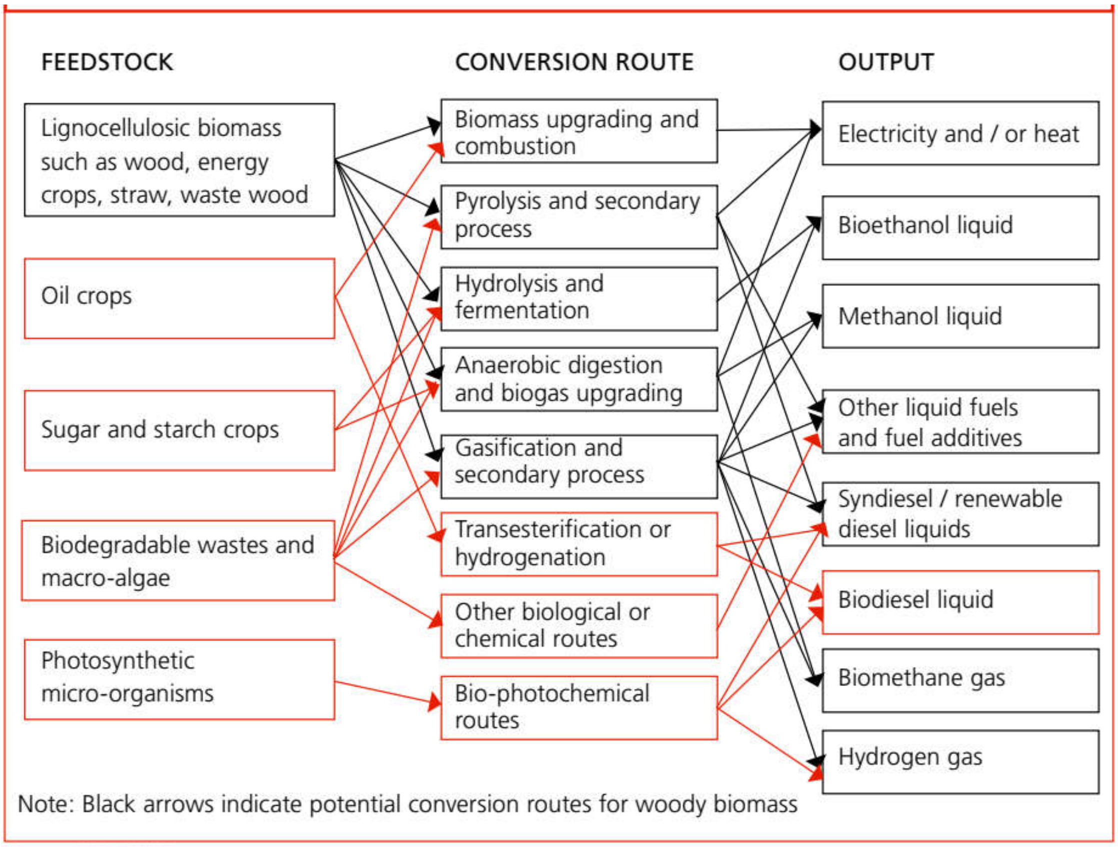
Pyrolysis entails heating organic materials to 400–500ºC in the near complete absence of free oxygen (Al-Rumaihi et al., 2022). Biomass pyrolysis produces fuels such as charcoal, bio-oil, renewable diesel, methane, and hydrogen.

Hydrotreating is used to process bio-oil (produced by fast pyrolysis) with hydrogen under elevated temperatures and pressures in the presence of a catalyst to produce renewable diesel, renewable gasoline, and renewable jet fuel.

Gasification entails heating organic materials to 800–900ºC with injections of controlled amounts of free oxygen and/or steam into the vessel to produce a carbon monoxide and hydrogen rich gas called synthesis gas, or syngas. Syngas can be used as a fuel for diesel engines, for heating, and for generating electricity in gas turbines. It can also be treated to separate the hydrogen from the gas, and the hydrogen can be burned or used in fuel cells. The syngas can be further processed to produce liquid fuels using the Fischer-Tropsch process.

A chemical conversion process known as transesterification is used for converting vegetable oils, animal fats, and greases into fatty acid methyl esters (FAME), which are used to produce biodiesel.

Biological conversion includes fermentation to convert biomass into ethanol and anaerobic digestion to produce renewable natural gas. Ethanol is used as a vehicle fuel. Renewable natural gas-also called biogas or biomethane-is produced in anaerobic digesters at sewage treatment plants and dairy and livestock operations. It also forms in and may be captured from solid waste landfills. Properly treated renewable natural gas has the same uses as fossil fuel natural gas.



Source: IEA, 2009a

Figure 2.11. Biomass conversion routes (MacQueen, 2011)

2.5.3. The role of biomass in the circular economy and sustainable development

Biomass holds a pivotal role in the circular economy, as highlighted by Sherwood (2020), contributing significantly to both material products and energy provision (Sherwood, 2020). To establish a circular bioeconomy, a thorough understanding of the practical implications of biomass utilisation is essential along the entire value chain, from product design to waste management. Plant-based biomass, serving as an alternative organic feedstock to crude oil and natural gas, is cultivated for various purposes, including food and animal feed, bio-based products, and renewable energy. Efficient reuse and recycling strategies are instrumental in managing the demand for biomass feedstocks, facilitating the substitution of unsustainable feedstocks with biomass in a circular bioeconomy.

Sustainable biomass is a prerequisite for a circular bioeconomy, ensuring the completion of the restoration cycle indefinitely (Sherwood, 2020). Certification agencies, emphasizing environmental sustainability, play a crucial role in assessing the sustainability of biomass across social, economic, and environmental domains. While certification schemes focus on current practices, they fall short in demanding operators to ensure the long-term viability of biomass production. Addressing fertilizers based on nitrogen, phosphorus, and potassium is vital, and optimistic projections suggest a significant reduction in mineral phosphate demand through phosphorus recovery from wastewater. A comprehensive approach is necessary to reduce biomass production's dependence on mineral reserves and natural gas-derived fertilizers.

Biomass, distinct from other renewable energy sources, serves as a material combusted for heat production or as a precursor to various products (Sherwood, 2020). Its usage in power stations as an energy source is increasingly prevalent. End-of-life biomass, particularly food waste, poses a notable concern due to its volume and emotional significance for consumers. Intercepting unavoidable food waste in the supply chain offers the potential to contribute to a circular bioeconomy by extracting valuable chemicals and materials for high-value products. Inedible food waste, subjected to various processes such as extraction, digestion, fermentation, chemical modification, and pyrolysis, can yield bio-based intermediates that align with the thermodynamic products of carbohydrate pyrolysis and dehydration.

Blair et al. (2021) underscore the crucial role of sustainably sourced biomass for bioenergy generation in supporting sustainable development, as reliance on this resource continues to grow. While the direct contribution of biomass supply to SDG 7 (Affordable and Clean Energy) is evident, its impact extends meaningfully to other SDGs. Authors reveal that at least half of them contribute significantly to SDGs 8 (Decent Work and Economic Growth), 9 (Industry, Innovation, and Infrastructure), and 12 (Responsible Production and Consumption). Different supply chains exhibit varied contributions, with agricultural supply chains, including energy crops and residues, more likely to influence SDG 2 (Zero Hunger) and SDG 6 (Clean Water and Sanitation). Waste and forest supply chains, on the other hand, are more likely to impact SDG 15 (Life on Land). Moreover, biomass supply for bioenergy generation indirectly contributes to socioeconomic-focused SDGs such as SDGs 1 (No Poverty), 4 (Quality Education), 5 (Gender Inequality), and 10 (Reduced Inequalities). These findings have broader applications beyond energy generation and are relevant to key stakeholders in bioeconomy.

The implications of biomass supply for bioenergy generation and its alignment with SDGs extend beyond direct contributions, encompassing a broad spectrum of societal and environmental aspects. Applying these insights to biomass supplied for non-energy uses is essential, offering a valuable framework for various stakeholders in the bioeconomy. For instance, integrating existing indicator frameworks with SDGs can enhance project-level reporting on progress toward SDGs. The identified SDG targets can serve as a practical 'sustainability checklist' for developers and biomass suppliers, building a robust rationale for bioenergy and influencing collaborative efforts. Furthermore, understanding the likelihood and nature of interactions identified in these supply chains can inform the development of comprehensive policies that foster sustainable practices and contribute to the broader agenda of global sustainable development.

2.6. Prospects of developing DSS for biomass supply chain with Life cycle thinking approach

The development of a DSS tailored for the biomass supply chain, infused with the principles of LCT, promises a holistic understanding of the intricacies involved. This approach allows for a comprehensive assessment of the environmental, social, and economic aspects throughout the entire lifecycle of biomass, from its origin to its eventual disposal. Incorporating LCT into the DSS can help decision-makers gain the ability to optimise biomass utilisation, identifying and addressing inefficiencies or environmental hotspots at various stages of the supply chain. This not only enhances decision-making processes but also ensures that biomass is harnessed sustainably, aligning with the evolving demands of responsible resource management.

In addition to optimising resource utilisation, the DSS serves as a powerful tool to ensure compliance with sustainability standards and certifications. Certification agencies play a crucial role in assessing the sustainability of biomass production, and integrating their criteria into the DSS ensures that decisions align with current environmental standards. Furthermore, the system can act as a dynamic platform for continuous improvement, pushing the boundaries of sustainability beyond the constraints of existing certification practices. This forward-thinking approach establishes a solid foundation for long-term viability and resilience in biomass production.

The DSS's potential extends beyond mere optimisation; it can become a helpful tool for transforming the biomass supply chain into a more circular and resource-efficient system. By identifying opportunities to intercept and repurpose unavoidable food waste within the biomass supply chain, the DSS aligns with the principles of a CE. This integration contributes not only to waste reduction but also to a more sustainable and regenerative approach. Additionally, the DSS's ability to align biomass supply chain decisions with specific SDGs showcases its broader societal and environmental impact. This alignment underscores the importance of the biomass supply chain in contributing to global sustainability objectives.

Summarise, the development of a DSS for the biomass supply chain with a LCT approach represents a crucial step towards a more sustainable and resilient bioeconomy. The integration of LCT not only enhances decision-making processes but also positions biomass utilisation as a key player in the broader sustainability agenda. This innovative approach combines technological advancements with environmental stewardship, paving the way for a future where biomass contributes significantly to a sustainable and circular economy.

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CHAPTER III. LITERATURE REVIEW

During the research process, a review of previous studies related to the topic was also conducted. The research focused on reviewing two issues: the application of circular economy and life cycle thinking to the biomass supply chain, and decision support systems based on multi-criteria decision-making methods in the context of sustainability. The review of applying circular economy and LCT to the biomass supply chain aimed to discover the application of circular economy principles and circular business models to the supply chain. Additionally, the application of life cycle thinking in sustainability assessment for biomass chains was considered, along with criteria for evaluating sustainability and circularity. The review of applying MCDM to build decision support systems aimed to provide a comprehensive assessment of these methods in the context of sustainability. The advantages and disadvantages of MCDMs in calculating criteria weights and ranking options were considered. Based on these reviews, proposals for developing support systems for companies in the LCT-based biomass supply chain will be presented in the following chapters.

3.1. Brief review: application of life cycle thinking and circular economy principles for biomass supply chain

3.1.1. Objective

CE is the key to sustainability. The adoption of CE and CBMs is widely recognized as a significant approach in driving the sustainable development of companies and organizations within the supply chains (Rovanto & Bask, 2021). In the BSC (biomass supply chain), the adoption of biochemical extraction technologies and utilization of biomass waste for energy purposes are identified to contribute to the transition from the linear economy into CE (Ellen MacArthur Foundation, 2013). At the same time, the application of multiple bioenergy technologies contributes to reducing greenhouse gases (GHGs) in various energy consumption sectors, plays the role of carbon sinks for other economic sectors and helps to fully decarbonize the socio-economy (Lund et al., 2022), which is one of the important goals of sustainable development. Due to the importance of biomass materials and the potential contribution of BSC in the transition to CE and aiming at sustainable development, the practical application of these concepts in the BSC recently attracted more attention (Awasthi et al., 2020; Chew et al., 2021; Fuentes-Grünewald et al., 2021; Gonçalves et al., 2021; Sheldon, 2020).

The concept of CE was introduced in 1990 by Pearce and Turner. Accordingly, the CE is developed on the principle that *"everything is input to something else*“ (Pearce & Turner, 1991). The European Commission (2015) stated that *"in a CE, the product value and raw materials are maintained for as long as possible; waste and resource use are minimized, and resources are kept in the economy when a product has reached the end of its life cycle, to be used to continue to create even more value"* (Zabaniotou et al., 2015). Currently, the concept of CE identified by the Ellen MacArthur Foundation is widely accepted, which defines CE as a restorative or regenerative industrial system (Ellen MacArthur Foundation, 2013). CE operates on the philosophy of recreating natural systems and maximizing the useful lifetime of products, supplies, and materials, while minimizing waste and pollution. It replaces the "end of life" of materials with the concept of recovery, switching to renewable energy, no use of harmful chemicals, and minimizing waste through the design of materials, products, engineering systems, and business models (Ellen MacArthur Foundation, 2013).

The adoption of CE has several advantages in both short and long terms. Firstly, it minimizes the resource consumption and waste generation, which ultimately reduce the businesses' cost for resource purchase and waste management. These extra economic benefits might be used for other investment, for example innovating equipment and factory, improving working environment, creating employees' social benefits, etc. In the short-term, CE brings direct economic and social benefits for enterprises, employees and consumers. Secondly, the reduction of resource consumption, in the long term, will save the earth's limited resources, reduce relevant environmental impacts, and ensure the clean and green environment for the next generations.

The application of CE is acknowledged on three different levels, namely macro-level (cities, nations and global), meso-level (industrial parks), and micro-level (products, enterprises, consumers). In general, it is presented in 10 principles, including reduce, reuse, recycle, recover, repair, refuse, rethink, refurbish, remanufacture, and repurpose (Han et al., 2020; Rovanto & Bask, 2021).

The CE application at the micro level encourages enterprises to redesign their business strategies and aim at CBMs (Rovanto & Bask, 2021; Salvador et al., 2021)). According to the Organisation for Economic Co-operation and Development (OECD), CBMs are different ways of producing and consuming goods and services (OECD, 2019). The CBM focuses on extending the product's life cycle to maintain the product's value for as long as possible, reducing environmental impacts and bringing economic benefits to customers (Salvador et al., 2021). There are different types of CBMs according to various classifications. OECD reclassifies CBMs into five categories, including, circular supply models, resource recovery models, product life extension models, sharing models, and product service systems models (OECD, 2019). Moreover, Ludeke-Freund et al. proposed six main CBMs, following the CE principles, including repair and maintenance, reuse and redistribution, refurbishment and remanufacturing, recycling, cascading and repurposing, and organic feedstock (Lüdeke-Freund et al., 2019).

According to Sherwood, biomass plays an important role in promoting CE and creating CBMs, as it can be exploited as an alternative organic feedstock to replace crude oil and natural gas (Sherwood, 2020). BSC comprises different processes, such as harvesting, collection, transportation, pre-treatment, storage, and end-use (Toka et al., 2010). A BSC with waste-free biorefineries utilises all the available biomass components to make products and energy consistent with the fundamental objective of a CE (Kapoor et al., 2020; B. Kumar &

Verma, 2021; Sherwood, 2020). While the role of biomass in the CE has been confirmed (Ellen MacArthur Foundation, 2013), the gap still exists in evaluating the application of CE to the BSC. Furthermore, the differences in CE concepts and CBM classifications make it difficult to apply them to the BSC. Because of the disparate concepts, there is also a lack of a standardised set of indicators to evaluate the degree of circularity for the BSC. As a result, the issue of applying CE principles and implementing CBMs to BSCs, as well as using CE indicators for assessing these chains needs to be fully clarified.

The production of bioenergy has been expected to contribute to sustainable development by reducing fossil fuel consumption and GHG emissions, for example, energy production from biowaste helps to decrease 60% of GHG emissions (Cusenza, Longo, Guarino, et al., 2021). Because biomass has many different origins, the benefits and drawbacks of energy production from biomass sources must be thoroughly evaluated. Regarding the environmental aspect, energy production from waste is believed to contribute to pollution reduction; however, the process also generates emissions and waste. In addition, the economic and social impacts of the bioenergy production process must also be assessed. The life cycle thinking (LCT) tools, including life cycle assessment (LCA), life cycle costing (LCC), social life cycle assessment (SLCA), and life cycle sustainability assessment (LCSA) are expected to provide the most reliable scientific evidence for evaluating the performance of BSC (Gheewala & Silalertruksa, 2021; LCANZ LCT, 2020). The variety of biomass materials, differences in biomass processing technology and multiple end-products lead to challenges in the application of LCT tools such as identifying sustainable hotspots, methodological aspects and impact indicators. This can also cause a trade-off in sustainable aspects leading to difficulty in the final result of assessment for sustainable alternatives. Therefore, applying LCT tools to BSC is necessary to be completely evaluated.

To the best of the author's knowledge, there is no previous review covering all topics of LCT, CE and biomass, and the existing reviews covered either CE or LCT in the biomass sector. For example, (Tabatabaei et al., 2020b) reviewed the innovations and optimizations in biogas production, covering upstream, mainstream and downstream biological technologies such as those for pre-treatment of biomass materials, biogas production and removal of impurities. The fundamentals and the technology for biogas production from lipids and lipid-rich wastes have been studied by (Diamantis et al., 2021), focused on the application of anaerobic technologies as potential technologies for facilitating CE. Huang et al. studied the performance of industrial sludge and waste biochar in facilitating a circular bio-economy (Huang et al., 2022). Hussin et al. reviewed the life cycle environmental impacts of hydrothermal technology applied for biomass conversion (Hussin et al., 2023).

Other review paper concerns the CE and LCT topics in general, without putting them in the BCS context. For example, Sassanelli et al. have reviewed the existing CE performance assessment methods for companies and concluded that there is a lack of methodologies regarding the overall evaluation of CE benefits (Sassanelli et al., 2019). The authors pointed out that life cycle assessment, material flow analysis, discrete event simulation, input-output, and multi-criteria approaches are aimed at considering and evaluating all the possible variables involved in the system, along its entire life cycle, while the design for X and some guidelines are specifically used for the product design and development. The strong tendency of these methodologies is to focus on the environmental level (Sassanelli et al., 2019). There are some gaps in these review papers. These review papers mainly focused on either life cycle environmental impacts of biomass based technologies or their benefits to CE. In addition, CBMs were not mentioned in the existing review. Finally, most of the existing reviews focused on one production technology.

This section aims to review the application of CE principles, CBMs, and LCT to the BSCs, covering multiple biomasses, production technologies, and products. Specifically, the research papers on the BSC, CE and LCT was searched and selected by following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline. In order to differentiate the application of CE at different levels, the searching term "CE principles" refers to as the application of CE in general, while the term "CBMs" denotes the application of CE principles at micro level. By reviewing the existing literature related to BSC, CE and LCT, this review will provide information on which and how CE principles, CBMs and CE indicators have been applied in the BSC. Furthermore, the application of LCT tools, sustainability hotspots and life cycle impact indicators in the BSC will be pointed out. From this review, benefits and limitations of applying CE principles, LCT tools and CBMs in the BSC will be identified, the issues that need to be studied in the future will be proposed. The findings of this article can be a good reference to scholars, businesses and policymakers in applying CE principles, CBMs and LCT tools in BSCs.

3.1.2. Methodology

The review is conducted in five steps of (1) defining the research problem, (2) identifying strategy for searching and selecting literatures for review, (3) searching and selecting literatures, (4) extracting data and analysing the information and (5) reporting the obtained results (Gulotta et al., 2023). In step (3), the process of selecting literatures for review is based on (Geissdoerfer et al., 2017; Ghaderi et al., 2016; Reim et al., 2019) and follows the (PRISMA) diagram (McMeekin et al., 2020), as shown in Figure 3.1.

The keywords relevant to CE, LCT and BSC were separated into two groups. The first group is composed of BSC keywords such as "biomass," "biofuel," and "bioenergy". The second group comprises keywords such as "circular economy," "circular business model," "life cycle thinking", "life cycle assessment", "life cycle costing", and "social life cycle assessment". The string chain ("biomass" OR "biofuel" OR "bioenergy") AND ("circular economy" OR "circular business model" OR "life cycle thinking" OR "life cycle assessment" OR "life cycle costing" OR "social life cycle assessment") was used to search the literature.

The literature search was conducted in the titles, abstracts and key words of the articles in two scientific databases such as ScienceDirect and Scopus, which are well-known academic search engines (Sassanelli et al., 2019). These databases offer extensive coverage, reliable sources, recent research, and advanced search tools. This search gave out 3,262 documents being published by the end of 2022. Book chapters, and articles in conference proceedings were excluded, because their full texts are inaccessible or provide inadequate information for the analysis (Smart et al., 2017). Only one conference paper is included in the review because it provides adequate and interesting information on the circularity strategies in the BSC. After excluding book chapters, articles in conference proceedings and duplicated articles, there were 640 papers which were collected for further analysis.

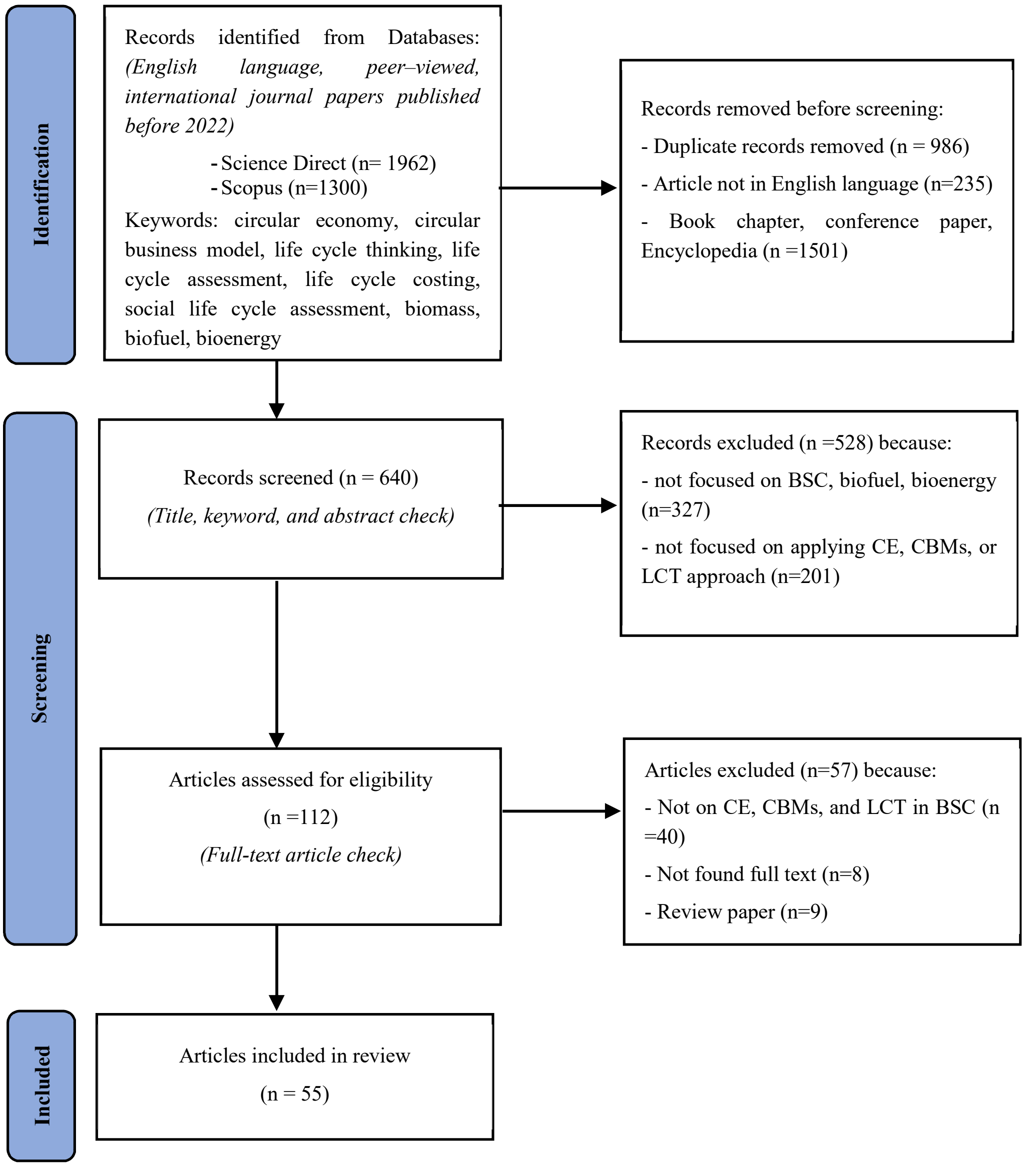

Figure 3.1. PRISMA diagram of papers collected

The screening examination was conducted through two steps. The first step was checking for titles, keywords, and abstracts to exclude articles which are not focused on BSC, CE or LCT. After this step, 112 articles were retained. Secondly, the full-text article check was conducted, with the same criteria (the articles must concern the application of either CE or LCT, in the BSC). Including and exclusion criteria for literature selection are employed during these screening examinations. Inclusion criteria include a comprehensive biofuel production process, integration of CE principles and CBMs within the BSCs, and the application of the LCT approach. The exclusion criteria ensured that three types of articles were excluded from consideration, including (1) articles focused on narrow aspects such as biomass properties, policy evaluation, technical specifications, CE and LCT in general, (2) review articles, and (3) articles with inaccessible full texts. As a result, the number of articles was narrowed down to 55, which were considered as case studies for this systematic review, including 13 articles relevant to CE, 38 LCT articles and 4 articles simultaneously applying CE and LCT in BSC.

3.1.3. Biomass supply chain

Starting from the analysis of the selected papers, it was possible to identify different aspects of the BSC in terms of end-products, biomass inputs, regions and applicable technologies.

The end-products of BSC in 55 case studies include biofuel, bioelectricity, and heat. Biofuel is the most popular end-product, which is studied in 34 papers. Bioelectricity is mentioned in 18 papers and 10 papers are about heat. It should be noted that bioelectricity and heat are frequently studied simultaneously, and there are several papers studying all types of bioenergy and agriculture/ forestry products such as wood, gas, electricity and fuels.

The types of biomass inputs being studied are remarkably diverse. 34 case studies refer to biomass from agricultural origin, 12 studies about forestry biomass, seven studies about waste, and five studies about algae. There are several studies mention a mixture of biomass from different origins, for example both agricultural and forestry biomasses, or both agricultural and algal biomasses. The majority of studies focus on the 'second generation' bioenergy, except the case of palm oil and algae.

The agricultural biomasses are either grain (rice, wheat, etc.) farming by-products in Asian countries (Luu & Halog, 2016; Ren et al., 2015, 2016; Shie et al., 2014), and bagasse and sugarcane by-products in Brazil and India (Hiloidhari et al., 2021), or palm oil in South East Asian countries (Lecksiwilai & Gheewala, 2020; Silalertruksa et al., 2012). Studies of forest biomass are mainly wood by-products and wood burning in the USA, EU and African countries (Afrane & Ntiamoah, 2012; Fantozzi & Buratti, 2010; González-García & Bacenetti, 2019; Kc et al., 2020; Mirkouei et al., 2016; Murphy et al., 2016; Okoko et al., 2018; Parajuli et al., 2017; Valente et al., 2011). The research on industrial and municipal waste, mainly from organic waste and food, beverage industrial waste, has received much attention from European countries (Allegue et al., 2020; Cadena et al., 2019; Foteinis et al., 2020; Ramos et al., 2020; Zeller et al., 2020). Algae studies are mostly conducted at laboratory scale (Kern et al., 2017; Resurreccion et al., 2012; Y. Zhang et al., 2013). It can, thus, be seen that producing bioenergy and biofuel from agriculture has received much research attention in countries with large-scale agricultural production such as South American and Asian countries. Meanwhile European countries and the USA mainly referred to production from industrial and municipal waste, and forestry biomass.

The applicable technologies are different according to the various types of biomass inputs and end-products. Anaerobic digestion (AD) and combined heat and power (CHP) are frequently used for agricultural biomass and organic waste for either bioelectricity (Fytili & Zabaniotou, 2022; González-García & Bacenetti, 2019) or biofuel (Gallejones et al., 2014; Ren et al., 2015, 2016; Sanz Requena et al., 2011; Silalertruksa et al., 2012; J.-J. Wang et al., 2014). Meanwhile forestry biomass is directly combusted or gasified for bioelectricity and heat generation (Afrane & Ntiamoah, 2012; González-García & Bacenetti, 2019; Murphy et al., 2016).

Figure 3.2 illustrates the end-products and biomass inputs, by regions in reviewed case studies. Half of the case studies were conducted in the EU. The input and outputs of these case studies were diverse and extended to all types of biomass inputs including agricultural, forestry and waste origins; as well as end-products of biofuel, bioelectricity and heat. A third of case studies were in Asia. Though the end products are composed of all types of bioenergy, these case studies mostly focused on agricultural biomass inputs. The number of case studies in Africa and American was small. While the inputs of American case studies were similar to those in the EU, the inputs of African case studies were similar to those in Asia. These African and American case studies did not concern all types of bioenergy end-products.

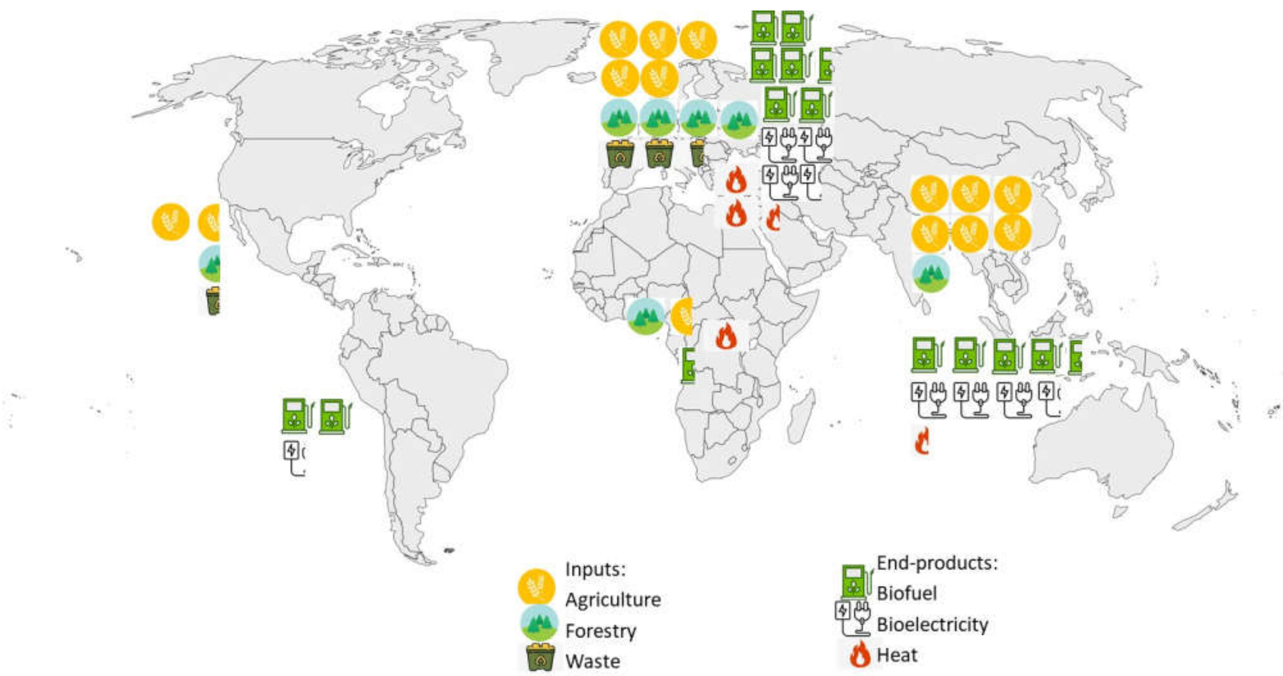

Figure 3.2. End-products and biomass inputs by regions

3.1.4. CE application in BSC

1. Description of the CE and CBMs case studies

Deng et al. proposed a cascading circular bioenergy system incorporating pyrolysis (Py) for production of biochar, syngas and bio-oil, with the primary use of biochar in AD to promote biomethane production through direct interspecies electron transfer (Deng et al., 2020). In this system, closed-loops are created for recycling organic waste. The solid digestate from AD plant is recycled for Py input, while biochar from Py is feeded to AD plant. The study showed that, the integrated AD-Py system leads to an increase of 17% in biomethane yield and an increase of 10% in bio-oil production compared to the individual AD and Py systems. Meanwhile, the digestate mass flow could be got a reduction of 26%, that may enable significant reductions in arable land requirement, transport cost, and greenhouse gas emissions associated with digestate application.

Zabaniotou et al. proposed pyrolyzing agriculture residues to make biochar to create an agriculture-closed loop (Zabaniotou et al., 2015). The waste products are used as feedstock in a pyrolysis reactor to produce an energy carrier (biooil) to supply the energy needed in milling (both heat and power) and biochar to be used as a soil amendment inside the olive grove. This study found that 70t of solid and semi-solid wastes from a 10-ha olive grove and milling process could be pyrolyzed into 13, 11, and 12t of liquid fuel, charcoal, and gas fuel, respectively. Liquid and gas fuels may meet the olive mill's energy needs and provide a 13 MWhel surplus, which could be sold for €4000. In this study, circular economy objectives include waste reduction, energy recovery, closed-loop production, and value generation.

Vega-Quezada et al. have assumed that the production of algae-based biodiesel has a high bio-economic potential as part of a set of initiatives that can be implemented by incorporating the concept of CE (Vega-Quezada et al., 2017). Systemic closed loops were created. This study considered the production of biogas through a mixture of municipal urban waste and livestock manure to generate power by burning biogas. CO2 from combustion biogas is used in the process of production of microalgae. The biomass obtained from microalgae production is processed through thermochemical liquefaction. This process allows the separation of lipids from proteins and carbohydrates to produce biodiesel through transesterification. The glycerin obtained during the transesterification process is sold on the local market. Furthermore, as the algal residue containing protein and carbohydrates is reused as animal feed, farmers are encouraged to collect livestock manure for transfer to the biogas plant. NPV (Net present value) and BCR (Benefit-Cost Ratio) were used as evaluation criteria to estimate the potential synergies. The results show that, under a systemic approach based on a circular economy, strategies are economically feasible and may have a promising future.

Mirkouei et al. presented a mixed biomass forest bioenergy supply chain to minimize GHG emissions (Mirkouei et al., 2016). The closed loop was also created in this supply chain to reuse heat from biochar and syngas. The critical fossil carbon-emitting operations in the bio-oil supply chain were extracting, gathering, and transporting forest biomass. Replacing the conventional strategy with the new mixed supply chain pathway reduced GHG emissions by 2-5%. Locating transportable biorefineries near harvesting and collecting locations might minimize processing costs and environmental consequences by minimizing truck trips and fuel use. The practice of the CBMs was mentioned, including changing the harvest site and delivery technique, which reduces energy usage, prices, and environmental effects.

Antoniou et al. studied digestate improvement via downstream gasification (Antoniou et al., 2019). This study used a closed-loop system to transform digestate into energy and fertilizer. This study demonstrated that digestate gasification was optimized at 850 °C and = 0.24, resulting in a medium heating value gas fuel with LHV (lower and higher heating value) of 2.88 MJ Nm-3 and H2/CO = 2.3, suitable for generating 971 kWhel day−1 to boost the economic sustainability of AD plant. R50 = 0.48 macronutrient-rich carbonaceous material appropriate for carbon sequestration was generated. The study proved the dual system's ability to boost renewable energy efficiency and provide carbonaceous material for agronomy, towards an inclusive CE. Closed-loop components differentiated linear from circular waste management models. Other, three main environmental benefits can be obtained, including i) sustainable digestate management, ii) less energy produced using traditional procedures, and iii) reduced GHG emissions in the atmosphere.

Zabaniotou et al. applied CE by designing a winery waste biorefinery to create a closed loop (Zabaniotou et al., 2018). This study found that by pyrolyzing the remaining solid wastes from pomace extraction, 0.52 t of biochar, 0.80 t of bio-oil, and 0.630 MWh of energy could be produced from 15 t of fresh grapes used to make 10.5t of red wine, 0.27t of hydrocolloids and 0.06t of grape-seed oil in winery and pomace biorefinery plants. The pyrolysis of biorefinery wastes has various benefits. Increasing the number of biorefinery products to 5 would create a 4470€ ha-1 economic advantage and eliminate 355 kg CO2/t of dry pomace. Pyrolysis biochar can be utilized as soil improver since it contains N, P, K, Ca, K, Na, Mg, Ca, P, Fe, Zn, and insignificant heavy metals.

Allegue et al. suggested a closed-loop integrated biorefinery to recover bioenergy resources and manufacture value-added products (Allegue et al., 2020). This application made the process sustainable and energy-efficient while reducing waste by 78.6%. Phototrophic hydrolysate treatment through a mixed culture based on purple phototrophic bacteria leads to biomass growth with high protein content (65% wt.). The system generated polyhydroxyalkanoates (PHA) and hydrogen, valorising 16.9% of the raw food waste's solids.

Bai et al. described optimizing wood inputs for a Mongolian and Chinese power plant (Bai et al., 2020). Electricity is produced from forest wood. The input supply chain includes harvesting, yarding, storing, and processing. A multi-objective optimization was chosen for maximizing economic, environmental, and social benefits. This paper also utilized the mixed integer linear programming model to optimize the raw material supply chain of companies producing forest biomass power. Optimizing the quantity and location of raw material purchase stations optimizes the wood biomass supply chain, according to research. In addition, technological advancements could help businesses optimize their aims. Therefore, the optimisation of the number, distribution of raw material purchasing stations, and technology improvement in the enterprise were considered the CBM practice in this article.

Pettersson et al. investigated various approaches and strategies for Swedish district heating (DH) operators to boost wood ash recycling (Pettersson et al., 2020). Co-incineration with waste wood produced so many pollutants that the ash was deemed unsafe. A case study of the DH plant was conducted at Ortofta, Sweden. Case study findings revealed that adding scrap wood caused ash pollution. This pollution made fly ash unsuitable for recycling in the forest, thus unable to close the material loop for forest fuel nutrients. Bottom ash was less harmful than fly ash but had less nutritious value due to its high bed sand concentration.

Fuentes-Grünewald et al. validated a CE idea employing microalgae at an industrial scale using a two-phase process (Fuentes-Grünewald et al., 2021). In the first phase, biomass was generated autotrophically. In the second phase, mixotrophic circumstances boosted growth. Microalgae cultures could develop, absorb, and bioremediate nutrients from the AD side-stream (digestate) to produce high-quality biomass (>45% protein) appropriate for animal feed, closed economic cycle for industrial applications. Implementing CE for algal biomass production from AD digestate reduced environmental pollution, recovered N & P, created a new industrial method, and promoted the development and implementation of innovative technologies.

González-González et al. provided a closed-loop system focused on nutrient recycling, including analysing available pre-treatments for cell disruption that may enhance biofuel production (González-González et al., 2018). This system is an integrated closed loop of biodiesel and biogas production using microalgae. In this system, water is reused to repeat algae cultivation. The defatted biomass is used as the substrate for anaerobic digestion to produce biogas. CO2 from biogas combustion is recycled for algae cultivation. The liquid phase of the digestate is used as an algal culture broth, and the solid phase can be used as a soil fertilizer. However, this study has not evaluated the efficiency and cost-effectiveness of biofuel generation technologies.

Zeller et al. analysed the environmental impacts of shifting biowaste flows from conventional to circular management systems to discover the optimal CE solution (Zeller et al., 2020). Overall and biowaste recycling rates were used to measure circularity. Quantitative environmental implications were assessed using consequential LCA, and the usual system boundary is 'bin to grave'. LCA findings demonstrated considerable advantages for the local AD system with the separate combined collection. Decentralized systems reduced resource usage, but industrial co-composting had more significant or equivalent impacts than the baseline. Local systems with combined food and green waste management profited if process emissions were appropriately regulated and by-products were employed in high-substitution applications. Changing to CE did not always have environmental benefits.

Pavan et al. studied CBMs for waste-to-energy conversion based on anchoring dynamics between sugar plants, alcohol plants and other biomass suppliers in the agro-industrial symbiosis network (Oliveira Pavan et al., 2021). This study focuses on solid urban waste (organic component), sewage sludge, swine, poultry, cow waste, and vinasse (a by-product of ethanol production). Two options of CBMs, including Centralized (CBM-A) and dispersed (CBM-B) AD, were proposed based on three CBMs, including recycling, cascading and repurposing, and organic feedstock models (Oliveira Pavan et al., 2021). In both CBMs, the plants played the anchor tenant role. Near the anchor tenant, smaller biogas-producing enterprises were used to cut waste emissions.

Fytili and A. Zabaniotou highlighted basic knowledge, concerns, and practices of a regional circular waste bioeconomy (CWBE) and gave a detailed list of actions and challenges to consider the level of bioenergy road mapping and deployment locally, nationally, and worldwide (Fytili & Zabaniotou, 2022). Thessaly was chosen as a case study. The Thessaly region's low carbon and bioenergy transition was assessed using SWOT (strengths, weaknesses, opportunities, and threats). This study indicated that the area handled waste inefficiently and lacked synergies and cooperation. Accelerating low-carbon CWBE for regional development and jobs requires territorial cohesion and regional symbiosis, increasing financial market opportunities for small and significant projects, and promoting awareness, skills, public knowledge, and responsibilities of young scientists and citizens.

Bastos et al. assess the reuse of black liquor (hydrolysate) as a sustainable and affordable technique to boost grass clippings' biodegradability and process economic feasibility (Bastos et al., 2021). The pretreatment efficiency was investigated using sequential anaerobic batches with the reuse of 5% (m/v) NaOH and KOH black liquor under moderate operating conditions. After alkaline pretreatments, the daily biogas production peak was lowered from 25 to 5 days, and the production of biogas rate was 82% greater than the untreated substrate. NaOH was more effective than KOH in removing lignin from the substrate, with considerable removal capacity for three reuse cycles, as seen by greater concentrations of Na+ than K+ in the first reuse hydrolysates.

Gonçalves et al. assessed forest biomass fluxes and stocks in Portugal and studied circularity and resource efficiency using a comprehensive set of metrics, making recommendations for their usage and development (Gonçalves et al., 2021). Paper, wood products and energy were included in material flow analysis (MFA) for 2015. Portugal used 49% of its forest biomass for energy and 51% for materials in 2015. Results demonstrated that circularity in Portugal's wood industry was diverse. In 2015, 27% of wood-based goods were recycled, according to the overall recovery rate. Only 7% of the fiber input to various industries was collected and recycled, according to RIR. In 2015, recycled paper made up about 39% of all paper produced. The paper RIR was 6%, meaning that just 6% of the fiber input to this sector was recovered and recycled.

2. CE principles, strategies and CBMs applied to BSCs

Among 10 CE principles, only four principles were employed for BSC, including reduce, reuse, recycle and recovery. Nine out of 17 case studies considered the recycle principle. The reduce principle was covered in seven studies, whilst reuse and recovery were considered in four studies. The recycle principle was frequently applied to waste management, while the reduce principle was applied in resource consumption, which consequentially decreases the production cost and mitigates environmental impacts. In some studies, different CE principles such as recycle and recovery, are simultaneously applied. For example, Gonçalves et al. assessed the circularity and resource efficiency of the forest biomass in Portugal, with the inclusion of recycle, recovery and other CE principles (Gonçalves et al., 2021). In 2015, Portugal used 49% of its forest biomass for energy and 51% for materials. The national wood industry's circularity was diverse, in which 27% of wood-based goods were recycled or recovered. On the input scale, the recycling rate was much lower, in which only 7% of the fiber input to various industries was collected and recycled (Gonçalves et al., 2021). The applications of different CE principles in the case studies will be further described in the following section.

These CE principles are applied by changing the applicable technologies during the life cycle of the product system and improving the operational practice within the BSC, or even extending the BSC to cover multi products or multi sectors. The applicable technologies include biomass waste treatment technologies for example AD, and supportive technologies of the biomass feedstock plantation such as sprinkler or drip irrigation technologies. By changing the waste management technologies, the waste will be recycled, hence the amount of generated waste and the amount of required virgin material/ energy can be reduced. An example is the combination of AD for organic waste management and CHP or pyrolysis for energy generation. These combined technologies are applied to culture algae (Fuentes-Grünewald et al., 2021; Kern et al., 2017; Vega-Quezada et al., 2017), to produce fertilizer (Allegue et al., 2020; Antoniou et al., 2019), biogas (Bastos et al., 2021) and power (Allegue et al., 2020; Bastos et al., 2021; Oliveira Pavan et al., 2021; Vega-Quezada et al., 2017; Zeller et al., 2020).

In other cases, CE principles were applied by changing operational activities during the BSC management. For example, in Mirkouei et al.'s study, by locating biorefineries near the harvest and collection sites, the number of truck trips and fuel use for feedstock transportation can be reduced, hence, minimizing processing costs and environmental consequences. The mixture of circularity strategies, such as improved technologies (heat recovery) and operational practice (optimized transportation operations) reduced GHG emissions by 2-5% (Mirkouei et al., 2016).

Similarly, Bai et al. proposed to change the quantity and location of woody input purchase stations to optimize the cost, energy consumption and GHG emissions of a Mongolian and Chinese power plant (Bai et al., 2020). In this case, the economic cost and GHG emissions are lowest, at 1.6 million Yuan and 4.1 thousand tCO_2e, respectively when the number of purchase stations significantly reduces (Bai et al., 2020). Moreover, energy consumption could be reduced by choosing an optimal distance between raw material collection sites and processing plants, and appropriate plants' capacities (J.-J. Wang et al., 2014).

In other case, Zeller et al. investigated the shift of the conventional biowaste flow management systems into the circular ones, which helps to increase the recycling rate from 0.4 to 1 (Zeller et al., 2020). The specific circular actions include changing the existing waste collection and treatment modes, and by-products management into the decentralized waste collection system, industrial co-composting, combination of local system and green waste (organic waste) and food waste management (Zeller et al., 2020).

It can be observed that the operational circular strategies mostly concentrate on logistic activities such as transportation, waste collection and treatment and optimization of site location, in order to reduce the transportation distance and fuel consumption for transportation. Besides, strategies relevant to feedstock, for example diversified biomass feedstock and appropriate selection of feedstock have been identified as circular strategies.

While the circular strategies applicable within the same BSC are quite common, there are not many studies extending the existing BSC to include other products. The extension of the existing BSC can only be found in Zabaniotou et al.'s studies, which extend the olive and winery supply chain into biomass - energy - fertilizer supply chain, by integrating the production of olive/ wine product, bioelectricity, fertilizers, and other valuable products from olive/ winery waste (Zabaniotou et al., 2015, 2018).

It should be noted that various circular strategies are frequently combined in the same studies. The majority of studies simultaneously applied both technological improvement and efficient operational activities to obtain the highest circularity benefits. The benefit of applying these strategies do not limit in reducing input consumption, for example consumption of energy, water, raw materials, but also extend to mitigate emissions and environmental consequences. Eventually, these strategies would help to reduce production cost, enhance the economic profile of the BSC and enterprises, and bring socio-economic benefits.

At micro scale, CE principles were applied through CBMs. Several CBMs have been applied in the existing literatures such as reuse, recycle and recovery; cascading and repurposing; circular supply model and organic feedstock models. A framework of CBM application is presented in Figure 3.3. The reuse, recycle and recovery models are frequently applied on the main products or by-product of the agriculture and forestry sectors. The residues and waste during plantation and husbandry activities are further processed with the application of innovative technologies. Through applying these technologies, the cascading and repurposing model is recognized. At this time, the waste becomes useful products, which are utilized in energy and other economic sectors; and/ or returned to the agriculture and forestry sectors. If these useful products are used in energy or other economic sectors, they may be reused, recycled and recovered in another supply chain. In some cases, these useful products are used in the same biomass supply chain, meaning that the circular supply model and resource recovery model have been applied.

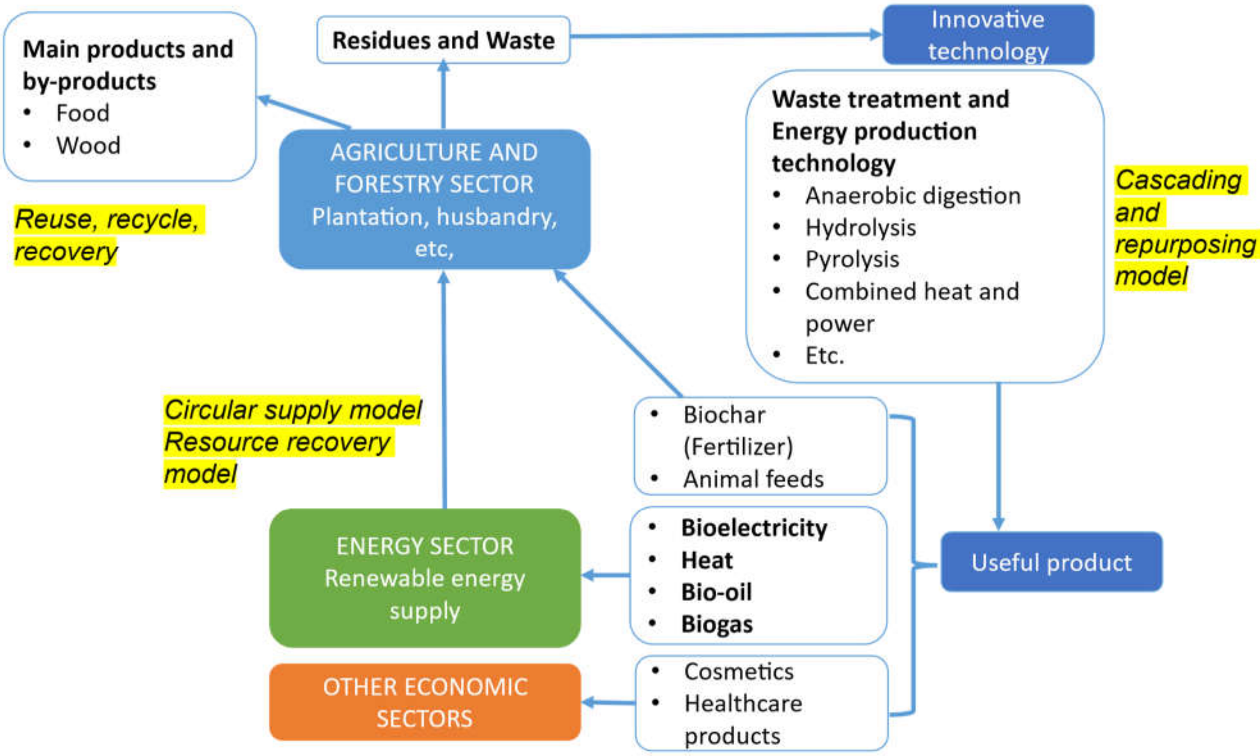

Figure 3.3. Framework of CBM application in BSC

The reuse, recycle and recovery CBMs could be found in several case studies (Allegue et al., 2020; Antoniou et al., 2019; Bastos et al., 2021; Deng et al., 2020; Fuentes-Grünewald et al., 2021; Vega-Quezada et al., 2017; Zabaniotou et al., 2015, 2018). Table 3.1 of the Supporting Information summarized CE principles and strategies, and CBMs applied in the case studies.

It is common that one study applies several CBMs, specifically the combination of reuse, recycle and recovery; and resource recovery or cascading and repurposing. For example, Zabaniotou et al. (2015) applied pyrolyzing technology on the solid wastes of olive plantation, e.g pomace and pruning, to produce biogas and biochar. Biochar is returned back to the olive plantation and being used as a fertilizer. Meanwhile, biogas is condensed into bio-oil and combusted to generate electricity. Before the pomace and pruning are pyrolyzed, they are dried by using electricity from bio-oil combustion. The electricity is also used in olive oil production. Besides, any waste heat from the waste drying process is used for olive oil production (Zabaniotou et al., 2015). In this study, firstly waste is recycled; secondly waste heat is recovered. At the same time, waste is transformed into two useful products such as biochar and electricity, e.g cascading and repurposing.

Similar, these CBMs are applied in Zabaniotou et al.'s study. In this study, the winery wastes (including pomace, stalks and lees) are gone through the primary refining process, becoming solid waste, hydrocolloids and grapeseed oil. While hydrocolloids can be used in health and medicine sectors, grapeseed oil is a common product for cosmetics and food purposes. The winery solid wastes are then gone through a similar procedure as the olive solid waste (Zabaniotou et al., 2018). By applying the cascading and repurposing CBM, at the end of the winery supply chain, apart from wine as the main product, several useful products have been obtained such as biogas, bio-oil, biochar, hydrocolloids and grapeseed oil, which can be used in the food and beverage sector, and extended to energy, fertiliser and healthcare sectors.

The studies of Vega-Quezada et al. (Vega-Quezada et al., 2017) and Fuentes-Grünewald et al. (Fuentes-Grünewald et al., 2021) simultaneously applied reuse, recycle, recovery; and resource recovery CBMs. Vega-Quezada et al. studied the third generation of bioenergy from algae (Vega-Quezada et al., 2017). Biodiesel and glycerine are produced by applying the transesterification process on algae biomass. The main product of the transesterification process, e.g. biodiesel is used for energy purpose; and the by-product, e.g. glycerine is commonly utilized by cosmetic and health care sectors. Waste of this process, e.g. algal residues are combined with municipal waste and livestock manure to produce biogas. Biogas is then used in combined heat and power plant to generate electricity and heat. The CO_2 emission from the electricity and heat production process is neutralized by the algae plantation process (Vega-Quezada et al., 2017). From energy production perspective, the algal residues are recycled, while from the waste management perspective, the applicable CBMs includes resource recovery model and organic feedstock. In this CBM, algal residues are diverting from disposal to recover the organic materials, being utilized as resources for other processes.

The CBMs in Fuentes-Grünewald et al.'s study was also applied in microalgae supply chain. The microalgae are utilized to make animal feed, which is used in husbandry. Animal waste from husbandry is put through anaerobic digestion to make N&P-rich digestate, which is consequently the input for microalgae plantation. In this study, the recycle CBM is applied on animal waste; and the resource recovery model indicates the recovery of biomass resources in microalgae and digestate. The CBMs reduced the doubling time of algae (the time for algae duplicated themselves) by 35%, from 2.1 days to 1.4 days; and the growth rate increased from 0.3 to 0.5 per day (Fuentes-Grünewald et al., 2021).

Table 3.1. CE principles and strategies, and CBMs applied in reviewed case studies

Author	Principle/ model	Innovative/ Improved technologies	Changing operational activities	Obtained results	Ref.
Zabaniotou et al.	Recycle, Recovery and Cascading and repurposing	Pyrolysis applied in an olive farm, inputs for the pyrolysis are olive pruning and olive pomace, outputs of the technology are energy for milling process and biochar to be used as fertilizer in the olive grove	N/A	The application of CE principles and CBMs generates electricity for own use in the olive supply chain and 13 MWh of electricity surplus, or 4000 EUR of extra income if the surplus electricity is sold to the grid	(Zabaniotou et al., 2015)
Mirkouei et al.	Recovery	N/A	Changing the harvest sites and delivery techniques (transportation of biomass inputs)	Mixed supply chain can reduce 2% to 5% of GHG emissions compared to the traditional forest biomass to bio-oil supply chain.	(Mirkouei et al., 2016)
Vega-Quezada et al.	Recovery and circular supply model	Bio digester, electricity generating plant, algae production, biodiesel plant	Exploiting synergies of agriculture and bioenergy	Cost and benefit of the individual initiative, for example using 100% available land for biodiesel production, ranges from 1,393 to 1,772 million USD. Cost and benefit of circular economy approach of biodiesel production may up to 1,726 to 2,068 million USD for microalgae crop (using 13% available land), plus other	(Vega-Quezada et al., 2017)

				benefit of CO_2 removal, rural development due to microalgae production	
Kern et al.	Recover	Anaerobic digestion and combined heat and power	Different business strategies of selling lipid extracted algae as animal feed and recovery nutrient and energy	Added investment in technologies for nutrient and energy recovery is larger than the benefits of selling feed meals	(Kern et al., 2017)
Zabaniotou et al.	Cascading and repurposing	Pyrolysis applied in a winery vineyard, input for the pyrolysis is solid waste from the hydrocolloids extraction process, outputs of the technology are biogas and bio-oil for energy purposes and biochar to be used as a fertilizer	N/A	The application of CE principles and CBMs helps to increase the number of useful products, increase the economic value of the winery supply chain (addition of 4,470 EUR per ha of vineyard) and reduce GHG emission of winery production (355 $kgCO_2$ per tonne of dry pomace)	(Zabaniotou et al., 2018)
González-González et al.	Recycle	Anaerobic digestion	N/A	The review on the application of CE principles in biofuel produced from microalgae indicates the ability of producing gas as main product and nutrient-rich digestate as extra product to be used as fertilizer. Water and carbon	(González-González et al., 2018)

				dioxide are also recycled during the biofuel production process.	
Antoniou et al.	Recovery, reuse	Anaerobic digestion and gasification	N/A	Benefits of the system include energy recovery, waste reduction and production of carbonaceous material (char for soil amendment and carbon sequestration). The anaerobic digestion plant used various agricultural waste to generate biogas, which then converted into electricity and heat in a combined heat and power plant. 10% of electricity and 20% of heat were internally reused for the anaerobic digestion plant. The excess heat from combined heat and power plant was used for drying the solid digestate (recover waste heat).	(Antoniou et al., 2019)
Allegue et al.	Recovery	Thermal hydrolysis, anaerobic digestion and photo-fermentation	N/A	The amount of waste to be disposed reduces by 78.6%.	(Allegue et al., 2020)

Bai et al.	Circular supply model	N/A	Change the quantity and location of woody input purchase stations	Reducing the number of purchase stations helps to minimize the economic cost and GHG emissions, at 1.6 million Yuan and 4.1 thousand tCO_2e	(Bai et al., 2020)
Zeller et al.	Recycle	N/A	Changing the existing waste collection and treatment modes, and by-products management into the decentralized waste collection system, industrial co-composting, combination of local system and green and food waste management	The application of CE principles helps to increase the recycling rate.	(Zeller et al., 2020)
Fuentes-Grünewald et al.	Reuse, recycle and recovery	Two-phase process of microalgae growing, and anaerobic digestion	N/A	In the first phase, biomass was grown autotrophically. Then biomass was concentrated using membrane technology. After that, in the second phase, mixotrophic conditions were applied to boost the growth. This innovative microalgae growing process reduce the doubling time of algae by 35%	(Fuentes-Grünewald et al., 2021)

Pettersson et al.	Recycle, Recovery	Technologies for recovering nutrients and chemical compounds from wood ash	Different operational measures along the forest biomass supply chain: replacing waste wood by forest fuels (logging residues, bark, sawdust); incinerate forest fuels and waste wood separately at different times of the year	Increasing the recycling rate of wood ash, and reduce the contaminations in wood ash	(Pettersson et al., 2020)
Deng et al.	Cascading model	Pyrolysis and anaerobic digestion	N/A	The system increased the biomethane yield by 17% and bio-oil yield by 10%; and reduce the digestate need by 26%	(Deng et al., 2020)
Bastos et al.	Reuse, recycle	Technology for alkaline pre-treatment for bioenergy production	N/A	The strategies is applied to grass clippings for bioenergy production. The innovative alkaline pre-treatment technique provides a good quality hydrolysate, that can be used 5 times (reuse 4 times). The biogas yields increase from 30.5% to 34.5%.	(Bastos et al., 2021)
Pavan et al.	Circular supply model	Centralised and distributed anaerobic digestion	Create a symbiosis of agriculture and energy sectors	The potential for waste-to-energy among the agro-industrial symbiosis network of sugar and alcohol plants and	(Oliveira Pavan et al., 2021)

				other biomass suppliers are up to 1,700 MW	
Fytili and Zabaniotou	Circular supply model	N/A	N/A	The study explored the barriers and opportunities of CE application in biomass and waste sector in Greece, and identified that the waste is inefficiently managed in the region and there is lake of synergies and collaborations between different stakeholders	(Fytili & Zabaniotou, 2022)
Gonçalves et al.	Circular supply model	N/A	N/A	The study analysed the circularity and resource efficiency of forest biomass supply chain in Portugal, and identified that paper and wood packaging were the most recycled products, while the panel sector used the largest amount of recycled products	(Gonçalves et al., 2021)

3. Circularity indicators

Circularity indicators are used to measure the circularity of the economy of a nation, a region or a business (Saidani et al., 2019). These indicators focus on measuring the circularity of material flows (Eurostat, 2023; Kirchherr et al., 2017; Preisner et al., 2022), the achievement of circular economy strategies on resource consumption (Eurostat, 2023; Kirchherr et al., 2017; Preisner et al., 2022), energy and environment, and benefits and potential impacts of the transformation from linear economy into circular economy (Eurostat, 2023; Kirchherr et al., 2017; Preisner et al., 2022). Sánchez-Ortiz et al. categorized circularity indicators into nine groups of:

(1) infrastructure for waste collection, reparation, reuse and recycle.

(2) regulatory and policy framework on product standard; reuse, recycle of raw material or product; waste management and resource management.

(3) participation of business into the material flow management according to circularity principles.

(4) application of circular business model.

(5) availability of the system for resource efficiency, for example the availability of the recyclable, reusable material.

(6) information, education, and social awareness on circular economy.

(7) voluntary program on encouraging the value chain, interdisciplinary initiative, and information sharing.

(8) integration of circular economy into public purchase.

(9) product standards relevant to circular economy strategies (Sánchez-Ortiz et al., 2020).

While the circularity indicators proposed by Sánchez-Ortiz et al. refer to CE in general, there are several indicators which are specific for energy production and consumption. Some examples of energy related indicators includes: energy recovery potential (ratio of energy generated per waste inputs consumed) (Preisner et al., 2022), and energy self-sufficiency (percentage ratio of energy production and consumption) (Sánchez-Ortiz et al., 2020). However, in reviewed case studies, energy related indicators are rarely used as circularity indicators, which may be explained by the fact that energy is an important input/ output, and it is frequently studied on its own in energy analysis, rather than being integrated into CE studies.

In the examined studies the circularity indicators are divided into three levels of macro, meso and micro. At the macro level, the indicators are used for supporting the decision makers in integrating economic, financial, and environmental policies, strategies and action plans on sustainable development, waste management and resource conservation. These macro indicators are relevant to material exchange between the economy and environment, international commerce and deposition in the national economy (Kusumo et al., 2022). The indicators at the meso level allow the detailed monitor and analysis of the material flows in the production and consumption sectors. These meso indicators help to identify any material inefficiency, pollutions and opportunities to improve the efficiency in a specific sector (Kusumo et al., 2022). The micro indicators provide detailed information for the decision making process at enterprises or local government, being relevant to a material, or specific product, in order to support the policy and decision on product development (Pollard et al., 2022; Sheldon, 2020). Several examples of micro indicators are environmental performance indicators, circular economy performance indicator, and key performance indicators (Sassanelli et al., 2019).

An example of meso indicators can be found in the Italian standard on methods and indicators for measuring the circularity of an organization[1] (UNI/TS 11820:2022). There are 71 indicators at total, being classified into seven categories of material resources; energy resources; waste and emissions; logistics; product and service; human resources, asset, policy, and sustainability.

In the reviewed case studies, the most common circularity indicator is recycling rate. For example, Zeller et al. used the recycling rates to assess the benefits of shifting biowaste flows from conventional to circular management systems (Zeller et al., 2020). When circular management systems were applied, the recycling rates increased, meaning that resource consumption reduced. The impact on natural resource decreased from 0.46 million USD per year to -0.08 million USD per year. However, circular management systems did not always bring environmental and social benefits. In this case, the human health impact of the conventional system was lowest, at less than 6 disability-adjusted life year (DALY) per year; and highest when local and decentralized composting systems are implemented, at 12 DALY per year. Besides, the ecosystem impacts of local and decentralized composting systems were highest, impacting 0.031 species-year per year (Zeller et al., 2020).

In the Gonçalves et al.'s study, some indicators related to recycling are applied, being called the recycled input rate and recovery rate (Gonçalves et al., 2021). The recycled input rate denotes the ratio between the input of recycled products and the total fiber inputs (Gonçalves et al., 2021a; Van Ewijk et al., 2018), thus focusing on recycling at material level. Meanwhile the recovery rate is the ratio between the amount of recycled products and the amount of produced products (Gonçalves et al., 2021), which conveys the recovery concept at product level. Besides, the study reported some other circularity indicators of the Portuguese forestry biomass such as cascade factor, material circularity indicator and recovery rate. The cascade factor present the use of virgin material. If all materials are virgin, the cascade factor equals 1. If a part of inputs is virgin, the other parts are recycled inputs, the cascade factor is larger than 1 (Gonçalves et al., 2021). The material circularity indicator was developed by the Ellen Macarthur Foundation and ANSYS Granta to measure the circularity

[1] https://www.certifico.com/normazione/358-news-normazione/18270-uni-ts-11820-2022

of material flows of a product taking into account the life span of the product, when compared to the industry average (Ellen MacArthur Foundation & ANSYS Granta, 2019).

Another case study on CE did not report circularity indicators; however, it provided relevant indicators, for example the increase of resource efficiency. Zabaniotou et al. created a closed loop of winery supply chain, in which winery waste is used for producing biofuel. The circularity of the supply chain was indicated in the Effective Mass Yield (EMY) to present the efficiency of resource consumption based on mass (the efficiency of using fresh grapes for different desired products). In this study the EMY of the supply chain from winery to biofuel is up to 81.5%, and that of the supply chain from winery waste to biofuel is 29% (Zabaniotou et al., 2018). Apart from red wine, hydrocolloids and grade seed oil, the winery supply chain (with 15 tonne of fresh graph) produced 0.52 tonne of biochar, 0.80 tonne of bio-oil, and 0.630 MWh of electricity. Other advantages of the circular winery supply chain are increasing the number of useful products (from 3 to to 6), creating an economic value of 4.47 thousand EUR per ha, and eliminating 355 kgCO_2e per tonne of dry grape pomace (Zabaniotou et al., 2018). Table 3.2 reported the circularity indicators in reviewed case studies.

Table 3.2. Circular indicators in the review case studies

Paper	Indicators	Products/ scenarios	Value	Formulas	Notes	Ref.
Gonçalves et al., 2021	Cascade factor	Total forest biomass system	1.59±10%	CF= $\left(B^i + R^i_{p,p,m} + R^i_{f,p,m} + R^i_{p,p,e} + R^i_{f,v,e}\right) / B^i$	• CF: Cascade factor (dimensionless) • B^i: Virgin forest biomass inputs per sector i (cubic meter of wood fiber equivalent (m^3f) • $R^i_{p,p,m}$: Industrial residues used in industrial processes for material (m^3f) • $R^i_{f,p,m}$: post-consumer residues used in industrial processes for material (m^3f) • $R^i_{p,p,e}$: Industrial residues used in industrial processes for energy (m^3f) • $R^i_{f,v,e}$: post-consumer residues used for energy (m^3f)	(Gonçalves et al., 2021)
		Industrial waste	1.15±16%	$\left(B^i + R^i_{p,p,m}\right) / B^i$		
		Recycled products	1.09±8%	$\left(B^i + R^i_{f,p,m}\right) / B^i$		
		Industrial waste and recycled products	1.24±13%	CF= $\left(B^i + R^i_{p,p,m} + R^i_{f,p,m}\right) / B^i$		
	Material circularity indicator	Paper	0.49±4%	$MCI = 1 - LFI \times F(X)$	• MFI: Material circularity indicator • LFI: Linear flow index • $F(X)$ Utility factor of a product Detailed approach to calculate MCI, LFI and F(X) can be found in (Ellen MacArthur Foundation & ANSYS Granta, 2019)	
		Wood panels	0.17±14%			
		Furniture	0.34±55%			
		Packaging	0.28±21%			
	Recycled input rate	Wood-based products	7%	RIR = Input of recycled products / Total input of fiber	• RIR: Recycled input rate	
		Paper	6%			
		Wood panels	8%			
		Furniture	7.70%			
		Packing	7.70%			
	Recovery rate	Wood-based products	27%	RR = Recycled products / production	• RR: Recovery rate	
		Paper	39%			
		Wood panels	4%			
		Furniture	16%			
		Packing	54%			

Paper	**Indicators**	**Products/ scenarios**	**Value**	**Formulas**	**Notes**	Ref.
Zeller et al. 2020	Recycling rate	Baseline	0.5		The current biowaste management system (in 2018), applied to the quantities managed in 2025	(Zeller et al., 2020)
		Scenario 0	0.74		Export of food waste in 2025	
		Scenario 1	1		Installation of a local co-composting facility in 2025	
		Scenario 2	1		Installation of a local AD facility in 2025	
		Scenario 3	1		Local, decentralized initiatives (home & neighbourhood composting, a small-scale composting) in 2025	

3.1.5. LCT application in BSC

1. Description of the LCT case studies

This Part is the summary of reviewed 39 LCT case studies. For each case study, the indicators, functional units (FUs), system boundaries, allocation procedures, important assumptions, data collection and obtained results are described and also presented in Table 3.3.

Fantozzi and Buratti utilized LCA to examine wood pellet combustion for heating (Fantozzi & Buratti, 2010). The study covered a cradle-to-grave system boundary, from biomass growth to ash disposal at the end of life of wood pallets. For biomass growth, transportation and wood pellet combustion, the data was taken from literature, whilst data for pellet production was taken from an existing Italian factory. Infrastructure and machinery construction's environmental impact was also studied. The pellet chain's EcoIndicator 99 life cycle environmental consequences were 3185.4 mill points. The biomass growing stage was responsible for half of the pellet chain's life cycle environmental consequences (47%), followed by 26% of the pellet production stage.

Requena et al. used LCA to analyse oil-derived biofuels from sunflower, rapeseed, and soybeans (Sanz Requena et al., 2011). This study examined the material, energy, and emission flow in numerous processes, including biofuel generation. The paper showed that Land use, fossil fuels, carcinogens, inorganic respiration, and climate change were the most critical environmental consequences. Rapeseed, sunflower, and soybean farming had significant environmental repercussions. Canola oil extraction consumed the most extraordinary fossil fuels. Sunflower seed production needed the most excellent acreage and had the most critical soil effect. Sunflower seeds create more waste than soybeans and canola.

Valente et al. calculated GHG emissions and costs of forest management, extraction, and transport in Norway's Hedmark and Oppland counties (Valente et al., 2011). The LCA of the wood supply chain was carried out from cradle to gate. Fieldwork provided primary data, whereas literature provided secondary data. Research results showed that the mountain forest system analyzed released 17,600 g of CO_2e per solid cubic meter of bark. Transportation to the terminal contributed 31% of emissions and 23% of expenses while packing contributed 25% and 19% of expenditures. The most significant GHG effect in the supply chain was transportation to the terminal, while disposing of forest leftovers is the most expensive. The study referenced CBM practice. These included upgrading forest management, logistics, and technology to cut emissions and operational costs.

Silalertruksa et al. compared the cost performance of palm oil biodiesel blends (B5, B10, and B100) in Thailand to diesel fuel when their externalities, the costs imposed on the environment and society, were incorporated into their production costs (Silalertruksa et al., 2012). This research includes oil palm agriculture, palm oil processing, CPO (crude palm oil) refinement, biodiesel generation, and all transit expenses. The income elasticity of willingness to pay was utilized as a multiplier to transfer Environmental Priority Strategies methodology values into the Thai context. This paper considers land use, fossil energy depletion, and air pollutant emissions, including CO_2, CH_4, N_2O, CO, NOx, SO_2, VOC, and PM10. The paper showed that because of the high cost of biodiesel feedstock, palm oil-based biodiesel (pure or mixed) costs more to produce in Thailand than diesel. The price of fresh palm fruits directly affected the cost of crude palm oil, which accounted for 69% of biodiesel manufacturing costs. Petroleum diesel's total costs (production cost plus environmental externalities) showed that environmental costs contributed 34%. Compared to diesel, biodiesel based on palm methyl ester (PME) has a 3–76% reduced overall environmental cost, depending on blending levels.

Afrane & Ntiamoah examined life cycle costs and environmental implications of Ghanaian cooking fuels (Afrane & Ntiamoah, 2012). Firewood, charcoal, kerosene, LPG, electricity, and biogas were analyzed. Two methods were employed to analyze these fuels' emissions. The ISO LCA approach was used to determine the environmental consequences of the cooking devices and their fuels from cradle to grave. In the cooking process, the Environmental Product Strategies (EPS) technique assigned a monetary value to the emissions. These gasoline prices were also calculated using LCC. The LCC results indicated that firewood, a common wood fuel in Ghana and other developing nations, has an annual environmental damage cost of US$36,497 per household, more than one order of magnitude more than charcoal at US$3,120. The LCA results indicated that wood fuels could damage the global ecosystem and local health. The second impact affected emerging nations more. These countries had minimal influence on the global environmental picture, but human health damaged their economy due to demand for facilities and lower national production.

Resurreccion et al. used LCA and LCC to analyze open pond (OP) systems and horizontal tubular photobioreactors (PBRs) for the cultivation of freshwater (FW) or brackish-to-saline water (BSW) algae (Resurreccion et al., 2012). The system boundaries were from cradle to wheel. Four possible scenarios were evaluated: OP–FW, OP–BSW, PBR–FW, and PBR–BSW. Four environmental effect categories were computed: energy resource depletion, climate change, water consumption, and net eutrophication potential. Production costs, including capital and annualized operating expenditures, were utilized to determine life cycle costs. Operating costs included nutrients, direct energy usage, waste disposal, maintenance, labor, insurance, and depreciation, while initial capital expenses included land, infrastructure, cultivation systems and reactors, major equipment, engineering, and contingencies. LCA studies indicated that OPs used 32% less energy for construction and operation than PBRs. The LCC results showed that all four systems are now undesirable investments, albeit Ops are less so than PBRs. BSW species performed better than FW in OPs and PBRs for energy, GHGs, and profitability.

Zhang et al. utilized LCA and LCC to study algal bioenergy production on small dairy farms (Y. Zhang et al., 2013). Four situations were considered: reference land-application (REF), anaerobic digestion with land-application of liquid digestate (AD), and anaerobic digestion with recycling of liquid digestate to an open-pond algae culture system (OPS) or an algae turf scrubber (ATS). All four scenarios involved "cradle-to-gate" dairy manure management systems, covering all treatment procedures. LCA models accounted for net energy usage (EN), net eutrophication potential (EUT), and net global warming potential (GWP). In contrast, LCC analyses computed net present value (NPV) for each system based on initial outlay, year running cost, and yearly revenue. All three "better" scenarios (AD, OPS, and ATS) were environmentally preferable to REF, with gains in net energy output up to 854 GJ/yr, decreases in net eutrophication potential up to 2700 kg PO_4-eq/yr, and reductions in global warming potential up to 196 Mg CO2-eq/yr. LCC found that integrated algae systems were financially more appealing than AD or REF, with NPVs of $853,250 for OPS, $790,280 for ATS, $62,279 for REF, and $211,126 for AD.

Lahiri & Acharjee estimated the cost of power production from stand-alone, off-grid biomass gasifiers (dual-fuel and pure gas type) and compared it with diesel generating units (Debabrata Lahiri & Acharjee, G, 2013). This computation was done for the biomass gasifier in Bharbari, Bihar (India), where the use of electricity was more in the case of irrigation (85.20%), followed by micro-enterprise (7.65%) and household lighting (7.15%). From 6:00 pm until 10:00 pm daily, residential illumination was intensified. The life cycle costs of a gasifier plant include equipment capital, fuel, operator salary, maintenance, loan interest, replacement cost, power-producing unit end-of-life value, discount rate, and equipment operational life. LCC's calculations demonstrate that a pure gas system's generating cost is cheaper than diesel and dual fuel, even if biomass prices rise (Rs 6.13 kWh from 7.82 kWh). Biomass energy for rural electrification was conceivable.

Gallejones et al. reported an attributional LCA for producing pure biofuels (biodiesel-B100 and bio-alcohol-E100) from wheat and rapeseed in Spain utilizing site-specific data (yield and loss of N: N_2O, NO_3, NH_3) collected after running the SIMSNIC model at the crop production level (Gallejones et al., 2014). Nonrenewable energy usage, GWP, acidification, eutrophication, and land competition were assessed. The crop production stage study was based on a 2005-2008 winter wheat-rapeseed-winter wheat field experiment in northern Spain. "Well-to-Tank" system boundaries included all resources, energy, and pollution emissions from raw material production to biofuel distribution. System expansion processed co-products. Simulations indicated lower N_2O emissions than Intergovernmental Panel on Climate Change (IPCC) projections. The IPCC range, which does not account for IPCC uncertainty, is 1.4 to 3.0 kg N_2O – N ha^{-1}. Using biodiesel and bioethanol made from rapeseed and wheat instead of conventional diesel and gasoline would reduce non-renewable energy dependency (-55%) and GWP (-40%), on average, but increase eutrophication (42 times more potential).

Shie et al. analyzed collection area capacities using energy LCA (Shie et al., 2014). The desirability of the energy indicators has been discussed and appraised. The system boundary in this research was cradle-to-grave. Syngas ($CO+H_2$), methane, CO_2, and black carbon residue were energy products. Data were collected to quantify the system's inputs and outputs to achieve research aims. The plant's capacity was 50,000–200,000 tons/year, and the transport was 50–100 kilometers. The total energy intake was 15.9% of the average energy production, and the net energy balance was 0.841. Every technology advancement has substantial energy advantages onsite. The findings also revealed that the projected transport route and handling capacities were less than 114.72 km and 251,533 tons/year, respectively. The energy return on investment (EROI) was more significant than 1. CBM practices to decrease energy usage include material collecting area and manufacturing capacity selection.

Wang et al. integrated optimization and life cycle inventory (LCI) for a biomass gasification-based BCHP (Building cooling, heating, and power) system to optimize biomass utilization (J.-J. Wang et al., 2014). Life cycle models, comprising biomass planting, biomass collection-storage-transport, BCHP plant building and operation, and BCHP plant destruction and recycling, were used to determine the economic cost, energy consumption, and CO_2 emissions across the whole service life. The biomass BCHP optimization model was then provided, comprising variables, objective function, and solution technique. This study was also conducted to optimize a BCHP plant case in Harbin, China. It showed that the best life-cycle cost was \$41.9/MWh and 55% of the yearly cost was biomass. The collection and transportation distance greatly influence the biomass cost. The biomass gasification-based BCHP system's life-cycle primary energy efficiency was 41%. The ideal life-cycle CO_2 emission factor of the biomass BCHP system was 56 kg MWh_{e1}, including diesel oil for the treatment gear, coal for supplementing the BCHP operation's energy, and parasitic emissions from steel and fertilizer manufacture.

Sawaengsak et al. used the LCC technique to assess large-scale microalgae-based biodiesel production in northern Thailand (Sawaengsak et al., 2014). Four algae-to-biofuel process scenarios were evaluated, including a basic case pond system (without omega-3 fatty acid synthesis), an alternate case pond system (with omega-3 fatty acid production), and a base case photobioreactor system (without omega-3 fatty acid production) (with omega-3 fatty acid production). 15-year net present value was utilized to compare production scenarios' profitability. Life cycle costs, including capital and operational expenses, were assessed for alternatives based on secondary sources, such as a U.S. algae culture facility. The LCC found that raceway ponds cost 68 THB/L and photobioreactors cost 191 THB/L to produce microalgal biodiesel. Biodiesel costs 224 THB/L for raceway ponds and 450 THB/L for photobioreactors. High capital and operational expenses created negative net present values in all cases. Thus, they must be decreased by at least 50% to make the systems economical.

Ren et al., (2015) created a model based on LCC to reduce biofuel supply chain costs under uncertainty (Ren et al., 2015). The system boundary in this research was cradle-to-grave (from raw materials to the consumer market). This research included three agricultural locations, two transit routes, two biofuel plants, and two market hubs. Interval linear programming was established. Cost per unit grain in agriculture, the cost for transporting per unit grain/biofuel per unit mileage, cost per unit biofuel production, grain yields, and market needs were unknown factors signified by interval numbers. The life cycle cost was used to form the linear cost function. According to the analysis, worst-case life cycle costs were 1.020365×10^{10} Yuan, and best-case costs were 7.585049×10^{9} Yuan. Decision-makers/stakeholders set credibility (example 0.8), then the desired aim (fa = 8.10876920×10^9 Yuan).

Ren et al. (2016) applied LCA in biofuel supply chain planning and design. Energy usage was assessed using the cradle-to-gate method (Ren et al., 2016). This work established a mixed-integer model for biofuel supply chain design under uncertainty. Optimization of the life cycle energy consumption and CO_2 emissions were taken. Crop yield and consumed feedstock were uncertainty variables represented by interval numbers. An example computational model was biofuel production from agricultural biomass in China. The optimal objective function has been constructed for the 'optimistic' and 'pessimistic' scenarios of the uncertain variable's interval boundary value. Stakeholders/decision-makers can reach a final compromise option by comparing the 'optimistic' and 'pessimistic' solutions to real conditions and other data. Under 'optimistic' conditions, the minimal power consumption was 1.258676×10^{10} MJ, while under 'pessimistic' ones, it was 1.475992×10^{10} MJ. Optimizing both criteria might reduce energy usage to 1.402105×10^{10} MJ and CO_2 emissions to 2.971174×10^8 to 3.420493×10^8 kg.

Murphy et al. utilized LCA to anticipate biomass-to-energy systems in Ireland in 2020 (Murphy et al., 2016). Pulpwood, forest wastes, sawmill residues, and local energy supplies were used in co-firing power plants and solo biomass-fuelled CHP facilities. The BSC was investigated from biomass harvest to energy generation, including biomass feedstock transit. Different biomass feedstocks, power plants, and CHP plants were independent, and no CE business model was employed. This study found that CHP plants fuelled with pure biomass had a superior GWP, AP, and EP than co-firing plants. Economic and social repercussions weren't assessed. Circularity and CE principles weren't considered.

Kern et al. used "real options analysis" (ROA) to measure algal biofuel production facility product flexibility. ROA applies financial options theory to scenarios where future input and/or product prices impact cash flow predictions and capital project net present value (NPV) (Kern et al., 2017). This study compared selling lipid-extracted algae (LEA) as animal feed and using a "closed-loop" approach to recover nutrients and create biogas for on-site combined heat and power (CHP). LCA GWP data determined environmental performance. Investing in plant flexibility did not boost NPV, according to this study. Due to the expense of feed powder, algae-derived from lipids wasn't recommended to restore nutrients and energy. This study showed that ROA provides plant design insights that standard engineering-economic modelling cannot. This study showed how LCA and TEA might be coupled for dynamic decision-focused modelling. The results confirmed ROA's applicability as a tool for handling algal biofuel design difficulties and enhancing economic and environmental sustainability under unpredictable market conditions.

Luu and Halog compared rice husk-based bioelectricity in Vietnam against coal-fired electricity (Luu & Halog, 2016). The boundary system was cradle-to-grave. The environmental, economic, and social consequences were estimated based on their economic worth, principal goods, and co-products. Ecoinvent, Social hotspot, power plant feasibility papers, and other relevant literature were used to calculate the effect. Health, social wellbeing, prosperity, ecological quality, and natural resources were examined. This research solely analysed quantitative effect indicators, not qualitative. Rice husk-based power generated higher negative health consequences per functional unit than coal-fired electricity and had negligible influence on ecosystem quality and natural resources. Its favorable societal effects were more significant than coal-fired power. Bioelectricity significantly harmed ecosystem quality and natural resources compared to electricity. Social well-being and prosperity were unaffected, and coal-fired energy was worse for human health.

Parajuli et al. employed LCA to examine the environmental footprint of willow, alfalfa, and spring barley straw as bioenergy feedstock (Parajuli et al., 2017). This study used GWP, Eutrophication Potential (EP), Non-Renewable Energy Use (NRE), Agricultural Land Acquisition (ALO), Potentially Toxic To Fresh Water Ecology (PFWTox), and Soil Quality as environmental indicators. The GWP generated by alfalfa and willow crops was 32% and 38% for straws. Willow, alfalfa, and straw produced 40%, 46%, and 68% of EP. Agrochemical manufacturing boosted NRE usage. Alfalfa, willow, and straw agrochemical production consumed 20%, 45%, and 47% of NRE. Alfalfa and straw had the lowest ALO. Straw, alfalfa, and willow were highest for PFWTox on farms. Compared to willow and alfalfa, straw degraded soil quality. Willow fared better than other biomass in energy production to input.

Odavic et al. estimated the CHP biomass plant's investment and operational expenses. Monte Carlo simulation was utilized to estimate setting variations and investment risk (Odavic et al., 2017). Some economic indicators were used to assess for CHP plant with capacity of 1MW, including NPV, IRR, ROI and life cycle cost. The life cycle cost includes initial, operating, interest and insurance, depreciation, maintenance and externalities cost. The assessment revealed the investment would be returned in 9 years (8 years and 44 days). NPV was 4,105,409 euros, IRR was 11.32%, ROI was 18.24%, and profitability was 15.48%.

Okoko et al. employed LCC to analyse firewood, charcoal, biogas, jatropha oil, and agricultural residue briquettes value chains in Kitui, Kenya, and Moshi, Tanzania (Okoko et al., 2018). The life cycle stages were analysed, including feedstock collection, feedstock processing, and consumption or use. Research results showed that LCC helps discover expenses and improvement opportunities in the value chain. Jatropha oil craft cost the most. Cost-effective stoves use firewood. Royalties raised charcoal prices in rural Moshi. Kitui biogas is less likely to be profitable. Briquettes outperform charcoal. Fuel expenditures much exceeded kitchen prices.

González-García & Bacenetti evaluated Italy’s energy and heat generation using LCA with a cradle-to-gate approach in four different energy scenarios (González-García & Bacenetti, 2019). Four evaluation scenarios comprise a bioenergy chain based on spontaneously regenerated forests, energy-intensive poplar, willow, and traditional poplar farming. The proposed scenarios for assessment have been analysed from an environmental perspective. The results showed that the use of biomass from the remains of conventional poplar plantations showed the lowest impact. Biomass combustion emissions were critical hotspots for particulate matter formation and human toxicity. When the generated bioenergy was compared with the reference system (i.e., the Italian electricity grid), the results were unfavourable for bioenergy systems.

Quispe et al. utilized LCA to examine rice husks' environmental effects in Peru (Quispe et al., 2019). This study examined the environmental impact of 1MJ from rice husks and coal. GWP, AP, EP, and water depletion (WD) were evaluated. The rice husk system analysed the agricultural, milling, and energy production consequences. The coal system boundaries were considered in coal extraction, processing, and energy generation. Four yield and dryer efficiency scenarios were tested. The environmental impact of obtaining 1 MJ from rice husk is 97%, 88%, and 80% lower than coal. In water depletion, coal's influence was 98 % points lower than rice husk.

Contreras-Lisperguer et al. used LCSA to examine cogeneration from sugarcane bagasse in Jamaica (Contreras-Lisperguer et al., 2018). This article analyzes two scenarios: cogeneration already established (Golden Grove in St. Thomas) to create 2.2 MW (baseline scenario) and cogeneration altered to produce 5 MW from bagasse (scenario 1). LCA and LCC systems included agricultural, bagasse production, and cogeneration. Eighteen environmental effects, 12 social hotspots, and one economic criterion were evaluated using LCA, SLCA, and LCC. The LCA results revealed that Scenario 1 had fewer environmental implications than Baseline Scenario. These results showed each life cycle stage's critical environmental effect indicators, such as the cogeneration stage's contribution to water depletion, photochemical oxidant creation, particulate material formation, terrestrial acidification, and human toxicity. In addition, these results indicated the influence of inputs on environmental indicators.

One SLCA indicator (Number of Jobs) was shown to have good social effect potential. Five indicators showed positive potential, depending on organizational policy and/or certification type. One sign (organizational risk assessment about material resource conflict) was likely negative. Five indicators indicated no present or foreseeable societal implications (child labor, forced labor, or employment conditioned). Also, According to LCC data, a novel cogeneration technology cuts bio-power generation costs in Jamaican sugar mills. Agriculture contributed significantly (65%) to the life cycle cost of generating bioelectricity per year in a traditional sugar mill in Jamaica, followed by cogeneration and bagasse production. When a new and efficient cogeneration system was created, the cogeneration process was the most significant contributor to bioelectricity's annual life cycle cost. The increased investment represents 92% of scenario 1's total cost.

Zhu et al. employed LCA and water flow evaluation to examine biomass direct-combustion power generation in Hubei, China (Zhu et al., 2019). Cotton straw was the plant's biofuel. This direct-combustion power system was cradle-to-cradle. This study's total water usage included material intake, precipitation, irrigation, assimilation, and operation and maintenance water. Green, blue, and grey footprints showed direct and indirect water usage. The system's overall life cycle water intensity was 11,708 L/MJ, lower than bioelectricity but higher than geothermal, solar photovoltaic, and wind energy. Biomass agriculture used 84.6% of total water, according to research. Direct green water flow accounted for the most, more than direct and indirect blue water flow combined. The immediate use of blue water, primarily for irrigation, is 21 times greater than the indirect consumption, suggesting that the choice of biomass feedstock and planting area was particularly essential for water-saving. Also, 15.13% of indirect grey water flow needs care since it might damage a significant region of the water body.

Wang et al. 2019 conducted an LCA for fuel based on several types of agricultural leftovers (Z. Wang et al., 2019). The cradle-to-grave system boundary includes feedstock production and collection of agricultural residues. This study used maize and corn stalks as feedstock, comparing the environmental effect of agricultural residue production and collecting with open burning. LCA was used to estimate feedstock-phase pollution emissions. This study dispersed effects based on agricultural residues-to-grain price (revenue) and weight ratios. Corn and corn stalks (agricultural residue) are allocated 91% and 11%, respectively. The crop's arable area coefficient and available energy usage factor determine the collecting radius. Collection radius, road conditions, and vehicle load affect emissions.

Cadena et al., 2019 used SLCA to analyse a Dutch biorefinery's process design (Cadena et al., 2019). The biorefinery can process $4.10x10^6$ tons of glycerol/year into biofuels, green chemicals, and food components. Labor practices and decent labor, product responsibility, human rights, and society were biorefinery social performance objectives. This study offered quantitative and qualitative information on the advantages and dangers of glycerol biofiltration. The biofilter system found three hotspots: OH&S, community, and compliance. Biorefinery systems must be compared to fossil fuel systems in six ways to improve their social performance: social endpoint, product responsibility endpoint, injury, employee welfare, innovation and competitiveness, and community. Adopting this method helps execute relevant social activities at the stakeholder level.

Bosona et al. used LCCA to estimate pruning biomass supply chain costs (Bosona et al., 2019). This analysis encompassed biomass harvesting, storage, and transit to end-users. This research evaluated bottom-up and top-down LCC techniques. The cost computation was based on published formulae, and both PV and NPV values were analysed. Six distinct analysis scenarios, scenarios 1, 2, 3, 4-1, 4-2, and 5, were designed to account for pruning species and processing methods, including baling and chipping. A basic scenario, 50 km transport distance (between farm and end-user), and a truck with a capacity of 90 m^3 have been considered. The results showed that the prototypes could perform good cost-wise. The life cycle cost varied from 50.06 €/tw.b. to 108.90 €/tw.b. The collection/harvesting stage was the most expensive (73% of total cost) followed by the storage (11%) stage. Operational costs represent about 73% of total costs respectively.

KC et al. optimized the environmental sustainability of forest biomass logistics (in terms of GHG emissions) using GIS and agent-based modeling (ABM) (Kc et al., 2020). The environmental effect was assessed using LCA, and the study's scope was gate-to-gate. The business strategy in this research increased forest owners' raw material availability using GIS and ABM technologies. GIS was utilized to evaluate local biomass supply locations (forest storage), road networks, biomass terminals, and power plants, and ABM simulated the delivery system. The BSC's LCA life cycle inventory was created using GIS and ABM. Due to this, LCA findings are close to real-world conditions. Biomass logistics GHG emissions ranged from 2.05 to 2.69 g CO_2-eq per MJ (or 7.38 to 9.6 kg CO_2-eq per MWh) depending on the supply area.

Chen et al. analysed China's biomass energy generation technology's environmental and economic impacts (S. Chen et al., 2020). Direct biomass burning, gasification, mixed combustion, biogas, and coal-fired power facilities underwent environmental impact evaluations. This study employed five environmental effect categories: GWP, AP, POCP, HTP, and SP. Literature and power plant field investigations provided plant emission data. The LCA and AHP were used to calculate environmental impacts. First, LCA was used to calculate effect categories. AHP was then utilized to calculate impact categories and plant environmental load. Biomass electrification has the lowest environmental burden (1.05×10^5), followed by biogas power generation (9.21×10^5), direct biomass combustion (1.23×10^4), and biomass mixed combustion (3.88×10^4). The decrease rates are 97.69%, 79.69%, 72.87%, and 14.56% for coal-fired thermal power.

Payback time, NPV, and IRR were chosen for economic analysis. According to technical and economic evaluation results, biomass direct burning electricity production had the best payback time (7.71 years) and IRR (19.16 %), followed by biogas power generation with a longer dynamic payback period (12.03 years) and lower IRR (13.49 %). Electric and mixed-fired power generating have extended payback times and poor IRRs. This study didn't analyse life cycle costs for economics.

Liu et al. created an integrated framework in the LCA to analyse the climate change implications of biomass use (Liu et al., 2020). This paradigm integrated six effect components: fossil fuel-derived GHG emissions, biogenic CO_2 emissions-loss, biogenic CO_2 emissions-combustion, emissions from land-use practice change, regrowth for compensation, and difference in carbon sequestration. System boundary was cradle-to-grave, specific from raw materials to biofuels. First, second, and third-generation biofuels were investigated. The life cycle GHG emissions for first-generation biofuels were more significant than for energy-equivalent fossil fuels. The corn-to-ethanol process emits the most GHGs (218 kg CO_2/GJ). Life cycle GHG emissions for soy-to-biodiesel were 144.1 kg CO_2/GJ. Second- and third-generation biofuels showed reduced positive GHG emissions (-62 to 53 kg CO_2/GJ) owing to land-use practice modification and carbon sequestration. The study reveals that biofuels' life cycle GHG emissions might be significantly greater than energy-equivalent fossil fuels and traditional LCA estimates without offsetting negative consequences. All biofuels except first-generation biofuels had detrimental effects.

Lecksiwilai et al. examined the advantages and environmental consequences of biofuels in Thailand using an LCA with the Thai Eco Scarcity approach (Lecksiwilai & Gheewala, 2020). Thai Eco Factors based on distance-to-target. This study evaluated the environmental implications of biofuel production and consumption in Thailand. This paper also considered consequential effects of more agricultural land being required, increased freshwater consumption, intensive chemical and pesticide usage, pollutants and emissions in biofuel conversion stages. The results showed that E85 (85% cassava ethanol blended with 15% gasoline) and palm biodiesel had 95% and 43% more influence than fossil fuels.

Foteinis et al. examined the environmental performance of biodiesel made from Used-cooking-oil (UCO) in Greece (Foteinis et al., 2020). LCA calculated UCO biodiesel's environmental performance. In this study, UCO was supposed to come from commercial sources, including fast-food restaurants and catering companies, and trash collecting tanks for domestically produced UCO. Rethymnon County had both UCO sources. Elin Verd SA in Volos, Greece, collects life cycle inventory data. Per tonne of biodiesel production, the overall carbon footprint is 0.55 t CO_2eq (14g CO_2eq/MJ) and 58.37 Pt. This is 40% lower than first-generation biodiesel, a magnitude lower than third-generation, and three times less pollution than diesel. Environmental hotspots include energy input to fuel the process and consumption of methanol (CH_3OH) and potassium methoxide (CH_3KO), Glycerol ($C_3H_8O_3$), and potassium sulfate (K_2SO_4), both process co-products. Furthermore, using UCO for biodiesel might reduce water pollution from its release into wastewater systems.

Cusenza et al. evaluated an anaerobic digester and a combined heat and power plant driven by agri-food bio-waste. Cradle-to-grave LCA was employed (Cusenza, Longo, Cellura, et al., 2021). The assessment included 15 environmental effect categories. This study analyzed an AD - CHP plant from two perspectives: generating renewable power and treating biowaste (1 kWh of grid-fed energy and 1 ton of processed bio-waste). The studied AD-CHP has been functioning in Sicily (Italy) since 2016 for 7200 h per year. Electrical and thermal close-loops were considered. The CHP plant’s energy was returned to the AD and CHP plants to increase bioenergy utilization. Research results showed that biomass transport and electricity use during operation contributed most (over 60%) to most impact categories. In addition, AD-CHP might achieve superior environmental and energy efficiency for power generation and biological waste management than the national grid's ecological electricity profile.

Ramos et al. evaluated the environmental, techno-economic, and social implications of gasifying cork wastes (Ramos et al., 2020). Four LCA scenarios were explored to analyze the gasification system's environmental effects and two LCC scenarios of operation regimes

(8 h/day and 365 days/year). Cork residue creation, collection, and transfer to treatment facilities were system limits (cradle to gate). LCA examined six environmental effect categories, whilst costs were distributed into capital goods (CAPEX) and operational expenses (OPEX). Once the viability of energy generation from cork industry wastes was demonstrated, the LCA findings indicated that Ecorkwaste gasification technology was a successful circular economy case study. This technique allows for more sustainable energy production than the usual method. The LCC found that 60% of spending was OPEX. Staff costs drove up OPEX. Plant building accounted for 30-40% of CAPEX. Both regimens showed viability with good NPV and reasonable payback times.

Cusenza et al., 2021 assessed the possible environmental implications of bio-char generation from pyrolysis of agro-industrial leftovers and various temperatures (Cusenza, Longo, Cellura, et al., 2021). Olive tree clippings, olive pomace, lemon peel, and orange peel were utilized to make biochar at 400, 500, and 650ºC. The life-cycle strategy was applied. Environmental and energy analyses were done during feedstock delivery, pre-treatment, and pyrolysis. Biochar's environmental impact is independent of pyrolysis temperature, according to research. Each type of biomass pyrolyzed at different temperatures had an environmental impact of less than 5%. The kind of feedstock affects pyrolysis' environmental impact. Orange peel biochar has a 16% lower environmental effect than olive tree clippings. This study found that operating power usage had the most consequences, followed by biological waste transfer. Electricity's contribution to the life cycle effect ranges from 44% (for cumulative energy consumption) to 91% (for terrestrial eutrophication). In contrast, transport contributed 4% to land and marine eutrophication and 36% to mineral, fossil, and renewable resource depletion.

Hiloidhari et al. employed LCA to analyse bagasse cogeneration in India (Hiloidhari et al., 2021). All districts evaluating the farm-to-gate border analysed the change in energy inputs and carbon and water emissions from bagasse-based cogeneration facilities. Carbon, energy, and water footprints of the sugarcane bioenergy were evaluated. Bagasse-generated power has 5–12 times less carbon impact than coal. Growing sugarcane contributed 88–95% of total emissions, followed by milling (4–8%) and cogeneration (1-3%). Coal-fired energy for irrigation and inorganic and organic fertilizers contributed to carbon emissions in farming. Bagasse-based electricity has a more significant water footprint than coal-fired power, which might limit its application. Maximizing irrigation efficiency during sugarcane growth was crucial. Replacing flood irrigation with a sprinkler or drip irrigation might lower irrigation water needs by 40–50%, affecting bagasse electricity. The average EROI across districts was 2.8. To reduce sugarcane's environmental effect, by-products including cane waste, press sludge, and bagasse ash should be employed.

Hosseinzadeh-Bandbafha et al. used LCA to analyse the environmental sustainability of bioethanol production in a safflower-based biorefinery (Hosseinzadeh-Bandbafha et al., 2022). This study's environmental evaluation focused on human health, ecosystem quality, climate change, and resource loss. The system boundary was cradle-to-grave, from resources and energy entering the safflower farm through bioethanol production. According to the results, the production of safflower and its processing into 1 MJ bioethanol in a safflower-based biorefinery caused 2.23E-07 disability-adjusted life years (DALYs), 2.35E-02 potentially disappearing parts (PDFs) * m2 * yr., 4.76E-01 kg CO2 eq., and 3.82 MJ of damage to human health, ecosystem quality, climate change, and resources, respectively. Damage to human health and climate change was reduced by 52% and 24%. The environmental consequences of the safflower-based biorefinery fell by 64% due to the generation of bioproducts, principally biodiesel and biogas. Safflower-based biofiltration reduced ecosystem quality and resource degradation by seven and two times.

Yang et al. calculated the life cycle cost of biomass co-firing facilities with or without CCS (CO_2 capture and storage) and how to maximize different incentives to increase the economic feasibility of BECCS (biomass energy with CO_2 capture and storage) plants (Yang et al., 2021). System boundary was cradle to grave, including raw material procurement, fuel delivery, power plant energy conversion, pollution management, and CCS. This study considers ten instances for biomass co-firing plants with or without CCS, including two coal-only cases, A0 and B0, and eight other scenarios with 10%, 20%, 40%, and 100% crop residues A1 to A4 and B1 to B4, respectively. The LCC results revealed that nearly 90% of delivered fuel comes from raw material acquisition and processing, and biomass costs roughly twice as much as coal (95.19 $/ton vs 54.68 $/ton). From a life cycle viewpoint, the LCOE of the Biomass plant was almost twice that of the Coal plant (e.g., 95.2 $/MWh vs 48.4 $/MWh), and capital cost and fuel use were the primary contributors. All CCS scenarios were less economical than their counterparts without CCS. Hence BECCS plants were not economically attractive in China.

Hossain et al. analyzed bioethanol-gasoline mix life cycle costs in Malaysian transportation (Hossain et al., 2021). Bioethanol, bio fertilizer, gasoline prices, and fuel heating value were acquired from journals, technical datasheets, gasoline company databases, and authenticating websites. The economic value of a bioethanol facility is projected using a life cycle cost study. Capital Cost, Operating Cost, Maintenance Cost, Feedstock Cost, Salvage Value, and By-product Cost were determined for a 20kton bioethanol facility. Bioethanol was made from rubberwood and palm trash. Payback periods for bioethanol produced from rubberwood and oil palm trash were 1.1249 and 1.048 years, respectively. Bioethanol from rubberwood waste (24278774 USD) was similarly more expensive than oil palm leftovers (15246081 USD). A 10% bioethanol/gasoline blend may save 1443.38 GJ of gasoline.

Table 3.3. LCT tools, system boundaries, functional units and data acquisition of reviewed case studies

No	Authors	Methodology			System boundary	Functional unit	Data acquisition		Remark	Ref.
		LCA	LCC	SLCA			Foreground processes	Background processes		
1	Fantozzi and Buratti	X			Cradle-to-Grave	1 MJ of thermal energy	Direct field observation	Literature	Evaluation of machines and infrastructure contribution in LCA analysis.	(Fantozzi & Buratti, 2010)
2	Requena et al.	X			Cradle-to-Grave	1 kg of biofuel		Ecoinvent	Comparison of environmental effects of biomass feedstocks.	(Sanz Requena et al., 2011)
3	Shie et al.	X			Cradle-to-Grave	The total amount of agricultural by-products available for fuel production.	Site survey		Using LCA for assessing energy consumption.	(Shie et al., 2014)
4	Wang et al.	X			Cradle-to-Grave	1 MWh	Site survey		Using LCA for optimisation of biomass gasification.	(J.-J. Wang et al., 2014)
5	Mirkouei et al.	X			Cradle-to-Grave	1 gallon of bio-oil		Literature, Ecoinvent	Quantifying life cycle GHG emissions of mixed mode	(Mirkouei et al., 2016)

									biorefineries and mixed transportation pathway of the bioenergy supply chain	
6	Murphy et al.	X			Cradle-to-Grave	1 ha of forest, 1MWh of electricity generation		Ecoinvent	Using LCA for energy-producing optimisation from biomass.	(Murphy et al., 2016)
7	Vega-Quezada et al.	X	X		Cradle-to-Grave	40,000 ha of food crop		Literature	Using LCT for assessing synergies and comparing GHG emissions, Benefit and Cost of different bioenergy production pathway	(Vega-Quezada et al., 2017)
8	Parajuli et al.	X			Cradle-to-Grave	1 tonne dry matter of the harvested biomasses.	Site survey	Ecoinvent	Using LCA for evaluating biomass input in bioenergy production.	(Parajuli et al., 2017)
9	Quispe et al.	X			Cradle-to-Grave	1MJ	Questionnaire survey	Literature, Ecoinvent	Comparison of environmental impacts in energy production from biomass and coal.	(Quispe et al., 2019)

10	Wang et al.	X			Cradle-to-Grave	The total amount of agricultural by-products available for fuel production	Site survey	Literature	Evaluating the environmental impact of the feedstock stage of agricultural residue-based biofuels.	(Z. Wang et al., 2019)
11	Liu et al.	X			Cradle-to-Grave	1 GJ of energy equivalent biofuel		Argonne National Laboratory Database	Comparison of environmental impacts of generations of power plants.	(Lecksiwilai & Gheewala, 2020)
12	Foteinis et al.	X			Cradle-to-Grave	1 tonne of biodiesel production		Ecoinvent	Using LCA for first- and third-generation biofuel assessment.	(Foteinis et al., 2020)
13	Cusenza et al.	X			Cradle-to-Grave	1 kWh of grid-fed energy and 1 tonne of processed bio-waste	Site survey	Ecoinvent	Assessment of potential energy and environmental impacts of an anaerobic digester.	(Cusenza, Longo, Guarino, et al., 2021)
14	Cusenza et al.	X			Cradle-to-Grave	1 MJ of thermal energy	Site survey	Ecoinvent	Role in improving the environmental performance of distributed heat systems.	(Cusenza, Longo, Cellura, et al., 2021)

15	Hosseinzadeh-Bandbafha et al.	X			Cradle-to-Grave	1 MJ of bioethanol	Conducting industrial-scale experiments	Ecoinvent	Analysis of production effects using biofuels.	(Hosseinzadeh-Bandbafha et al., 2022)
16	Valente et al.	X			Cradle-to-Gate	1 solid cubic meter of woody biomass over bark	Site survey		Analysis of forestry management in bioenergy production.	(Valente et al., 2011)
17	Ren et al., 2016	X			Cradle-to-Gate	1 t bioethanol production, and 1 hectare of wheat, corn, and cassava	Site survey		Optimisation of biofuel supply chain in uncertain conditions.	(Ren et al., 2016)
18	González-Garca et al.	X			Cradle-to-Gate	1 kWh of electricity	Direct estimation	Literature	Transport distance is a hotspot environmental impact on biomass supply.	(González-García & Bacenetti, 2019)
19	Zhu et al.	X			Cradle-to-Cradle	1MJ	Site survey	Literature	Usage of LCA for calculating water use in bioenergy production.	(Zhu et al., 2019)
20	Hiloidhari et al.	X			Farm-to-Gate	1 kWh of electricity	Interviews with expert	Literature	Emphasizing of the role of local energy planning and water and carbon energy	(Hiloidhari et al., 2021)

									management in sugarcane energy production.	
21	Lecksiwilai and Gheewala	X			Well-to-Wheel	100 MJ of fuel		Literature and Ecoinvent	Usage of LCA results as evidence for making policy decisions.	(Lecksiwilai & Gheewala, 2020)
22	Gallejones et al.	X			Well-to-Tank	1 MJ of biofuel		Literature and Ecoinvent	Environmental impact assessment of the crop production stage.	(Gallejones et al., 2014)
23	Lahiri and Acharjee		X		Cradle-to-Grave	50 kW	Site survey		Calculating the electricity production from stand-alone, off-grid devices biomass gasifiers.	(Debabrata Lahiri & Acharjee, G, 2013)
24	Sawaengsak et al.		X		Cradle-to-Grave	1l of algal biodiesel production	Site survey		emphasizing of initial and operating costs in algal biodiesel production.	(Sawaengsak et al., 2014)
25	Ren et al.		X		Cradle-to-Grave	The total amount of agricultural by-products	Site survey		Usage of interval linear for optimization of life cycle cost.	(Ren et al., 2015)

						available for fuel production.				
26	Odavić et al.		X		Cradle-to-Grave	1MW of the biomass power plant.	Site survey		Usage of the LCC method for calculating investment effects of the biomass power plant.	(Odavic et al., 2017)
27	Okoko et al.		X		Cradle-to-Grave	A meal cooked	Site survey		Identification of the best cost efficient in cooking.	(Okoko et al., 2018)
28	Yang et al.		X		Cradle-to-Grave	one MWh of net power	Site survey		Comparison of the cost between two technology of biomass power plant.	(Yang et al., 2021)
29	Hossain et al.		X		Cradle-to-Grave	20 thousand tonne bioethanol	Site survey		Usage of LCC for analysis of using biofuels economic efficiency in transportation.	(Hossain et al., 2021)
30	Silalertruksa et al.		X		Cradle-to-Grave	A milling site capacity of 1000 tonne of fresh fruit bunches per day.	Site survey	Literature	evaluation of environmental costs contribution in total costs for biofuel production.	(Silalertruksa et al., 2012)

31	Bosona et al.		X		Gate-to-Gate	1 tonne of biomass over a wet basis		Literature	Operational cost was the most contribution of total life cycle cost in agricultural pruning energy production.	(Bosona et al., 2019)
32	Cadena et al.			X	Cradle-to-Grave	The biorefinery with a capacity of $4.10x10^6$ tonne of glycerol/year	Site survey	Literature	Development new methodology to SLCA for production process design assessment.	(Cadena et al., 2019)
33	Afrane and Ntiamoah	X	X		Cradle-to-Grave	1 MJ fuel	Site survey	Ecoinvent, Gabi database	Using LCA and LCC results for selection of cooking energy sources.	(Afrane & Ntiamoah, 2012)
34	Resurreccion et al.	X	X		Cradle-to-Wheel	20,000 vehicle kilometers travelled (VKT) /year	Site survey		Comparison economic and environmental impacts of algae cultivation methods.	(Resurreccion et al., 2012)
35	Zhang et al.	X	X		Cradle-to-Gate	Treatment of waste produced by 100 cows per year	Site survey		LCA and LCC results were used to make policy for sustainable nutrient management systems.	(Y. Zhang et al., 2013)

36	Ramos et al.	X	X		Cradle-to-Gate	1 MWh of energy	Site survey		The gasification strategy had a sustainable profile with lower environmental impacts than the conventional scheme of energy production.	(Ramos et al., 2020)
37	Kern et al.	X			Well-to-Wheel	10 million gallons of biodiesel fuel		Literature	LCA method could provide many useful insights regarding plant design.	(Kern et al., 2017)
38	Luu and Halog	X	X	X	Cradle-to-Grave	1MWh of bio-electricity generation		Literature, Ecoinvent	The rice husk-based bioelectricity is more sustainable than coal-fired counterpart.	(Luu & Halog, 2016)
39	Contreras-Lisperguer et al.	X	X	X	Cradle-to-Grave	2.2 MW and 5 MW	Site survey		Evaluating sustainability of generation of electricity from cogeneration derived from bagasse based on LCA, LCC and SLCA results.	(Contreras-Lisperguer et al., 2018)

40	Zeller et al.	X			Bin-to-Grave	50,000 Mg	Site survey	Ecoinvent	Using LCA to assess and compare the environmental impact of different waste management strategies	(Zeller et al., 2020)
41	KC et al.	X			Gate-to-Gate	1 year of operation of a large scale CHP plant in Finland, 1 MWh of wood fuel	Site survey	Ecoinvent	LCA was used to design network transport for bioenergy production.	(Kc et al., 2020)
42	Chen et al.	X	X		Cradle-to-Cradle	1 kWh of generating capacity		Literature	integrating analytic hierarchy process into LCA framework for environmental impact assessment.	(S. Chen et al., 2020)

2. Some methodological aspects applying LCT approach in BSC

The economic, environmental, and social impact assessments, considering the LCT approach are conducted with applications of LCC, LCA and SLCA method, respectively. Among 42 case studies applying LCT approach, 32 studied used LCA method, 17 cases considered LCC method, while there are three studies considered SLCA method. Besides, eight studies used several LCT tools simultaneously, either combining LCA and LCC, or all three LCT tools for LCSA. The summarization of applicable tools, system boundaries, functional units (FU), and data acquisition of reviewed case studies is presented in the Supporting Information, Tables 3.3.

Regarding system boundary, 31 out of 42 LCT case studies considered the whole BSC from cradle to grave (Afrane & Ntiamoah, 2012; Cadena et al., 2019; Contreras-Lisperguer et al., 2018; Cusenza, Longo, Cellura, et al., 2021; Debabrata Lahiri & Acharjee, G, 2013; Fantozzi & Buratti, 2010; Foteinis et al., 2020; Gallejones et al., 2014; Hosseinzadeh-Bandbafha et al., 2022; Kern et al., 2017; Lecksiwilai & Gheewala, 2020; Liu et al., 2020; Luu & Halog, 2016; Mirkouei et al., 2016; Murphy et al., 2016; Odavic et al., 2017; Okoko et al., 2018; Parajuli et al., 2017; Quispe et al., 2019; Resurreccion et al., 2012; Sanz Requena et al., 2011; Shie et al., 2014; Silalertruksa et al., 2012; Vega-Quezada et al., 2017; J.-J. Wang et al., 2014; Yang et al., 2021). In these case studies, sometimes the terms such as "from well to tank", "from well to wheel", or "from cradle to wheel" were used, with the same meaning of "from cradle to grave". These case studies quantify the impacts from the stage of biomass feedstock plantation to the consumption of biofuels for transportation (e.g. tank or wheel) or the end of life of bioenergy. There are seven case studies considering the impacts from cradle to gate (González-García & Bacenetti, 2019; Hiloidhari et al., 2021; Ramos et al., 2020; Ren et al., 2016; Valente et al., 2011; Zeller et al., 2020; Y. Zhang et al., 2013), and two studies from gate to gate (Bosona et al., 2019; Kc et al., 2020). Interestingly, two studies considered the BSC from cradle-to-cradle (S. Chen et al., 2020; Zhu et al., 2019).

There were multiple FUs in 42 case studies. FUs for energy products such as 1MJ, 1 GJ, 1kWh, 1MWh were the most common FU, occurred in 21/39 case studies (Afrane & Ntiamoah, 2012; S. Chen et al., 2020; Contreras-Lisperguer et al., 2018; Cusenza, Longo, Cellura, et al., 2021; Debabrata Lahiri & Acharjee, G, 2013; Fantozzi & Buratti, 2010; Gallejones et al., 2014; González-García & Bacenetti, 2019; Hiloidhari et al., 2021; Hosseinzadeh-Bandbafha et al., 2022; Liu et al., 2020; Luu & Halog, 2016; Murphy et al., 2016; Odavic et al., 2017; Oliveira Pavan et al., 2021; Quispe et al., 2019; Ramos et al., 2020; J.-J. Wang et al., 2014; Yang et al., 2021; Zhu et al., 2019). Mass based FUs such as 1 ton, or volume based FUs such 1 litre, 10 million gallons are also frequently applied, for example 1 kg of biofuel (Sanz Requena et al., 2011), 1 tonne of biodiesel/ bioethanol (Foteinis et al., 2020; Ren et al., 2015), 20 kt of bioethanol (Hossain et al., 2021), 1 litre of algal biodiesel (Sawaengsak et al., 2014), 1 gallon of bio-oil (Mirkouei et al., 2016a), 10 million gallons of biofuel (Kern et al., 2017). It is quite interesting that FUs for energy products such as biofuel and electricity are frequently applied, being used in 70% of LCT case studies. This can be explained by the fact that final product of the BSC which attracts a lot of attention is the energy product. Meanwhile, FUs of biomass feedstock or bio-waste is less common, e.g. 1 tonne of dry (or wet) matter of biomass (Bosona et al., 2019; Parajuli et al., 2017), 1 cubic meter of biomass (Valente et al., 2011), 1 ha of forest (Murphy et al., 2016), 40 thousand ha of food crop (Vega-Quezada et al., 2017), the total amount of agricultural by-products available for fuel production (Ren et al., 2016; Shie et al., 2014; J.-J. Wang et al., 2014), a milling site capacity of 1000 tonne of fresh fruits bunches per day (Silalertruksa et al., 2012), the biorefinery with a capacity of 4.10 million tonnes of glycerine per year (Cadena et al., 2019), 1 tonne of processed bio-waste (Cusenza, Longo, Guarino, et al., 2021), 50 thousand tonne of green and food waste (Zeller et al., 2020), treatment of waste produced by 100 cows per year (Y. Zhang et al., 2013). The least common FUs are the ones neither used for energy product, nor biomass feedstock/ bio-waste, such as 1 year of operation of a large scale CHP plant in Finland (Kc et al., 2020), a meal cooked (Afrane & Ntiamoah, 2012), 20,000 vehicle kilometre travelled/year (Resurreccion et al., 2012).

The case studies collected data from a variety of sources, such as directly obtained from fieldwork and indirectly extracted from inventory databases, modelling, and literatures. In these cases, the primary data are used for foreground processes, while the secondary and proxy data from inventory databases, modelling, and literatures are used for background processes. The most popular source for secondary data is Ecoinvent.

3. Environmental, economic and social hotspots

The LCA results indicated that most of environmental impacts of the BSC lie in the harvesting and collection of biomasses (Lecksiwilai & Gheewala, 2020). Most of fossil material and mineral (fertilizer and pesticides) consumption is for resource production and transportation stages (Cusenza, Longo, Cellura, et al., 2021; Lecksiwilai & Gheewala, 2020). Besides, resource production is the stage causing most of ecosystem impacts such as land use, eutrophication potential. The consumption of chemical resources such as energy and water during this stage accounts for the largest share of total life cycle resource consumption. At the same time, LCC studies used the initial cost (capital cost) and operation cost for calculating life cycle cost, and revealed that the cost for resource production and transportation activities are the most significant cost categories (Bosona et al., 2019; Silalertruksa et al., 2012; Yang et al., 2021). Therefore, the resource production and transportation stages are identified as the environmental and economic hot-spots of the BSC.

The SLCA case studies showed that several social concerns during the general BSC are employees, suppliers, product users, local communities, and host governments (Contreras-Lisperguer et al., 2018). At the same time, the social concerns being identified during the life cycle of biorefinery systems include occupational health and safety, local community, and compliance (Cadena et al., 2019). Despite the limited number of studies relevant to social aspects, it is agreed that local community need to be taken into account when evaluating and assessing social impacts of the BSC.

4. Sustainability indicators

To assess environmental sustainability, two case studies used endpoint environmental indicators (Hosseinzadeh-Bandbafha et al., 2022; Luu & Halog, 2016), remaining cases considered midpoint indicators.

With regards on environmental sustainability indicators, the number of indicators was different among case studies. There are several indicators being studied in the case studied, including Global Warming Potential (GWP), Ozone Depletion Potential, Human Toxicity, Particulate Matter Formation, Ionizing Radiation, Photochemical Ozone Formation, Acidification, Eutrophication, Ecotoxicity, Resource depletion, Land use and Water consumption. Among these indicators, the most common ones are GWP and energy consumption. The environmental indicators are frequently studied in combination. It is rare that only one indicator is applied, for example water usage (Zhu et al., 2019), and GHG indicator (Valente et al., 2011).

The GHG emissions, and other similar indicators such as CO_2 emissions, climate change, GWP are the most frequently assessed indicators, which were used in 29 studies. The GHG indicator was used in five case studies using LCA and LCC to assess economic and environmental impacts (Afrane & Ntiamoah, 2012; S. Chen et al., 2020; Ramos et al., 2020; Resurreccion et al., 2012; Y. Zhang et al., 2013). In 24 remaining cases, GHG was used to determine the ecological effects of BSC globally whilst for evaluating local environmental impacts, eutrophication potential, water consumption, and land use were used. Results of GHG emissions in the case studies is reported in Table 3.4.

Table 3.4. GHG emissions in review case studies

Paper	Indicators	Units	Value	Ref
Chen et al., 2020	GHG	kg per kWh of electricity	1.05 to 0.79	(S. Chen et al., 2020)
Mirkouei et al. 2016	GHG	$kgCO_2e$ per liter of bio-oil	1.82-1.86	(Mirkouei et al., 2016)
Murphy et al., 2016	GHG	$kgCO_2e$ per MWh of electricity	619.9 - 839.6	(Murphy et al., 2016)
Valente et al., 2011	GHG	$kgCO_2e$ per m^3 of woody biomass	17.60	(Valente et al., 2011)
Kc et al., 2020	GHG	$kgCO_2e$ per MWh of electricity	2.72 - 3.46	(Kc et al., 2020)

Paper	Indicators	Units	Value	Ref
Resurreccion et al., 2012	GHG	$kgCO_2e$ per 20,000 VKT per year	260 - 730	(Resurreccion et al., 2012)
Zhang et al.	GWP	tCO_2e per year	196	(Y. Zhang et al., 2013)
Wang et al., 2014	CO_2 emissions	kg per MWh of electricity	59.60	(J.-J. Wang et al., 2014)
Ren et al., 2015	CO_2 emissions	kg per tonne of bioethanol	$2.97*10^8$ to $3.42*10^8$	(Ren et al., 2015)
Liu et al., 2020	GHG	kg per GJ	144.1-218	(Liu et al., 2020)
Ren et al., 2016	total CO_2 emissions	kg per total amount of biomass available	$2.97*10^8$ - $3.25*10^8$, $3.13*10^8$- $3.42*10^8$	(Ren et al., 2016)
Quispe et al. 2019	GWP	gCO_2e per MJ of biofuel	4.29	(Quispe et al., 2019)
Parajuli et al., 2017	GWP	$kgCO_2e$ per tonne dry matter	84-246	(Parajuli et al., 2017)
Contreras-Lisperguer et al., 2018	Climate change	$kgCO_2e$ per 2.2 MW installed capacity of biofuel plant	-3,574,623	(Contreras-Lisperguer et al., 2018)
Foteinis et al., 2020	Climate change	$kgCO_2e$ per tonne of biofuel	553	(Foteinis et al., 2020)
Ramos et al. 2020	GWP	$kgCO_2e$ per MWh of electricity	121.8	(Ramos et al., 2020)
Cusenza et al. 2021.	GWP	$kgCO_2e$ per kWh of electricity	1123	(Cusenza, Longo, Guarino, et al., 2021)
Hosseinzadeh-Bandbafha et al., 2021	Climate change	$kgCO_2e$ per MJ of bioethanol	0.363	(Hosseinzadeh-Bandbafha et al., 2022)
Cusenza et al. 2021	GWP	$kgCO_2e$ per MJ of heat	2.34	(Cusenza, Longo,

Paper	Indicators	Units	Value	Ref
				Cellura, et al., 2021)

To evaluate the economic sustainability, some indicators such as the life cycle cost, revenue, net present value (NPV), interest rate of return (IRR), return on investment (ROI), and payback period were used. 13 studies used life cycle cost, NPV was considered in five studies, and there were two cases considering IRR (S. Chen et al., 2020; Odavic et al., 2017). Besides that, there were two cases considering the payback period for financial analysis (S. Chen et al., 2020; Odavic et al., 2017). Results of economic sustainability in the case studies is reported in Table 3.5.

Table 3.5. Economic sustainability indicators in the case studies

Paper	Indicators	Units	Value	Ref.
Chen et al., 2020	Payback period	year per kWh of electricity	7.71 - 12.03	(S. Chen et al., 2020)
	IRR	%	19.16 - 13.49	
Odavić et al., 201	NPV	Million EUR per 1MW biomas plant	4.10	(Odavic et al., 2017)
	IRR	%	11.32	
	ROI	%	18.24	
	Profitability	%	15.48	
Valente et al., 2011	Cost	Norwagian Krone per m^3 of woody biomass	463	(Valente et al., 2011)
Silalertruksa et al., 2011	Total cost	Thai Baht per litre of diesel equivalent	32.29-38.13	(Silalertruksa et al., 2012)
Afrane et al., 2012	Annual environmental damage cost	USD per household	36.497	(Afrane & Ntiamoah, 2012)
Okoko et al., 2018	Life Cycle Cost	USD per meal	0.03-0.04	(Okoko et al., 2018)
Zhang et al., 2013	NPV	Million USD per year	-0.06 to 0.85	(Y. Zhang et al., 2013)
Sawaengsak et al., 2014	Cost	Thai Baht per litre of biodiesel	68-450	(Sawaengsak et al., 2014)
Lahiri & Acharjee	Life Cycle Cost	Indian Rupee per kWh of electricity	7.86-10.43	(Debabrata Lahiri &

Paper	Indicators	Units	Value	Ref.
				Acharjee, G, 2013)
Wang et al., 2014	Life Cycle Cost	USD per MWh of electricity	41.9	(J.-J. Wang et al., 2014)
Yang et al., 2021	Carbon capture cost	USD per tCO2	37.76 - 89.21	(Yang et al., 2021)
	Avoided cost	USD per tCO2	68.22 - 158.85	
Zabaniotou et al., 2015	Extra income	Thousand EUR	4	(Zabaniotou et al., 2015)
Vega-Quezada et al., 2016	NPV	Billion USD	1.4-1.8	(Vega-Quezada et al., 2017)
	Benefit-Cost Ratio		5.48-5.70	
Luu and Halog, 2016	Total cost	USD per MWh of electricity	57.91	(Luu & Halog, 2016)
Contreras-Lisperguer et al., 2018	Life Cycle Cost	Jamaican Dollar per 2.2 MW installed capacity of biofuel plant	106,192,327	(Contreras-Lisperguer et al., 2018)
Bosona et al., 2019	Life Cycle Cost	EUR per tonne of biomass (wet basis)	50.06 - 108.90	(Bosona et al., 2019)
Ramos et al. 2020	NPV	Million EUR per MWh of electricity	0.11	(Ramos et al., 2020)
	Life Cycle Cost	Million EUR per MWh of electricity	0.06	
	Payback period	Year	10	
	IRR	%	9.12	

Some social indicators, which were employed to examine the social sustainability, include knowledge-intensive jobs, total employment, child labor, forced labor, regional income, and global inequalities (Cadena et al., 2019; Contreras-Lisperguer et al., 2018). These indicators are quantitative, while some qualitative are less common. Results of social sustainability in the case studies is reported in Table 3.6.

Table 3.6. Social sustainability indicators in the case studies

Paper	Indicators	Unit	Value	Ref.
Luu and Halog, 2016	Total employment per MWh of electricity	Hour	0.21	(Luu & Halog, 2016)
	Child labor per MWh of electricity	Hour	0.0321	
	Forced labor per MWh of electricity	Hour	0.00215	
Contreras-Lisperguer et al., 2018	Change of seasonal jobs to the same number of full-time jobs per 2.2 MW installed capacity of biofuel plant		>200	(Contreras-Lisperguer et al., 2018)

3.1.5. Advantages and barriers of applying LCT tools and CE principles to BSC

Results of CE and LCT studies are useful for developing a resource/material efficiency business strategy. Three studies have outlined the plan on efficient use of biomass, energy, fossil fuels, and water (Bai et al., 2020a; Ren et al., 2015a; Y. Zhu et al., 2019b). For example, Bai et al. aim at reducing resource inputs for a Mongolian and Chinese biomass-based power plant. By optimizing the quantity and the location of raw material purchasing stations, as well as improving existing technologies, the consumption of biomass and fossil fuels reduces, which consequently maximizes the environmental, economic and social benefits (Bai et al., 2020). Similarly, Ren et al. considered the amount of feedstock, transportation activities, technology and market demand under uncertain conditions. The authors identified that the mixture of feedstock and technology selection, and improved transportation efficiency help to reduce the life cycle energy consumption, CO_2 emissions of the BSC, and bring economic profit (Ren et al., 2015). Besides, Zhu et al. examined life cycle water consumption of the biomass-based power generation in Hubei, China. The system's life cycle water intensity was 11,708 litre/MJ, in which biomass plantation consumed 84% of the life cycle water use. As biomass plantation is a water intensive stage, it is suggested that the choice of biomass feedstock and planting area is particularly essential for water-saving (Zhu et al., 2019).

Moreover, the results of CE and LCT case studies are the scientific basis to support decision-makers in selecting raw materials. Three LCA studies compared different types of biomass feedstocks for choosing the most environmental friendly feedstock profile (Murphy et al., 2016; Parajuli et al., 2017; Sanz Requena et al., 2011). Specifically, Murphy et al. predicted environmental impacts of biomass-to-energy systems in Ireland by 2020. Various feedstocks such as pulpwood, forest wastes and sawmill residues were compared. The study found that the combustion of one feedstock in CHP plants has lower GWP, acidification and eutrophication potentials than co-firing, e.g. mixing several types of feedstocks (Murphy et al., 2016). Besides, Sanz Requena et al. compared land use, fossil fuel consumption, carcinogen effect, inorganic respiration and climate change impacts of biofuels from sunflower, rapeseed, and soybeans. The paper showed that rapeseed oil extraction consumed the greatest amount of fossil fuels, while sunflower seed production required the largest land area, and caused the most critical soil effect (Sanz Requena et al., 2011), Parajuli et al. examined the environmental footprint of willow, alfalfa, and spring barley straw, and identified that straw requires less agricultural land than the other two counterparts, but causes the largest negative impact on soil quality (Parajuli et al., 2017).

The results of CE and LCT case studies informed that the application of LCT and CE also identified environmental and economic hotspots during the BSC (Bosona et al., 2019; Contreras-Lisperguer et al., 2018; Cusenza, Longo, Guarino, et al., 2021, 2021; Fantozzi & Buratti, 2010; Hiloidhari et al., 2021; Shie et al., 2014; Valente et al., 2011)_ Biomass plantation and transportation accounted for the largest shares of environmental impacts (Cusenza, Longo, Guarino, et al., 2021; Fantozzi & Buratti, 2010; Hiloidhari et al., 2021; Valente et al., 2011)_and consequently implying the greatest impact on the total biomass/ bioenergy cost (Z. Wang et al., 2019). These information on environmental and economic impacts would help authorities adjust renewable energy development policies toward sustainable development goals. The result of nine case studies have provided comprehensive and scientific-based evidence of environmental, economic, and social benefits (or disadvantages) of biomass feedstocks and bioenergy generation technologies, so that the decision-maker can select the most effective option (Cadena et al., 2019; Hosseinzadeh-Bandbafha et al., 2022; Kern et al., 2017; Lecksiwilai & Gheewala, 2020; Odavic et al., 2017; Okoko et al., 2018; Quispe et al., 2019; Ren et al., 2015).

However, no literature comprehensively assesses circularity and sustainability impacts. In 55 case studies, four papers considered the application of both CE principles and LCT tools to BSC (Kern et al., 2017; Mirkouei et al., 2016; Vega-Quezada et al., 2017; Zeller et al., 2020). Among different LCT tools, only the LCA was used to assess environmental impacts, while LCC and SLCA, were not considered. Therefore, the CE measures are only evaluated in their environmental aspects, disregarding the economic aspects, while economic indicators are important components of CE. CE principles and LCT tools involved in these studies are shown in Table 3.7.

In addition, there were very few studies evaluating the sustainability of the BSC on all three pillars. Only two studies simultaneously applied three LCT tools, including LCA, LCC and SLCA for assessing the sustainability of BSC (Contreras-Lisperguer et al., 2018; Luu & Halog, 2016). Five studies combined LCA and LCC for evaluating project's environmental impacts and economic feasibility (Afrane & Ntiamoah, 2012; S. Chen et al., 2020; Ramos et al., 2020; Resurreccion et al., 2012; Y. Zhang et al., 2013).

Table 3.7. Case studies on CE and LCT application

Author	Ref.	CE principles	LCT tool
Mirkouei et al.	(Mirkouei et al., 2016)	Reduction, Reuse, Replacement	LCA
Vega-Quezada et al.	(Vega-Quezada et al., 2017)	Reuse, Recycling, Reduction	LCA, LCC
Zeller et al.	(Zeller et al., 2020)	Recycling	LCA
Kern et al.	(Kern et al., 2017)	Recycling, recovery	LCA

3.1.6. Discussion

This review provides a comprehensive assessment of the application of CE and LCT to the BSC. It encompasses multiple biomasses, production technologies and bio-products. Results of the CE review reveal which CE principles (such as reuse, recycle, reduction and recovery) were priority used and activities to create closed loops as well as which CBMs (for example, recycle and recovery; resource recovery; cascading and repurposing; and circular supply) were implemented. Furthermore, it identifies the circularity assessment indicators that have been employed in bioenergy contexts. The review also highlights specific processing technologies (anaerobic digestion, microalgae cultivation, gasification, pyrolysis) that are being leveraged to enhance circularity are also indicated. Therefore, this article provides information for the academic community, industries and policymakers on CE principles and how to deploy the circular strategies and CBMs in their work.

Additionally, this review has fully evaluated significant methodology aspects of LCT tools in the biomass production context. Furthermore, the results of this review provide insights into sustainable hotspots and sustainable indicators values of BSCs, offering a holistic view of sustainability across different stages of BSCs ranging from cradle to grave. Thus, the findings about the LCT and BSCs of this study can be a good reference to measure sustainability and a benchmark for comparison. They are also valuable notes for researchers when they perform assessment with LCT approach. Moreover, this review article addresses the relevance of its findings to the broader field of bioenergy technology relevant to hot topics such as CE, LCT, biofuels, and renewable energy. Therefore, it provides a valuable reference view for researchers and scientists, aiding them in identifying future research directions within the dynamic and ever-evolving realm of bioenergy technology.

However, this review paper has some limitations in the results obtained. The social assessment for BSCs is carried out with a limited number of studies (three case studies) for certain production processes and biomass, so the assessment results make it difficult to cover all remaining cases of biomass. In addition, there is a lack of methods for identifying social indicators. There are some indicators to be practised in calculation values, remaining qualitative indicators are mostly theoretically discussed. The application of CE also only takes place for certain processing processes, which are heavily related to biogas production and only 4/10 CE principles are applied. Furthermore, there are several recommended CBMs (theoretically) which have not mentioned or analysed in the reviewed case studies; therefore, the role of CE applications for BSCs has not been fully evaluated. The CE indicators used to measure the level of circularity were limited, so they do not completely reflect the circularity of BSCs.

3.2. Brief review: the decision support system based on Multi - Criteria Decision Making in the sustainability context

3.2.1. Objective

Sustainability is an urgent objective that has attracted the attention of many organisations, policymakers, businesses, and governments in many countries. They consider sustainability as a goal of development. Many scholars and policymakers have studied and applied sustainability to all areas of life, such as cultural development, tourism, industry, energy, transportation, and construction (Robert et al., 2005; United Nations, 2015). Sustainability is considered under multiple criteria in three aspects: environmental sustainability, economic sustainability, and social sustainability (Santoyo-Castelazo & Azapagic, 2014; Zarte et al., 2019). These aspects are also used as goals in developing sustainable options, while criteria are used for evaluating the sustainability of these options. For example, in terms of environmental sustainability, criteria of environmental impacts such as greenhouse gas emissions and ozone depletion, or maximizing the potential for resource conservation, are used. Economic sustainability, on the other hand, is evaluated based on reducing costs and increasing revenue. Creating jobs, social acceptance and working conditions for workers are used to assess social sustainability (Tom & Tomkin, 2014). However, different sustainable options often have trade-offs among the three aspects of environment, economy and society (Gružauskas et al., 2018; Kheir et al., 2022; Munawaroh et al., 2018; Triana et al., 2022). Sometimes, options that are beneficial for the environment tend to sacrifice economic criteria, whereas options that are beneficial for the economy tend to be less advantageous for the environment and society. A business model may aim to adopt environmentally friendly practices, but doing so could come at a high initial cost and short-term economic sustainability risks for the business (Munawaroh et al., 2018). The trade-off between sustainability and cost-effective performance is also mentioned in Gružauskas et al. (2018). The outcomes of this research demonstrate that the trade-off varies depending on the supply chain's size. It showed that the consolidation of warehouses for more sustainable supply chain led to a 19% reduction in transportation costs and a 55% decrease in CO2 emissions for markets with smaller cargo amounts. However, larger markets benefit from a just-in-time distribution strategy to reduce transportation costs by 18.4%, but the associated 43% increase in CO2 emissions. Whenever a trade-off exists, the selection of the best sustainable option is difficult for all organisations.

In this context, the decision support systems (DSSs) are useful tools for evaluating and selecting the optimal option that balances economic, environmental, and social considerations. The majority of them employ methodological models with multiple criteria and objectives (multi-criteria decision analysis (MCDA) or multi-criteria decision-making (MCDM)), including:

- Analytical Hierarchy Process (AHP) (Ahmad & Tahar, 2014; Alyamani & Long, 2020; Calabrese et al., 2019; Cellura et al., 2002; Halide et al., 2009; Kara & Köne, 2012; R. Kumar et al., 2015);
- Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) (Afsordegan et al., 2016; Kaya & Kahraman, 2011; Mateusz et al., 2018; Memari et al., 2019; Şengül et al., 2015);
- Analytic network process (ANP) (García-Melón et al., 2010; Turan et al., 2009);
- Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) (Morfoulaki & Papathanasiou, 2021; Ogrodnik, 2017; Talukder & W. Hipel, 2018; Vinodh & Girubha, 2012); and
- Vise Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) (Luthra et al., 2017; Mateusz et al., 2018; X. Zhang & Xing, 2017).

Besides that, sustainable criteria are considered risk problems such as climate change (Constable et al., 2022). The decisions relevant to manage risk involve human processes that influence the results of decisions. In this context, Subjective Expected Utility (SEU) theory is used for decision making under risk to improve the correctness of selection (Shanteau J & Pingenot A, 2009). This theory allows for subjective evaluation of both the variables under consideration and the probabilities associated with them (Shanteau J & Pingenot A, 2009). However, this method is not designed to solve uncertainties involved in the decision itself, ambiguity and value uncertainty are not quantified (Constable et al., 2022). In addition, the decision-making structure needs to be clarified and defined in the decision process. Meanwhile, fuzzy language is used in DSS based on MCDM methods to reduce the dependence on the subjectivity of experts in decision-making systems, as its representation is an approximate value rather than a specific value (Alyamani & Long, 2020; Bas, 2013; Calabrese et al., 2019; Fetanat & Tayebi, 2022; Jiskani et al., 2022; Kaya & Kahraman, 2011; Khalili-Damghani & Sadi-Nezhad, 2013; Memari et al., 2019; Şengül et al., 2015; Shaw et al., 2012; Tayyab & Sarkar, 2021; Tirkolaee & Aydin, 2022; L. Wang et al., 2007; X. Zhang & Xing, 2017). The fuzzy is also used in MCDM to solve uncertain situations.

Although the DSS-based MCDM are designed to assist decision-makers in choosing the best choice, there are no publications that discuss in detail the advantages and disadvantages of these techniques, as well as that classify assessment criteria and different levels of sustainability evaluation. Thus, several issues need to be comprehensively considered and analysed in the above context, including:

- Methodological approaches and techniques: a review of the methodologies and techniques employed within the sustainability context, along with an evaluation of their respective advantages and limitations in practical applications.
- Scale of application and sustainability assessment criteria: an investigation into the appropriate application scale of DSS, for example at an enterprise, or for a country, and the selected sustainability assessment criteria, and the classification of criteria and sub-criteria utilized in assessing sustainability at these distinct scales.
- Enhancing the effectiveness of the decision making process: exploration of strategies to improve the effectiveness of the decision making process on selecting the most "sustainable" options under different conditions such as selected sustainability assessment criteria, trade-offs among different sustainability goals and inherent uncertainties.

The main contribution of this review is providing a systematic evaluation, following the PRISMA approach, of the application of DSS-based MCDM in the context of sustainability, and highlighting the opportunities and challenges associated with their application. Several aspects are studied and discussed, including the methodology of DSS, the advantages and disadvantages of these methodologies of their effectiveness in promoting sustainability, the sustainable criteria which are used to evaluate the sustainability of DSS, including environmental, social, and economic aspects. The results of this analysis will be useful for researchers, practitioners, and policymakers seeking to understand the role of DSS in the process of making sustainable choices.

3.2.2. Methodology

In this review, the PRISMA approach, which is an evidence-based set of guidelines designed to help authors to conduct and report systematic reviews and meta-analyses, was used to visually present the process of choosing studies for systematic literature reviews (Johnson et al., 2016; McMeekin et al., 2020). This approach offers a consistent way of recording and reporting the search process and supports making sure that the studies chosen are accessible, comprehensive, and well-documented. This will help reviewers to avoid biases and make sure that the literature search is accurate and relevant to the research question (Johnson et al., 2016). The PRISMA diagram describing the adopted approach is presented in Figure 3.4.

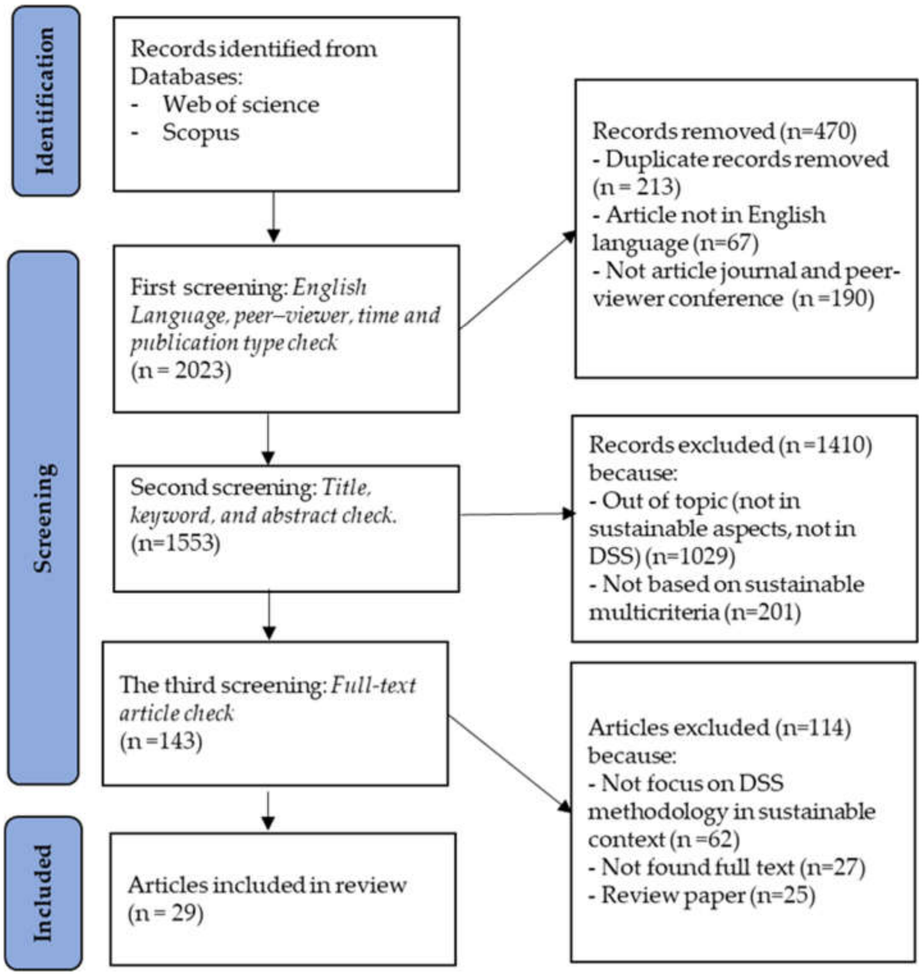

Figure 3.4. PRISMA approach for searching documents

For searching literature, the keywords are used, including "decision support system", “decision making”, "multi-criteria”, “fuzzy logic of decision support”, “sustainable” and "sustainability.” They are selected based on the issues identified in the introduction section. The integrated string ("decision support system" OR "decision making" OR "multi-criteria" OR "fuzzy logic decision support") AND ("sustainability" OR “sustainable”) was created to search the literature.

Reviewed literature was defined by using keywords for searching on scientific websites databases. After searching, 2023 documents were recorded. 470 documents were excluded after the first screening. The second screening was the title, keywords, and abstract check. 1410 documents were excluded from topics such as not being in DSS, sustainable aspect, and not based on sustainability multicriteria. In the last screening, 143 documents were read with the full content. Some criteria were used for selecting literature, including methodology framework for decision-making, type of articles (research or review), and the availability of full text. The authors have selected 29 final papers as case studies for deep review and evaluation.

3.2.3. Case study summary

This sub-section describes case studies of the development of decision support systems in the context of sustainability. The cases are described below.

Cellura et al. defined a mathematical model to assess the whole environmental performance of urban systems and control the developing sustainability trends due to different human management scenarios (Cellura et al., 2002). This paper's decision support software was built with the indicator's weights calculation and sensitivity analysis module. The Direct Assignment Method in the AHP Procedure was applied to calculate the weights. This software was used to assess the sustainability of Palermo city (Italy). The results show that the software calculates the current index, determines the scenarios, and calculates the selection of scenarios. This software can calculate indicators according to user-oriented scenarios. In addition, the evaluation index can be changed by the uncertainty of the situation, which allows the decision-maker to make the best decision.

Buchholz et al. assessed the potential of Multi-Criteria Analysis (MCA) to facilitate the design and implementation of sustainable bioenergy projects (Buchholz et al., 2009). Nine sustainability criteria were used to evaluate the bioenergy system. Four MCA tools (Super Decisions, DecideIT, Decision Lab, NAIADE) are reviewed for their suitability to assess the sustainability of bioenergy systems with a particular focus on multi-stakeholder inclusion. These MCA tools use four methods such as AHP, DELTA, PROMETHEE II, and NAIADE (Novel Approach to Imprecise Assessment and Decision Environments) for sustainability assessment. Research results show that different tools can give different results. Social criteria, not cost, play an essential role in making bioelectrical systems viable for a rural community in Uganda. MCA can assist with stakeholder integration and communication on complex decisions.

Blanco et al. presented a DSS for installing micro-hydropower (MHP) plants in the Brazilian Amazon under a sustainable development perspective (Blanco et al., 2008). The study considers two plant installation alternatives: one turbine and two turbines with a total installed capacity of 40MW. Sustainability criteria such as energy and economic expectations are considered for selecting installation alternatives. The results show that energy planning favors a two-turbine approach to determining maximum energy output during peak demand periods. Economic aspects showed that the cost of energy generated by MHP plants was comparable to that of the rural grid and lower than that of diesel generators.

Halide et al. presented a DSS to assist cage aquaculture managers (Halide et al., 2009). In this paper, The AHP tool was employed to evaluate the best site from several alternatives. Given a holding density, cage volume, the survival rate of fish seed, mean fish weight at harvest, feed conversion ratio, cost of seed, feed, and cage (for construction and operation), the interest rate on borrowed funds, and the fish price at harvest, the break-even price (BEP) and the return on investment (ROI in percent) are calculated.

Turan et al. proposed software based on the ANP method to calculate sustainability (Turan et al., 2009). This paper presented a supporting tool built on the foundation of the ANP method called the BOCR model. Under each node of the BOCR model, three subnets are delineated - economic, environmental, and social. The decision-maker makes a series of pairwise comparisons. Using the summation formula to combine the four control values, the absolute priorities of the five project alternatives are inferred.

Kaya et al. proposed a model for evaluating and choosing between different energy technologies (Kaya & Kahraman, 2011). The modified fuzzy TOPSIS method proposed in this study uses linguistic variables to assess criteria and alternatives. Seven options are mentioned in their research, including conventional (A1), nuclear (A2), solar (A3), wind (A4), hydraulic (A5), biomass (A6), and CHP (A7). The fuzzy AHP method was used to allow a pairwise comparison for the weighting of selection criteria. The modified fuzzy TOPSIS method was used for power source selection for planning. The results of the fuzzy TOPSIS analysis ranked the alternatives in descending order of A4, A6, A3, A7, A5, A2, and A1.

S. Vinodh, R. Jeya Girubha used the PROMETHEE II method as a computationally and cost-effective selection method that has been used to improve sustainability in a manufacturing company by changing and prioritizing material, product, and process orientations (Vinodh & Girubha, 2012). Research results also show a need for material change, that is, selecting appropriate materials to achieve sustainability, which must effectively respond to mechanical, environmental, and economic factors. Material properties and choice are crucial in sustainable production. In this case study, the sustainability orientations are manufacturing methodology, material, and product.

Kara et al. presented a multi-criteria decision-making model to rank and compare regions in terms of environmental sustainability (Kara & Köne, 2012). The AHP model has been applied to the Northwestern areas of Turkey. Two different groups of alternatives - one from NUTS (nomenclature of territorial units for statistics) level 2 and the other from NUTS level 3 - were identified. The results indicate that at NUTS level 2, İstanbul (TR10) is ranked first. At NUTS level 3, TR424 Bolu has the highest rank. Research results have highlighted that İstanbul has meaningful interdependent economic relationships with neighboring regions (Kocaeli, Tekirdağ, Bursa, Yalova, and Sakarya). They are the most environmentally unsustainable regions. İstanbul needs special attention to achieve sustainable development goals as the practices of these regions have consequences for the country as a whole.

Shaw et al. presented an integrated approach to selecting the appropriate supplier in the supply chain, addressing carbon emissions, using fuzzy AHP and fuzzy multi-objective linear programming (Shaw et al., 2012). In this model, fuzzy AHP was first used to calculate the weights of the criteria, and then fuzzy linear programming was used to find the optimal solution to the problem. The results of the fuzzy-AHP analysis showed that the cost has the highest weight for supplier selection, and the weights of quality, GHG emission, lead time, and demand come after that. These weights of these criteria are used in fuzzy multi-objective linear programming for supplier selection and quota allocation.

Ahmad et al. developed a multi-criteria model for selecting renewable energy sources for Malaysia's sustainable development of power generation (Ahmad & Tahar, 2014). Four primary resources, municipal, solar, wind, and biomass (including biogas and solid waste), are considered. The multi-criteria analysis method was applied according to the AHP method for evaluation. The results showed that economic and technical aspects are the essential criteria, with relative weights of 0.52 and 0.26, respectively. The priority weight of solar power is 0.358, followed by 0.246 for biomass, 0.235 for hydrogen, and finally 0.171 for wind. The model also shows that each resource is oriented toward a particular criterion, solar towards economic, biomass towards social, Greater towards technical, and wind towards the environmental aspect.

Khalili-Damghani and Sadi-Nezhad developed a DSS to solve sustainable Multi-Objective Project Selection problems with Multi-Period Planning Horizon (MOPS-MPPH) (Khalili-Damghani & Sadi-Nezhad, 2013). TOPSIS-based fuzzy goal programming (FGP) for the MODM problem was used. The proposed DSS was applied to historical Iranian financial and credit institutions' project selection data. The projects had been treated as investment chances. A set of four different investment chances, including the development of Public Transportation, Nano-technology, Hybrid Electricity Powerhouse, and Refinery of Crude Oil.

Mattiussi et al. presented a framework for an energy supply DSS for sustainable plant design and production, utilizing an innovative use of multi-objective and multi-attribute decision-making (MODM, MADM) modeling together with impact assessment (IA) of the emission outputs (Mattiussi et al., 2014). This DSS was built based on the AHP method. LCA, MODM, and MADM were the methodology to use in these DSS stages. Three alternatives for plant design were considered (ICE and PV plant, FC + PV, business-as-usual). Calculation results have shown that ICE + PV is the best alternative from the point of view of the economy - technology, decision-maker, and equal weight. From an environmental point of view, FC + PV is the best alternative.

Sengül et al. developed the multi-criteria decision support framework for Turkey's ranking renewable energy supply systems (Şengül et al., 2015). The fuzzy TOPSIS method was employed for the analysis. Four alternatives, including Regulator (R), Hydropower Station (HPS), Wind Power Station (WPS), and Geothermal Power Station (GPS), are considered. In this paper, the weights of each criterion are calculated using Fuzzy Shannon's Entropy. After that, Fuzzy TOPSIS is utilized to rank the alternatives. The results showed that the first criterion in preference ranking of renewable energy sources in Turkey is the Amount of Energy Produced, followed by the ranking systems Land use, Operation and maintenance cost, Installed capacity, Efficiency, Payback period, Investment cost, Job creation, and Value of CO_2 emission. This study showed that the Hydro Power Station is the most renewable energy supply system in Turkey. Additionally, the Geothermal Power Station, Regulator, and Wind Power Station are determined to be the second, third and fourth, respectively.

Aydin et al. developed a DSS for the technical sustainability assessment of water distribution systems (WDS) (Aydin et al., 2015). Technical sustainability is assessed based on the sustainability index methodology using reliability, resiliency, and vulnerability as performance criteria. The results show that the DSS effectively illustrates time-dependent variables in the WDS and that a sustainability index methodology is a credible approach to comparing scenarios and identifying problematic locations. This study also shows that the sustainability indices are sensitive to the thresholds defined for the node pressure and water age parameters. These thresholds are site-specific and should be determined based on expert knowledge. Furthermore, this study focuses on the technical sustainability of WDS. Environmental, social and economic criteria are not currently included in the sustainability assessment.

García-Melón et al. evaluated the sustainability of touristic strategies for coastal national parks of Venezuela (García-Melón et al., 2010). The specific calculation for "Los Roques" National Park. The Analytic Network Process (ANP) technique was proposed to help managers make decisions about this sustainability. Calculation results showed that the criteria of Income per capita and Habitat of species are highest for the coastal National Park "Los Roques," the criteria of Landscape beauty and educational level are evaluated the lowest.

Kumar et al. provided a methodology for determining the sustainability of a public transport system, including pedestrian and transit services in the South Delhi region, representing areas of a developing country (R. Kumar et al., 2015). This paper presents an integrated decision-making approach based on Analytical Hierarchy Process (AHP) to assess transport measures for city sustainability. The obtained results show different weights compared to the three primary parameters determining sustainability. Compared to the global index, the index for the studied city is 54,159/100. Preliminary results show that the most influential parameters are air pollution in the environmental group, public health in the social group, and productivity in the economic group.

Afsordegan et al. proposed a modified TOPSIS method for multi-criteria group decision-making with qualitative language labels (Afsordegan et al., 2016). This method deals with measurement uncertainty taking into account different levels of accuracy. Seven energy alternatives according to nine criteria were evaluated in the opinion of three environmental and energy experts. Fuzzy AHP determines the weights of the criteria, and the alternatives are ranked using qualitative TOPSIS. The calculation results show that the best alternative is wind energy. The arrangement of remaining alternatives is biomass, solar, CHP, nuclear, hydraulic, and conventional energy.

Luthra et al. proposed a framework for evaluating sustainable supplier selection using the Integrated Analytical Analytical Process (AHP), ViseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), a solution approach to compromise and optimize multi-criteria (Luthra et al., 2017). Five suppliers (S1, S2, S3, S4, S5) are presented for consideration. The AHP method is used to rank the criteria, and the VIKOR method is used to rate the supplier. According to the research results, "Environmental cost" ranks first with the highest weighted value (0.0873), and "Technological and financial capabilities" takes the last place with the lowest weighted value (0.0162) in all evaluation criteria. Calculation results from the VIKOR method ranking suppliers in S3>S5>S1>S4>S2.

Rahmanpour and Osanloo presented the use of a decision support system in choosing the design option of Ultimate Pit Limit (UPL) according to sustainability criteria (Rahmanpour & Osanloo, 2017). In the DSS, a matrix method is used to evaluate the sustainability of UPL options. This study's DSS procedures were applied in the Sungun Copper Mine (SCM) to determine the ultimate pit limits concerning sustainable development. The results show that the sustainable UPL option is far better than the economic UPL option.

Zhang and Xing examined a practical use of the VIKOR (ViseKriterijumska Optimizacija I Kompromisno Resenje) method regarding selecting the appropriate period for a fashion company to deploy green raw materials (X. Zhang & Xing, 2017). The newly developed probabilistic language VIKOR technique has been applied to calculating weighted criteria and alternative ratings. The results of calculating the weights of the criteria show that the criterion "Marketing" has the highest weight (0.305), and the criterion "Logistics" has the lowest weight (0.1484). The ranking of alternatives shows that eight months of green raw material implementation (a3) is an appropriate period for the fashion company and should be recommended out of the four possible periods.

Balaman et al. contributed by presenting a novel bi-level DSS to aid modeling and optimization of multi-technology, multi-product supply chains and co-modal transportation networks for biomass-based (bio-based) production combining two multi-objective mathematical models (Balaman et al., 2018). The first level of the DSS optimizes the supply chain configuration. In the second level, the transportation network is designed to specify the most appropriate transportation mode and related transportation options under transfer station availability limitations. A hybrid solution methodology is proposed that integrates fuzzy set theory and the ε-constraint method. Based on the weighting for optimization goals, scenarios were selected.

Calabrese et al. propose to apply the Fuzzy AHP method to select the most relevant sustainability issues to create common value for both business and society, and that should be at the heart of strategic planning and management (Calabrese et al., 2019). in this study the problems of sustainability are built upon those that are listed in the ISO 26000 standard. The proposed fuzzy AHP method is structured to allow direct stakeholder engagement in assessing the relevance of ISO topics and issues. The results showed that the company could also identify specific sustainability initiatives to integrate into its business processes with this proposed method.

Memari et al. presented an intuitionistic fuzzy TOPSIS method to select the right sustainable supplier that concerns nine criteria and thirty sub-criteria for an automotive spare parts manufacturer (Memari et al., 2019). Three suppliers, AA, RFA, and MF, are considered for evaluation. These suppliers supply cast iron parts to the manufacturing company S.S. he developed intuitionistic fuzzy-TOPSIS to evaluate each alternate supplier. Calculation results are ranked three suppliers, AA, RFA, and MF, according to nine criteria and three experts. This calculation result was compared with the result calculated by the fuzzy TOPSIS method. The comparison results show that AA supplier is the best choice for sustainability in both approaches.

Talukder and W. Hipel referred to the PROMETHEE method applied to five different types of agricultural systems in coastal Bangladesh to rank alternatives from best to worst according to a series of indicators of Sustainability (Talukder & W. Hipel, 2018). The five agricultural systems are the Shrimp-based farming system (S), Rice-based farming system (SR), rice-based farming system (R), Integrated rice-vegetable farming system (I), and traditional practice-based agricultural systems (T). Calculation results for this case show that "I" (0.54) is first in terms of sustainability on the rank list, while "S" and "T" were the lowest-ranked −0.66 and −0.2, respectively. The results of this case study also indicate that "I" has a higher degree of sustainability in agriculture than "R," "SR," "T," and "S" and is characterized by a positive score for all kinds of sustainability.

Mateusz et al. used TOPSIS and VIKOR methods to study the level of sustainable development of EU countries. In this study, 14 indicators were selected out of 14 SDG goals (Sustainable Development Goals), and 27 European countries were analyzed for sustainability (Mateusz et al., 2018). The results show that the ranking results of the first-class countries include the most developed countries in the EU, which was consistent with the confirmation in the identified indicators. Compared with the TOPSIS method, the VIKOR method showed some changes in the classification of countries. First-class France and England replaced Finland and Luxembourg. In the fourth class, two countries, Spain and Estonia, replaced the other two, Bulgaria and Latvia. And Poland in 4th place came in first, a closer reflection of the country's actual development progress than the TOPSIS ranking.

Alyamani and Long implemented fuzzy AHP methodology (FAHP), a multi-criteria decision-making (MCDM) approach to develop a sustainable project selection tool to quantify and rank five critical sustainability project criteria based on importance (Alyamani & Long, 2020). The sustainability criteria in this study were novelty, uncertainty, team skills and experience, technology information transfer, and project cost. The results showed that the essential criterion in sustainable project selection is project cost (C1), with an importance weight (BNP) of 0.528. The second and third most important criteria for sustainable project selection in this research are novelty (C2) and uncertainty (C3), with BNPs of 0.216 and 0.206, respectively. Based on the selected experts ' opinions, the two most minor critical criteria out of the five considered in this research are skill and experience (C4) and technology information transfer (C5), with BNPs of 0.101 and 0.100, respectively.

Ogrodni selected a multi-criteria analysis method for Polish cities based on sustainable development goals (Ogrodnik, 2017). In this paper, the PROMETHEE method was used to assess. Four cities (Bialystok, Lublin, Chorzow, and Czestochowa) were selected based on 66 sustainability indicators. The calculation results show that the top four cities in the social, economic, environmental, and political sectors are Bialystok, Lublin, Bialystok, and Lublin, respectively.

Morfoulaki and Papathanasiou applied the PROMETHEE method to rank alternatives in sustainable urban mobility planning (Morfoulaki & Papathanasiou, 2021). In the research, the author has built a framework of evaluation criteria, including SUMP (Sustainable Urban Mobility Plan) targets and the difficulty of their applicability. SUMP's 15 targets and five difficulty levels are covered. The PROMETHEE method was used to assess ranking criteria and mobility measures. Ten experts were selected to share their experiences and feedback on this framework's proper development and testing. Calculation results show that "Redesign of the existing public transport system" ranks highest and "Development of a shared system of electric and conventional bicycles as well as small-capacity electric cars" ranks lowest.

Alavi et al. proposed a dynamic DSS for sustainable supplier selection in circular supply chains (Alavi et al., 2021). Fourteen criteria, including five economic, four circular, and five social criteria, were used to select the sustainable suppliers. The fuzzy best-worst (FBW) method customized and weighted these criteria. Ten suppliers were considered, and the fuzzy inference system (FIS) selected the most suitable supplier. Five scenarios were considered, and the results of the DSS can help managers and decision-makers make informed decisions efficiently and effectively.

3.2.4. MCDM methods for DSS frameworks in the sustainability context

A methodological framework is a tool to guide the developer and user through a sequence of steps to complete a procedure. The methodology is identified as the group of methods used in a specified field, and a framework is defined as a structure of rules or ideas (McMeekin et al., 2020). According to methodologies used in case studies, multiple criteria for sustainability assessment were the significant approach for creating the DSS framework. In addition, this review section shows that MCDM methods are the most used for building DSS, which are applied to areas of energy planning, production planning, supply chain management, agricultural sector, and economic and environmental planning and assessment. Besides that, other methods are applied for DSS in sustainability context as fuzzy logic, interval methods, mathematical method and matrix method.

The MDCM methods are commonly integrated within DSS frameworks for sustainability assessment. Essentially, these frameworks include some stages illustrated in Figure 3.5. Under this framework, the first step is the selection of indicators for sustainability assessment and using them as sustainable criteria, followed by proposing weighting factors of sustainability criteria. The total of all weighting factors equals one. At the same time, different sustainability scenarios are evaluated according to each criterion. Finally, the sustainability criteria and weighting factors are combined to rank different scenarios.

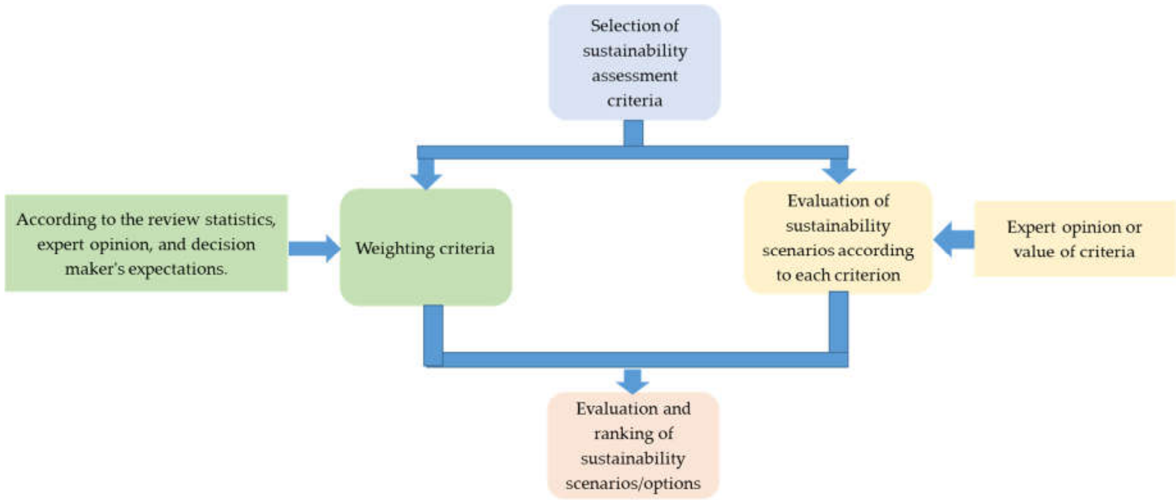

Figure 3.5. Decision support system stages in the sustainability context

The reviewed studies show that the most popular MCDM methodologies used for DSS in the sustainability context are AHP, ANP, PROMETHEE, TOPSIS, and VIKOR (Zarte et al., 2019). VIKOR and TOPSIS methods are the reference point approach, while PROMETHEE methods are the outranking approach. The ANP and AHP methods are the pairwises comparison and hierarchy approach (Madhu et al., 2020). The following sections will describe each of these methods and followed by a comparison of these methods.

1. Analytical Hierarchy Process (AHP) method

AHP and Fuzzy AHP (FAHP) are quantitative methods used to sort decision alternatives and select an option that satisfies given criteria based on the pairwise comparison principle (Ahmad & Tahar, 2014; Alyamani & Long, 2020; Gõrener, 2012; Kara & Köne, 2012; R. Kumar et al., 2015; OğuztiMur, n.d.; Saaty, 2013; L. Wang et al., 2007). This best choice meets the decision maker's criteria by comparing pairs of options through a specific calculation mechanism (Saaty, 2013). By employing the relative scale measurement, a set of pairwise comparison matrices for each of the lower levels, with one matrix for each element in the level, is generated. Pairwise comparisons are made regarding which element is preferred over the other (R. Kumar et al., 2015). The model of the AHP method is presented in Figure 3.6.a.

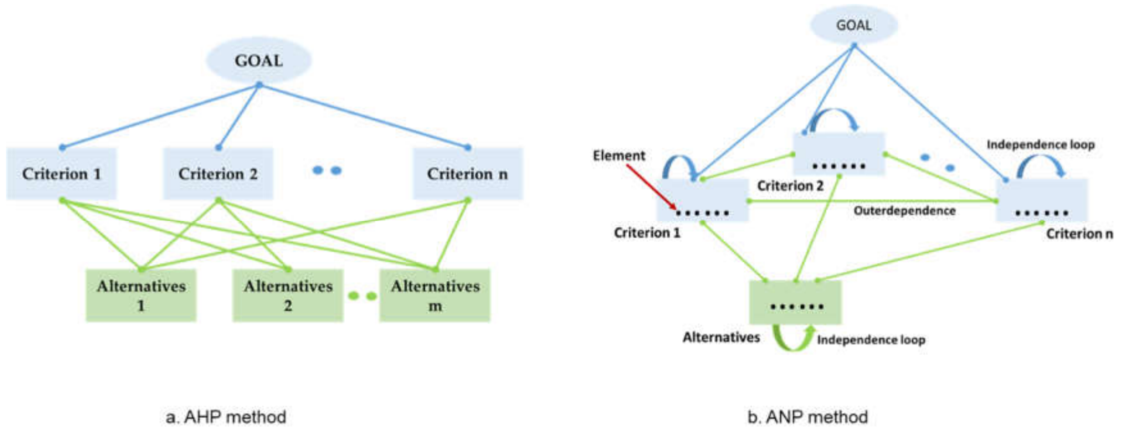

Figure 3.6. The decision making model of the pairwise comparison and hierarchy approach

The AHP is also one of the most popular methods to assess sustainability in the field. There are 14 case studies used AHP method (Afsordegan et al., 2016; Ahmad & Tahar, 2014; Alyamani & Long, 2020; Buchholz et al., 2009; Calabrese et al., 2019; Cellura et al., 2002; Halide et al., 2009; Kara & Köne, 2012; Kaya & Kahraman, 2011; R. Kumar et al., 2015; Luthra et al., 2017, 2017; Mattiussi et al., 2014; Shaw et al., 2012). For example, Cellura et al. (2002) used AHP to calculate the weights in the mathematical model to evaluate the whole environmental performance of urban systems and control the developing sustainability trends due to different human management scenarios for Palermo City in Italy. Halide et al. (2009) applied AHP to evaluate the best site from several alternatives to assist cage aquaculture managers based on the holding density, cage volume, the survival rate of fish seed, mean fish weight at harvest, feed conversion ratio, cost of seed, the interest rate on borrowed funds, etc. Kara & Köne (2012) presented a multi-criteria decision-making model that applied the AHP method to rank and compare regions regarding environmental sustainability. The AHP method was also used by Kumar et al. (2015) to determine the sustainability of a public transport system, including pedestrian and transit services in the South Delhi region, India (R. Kumar et al., 2015), and by Calabrese et al. (2019) to select the most relevant sustainability issues to create common value for both business and society.

However, when the number of criteria is large, the pairwise comparison of the options according to each criterion may be huge. To reduce the quantity of comparison, the AHP method was combined with other methods such as VIKOR to form a framework of DSS. In these frameworks, AHP methods were used to calculate the criteria weights (Kaya & Kahraman, 2011; Luthra et al., 2017), or to rank alternatives (Mattiussi et al., 2014). For example, Luthra et al. (2017) employed AHP to obtain the weights of sustainable supplier selection dimensions and their respective criteria and then these weights were used by VIKOR to select the most efficient sustainable suppliers. In addition, sustainability criteria can be quantitative or qualitative. If they are quantitative, the weighting matrix is established based on a direct transition to the AHP rating scale. If the criteria are qualitative, the hierarchical value is based on the expert's judgment and is expressed in the fuzzy logic language. The decision-makers can also consider their subjective orientation by allocating weights to the criteria.

2. The Analytic Network Process (ANP) method

The ANP method is a network analysis method that considers the hierarchy and the interaction between the criteria in the system (Turan et al., 2009; García-Melón et al., 2010; Gõrener, 2012; Saaty, 2013; Atabaki et al., 2022). In practice, ANP is a combination of two parts: one is a network of standards and criteria, and the other is a network of influences between factors and criteria clusters (García-Melón et al., 2010). The model of the ANP method is presented in Figure 3.6b (Gõrener, 2012).

The ANP method is well-suited for complex decision-making problems (Alsalem et al., 2018). It provides a more accurate analysis by taking into account the interdependence and interrelationships between several criteria. Additionally, ANP provides a clear method for weighting criteria, reducing subjectivity in the decision-making process. However, the method requires significant expert knowledge and can be computationally complex, making it time-consuming and resource-intensive. Furthermore, it presumes a linear relationship between options and criteria, which could lead to different conclusions depending on slight changes in the input (Alsalem et al., 2018).

Turan et al. (2009) proposed a software based on the ANP method to calculate sustainability. This research presented a supporting tool built on the foundation of the ANP method called the Benefits, Opportunities, Costs and Risks (BOCR) model. Under each node of the BOCR model, three subnets are delineated - economic, environmental, and social. The decision-maker makes a series of pairwise comparisons. Using the summation formula to combine four control merits (i.e., bB+oO+cC+rR, in where: B - benefits; O - opportunities; C- costs; R - risks; and b, o, c, r - factors) (Turan et al., 2009), the absolute priorities of the five project alternatives, including Capacity Expansion, Green Power Applications, Emissions Control, Financial Performance Improvement and the Workforce Refreshment Project, are inferred. García-Melón et al. (2010) evaluated the sustainability of touristic strategies for coastal national parks of Venezuela. The ANP technique was proposed to help managers make decisions about this sustainability.

3. The Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) method

The PROMETHEE is an outranking method for ranking a finite set of alternative actions when multiple criteria are often conflicting and various decision-makers are involved. PROMETHEE uses partial aggregation, and pairwise comparison of alternative actions allows one to verify whether, under specific conditions, one step outranks or not the others (Cunha et al., 2022; Madhu et al., 2020; Morfoulaki & Papathanasiou, 2021; Nasution et al., 2019; Ogrodnik, 2017; Simamora et al., 2021; Talukder & W. Hipel, 2018; Vinodh & Girubha, 2012). The model of the PROMETHEE method is shown in Figure 3.7.

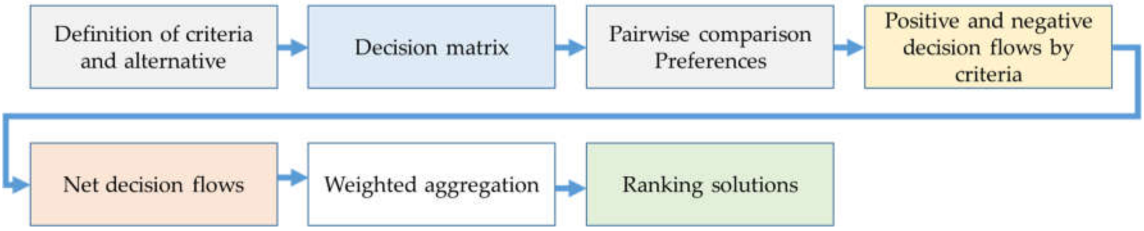

Figure 3.7. The model of the PROMETHEE method (Simamora et al., 2021)

Overall, there are five studies that used PROMETHEE method for evaluating sustainable problems (Buchholz et al., 2009; Morfoulaki & Papathanasiou, 2021; Ogrodnik, 2017; Talukder & W. Hipel, 2018; Vinodh & Girubha, 2012). Ogrodnik (2017) selected a multi-criteria analysis method for Polish cities based on sustainable development goals. The PROMETHEE method was used to rank top cities in the social, economic, environmental, and political sectors. Four cities (Bialystok, Lublin, Chorzow, and Czestochowa) were selected based on 66 sustainability indicators. Morfoulaki & Papathanasiou (2021) applied the PROMETHEE method to rank criteria and mobility measures in Sustainable Urban Mobility Plan (SUMP). SUMP's 15 targets and five difficulty levels were covered. Ten experts were selected to share their experiences and feedback on this framework's proper development and testing. Calculation results show that "Redesign of the existing public transport system" ranks highest and "Development of a shared system of electric and conventional bicycles as well as small-capacity electric cars" ranks lowest. Vinodh & Girubha (2012) used the PROMETHEE method as a computationally and cost-effective selection method that has been used to improve sustainability in a manufacturing company by changing and prioritizing material, product, and process orientations. Talukder & W. Hipel (2018) referred to the PROMETHEE method applied to five different types of agricultural systems in coastal Bangladesh to rank alternatives from best to worst according to a series of indicators of sustainability.

To summarize, PROMETHEE has been shown to be effective for multi-criteria ranking in sustainability studies due to its ability to handle uncertainty, provide a clear ranking of alternatives, and reduce subjectivity in decision-making. However, the method does not provide weighting criteria, can be computationally complex, and may lack transparency. Validation of results can be challenging as the method relies on subjective judgments and preferences. The method requires complete and accurate data, which may not always be available (Nasution et al., 2019).

4. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method

TOPSIS, which is one of methods of the multi-criteria decision making, is founded on the fundamental premise that the best solution has the shortest distance from the positive ideal solution and the longest distance from the negative ideal solution (Afsordegan et al., 2016; Bas, 2013; Chakraborty, 2022; Kaya & Kahraman, 2011; Madhu et al., 2020; Mateusz et al., 2018; Memari et al., 2019; Şengül et al., 2015; Tarawneh, 2021). Therefore, alternatives are evaluated using a global index based on their distance from the optimal solutions (Chakraborty, 2022). The model of the TOPSIS method is shown in Figure 3.8.

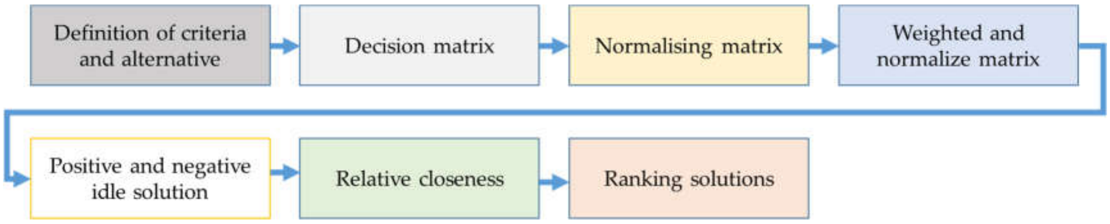

Figure 3.8. The model of the TOPSIS method (Gõrener, 2012; Tarawneh, 2021)

The TOPSIS method is commonly employed for ranking and selecting sustainable options with sixe studies in overall case studies (Afsordegan et al., 2016; Kaya & Kahraman, 2011; Khalili-Damghani & Sadi-Nezhad, 2013; Mateusz et al., 2018; Memari et al., 2019; Şengül et al., 2015). It is usually utilized to create DSS by integrating with other methods, such as AHP and VIKOR, to assess alternative sustainability scenarios with unclear information and challenging-to-define criteria such as flexible working arrangements (Memari et al., 2019) or social acceptability criteria (Şengül et al., 2015). Memari et al. (2019) presented an intuitionistic fuzzy TOPSIS method to select the most sustainable supplier, concerning nine criteria such as cost, quality of products, service performance, environmental efficiency, green image, pollution reduction, green competencies, safety and health, employment practices, and 30 sub-criteria for a manufacturer of automotive spare parts. Three suppliers who provide cast iron parts to the manufacturing company are considered for evaluation. The authors developed intuitionistic fuzzy-TOPSIS to evaluate each supplier. First, three suppliers were ranked on the expert basis, according to nine criteria. After that, this expert based result was compared with the result calculated by the fuzzy TOPSIS method. Based on the calculation, one of the suppliers is selected as the best choice for sustainability. Şengül et al. (2015) developed the multi-criteria decision support framework for ranking renewable energy supply systems in Turkey. The weights of each criterion are calculated using Fuzzy Shannon's Entropy. After that, Fuzzy TOPSIS is utilized to rank the alternatives. The results showed that the first criterion in preference ranking of renewable energy sources in Turkey is the amount of energy generation, followed by land use, operation and maintenance cost, installed capacity, efficiency, payback period, investment cost, job creation, and the amount of CO2 emission. This study showed that the hydro power station is the best (or the most sustainable) renewable energy supply system in Turkey (Şengül et al., 2015).

TOPSIS method is one of the well-known classic multi-criteria decision making (MCDM) methods that reduce subjectivity and can be applied to a wide range of decision-making problems (Alsalem et al., 2018). This technique is based on the concept that the ideal alternative has the best level for all attributes, whereas the negative ideal is the one with all of the worst attribute values. However, the method does not provide a clear method for weighting criteria and can be sensitive to small variations in input data (Tarawneh, 2021).

5. The Vise Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method

This method evaluates the solutions based on their distance to ideal and anti-real points. For individual decision-making variants, the weighted average distance from the ideal solution, the maximum weighted distance from this point, and the so-called comprehensive criteria are determined (Mardani et al., 2016; Mateusz et al., 2018; Tarawneh, 2021; X. Zhang & Xing, 2017). The model of the VIKOR method is shown in Figure 3.9.

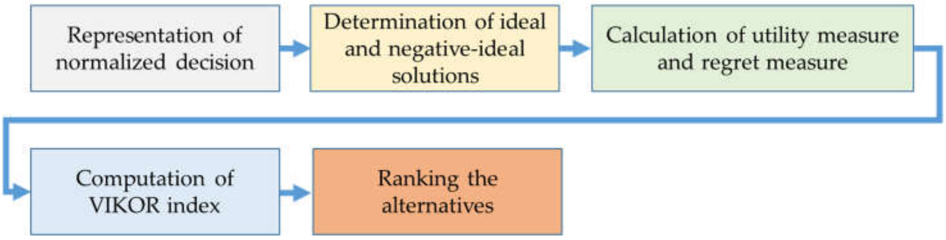

Figure 3.9. The model of the VIKOR method (Gõrener, 2012; Tarawneh, 2021)

The VIKOR method is used to solve complex decision-making problems in sustainable context with clear values. One case used the method to choose a sustainable supplier (Luthra et al., 2017) and assess the sustainability of the suppliers (Mateusz et al., 2018). Zhang & Xing (2017) examined a practical use of the fuzzy VIKOR method regarding selecting the appropriate period for a fashion company to deploy green raw materials. The newly developed probabilistic language VIKOR technique has been applied to calculating weighted criteria and alternative ratings. The results of calculating the weights of the criteria show that the criterion "Marketing" has the highest weight (0.305), and the criterion "Logistics" has the lowest weight (0.148). The ranking of alternatives shows that eight months of green raw material implementation is appropriate for the fashion company and should be recommended out of the four possible periods. The combination of fuzzy logic and VIKOR would increase the method's efficiency to give high-quality decisions in conditions with unclearly sustainability criteria.

According to Alsalem et al. (2018), the VIKOR method is a typical MCDM method that is a widely accepted multi-attribute decision-making technique due to its sound logic. However, it may not effectively weight criteria, leading to subjectivity, and results may vary based on small input variations. It assumes the existence of an ideal solution, which may not be feasible in real-world situations or unsuitable for complex decision-making problems. The method also assumes a linear relationship between alternatives and criteria, which may not always be the case. Furthermore, it can be computationally complex for large problems (Alsalem et al., 2018).

6. Other methods

Other methods were also developed in a specific situation for the object. Buchholz et al. (2009) assessed the potential of Multi-Criteria Analysis (MCA) to facilitate the design and implementation of sustainable bioenergy projects. These MCA tools use four methods AHP, Delta, PROMETHEE II, and Novel Approach to Imprecise Assessment and Decision Environments (NAIADE), for sustainability assessment. Research results show that different tools can give different results. Shaw et al. (2012) presented an integrated approach to select the appropriate supplier in the supply chain, addressing carbon emissions, using fuzzy AHP and multi-objective linear programming. In this model, fuzzy AHP was first used to calculate the criteria weights, and then fuzzy linear programming was used to find the optimal solution to the problem. Khalili-Damghani & Sadi-Nezhad (2013) developed a DSS using TOPSIS-based fuzzy goal programming (FGP) to solve sustainable Multi-Objective Project Selection problems with Multi-Period Planning Horizon (MOPS-MPPH). Mattiussi et al. (2014) presented a framework for an energy supply DSS based on the AHP method for sustainable plant design and production, utilizing an innovative use of multi-objective and multi-attribute decision-making (MODM, MADM) modelling together with impact assessment of the emission outputs. Other methodologies were explored by Aydin et al. (2015), Blanco et al. (2008), Rahmanpour & Osanloo (2017), Balaman et al. (2018), Mateusz et al. (2018) and Alavi et al. (2021). For example, Aydin et al. (2015) used the sustainability index methodology to assess water distribution systems; Rahmanpour & Osanloo (2017) employed the mathematical and the matrix methods for selecting the design option of the ultimate pit limit; and Alavi et al. (2021) utilised the fuzzy best-worst (FBW) method to choose a sustainable supplier. Meanwhile, Balaman et al. (2018) optimised multi technology, multi product supply chains, and co-modal transportation networks for biomass-based production by using the fuzzy ε-constraint method. Blanco et al. (2008) used the rainfall run-off model to set up micro-hydro power plants under a sustainable development perspective such as the hydrological, topographical, geotechnical, environmental, energy, economic, and social aspects.

7. The strength and weaknesses of the MCDM methods

The analysis shows that these MCDM methods are suitable for designing and developing DSSs in a sustainable context. AHP and ANP are suitable for hierarchical sustainable decision problems, with ANP being more applicable for complex systems with interdependencies. PROMETHEE focuses on outranking sustainable alternatives based on clear preferences, while TOPSIS and VIKOR aim to identify the best sustainable alternative using different approaches to evaluate distances from the ideal and anti-ideal solutions.

Different MCDM methods could be combined to fully exploit the effectiveness of methods, for example, AHP with TOPSIS (Afsordegan et al., 2016; Kaya & Kahraman, 2011), TOPSIS and VIKOR (Mateusz et al., 2018) and AHP with VIKOR (Luthra et al., 2017). These integrations improve the accuracy of decisions, reduce the number of calculations and make them more objective and less dependent on expert judgement. Furthermore, the integrated methods improve the efficiency of the DSSs concerning uncertain criteria (Afsordegan et al., 2016; Alyamani & Long, 2020; Calabrese et al., 2019; Memari et al., 2019).

These MCDM methods are combined with fuzzy logic when users seek to develop a tool for evaluating intricate objects encompassing both quantitative and qualitative criteria. It is important to note that DSS frameworks, designed for specific audiences, should only be applied within those target groups. In DSS frameworks utilizing expert opinions for assessment, the evaluation quality is highly dependent on the expertise of the involved stakeholder. Fuzzy logic presents an alternative solution, aiding decision-makers in selecting the best option with minimal reliance on experts.

Disadvantage of these integrated methods is their complex structure. Moreover, they require users to be familiar with a wide range of computation methods. It is a challenge for users to assess sustainability. As a result, these methods are not generally explored and utilized, even though they can produce high-quality evaluation outcomes. The choice of either individual and specific method or integrated methods depends on the problem that need decisions and the advantages which the methods bring to the decision-makers. Table 3.8 presents the strengths and weaknesses of the MCDM methods in the sustainability context.

Table 3.8. Strengths and weaknesses of methods in the sustainability context

Method	Strength	Weakness	Remarkable	Reference
AHP	Simple, easy to understand and advantageous in applying with a small number of criteria and alternatives. Allowing pairwise comparisons of criteria and alternatives. Can handle both quantitative and qualitative data. Easy integration with another method. Increasing decision confidence by using fuzzy logic.	Limited by the consistency ratio — if not consistent, results may be unreliable. Requiring many comparisons between criteria and alternatives in each criterion. The pairs of comparison are quickly increased when the number of criteria increases. Value of comparison pairs affects the accuracy of decisions. Assuming criteria independence, which may not always be true. The result of the decision may be changed if adding or reducing one alternative.	Hierarchical decision sustainable problems where criteria can be organised into levels and sub-levels.	Afsordegan et al., 2016; Ahmad & Tahar, 2014; Alyamani & Long, 2020; Calabrese et al., 2019; Cellura et al., 2002; Halide et al., 2009; Kaya & Kahraman, 2011; Kumar et al., 2015; Luthra et al., 2017; Mattiussi et al., 2014; Shaw et al., 2012; Kara & Köne, 2012
ANP	An extension of AHP that accommodates	More complex than AHP and may be harder to understand.	This method is suitable for complex decision sustainable	Turan et al., 2009; García-Melón et al., 2010

	interdependencies among criteria and alternatives. Handles both quantitative and qualitative data. Less dependent on consistency ratio than AHP. Increasing decision confidence by using fuzzy logic.	Requires additional judgment to determine interdependencies among criteria.	issues with multiple layers and interdependent criteria.	
PROMETHEE	Straightforward ranking of alternatives. Considers preference functions for each criterion, reflecting decision-makers preferences. Transparent and visual approach for outranking. Increasing decision confidence by using fuzzy logic.	Using weighting criteria from another source, so it makes the decision more subjective and less accurate. Require more effort to define appropriate preference functions (It has six preference functions). Sensitive changes in weights or criteria scores.	This method is suitable for decision problems where decision-makers want to outrank alternatives based on clear preferences.	Morfoulaki & Papathanasiou, 2021; Talukder & W. Hipel, 2018; Vinodh & Girubha, 2012
VIKOR	Considers both utility and regret in decision-making. Balances compromise and dominance concepts.	Using weighting criteria from another source. Requiring normalisation of data. It may be sensitive to changes in weights or criteria scores.	This method is suitable for decision problems with conflicting and trade-off criteria, where a balance between the best possible	Luthra et al., 2017; Mateusz et al., 2018; Zhang & Xing, 2017

	Provides a ranking of alternatives and a compromise solution. Relatively simple to apply. Increasing decision confidence by using fuzzy logic.		outcomes and minimising potential losses is desired.	
TOPSIS	Identifies ideal and anti-ideal solutions. Ranks alternatives based on their proximity to the ideal solution and distance from the anti-ideal solution. Relatively simple to apply. Provides a straightforward ranking of alternatives. Increasing decision confidence by using fuzzy logic.	Using weighting criteria from another source. Requiring normalisation of data. Sensitive changes in weights or criteria scores.	This method is suitable for decision problems with multiple criteria and a large number of alternatives, where an ideal solution is sought.	Afsordegan et al., 2016; Kaya & Kahraman, 2011; Khalili-Damghani & Sadi-Nezhad, 2013; Mateusz et al., 2018; Memari et al., 2019; Şengül et al., 2015 .

3.2.5. Criteria and sub-criteria in the sustainability context

Pavlovskaia (2014) asserted that sustainability criteria and their content should be linked to the concept of sustainable development and sustainability. Pavlovskaia (2013) described sustainability criteria as requirements for a product's sustainable quality and its sustainable production process, which must be satisfied to achieve sustainable status or certification. Zink (2005) posited that these criteria are applied to assess opportunities and risks arising from economic, environmental, and social sustainability facets. Meanwhile, Koplin et al. (2007) emphasized that environmental sustainability criteria establish requirements for suppliers, aiming to reduce natural resource inputs and mitigate environmental risks through enhanced supplier efficiency.

Sustainability criteria play a crucial role in incorporating a sustainability perspective effectively (Hallstedt, 2017). These criteria support long-term sustainability assurance, investment protection, and measurement of decision-makers expectations. The criteria create a standard framework for sustainability to guide development for businesses and for a country. The present review indicates that the selected sustainability criteria in the case studies are based on four pillars:

- Technology (Afsordegan et al., 2016; Ahmad & Tahar, 2014; Kaya & Kahraman, 2011; Şengül et al., 2015).
- Economy (Afsordegan et al., 2016; Ahmad & Tahar, 2014; Kaya & Kahraman, 2011; R. Kumar et al., 2015; Luthra et al., 2017; Memari et al., 2019; Şengül et al., 2015).
- Environment (Afsordegan et al., 2016; Ahmad & Tahar, 2014; Kaya & Kahraman, 2011; R. Kumar et al., 2015; Luthra et al., 2017; Memari et al., 2019; Şengül et al., 2015).
- Society (Afsordegan et al., 2016; Ahmad & Tahar, 2014; Kaya & Kahraman, 2011; R. Kumar et al., 2015; Luthra et al., 2017; Memari et al., 2019; Şengül et al., 2015).

The literature review shows that the sustainable criteria and sub-criteria are divided into quality and quantity. For example, the reliability of the technology, technical risk, and product quality are qualitative (Alyamani & Long, 2020), while CO2 emission and energy consumption are quantitative. The value of qualitative criteria depends on decision-makers or expert opinions, so they have subjective character. In addition, some criteria have uncertain value; they vary on stakeholders, such as the product price and investment cost. In these conditions, fuzzy logic is used to present the value of the criteria (Alyamani & Long, 2020) as an interval value. Fuzzy language features are also interested in increasing the accuracy of the decision system, including intuitionistic fuzzy and triangular fuzzy (Memari et al., 2019). However, using fuzzy logic increases the complexity of calculation and decision. It is also a requirement for understanding users and decision-makers about fuzzy logic and how to use it. Therefore, fuzzy logic is suitable for small-size applications and for specific fields (Alyamani & Long, 2020).

In 29 reviewed papers, 14 studies considered the hierarchy of sustainability assessment criteria, including criteria and sub-criteria (Afsordegan et al., 2016; Ahmad & Tahar, 2014; Calabrese et al., 2019; Cellura et al., 2002; Halide et al., 2009; Kaya & Kahraman, 2011; R. Kumar et al., 2015; Luthra et al., 2017; Mattiussi et al., 2014; Memari et al., 2019; Şengül et al., 2015; Talukder & W. Hipel, 2018; Turan et al., 2009; X. Zhang & Xing, 2017). For example, Ahmad & Tahar et al. (2014) used four criteria (technical, economic, social, and environmental criteria) and 12 sub-criteria to select renewable energy sources. Three criteria (technical, economic and environmental criteria) with 24 sub-criteria were considered in Mattiussi et al. (2014) paper. Besides, Luthra et al. (2016) employed 22 sub-criteria and divided them into three criteria (economic, environmental and social). In these studies, 7/9 cases used economic, environmental, and social pillars as criteria. The 2/9 remaining cases employed other criteria, such as productivity, stability, efficiency, durability, compatibility, and equity, for assessing sustainability in agriculture (Talukder & W. Hipel, 2018). In addition, four out of nine cases considered technology as an additional sustainability criteria. The criteria were also divided into qualitative and quantitative criteria. For example, social acceptability was used as a qualitative criterion (Afsordegan et al., 2016), whilst transportation cost and CO2 emission were quantitative. Besides that, the criteria were used at different scales of a countries or an enterprise. For example, Mateusz et al. (2018) used 14 SDGs to evaluate the level of sustainable development of EU countries, whilts Shaw et al. (2012) used specific criteria for supplier selection. The number of criteria was different in studies. García-Melón et al. (2010) used 13 criteria, while there were 16 criteria in Vinodh & Girubha (2012).

The weighting of criteria is an essential step in the DSSs using MCDM methods. However, the process of this step vary depends on the specific case studies and relevant context. The pairwise comparison, point allocation, rating methods, trade-off analysis, and ranking methods are commonly used methods for weighting of indicators (Kalbar & Das, 2020). The AHP method is the pairwise comparison method used to weight the criteria in Tarawneh (2021). In addition, some MCDM methods are only used for weighting criteria such as the Entropy method (Wu et al., 2011). This method is usually employed to cooperate with another MCDM method to create DSS (Cao & Xu, 2022; C.-H. Chen, 2021; Li et al., 2011; Shen & Liao, 2022).

The aggregated criteria and sub-criteria used to assess and select options at the company level are shown in Figure 3.10.

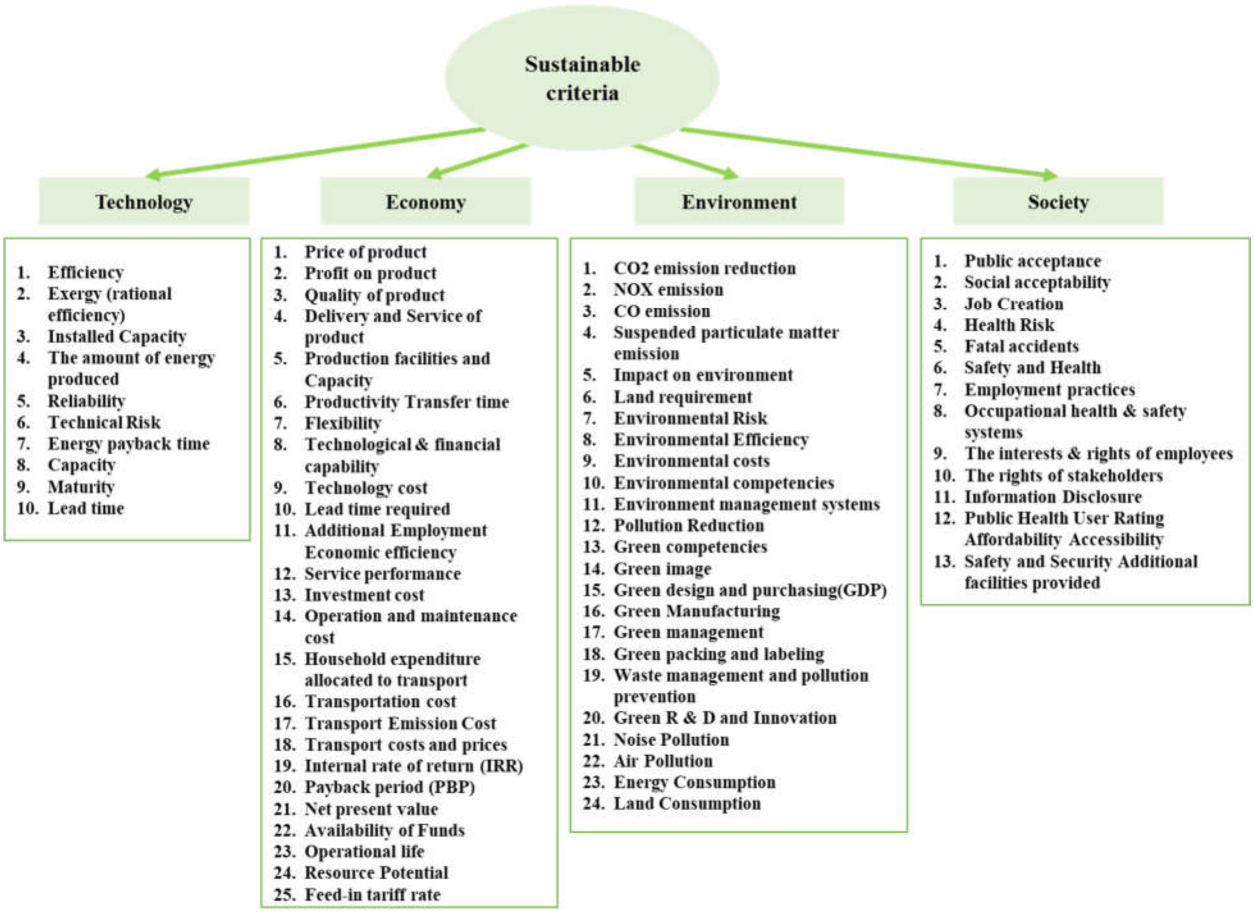

Figure 3.10. Main sustainable criteria and sub-criteria at the company level from the literature

3.2.6. Scales and benefits for application of decision support in the sustainability context

The scales of the DSSs in the sustainability context could be divided into two main categories: the enterprise level, and the regional and national levels (Thumba et al., 2022).

At the enterprise level, DSSs have been employed in numerous research for a broad range of applications. Four studies employed DSSs to help enterprises choose the best supplier (Alavi et al., 2021; Luthra et al., 2017; Memari et al., 2019; Shaw et al., 2012). DSS was employed in two studies to select the design of the energy systems (Blanco et al., 2008; Buchholz et al., 2009). In the other researchs, DSSs were used for selecting design options (Rahmanpour & Osanloo, 2017), identifying development strategy (Alyamani & Long, 2020), and evaluating sustainability projects (Turan et al., 2009). Two studies utilized DSSs to define the significant criteria and essential factors for sustainable development (Alyamani & Long, 2020; Vinodh & Girubha, 2012). Furthermore, DSSs have been employed to select plans for utilizing green materials (X. Zhang & Xing, 2017), identify key development strategy goals (Calabrese et al., 2019), and manage cage aquaculture by assisting with site classification, selection, holding capacity determination, and economic appraisal (Halide et al., 2009).

At the regional and national levels, DSSs were used in four studies to select the best options for energy and renewable energy development (Ahmad & Tahar, 2014; Balaman et al., 2018; Mattiussi et al., 2014; Şengül et al., 2015). DSSs were considered in one study as a tool to help managers evaluate alternatives in urban planning and city development planning, such as assessing sustainable residential development in terms of culture and life (Morfoulaki & Papathanasiou, 2021). There were three cases employing DSSs to evaluate the sustainability of cities as a primary planning future development policy (Cellura et al., 2002) and rank cities according to the criteria of sustainability (Ogrodnik, 2017). Kumar et al. (2015) considered the DSS as a tool to help Indian managers for developing the strategy on sustainable transport system (R. Kumar et al., 2015). Talukder & W. Hipel (2018) employed the DSS to select sustainable agricultural development plans for localities (Talukder & W. Hipel, 2018). Another study used DSS to help managers evaluate the effectiveness of tourism planning and development (García-Melón et al., 2010). Additionally, two other studies utilized DSS to assess the sustainability ratings of different regions and cities and identify areas that need special attention to achieve common sustainable development goals (Kara & Köne, 2012; Ogrodnik, 2017). Lastly, one study used the DSS to evaluate countries' sustainability ratings against each other (Mateusz et al., 2018), which was the basis for assessing the effectiveness of countries sustainability policy implementation.

The division of the DSS applications by scale are presented in Figure 3.11.

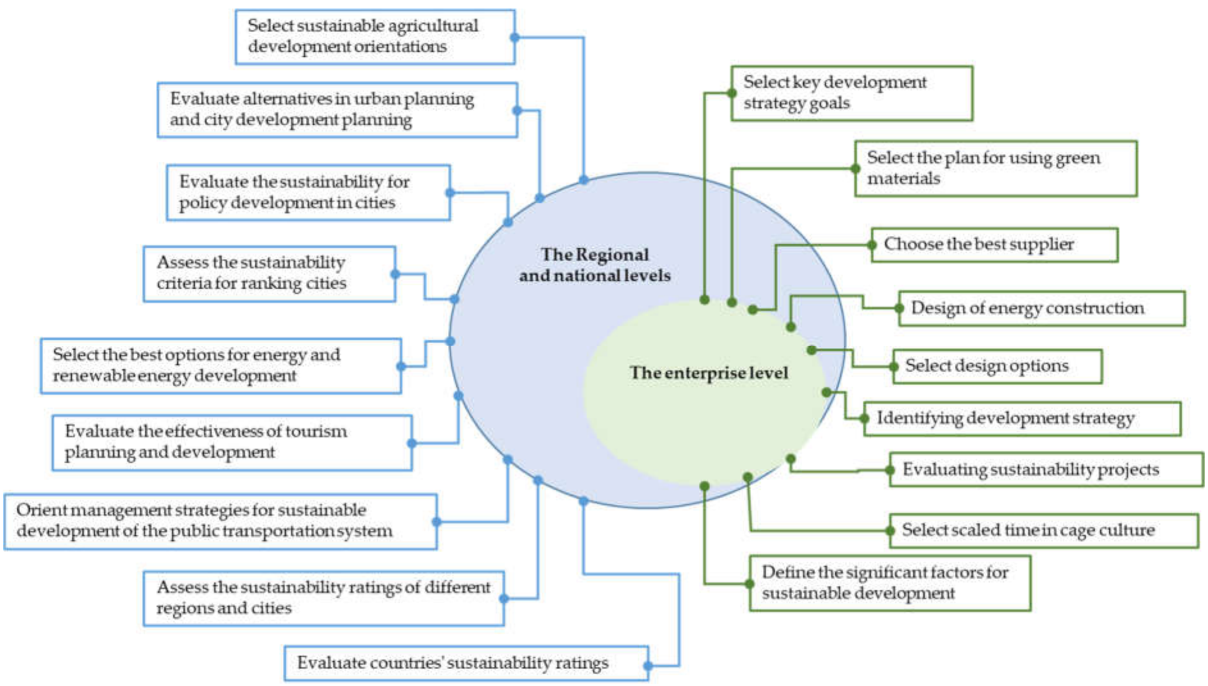

Figure. 3.11. Divisions of the DSS applications by scale

Although some sustainability criteria are qualitative and difficult to use for selection, DSS can help decision-makers make the best selection. Five studies applied judgment integration support tools to assess qualitative and uncertainty criteria (Afsordegan et al., 2016; Alyamani & Long, 2020; Memari et al., 2019; Turan et al., 2009). In these cases, the best choice could still be taken. In addition, in conditions of lack of experts or to ensure objectivity, fuzzy methods were used in seven studies to ranking or assess sustainability (Afsordegan et al., 2016; Alyamani & Long, 2020; Calabrese et al., 2019; Kaya & Kahraman, 2011; Memari et al., 2019; Şengül et al., 2015; Shaw et al., 2012). Besides that, six cases used integrated methods in the DSSs to make the decision more accurately (Afsordegan et al., 2016; Kaya & Kahraman, 2011; Luthra et al., 2017; Mateusz et al., 2018; Rahmanpour & Osanloo, 2017; Shaw et al., 2012). Half of these cases used the AHP method to rank the criteria (Afsordegan et al., 2016; Kaya & Kahraman, 2011; Luthra et al., 2017), while the other method was employed to rank alternatives. The benefits of applying DSS from the literature are shown in Table 3.9.

Table 3.9. The scale and benefits of applying DSS from the literature

Scale	Paper	Benefits
National	Şengül et al. (2015)	Defining the most significant criterion in preference ranking of renewable energy sources and the best renewable energy supply system in Turkey.
	Ahmad & Tahar (2014)	Identifying the most important economic and technological criteria as well as priorized energy sources for Malaysia.
	Afsordegan et al. (2016)	Allowing the evaluation of alternatives in energy planning without the need for precise variable values.
	Balaman et al. (2018)	Allowing users to select the design of full or separately supply chain and transportation network. Defining the configuration of the supply chain or give the configuration to plan the transportation network.
	Mateusz et al. (2018)	Assessing the sustainability of the EU country suitable with the real condition.
	Ogrodnik (2017)	Assessing the sustainability of cities and building on other well-known concepts.
Regional	Cellura et al. (2002)	Allowing decision makers to choose the best option based on user-oriented and indicators.
	Kara & Köne (2012)	Showing the strengths and weaknesses of sustainability for a region.

Scale	Paper	Benefits
	Mattiussi et al. (2014)	Identifying the best alternative from the point of view of the economy - technology, decision-maker, and equal weight for energy plant designs.
	García-Melón et al. (2010)	Determining the highest and lowest criteria in the sustainable assessment of the coastal National Park “Los Roques”.
	Kumar et al. (2015)	Identifying the most influential parameters to sustainability in transportation.
	Talukder & W. Hipel (2018)	Allowing analysts and decision makers to provide methodological advice for agricultural sustainability assessments.
	Morfoulaki & Papathanasiou (2021)	Allowing decision-makers to rank the highest and lowest alternative in the sustainability of Greek city mobility.
Company	Buchholz et al. (2009)	Assisting decision makers to choose the best option based on social criteria.
	Blanco et al. (2008)	Supporting in selecting the appropriate technology for sustainable development.
	Halide et al. (2009)	Assisting users in selecting the ideal website in accordance with their preferences
	Turan et al. (2009)	Verifying by mapping the model with practical applications.
	Kaya & Kahraman (2011)	Selecting the best energy technology based on quantitative and qualitative criteria.
	Vinodh & Girubha (2012)	Selecting the material that responds to mechanical, environmental, and economic factors for sustainability.
	Shaw et al. (2012)	Proposing a very useful decision-making tool for mitigating environmental challenges according to the manager's requirements
	Khalili-Damghani & Sadi-Nezhad (2013)	- Determining a set of four different investment chances with the priority of effectively achieving a certain level of fuzzy goals . - Generating high-quality solutions in the sense of sustainability.

Scale	Paper	Benefits
	Aydin et al. (2015)	Defining threshold points of technical parameters to ensure sustainability in the water supply system.
	Luthra et al. (2017)	Helping business managers and professionals distinguish essential supplier selection criteria and evaluate the most effective supplier in terms of sustainability within the supply chain while remaining competitive in the marketplace.
	Rahmanpour & Osanloo (2017)	Determining Ultimate Pit Limit (UPL) alternative based on the calculated UPL sustainability score.
	Zhang & Xing (2017)	Selecting the appropriate time frame for the implementation of green raw materials in a fashion retail company.
	Calabrese et al. (2019)	Permiting the company to incorporate the sustainability approach into its strategic management, identify the areas of reciprocal influence between the company and society.
	Memari et al. (2019)	Allowing more accuracy in result calculation using intuitive fuzzy for weighting criteria and ranking of alternatives.
	Alyamani & Long (2020)	Allowing project managers and decision-makers to identify selection criteria with higher weights.
	Alavi et al. (2021)	Allowing users to use historical data on suppliers for selection and define the importance of chosen criteria.

3.2.7. Discussion

In this section, various DSSs based on MCDM methods have effectively addressed sustainability-related choice issues such as planning, technology, production processes, and suppliers, as well as sustainability ranking, when assessing the overall and specific sustainable aspects of an organisation, company, or production chain. Critical issues with these decision support systems include:

- Defining the objective.
- Selecting sustainable criteria and standards.
- Choosing a methodology for decision support.

The effectiveness of MCDM has been demonstrated through its widespread application in various research cases.

This review also reveals that there are still several challenges when using DSSs in the context of sustainability. The first challenge relates to determining the quantity and classification of criteria. Criteria at different levels vary in amount and character. Criteria at the regional and national levels often have micro-level characteristics and tend to assess policy aspects based on the UN's sustainable development criteria. Meanwhile, criteria at the macro level are more specific. Additionally, classifying company-level criteria typically follows the three pillars of sustainability and technology. The challenge for decision-makers is establishing a standard set of criteria for all sustainability levels and determining how many criteria are sufficient to ensure the selection quality. Furthermore, the criteria weights also impact the selection results, especially in decision support systems that use MCDM methods. While there are many different methods for determining weights, the choice of weight determination method is also a challenge.

A challenge related to methodology usage is present. Although MCDM is considered an effective method for decision-making in the context of sustainability, many methods are available, making selecting a suitable method a challenge. AHP/ANP is trusted by many scholars for its simplicity and effectiveness at small scales across all levels, while PROMETHEE, TOPSIS, and VIKOR are effective for larger quantities of criteria, especially qualitative criteria.

A challenge related to the quality of experts and the number of experts used in decision support systems exists. The literature review shows that some decision support systems use expert judgments to determine the weights of criteria and criterion values for alternatives. They are considered adequate when criteria information is qualitative and uncertain. Expert assessments greatly influence the results. However, not all experts have sufficient knowledge to provide high-quality judgments in areas outside their expertise for decisions involving multiple stakeholders and various fields. Thus, seeking and determining the number of experts needed for decision support is also challenging. In addition, sustainability challenges also vary significantly in scale and context. What works in one region or industry might not be applicable elsewhere. Decision support systems need to be adaptable and customizable for different contexts.

A challenge relates to incorporating new technological advancements into decision support systems. Scientific and technological advances in information technology, such as fuzzy logic, AI, and machine learning, also promote their application in developing decision support systems. Studies show effectiveness in using fuzzy logic techniques to introduce objectivity and precision into decision-making. However, these are new techniques, and performing calculations is a complex process requiring segmentation and sufficient trial samples. Therefore, constructing trial samples and testing methods are challenges that need further research.

3.3. Scientific literature review contribution

3.3.1. CE and LCT review

The CE and LCT review studied the application of CE and LCT tools in BSC. The CE applied to the BSC covers both CE principles and practices of the CBMs at enterprises, whilst the application of LCT focuses on using LCT tools to assess environmental, economic, and social sustainability. By applying CE, it is expected to reduce fossil energy use, increase energy efficiency, improve recycling efficiency, and mitigate environmental negative impacts of bioenergy. In that context, the LCT tools measure the sustainability indicators and provide evidence for effective decision-making.

The present work shows that applications of CE principles for BCS focus on four principles such as reuse, recycle, reduction and recovery, and the application of CE principles are conducted in three forms of strategies, including applying innovative technologies, improving operational activities and extending the BSC to cover a larger supply chain. At enterprise scale, specific CBMs includes reuse, recycle, recovery; cascading and repurposing; and circular supply and organic feedstock models. In most of the cases, the application of these CE principles, strategies and CBMs contribute to a more environmental-friendly, resource-efficient and cost-effective BSC.

There are not many studies on circularity indicators in BSC. Several circularity indicators have been proposed, such as recycling (input) rate, recovery rate, material circularity indicator, and cascade factor. This is a good start for quantifying the circularity indices of product system or sector; and they are so novel that there are not many case studies reviewing the appropriateness and accuracy of these indicators. The quantified circularity indicators in one case study pointed out that the application of CE does not always bring environmental positive impacts.

Besides, this review indicates the usefulness of LCT tools in thoroughly assessing the performance of the BSC in sustainability aspects. Though environmental and economic sustainability are frequently assessed, the social aspect of bioenergy is sometimes neglected. The environmental, economic and social impacts of bioenergy are various depending on the types of biomass inputs, end-products, goals and scopes of the LCT-based studies. In contrast with circularity indicators, sustainability indicators are well-developed and comprehensive, covering all three aspects of sustainable development.

Unfortunately, there are no existing list of indicators for assessing both circularity and sustainability of the BSC at national and business scales, except the above cited Italian standard UNI/TS 11820:2022). It is suggested that a comprehensive list of circularity and sustainability indicators for BSC should be developed in the near future. This list of indicators will serve as a basis for comparing technological as well as operational options, aiming at a more sustainable and circular supply chain.

Moreover, the review indicates the lack of a holistic tools which can fully assess all aspects of both circularity and sustainability of the BSC, which suggests the need to develop such a decision-supporting tool for businesses. First, this tool should be user-friendly so that the enterprises can easily and quickly utilize it to evaluate their CBMs' circularity and sustainability. Second, it is necessary to incorporate both quantitative and qualitative data in the tool, because the circularity and sustainability indicators frequently goes beyond quantitative and monetarized results to include qualitative social benefits. Finally, this tool will identify any sustainable hotspots during the BSC, for initiating circular and sustainability measures applicable to the enterprises, taking into account their needs and budget. This feature is crucial as in case of limited budget, the enterprises will have various needs and they need to know the sustainable and circular hotspots which should be prioritized to invest.

Other future research that may be useful for developing a more sustainable BSC with higher level of circularity, includes: (1) technological research and (2) multi-disciplinary research. The technological research should focus on innovative processes and technologies to reduce, reuse and recycle of biomass materials and energy. Some examples of these innovative technologies are advanced anaerobic digestion methods with biological treatment for upstream and downstream processes (Tabatabaei et al., 2020b, 2020a), gasification of biomass waste with consideration of energy, environment and economic benefits (Sanaye et al., 2022) and microwave pyrolysis techniques and integration of catalytic upgradation of bio-oil to improve the product quality (Dhyani & Bhaskar, 2018). Besides, the multi-disciplinary research is recommended as BSCs are connected to various sectors in the economy. Therefore, it is an opportunity to obtain the potential synergies from implementing CE principles in BSCs across economic sectors such as agriculture, forestry, energy, and waste management.

3.3.2. Decision support system for sustainability context review

This review provides a comprehensive review of the DSS frameworks based on MCDM methods which are being applied in the sustainability context. This study has gathered multiple case studies applying various methods, including AHP, ANP, PROMETHEE, TOPSIS, and VIKOR. These methods have been used in sustainability decision-making processes to evaluate environmental performance, select suppliers, and assess various renewable energy systems, which are presented and discussed. Each method has its advantages and limitations, and their suitability depends on the specific decision-making context and available data.

The review also discusses the importance of sustainability criteria for assessing different options (technologies or scenarios), consequently, selecting the most suitable sustainability options. The four pillars of sustainability criteria are technology, economy, environment, and society. The DSSs can be used to assess sustainability at different scales, such as enterprises, regional and national levels.

Navigating decision-making methodologies in sustainability poses challenges. Selecting the right approach is intricate due to the plethora of available methods. Combining AHP/ANP for simplicity and effectiveness in smaller-scale decisions, with PROMETHEE, TOPSIS, or VIKOR for larger and more intricate scenarios, can enhance decision frameworks. Expert quality and quantity present hurdles, demanding a rigorous selection process, diverse panels, and sensitivity analysis. Ensuring decision support systems are adaptable and customizable across varied contexts is vital. To incorporate technological advancements like fuzzy logic, AI, and machine learning, collaboration with experts is crucial. Robust testing methods and trial samples are essential for validating the effectiveness and precision of these advancements.

The rapid development of technology in the near future requires that the DSSs in the sustainability context should be flexible and enable the participation of multiple stakeholders. By engaging multiple stakeholders in the decision-making process, organizations can gather the collective knowledge and perspectives of diverse stakeholders, leading to more comprehensive and robust decision outcomes. However, the incorporation of various features within DSSs to facilitate information sharing, and bring good communication and consensus among decision-makers is accompanied by an exponential increase in data volume. The integration of big data analytics and machine learning techniques becomes crucial to effectively handle this massive data volume. Through the integration of big data and machine learning, DSSs can uncover patterns, trends, and correlations within the data, enabling decision-makers to make data-driven decisions and gain a deeper understanding of complex business environments.

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CHAPTER IV. DETERMINING SUSTAINABILITY AND CIRCULARITY INDICATORS

4.1. Introduction

Researching biomass in CE and sustainable development has focused on using biomass and applying CE and LCT to biofuel and bioenergy production based on biomass. The role of biomass in the CE has been confirmed (Ellen MacArthur Foundation, 2013). However, the gap still exists in evaluating the application of CE to the BSC. The review of application CE and LCT (chapter 3) shows the lack of holistic tools which can fully assess all aspects of both circularity and sustainability of the BSC, which suggests the need to develop such a decision-supporting tool for businesses. The lack of a standardised set of indicators to evaluate the degree of circularity for the BSC is also revealed. Besides, this review indicates the usefulness of LCT tools in thoroughly assessing the performance of the BSC in sustainability aspects.

In addition, the review results on decision support models in the context of sustainability show that MCDM is widely used by decision-makers to evaluate options, such as AHP, PROMEETHEE, TOPSIS, VIKOR, DEMATEL, etc. They are also the feasible method for solving trade-off sustainability alternatives. Meanwhile, trade-off always is available in circularity and sustainability alternatives. Zeller et al. showed that an environmentally superior solution might not be more circular (Zeller et al., 2020). For example, in circularity alternative has GWP at 4953ton CO_2/year higher than the baseline at 1485tonCO_2/year, while resource use of the circularity alternative is at 205E+3 USD/year lower than 460E+3 USD/year of the baseline alternative. Similarly, comparing the "closed-loop" approach to enhance circularity in algae-based oil production with the existing method, Kern et al. declared that a circularity alternative might be less cost-effective (Kern et al., 2017). Direct trade-offs were identified between resource consumption, global warming potential, and financial viability (Kern et al., 2017). Similar trade-offs exist within the pillars of sustainability. Zhang et al. demonstrated that different biomass energy production processes from algae have contrasting environmental and economic benefits (Zhang et al., 2013). Given the trade-offs between sustainability and circularity, DSS based on LCT is a promising tool for selecting the best circularity and sustainability alternative.

The LCT approach for DSS was considered by scholars in the selection of sustainability options. Torkayesh et al. presented a framework for integrating LCA- MCDM approaches to assess sustainable waste management. In this framework, the LCT approach was used to define criteria of sustainability, scope, data gathering and sustainable impact while MCDM methods are used to weigh criteria and rank sustainable waste management options (Torkayesh et al., 2022). Martín-Gamboa et al. addressed the combination of life-cycle approaches and Data Envelopment Analysis (DEA) within multi-criteria decision analysis for the sustainability assessment of energy systems (Martín-Gamboa et al., 2017). According to their research, a new framework is proposed: modelling energy system abundance through (i) integrating intrinsic life cycle indicators and (ii) ranking and comparing energy scenarios based on sustainability criteria using dynamic DEA. De Luca et al. showed three ways of the combination of the life cycle tools with Multi-Criteria Decision Analysis (MCDA) in agriculture for sustainability assessments (De Luca et al., 2017). First, the MCDA methods were applied as a part of a life cycle framework to complement sustainable evaluation results. For example, MCDAs are used to choose the scenarios assessed, the functional unit, the categories of impact for the goal and the scope of the life cycle assessment. In addition, normalization, elicitation techniques, weighting and providing background information (typical elements of MCDA) are employed for the final evaluation result of the life cycle tool. Second, the life cycle results were considered as criteria information to provide to MCDAs. Third, considered life cycle tools and MCDA methods on the same level and with the same importance, and therefore, they were fully merged. According to De Luca et al., life cycle tools, including life cycle assessment LCA, SLCA and LCC, were integrated using a multicriterial and participative method, the AHP (De Luca et al., 2018). LCA, SLCA, and LCC methods are used to calculate indicator values of environmental, social and economic sustainability. After measuring indicators, the overall sustainability of the scenarios was assessed using the multi-criteria approach with the presented AHP approach. Ekener et al. developed a decision-making tool based on the Multi-Attribute Value Theory (MAVT) technique with the Life Cycle Sustainability Assessment (LCSA) approach for assessing the sustainability performance of products (Ekener et al., 2018). This study used LCSA to calculate life cycle impact indicators, and the MAVT was used to weigh and rank these indicators. Ren & Toniolo and Ren et al. employed LCA, LCC, and SLCA to obtain data on the alternative hydrogen production pathways concerning the environmental, economic, and social criteria, respectively (Ren et al., 2015; Ren & Toniolo, 2018). According to the results of LCA and LCC, the data of the alternative hydrogen production pathways concerning the environmental and economic criteria was determined. SLCA was used to determine the data concerning the criteria in the social aspect. Subsequently, a decision-making matrix of various alternatives and criteria can be obtained. This study used the Decision Making Trial and Evaluation Laboratory technique to rank alternatives.

However, these decision-support tools have some limitations. These tools are subjective and challenging to use for companies. For example, the tool developed by Ren et al. (2015) used some qualitative indicators and compared pairs of indicators that are based on expert judgements, which makes decision results variable depending on the experts' knowledge and experience. De Luca et al. (2018) used the AHP method for weighting criteria, but this study employed 15 experts to express their subjective opinions in pairwise comparisons of criteria. Ekener et al. (2018) only focused on identifying environmental indicators, while social and economic indicators were sourced from the available literature, which might not exactly reflect the situation of the supply chain. Furthermore, to the author's knowledge, no research considered both sustainability and circularity indicators. In addition, the available literature only focused on describing methodology development, not to mention the creation of a computational tool.

To overcome the lack of DSS tools considering both the sustainability and circularity of companies and supply chains, solving conflict and trade-offs in sustainability and circularity aspects, as well as reducing subjective selection, this thesis proposed and developed a comprehensive and helpful tool. The tool is called "HMI_DSS: Holistic Multi-Indicator Decision Support System". In this tool, the LCT approach is combined with multi-criteria methodologies, including the PROMETHEE II and entropy methods. The HMI_DSS is a flexible tool for selecting the best alternative or scenario for the company within the supply chain based on different sustainability and circularity aspects, for example, choosing according to one of four aspects of environment, economy, society and circularity, or total aspects. A set of sustainability and circularity indicators has been developed to use as criteria in this tool that aligns with the United Nations SDGs and the European Commission's guidelines on transition to CE (European Commission, 2020). Furthermore, in this thesis, a new methodology framework for the HMI_DSS tool is also introduced. This framework allows not only ranking alternatives but also calculating indicators for sustainability and circularity assessments of the company's present situation. In this framework, the weighting indicators are taken in multiple ways, which can help users analyze the sensitivity of sustainable alternatives according to indicator weight. By using PROMETHEE II and entropy methods, the ranking process directly uses results from the LCT approach. This is necessary to have a comprehensive assessment and reduce subjective and expert-dependent decision-making. The HMI_DSS tool can be used for guiding enterprises in the supply chain in the application of circular economy and sustainable models based on a LCT approach and, the achievement of SDGs.

The detailed content relevant to the development of the new methodology framework for the decision support system and the software of the HMI_DSS tool is presented in Chapters 4 and 5. Chapter 4 focuses on the first primary issue: proposing a methodology for developing the methodology framework of DSS and selecting sustainability and circularity indicators based on the LCT approach.

4.2. Methodology for developing decision support system tool

To develop the tool, a new methodological approach encompassed by several steps was proposed (Figure 4.1). This approach primarily focuses on solving two key issues: the selection of indicators for comprehensive evaluation of the circularity and sustainability of biomass chains. This process involves gathering, selecting, and classifying appropriate indices using a LCT approach and MFA. The second issue involves creating a decision support system tool. It encompasses the selection of MCDM methods for weighting indicators and ranking alternatives, proposing a methodology framework for DSS by combining the LCT approach and MFA with multiple-criteria methods and developing tools based on suitable programming languages. The eight specific steps of the methodology for developing the HMI_DSS tool are shown in Figure 4.1.

- Step 1 defines the main problem that needs to be solved. The problem need is to create a tool for companies in supply chain to assess and select circularity and sustainability alternatives, that includes the identification of sustainability and circularity indicators and a methodology framework for DSS applied to a company.
- Steps 2 to 3 aim to divide sustainability and circularity indicators into groups according to the LCT approach and then identify a specific formula for calculating the value of each indicator.
- In step 4, the selection of the MCDM method for decision-making is taken. This selection considers the type of indicators to be examined (quantitative and qualitative indicators), the potential for addressing trade-offs, the representation of results (performance score, distance to target, ranking, visual interpretation, probability), method transparency, computational time, and data collection cost.
- Step 5 is related to the selection of the method for indicator weighting. Here, multiple weighting methods can be selected due to the specific requirements of indicator weighting. They include requirements such as reducing subjectivity, analyzing sensitivity, and incorporating decision-makers' preferences.
- Step 6 involves creating a methodology framework for a DSS with LCT approach and MFA. This step entails considering utilisations of indicator calculation results obtained by the LCT approach and MFA for MCDM methods to address two key issues: weighting indicators and ranking alternatives. Based on these combinations, the methodology framework is developed, adhering to the following requirements: transparent presentation and the establishment of favourable conditions for developing a flexible DSS tool.
- In step 7, the DSS tool is developed. First, this step involves designing the structure of the DSS tool based on the methodology framework developed in step 6. Then, the programming language is selected to be compatible with indicator formulas and the mathematical basics used in MCDM methods. After that, the programming process created DSS tool is taken. This process considers some criteria of the DSS tool, such as facilitating easy collection and importation of data, enabling monitoring and storage of results, and providing visibility into each calculation step. The result of this step is a new DSS tool created.
- The final step is the testing and validation of the tool. In this step, the tool is applied to a specific case study. The obtained results are used to test how the tool works. The weaknesses and strengths of the tool are also assessed.

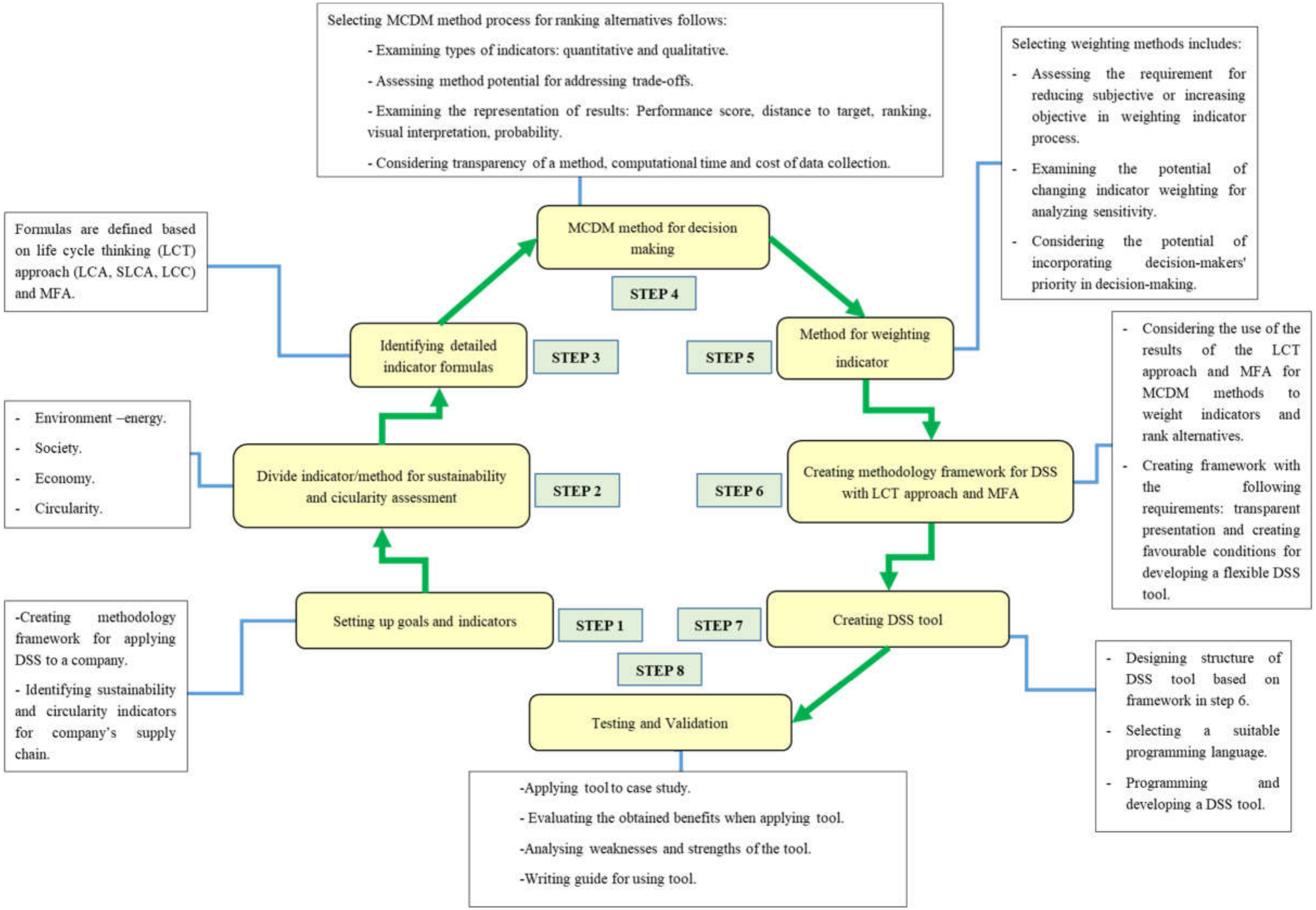

Figure 4.1. Methodology of developing HMI_DSS tool

4.3. Developing the Circularity and Sustainability Indicator Set for Companies in the Biomass Supply Chain

4.3.1. Introduction

Choosing the optimal circular and sustainable alternative for a company proves challenging due to the multifaceted nature of circularity and sustainability, encompassing environmental, social, and economic impacts, and circularity performance. Several researchers have used circularity and sustainability indices in earlier studies. Azevedo et al. (2017) proposed a sustainable circular index to measure the sustainability and circularity of manufacturing companies. This index consists of 17 indicators, including seven social sustainability, three economic sustainability, four environmental sustainability and four circulations. Since they can evaluate the sustainability and circulation practices of manufacturing companies, these circularity sustainability indicators are adaptable and straightforward. They align with the United Nations report, which supports the idea that indicators should be clear, concise, and uncomplicated (United Nations, 2017). However, this index is only intended for individual businesses' use, not supply chains.

More over, Sánchez-Ortiz et al. identified indicators and developed models to assess the circularity of manufacturing processes and products (Sánchez-Ortiz et al., 2020). 19 indicators were considered in this study to evaluate the circularity at the micro, meso, and macro levels. Indicators were created by Pollard et al. to assess the performance of electrical and electronic products towards the CE transition (Pollard et al., 2022). There are 25 environmental circularity indicators, nine social circularity indicators, and six economic circularity indicators that make up these indicators. This study examined how the metrics related to the product's life cycle stages. A thorough overview of the CE indicators was given by Pascale et al. (2020). In this study, 61 indicators were used, including 22 at the micro level, 15 at the medium level, and 14 at the macro level. Additionally, there are general CE indicators of the European Commission (EC) (Rincón-Moreno et al., 2021) and the Ellen MacArthur Foundation release CE indicators (Maia et al., 2019). Up to the authors' knowledge, currently, there is no set of circularity and sustainability indicators for the company in the BSC.

In addition, the variety of CE approaches and indicators makes it difficult to convert from linear business models into circular ones (Rincón-Moreno et al., 2021). The sustainability and circularity performance of companies are considered at the micro level while the BSC should be studied at the meso level. The indicators for both micro and meso levels are neither fully developed nor adopted (Rossi et al., 2020). Therefore, selecting a comprehensive set of simple and practical criteria for assessing circularity and sustainability in the biomass supply chain for energy production is essential to enhance the resource efficiency and facilitate the decision-making process. In this study, an integrated framework that combines sustainability and circularity indicators is proposed to evaluate the circular and sustainability performance of companies in the BSC. The proposed indicators will consider various stages during the BSC, such as feedstock plantation, processing, transportation, energy conversion, and end-of-life management, being aligned with the United Nations Sustainable Development Goals (SDGs) and EC's guidelines on transition to CE.

4.3.2. Methodology of indicator selection

To determine the indicators, the following steps are taken (figure 4.2). Step 1 gathers circularity and sustainable indicators. Step 2 selects overall sustainable and circularity indicators. Step 3 determines circularity and sustainable indicators for companies in the biomass supply chain (BSC. Finally, the indicators with similar content are consolidated and re-described into evaluation indicators for bioenergy companies.

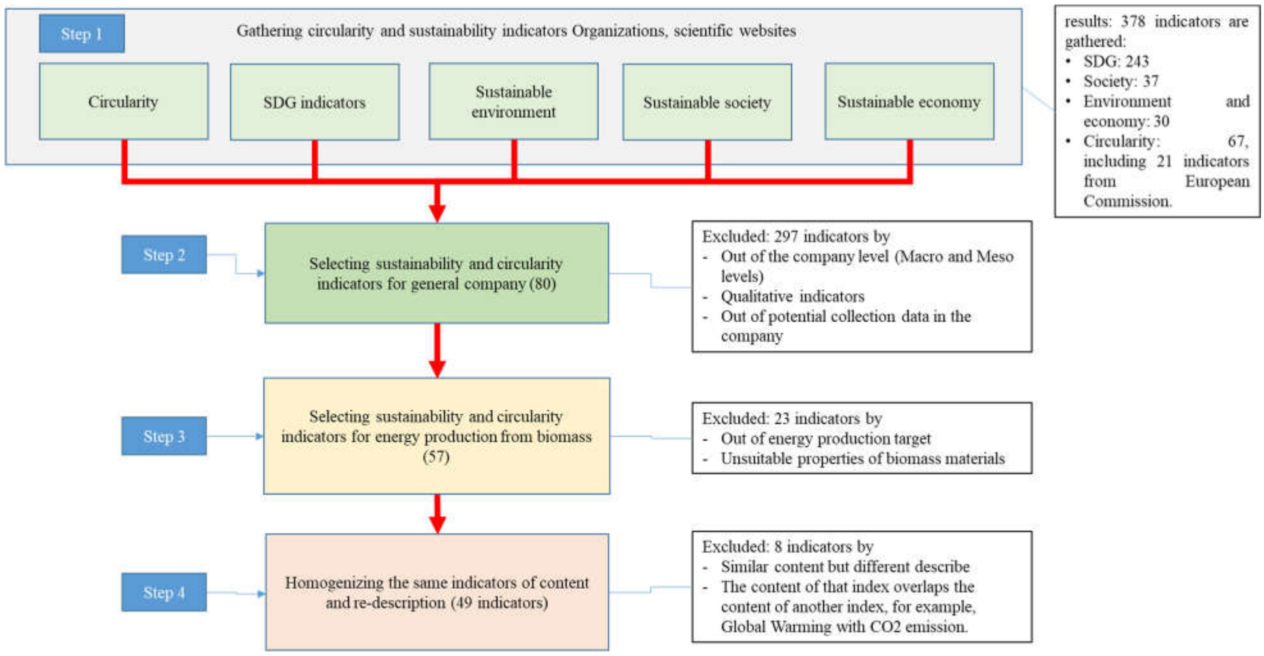

Figure 4.2. Methodology for searching and selecting indicators.

In step 1, the sustainable indicators have been collected, including SDGs, environment, economy, and social (United Nations, 2015). The SDGs indicators consist of 243 different indicators of 17 targets. Environmental and economic indicators are collected from the literature (Cusenza et al., 2019, 2021; Fusi et al., 2016; Gavaldà et al., 2022; Huijbregts et al., 2017; Morales-Vera et al., 2022; Odavic et al., 2017; Ren & Toniolo, 2018; Tan et al., 2022; Yuan et al., 2021), including 30 indicators, which are used to assess the biomass chain's environmental impact and calculate economic performance by life cycle cost (LCC). The environmental indicators have been prioritised and collected from ReCiPe midpoint indicators for simplicity in indicator calculation (Huijbregts et al., 2017). They also include the environmental and economic criteria of sustainable decision support systems. The social sustainability indicators have been collected from the UNEP/SETAC (2009) social impact assessment criteria (subcategories) with 37 criteria and from the social impact evaluation documents of the biomass supply chain when applying social life cycle assessment (SLCA) and the social criteria used in decision-making support systems for sustainability (Ren et al., 2015; UNEP/SETAC, 2009). The circularity indicators are collected from the European Commission's indicator set and in research documents (Moraga et al., 2019). There are 21 CE indicators proposed by the European Commission (EC) and 46 indicators used for CE assessment from the literature. There were 378 indicators gathered for further processing.

In step 2, the sustainability and circularity indicators gathered in step 1 were evaluated to select suitable indicators for assessing general companies (micro level). The first criterion is the indicator's applicability level, such as micro, meso, or macro. Some indicators collected from the SDGs can only be applied at the macro or meso levels. The macro and meso indicators are also analyzed to determine their applicability for companies in the supply chain. For example, the company's revenue indicator may be used instead of measuring GDP.

The second criterion is the characteristics of the indicators. The indicator's quantitative ability is also considered for selection. Although qualitative and quantitative indicators can be used to evaluate circularity and sustainability for companies, the value of qualitative indicators varies and depends on users' understanding. In addition, qualitative indicators also cause limitations in using multi-criteria decision support systems in comparing sustainability alternatives. Thus, qualitative indicators were excluded in this study—for example, some social sustainability indicators, such as social acceptance. Finally, the accessibility of data to calculate qualitative indicators is also considered, as some indicators may be accessible for some companies but not others. In this step, 80 indicators were selected, and 297 were excluded by running out of level, quality and potential data collection.

In step 3, the indicators are analysed to assess their suitability for application to a company in the biomass supply chain. The SDG indicators are selected based on the relationship between the goals and biomass energy production (Blair et al., 2021). For example, indicators of SDG16 and 17 are not relevant to the biomass supply chain, while indicators of SDG7 and 12 are closely relevant. Meanwhile, some circularity indicators chosen in Step 2 may be excluded when considering their relevance to the properties of biomass material and process stages. In this step, 23 indicators were excluded, and the remaining 57 were included for further processing.

In the final step, the selected indicators from various sources may lack uniformity in their descriptions, even though they reflect similar content. These indicators are harmonised in terms of their narratives. Additionally, some indicators at different levels related to the same content will be consolidated and used at a level equivalent to other indicators with additional content. For example, the Global Warming indicator covers the CO_2 emission indicator. As a result of this step, eight indicators were excluded, and 49 indicators remained. Subsequently, these indicators were re-described and used as evaluation criteria for the decision support system. The list of total indicators and explanation of them are presented in Table 4.1.

Table 4.1. Indicators of circularity and sustainability for company in supply chain

No	Indicator	Explanation	Unit	Measuring
1	Abiotic depletion potential	This index is a measure of the potential depletion of non-renewable resources in the Earth's crust due to supply chain activities, which are the unsustainable use of non-renewable resources, such as minerals (metals) and fossil fuels (diesel, natural gas, crude oil, coal) in stages of the supply chain.	kgSbeq	Sustainability (Environment)
2	Acidification	This index measures emissions of acidic substances like sulphur dioxide and nitrogen oxides, which can lead to acid rain. This acid rain can harm aquatic and terrestrial ecosystems, affecting aquatic life and soil quality.	kg SO_2 eq	Sustainability (Environment)
3	Ecotoxicity, freshwater	This index measures the amount of agricultural runoff, heavy metals, and other pollutants introduced into rivers, lakes, and streams as a result of supply chain activities. These pollutants can harm aquatic life, disrupt ecosystems, and affect water quality.	kg 1,4-DCB	Sustainability (Environment)
4	Ecotoxicity, marine	This index measures the amount of pollutants released into the marine environment as a result of supply chain activities such as heavy metals, industrial chemicals, pesticides, oil spills, and plastic waste. That leads to ecotoxicity and harm to marine life.	kg 1,4-DCB	Sustainability (Environment)
5	Eutrophication, freshwater	This index quantifies the excess nutrients, such as nitrogen and phosphorus, that enter water bodies through the activities in the supply chain. The excess nutrients are also relevant to processes in the supply chain such as fertiliser use, waste management, and inadequate wastewater treatment.	kgPeq	Sustainability (Environment)
6	Eutrophication, marine	This index reflects the excessive nutrient enrichment of coastal waters, primarily from activities of the supply chain. It can lead to harmful algal blooms, oxygen depletion, and damage to marine ecosystems.	kgNeq	Sustainability (Environment)
7	Eutrophication, terrestrial	This index reflects the excessive runoff of nutrients, such as nitrogen and phosphorus, from the supply chain. This nutrient runoff can lead to nutrient-rich soil in non-agricultural areas, disrupting natural ecosystems.	molNeq	Sustainability (Environment)
8	Global warming potential	This index reflects the climate impacts (additional radiative forcing caused by greenhouse gas emissions) of supply chain activities on the environment.	$kgCO_2eq$	Sustainability (Environment)
9	Human toxicity, cancer	This index measures the potential of carcinogenic substances that are used or emitted in supply chain activities. During working hours, supply chain employees may be exposed.	kg 1,4-DCB	Sustainability (Environment)
10	Human toxicity, non - cancer	This index measures the potential release of various hazardous substances into the environment of the supply chain, like sulphur dioxide (SO_2), nitrogen oxides (NOx), volatile organic compounds (VOCs), and particulate matter into the air. These substances can have harmful effects on human health when they are ingested, inhaled, or come into contact with the skin.	kg 1,4-DCB	Sustainability (Environment)
11	Ionizing radiation, ecosystem	This index reflects the ecosystem impacts of ionizing radiation caused by supply chain activities. It encompasses various forms of ionising radiation, including X-rays, gamma rays, alpha particles, beta	kg CTU eq	Sustainability (Environment)

No	Indicator	Explanation	Unit	Measuring
		particles, and neutrons, which may be encountered during these activities.		
12	Ionizing radiation, human health	This index measures the potential human health impact of ionising radiation resulting from supply chain activities. It encompasses various forms of ionizing radiation, including X-rays, gamma rays, alpha particles, beta particles, and neutrons, which may be encountered during these activities.	kBqU235eq	Sustainability (Environment)
13	Land use	This index reflects the allocation and management of land resources to support various stages of the production, distribution, and consumption of the supply chain. It refers to the relative species loss caused by a specific land use type (annual crops, permanent crops, mosaic agriculture, forestry, urban land, pasture) in the supply chain.	m^2a	Sustainability (Environment)
14	Ozone depletion	This index reflects the potential for supply chain activities to release chlorofluorocarbon (CFC) gases into the atmosphere, contributing to the depletion of the ozone layer.	kgCFC-11eq	Sustainability (Environment)
15	Particulate matter	This index reflects the potential of particulate matter emissions from supply chain activities on the environment. It refers to the presence of tiny solid or liquid particles in the air at various stages of the supply chain. These particles can originate from manufacturing processes, transportation, and other supply chain activities.	kgPM2.5eq	Sustainability (Environment)
16	Photochemical ozone formation	This index reflects the contribution to photochemical ozone formation by emitting volatile organic compounds (VOCs) and nitrogen oxides (NOx) from transportation, industrial processes, and shipping associated with supply chains.	kg Nox eq	Sustainability (Environment)
17	Primary energy consumption	This index is a measure of the total energy consumption within the supply chain. It takes into account various sources of energy, including electricity (both from the grid and self-generated), heat, and energy fuels like gas, diesel, oil, and coal. This index provides valuable insights into the supply chain's overall energy efficiency and sustainability.	MJ	Sustainability (Environment)
18	Water consumption	This index quantifies the amount of water, including sources like tap water, rivers, lakes and groundwater, used at different stages of goods and services in supply chain.	m^3	Sustainability (Environment)
19	Internal rate of return (IRR)	This index is used to assess the attractiveness and profitability of the company. IRR calculates the discount rate at which the present value of the project's expected cash flows equals the initial investment.	year	Sustainability (Economy)
20	Net present value (NPV)	This index is used to evaluate the profitability and feasibility of the company for investment. It involves estimating the present value of future cash flows associated with the project and comparing it to the initial investment.	euro	Sustainability (Economy)
21	Revenue	This index is used to calculate the total amount of income generated by the company from its business activities, such as the sale of goods and services, royalties, licencing fees, and other sources.	euro	Sustainability (Economy)
22	Total cost	This index is a comprehensive financial metric that accounts for all the expenses incurred by company activities such as initial cost, operation cost, and maintenance cost.	euro	Sustainability (Economy)

No	Indicator	Explanation	Unit	Measuring
23	Child Labour	This index is used to assess child use as labour in the company. This is the total of hours employing children under the age of 15 or 16 in the company, including direct and indirect child labour.	risk hour	Sustainability (Society)
24	Fair Salary	This index reflects the working hour cost in the company compared with the regional or national average working hour cost.	times	Sustainability (Society)
25	Fatal and non-fatal occupational injuries	This index is used to evaluate workplace safety and working conditions within the company activities and reflects the effectiveness of occupational health and safety measures, potential hazards, and risks in working conditions of the company. This is the total cases of fatal and non-fatal injuries relevant to the company.	case	Sustainability (Society)
26	Forced Labour	This index is used to assess the number of employees with a long contract in the company.	person	Sustainability (Society)
27	Job creation	This index is used to assess the generation of new employment opportunities resulting from the activities and processes within the company. It includes direct jobs in manufacturing, transportation, and distribution, as well as indirect jobs in supporting industries such as research, product development, and management.	man year	Sustainability (Society)
28	Income generated by jobs	This index is defined as the cumulative earnings received by individuals employed in various roles and processes within a company's, industry's, or sector's supply chain. It is used to assess the job income impacts of the company on social sustainability.	euro	Sustainability (Society)
29	Local employment	This index reflects the level using local labour in the company. This is total labour, directly and indirectly, participating in all departments, units or areas of the company such as operating man, management labours, transportation and distribution labour.	person	Sustainability (Society)
30	Number of health workers in the company	This index reflects the availability and accessibility of healthcare services for employees, reflecting the company's commitment to promoting employee health, well-being, and safety.	person	Sustainability (Society)
31	Proportion of employment with education and training out of total employment	This index reflects the skill level, qualifications, and preparedness of the workforce, as well as the effectiveness of educational and training programs in meeting the needs of employers in the company.	%	Sustainability (Society)
32	Proportion of informal employment out of total employment	This index provides insights into the size and characteristics of the informal labour market for the company. It refers to short-term labour demand in the company, for example, cleaning labour and renovation building labour.	%	Sustainability (Society)
33	Proportion of women in managerial positions out of total employment	This index is used to measure gender equality, diversity, and inclusiveness in the workplace, reflecting the extent to which women have equal opportunities for career advancement and representation at higher levels of management in the company. It refers to the representation of women in leadership roles across various functions and levels of the company.	%	Sustainability (Society)

No	Indicator	Explanation	Unit	Measuring
34	Research and development expenditure as a proportion of revenue	This index is used to serve as an indicator of a company's commitment to innovation, technological advancement, and long-term growth. It is defined by the rate of Research and development expenditure out of revenue.	euro	Sustainability (Society)
35	Social investment	This index is used to evaluate the company's contribution to social sustainability within the supply chain and local communities, such as investing in improving labour working conditions, fostering positive social outcomes, and creating shared value across all stakeholders. This indicator can include activities such as social programs, human resource management, protecting the working environment, social relationships, and contributing to important social issues.	euro	Sustainability (Society)
36	Working Hours	This index refers to the aggregate number of hours worked by all employees of the company within a specified period, which, in this research, spans a year. By tracking and analyzing total working hours, companies can optimize resource allocation, improve workforce planning, and enhance overall business performance.	hour	Sustainability (Society)
37	Circular investment	This index reflects the practice of businesses investing in sustainable circularity activities or applying CBM to a company. For example, the costs used to improve recycling, productivity or producing new products.	euro	Circularity
38	Circular material use rate	This index refers to the proportion of materials (secondary materials) within a system or process that are reused, recycled, or remanufactured rather than being disposed of as waste. For a company, it is identified by the ratio of the amount of secondary raw materials to the total material consumption.	%	Circularity
39	Employee participation in the circular model	This index refers to the involvement of workers in the implementation and promotion of CE principles or CBMs, within the company.	person	Circularity
40	Food waste	This index reflects the waste from food generated by employees and processes within the company. It refers to the loss or disposal of edible food at various stages of the company.	ton	Circularity
41	Generation of waste	This index reflects the waste generated by the company, such as liquid and solid waste. It also presents the level of sustainability performance and the effectiveness of applying the CE principle in the company for reducing waste.	ton	Circularity
42	Percentage of recycling rate of all waste	This index is the share of recycled waste in the total waste generated in the company.	%	Circularity
43	Percentage of recycling rate of paper and paperboard	This index is the share of recycled paper and paperboard in the total waste generated in the company.	%	Circularity
44	Percentage of recycling rate of plastic waste	This index is the share of recycled plastic waste in the total waste generated in the company.	%	Circularity
45	Primary renewable energy share in the total primary energy consumption	This index reflects the commitment of businesses to incorporate clean and sustainable energy solutions in their supply operations, reducing reliance on fossil fuels.	%	Circularity

No	Indicator	Explanation	Unit	Measuring
46	Proportion of material losses in primary material cycles.	This index refers to the percentage of materials that are lost or wasted during processes of primary materials within the company, such as extraction, production, manufacturing, or distribution. It measures the efficiency of material used within the primary material cycles and reflects the extent of resource loss or inefficiency.	%	Circularity
47	Reuse, manufacturing process	This indicator is employed to quantify the extent of resource, material, and equipment reuse within the production processes of the company. These materials are used in manufacturing processes but are not directed towards the production of products. For instance, water can be recycled in a closed-loop system for cooling or heating devices.	%	Circularity
48	Self-sufficiency of raw materials	This index reflects the reliance within the company on raw materials from imports.	%	Circularity
49	Use of raw materials for producing one unit of the main product	This index serves to evaluate the efficiency of primary material utilisation, indicating the quantity of raw materials employed as inputs throughout the company relative to the total output of the final product.	ton	Circularity

4.3.3. Hierarchical indicators

Table 4.1 reveals that some selected indicators can be used to measure both the sustainability and circularity of the biomass supply chain. However, they should re-hierarchy into sub-index and sub-indicators for advantage in applying methods for identification of their value. To assess sustainability indicators (environment, society and economy), LCT tools are popularly employed, including LCA, LCC and SLCA. Meanwhile, LCA, MFA and LCA, MFA and Input-Output analysis are important methods used to calculate circular economy indicators, they are considered the three “backbone” frameworks for CE assessment (Barkhausen et al., 2023; Corona et al., 2019). Therefore, in this thesis, In this paper, LCA, SLCA, LCC, and MFA are chosen for developing the HMI_DSS tool.

According to the LCT approach and MFA, 49 sustainability and circularity indicators are divided into two sub-indexes: the sustainability sub-index, which has three indicator groups for energy-environment, social, and economic, with a total of 19, 15, and five indicators, respectively; and the circularity sub-index (also circularity group), which has 10 indicators (Table 4.2). These indicator groups are classified based on the potential of applying methods for defining indicator values. For example, the energy-environment indicators are calculated using the LCA method and the circularity indicators are determined by MFA. Additionally, social and economic indicators are identified through the utilisation of SLCA and LCC.

Table 4.2. An overview of sustainability and circularity indicators applicable to companies within the biomass supply chain.

Index	Sustainability and Circularity indicators	
Sub - index	Sustainability	Circularity

Indicator groups	Energy - Environmental sustainability	Social sustainability	Economic sustainability	
indicator	1. Water consumption	1. Proportion of employment with education and training out of total employment,	1. Total cost	1. Self-sufficiency of raw materials
	2. Primary energy consumption	2. Proportion of women in managerial positions out of total employment	2. Revenue	2. Generation of waste
	3. Global Warming Potential	3. Proportion of informal employment out of total employment	3. Net Present Value	3. Percentage of recycling rate out of all waste
	4. Particulate Matter	4. Fair Salary	4. Internal Rate of Return	4. Percentage of recycling rate of plastic waste
	5. Eutrophication, marine	5. Child Labour	5. Circular investment	5. Percentage of recycling rate of paper and paperboard
	6. Ozone depletion	6. Fatal and non-fatal occupational injuries		6. Circular material use rate
	7. Ionizing radiation human health	7. Research and development expenditure as a proportion of revenue		7. Proportion of material losses in primary material cycles
	8. Ionizing radiation ecosystem	8. Social investment		8. Use of raw materials for producing one unit of main product
	9. Photochemical ozone formation	9. Number of health workers in company		9. Reuse, manufacturing process
	10. Acidification	10. Forced Labour		10. Food waste
	11. Eutrophication, freshwater	11. Local employment		
	12. Eutrophication, terrestrial	12. Job creation		
	13. Human toxicity, non-cancer	13. Income generated by jobs		
	14. Ecotoxicity, marine	14. Working Hours		
	15. Ecotoxicity, freshwater	15. Employee participation in the circular model		
	16. Human toxicity, cancer			
	17. Land use			
	18. Abiotic depletion potential			

	19. Primary renewable energy shares in the total primary energy consumption

Table 4.2 shows that the environmental indicators include global and local indicators. For example, global warming potential (GWP) and ozone depletion are global indicators, while water consumption and eutrophication are local indicators. The critical indicators to assess economic performance are the net present value (NPV), internal rate of return (IRR) and total cost. Job creation, local employment and child labour are indicators for reflecting social impacts. Finally, self-sufficiency of raw materials, generation of waste, circular material use rate and percentage of recycling rate out of all waste are essential to evaluate circularity.

4.4. Identifying formulas for sustainability and circularity indicators

4.4.1. Identifying formulas energy-environmental indicators

LCA is employed to determine the environmental sustainability and circularity indicators. Various environmental impact categories can be obtained as the environmental sustainability and circularity indicators. The environmental impact categories include Water consumption (WTC), Primary energy consumption (PEC), Global warming potential (GWP), Particulate matter (PAM), Food waste (Fw), Eutrophication, marine (EUm), Ozone depletion (OZD), Ionizing radiation human health (IORH), Ionizing radiation ecosystem (IORE), Photochemical ozone formation (PHOF), Acidification (AP), Eutrophication, freshwater (EUf), Eutrophication, terrestrial (EUt), Human toxicity, non - cancer (HUTno), Ecotoxicity, marine (Ecm), Ecotoxicity, freshwater (ECfw), Human toxicity, cancer (HUTca), land use (LU), Abiotic Depletion Potential (ADP) and Primary renewable energy consumption in total energy use (Rec).

Indicators of environmental sustainability are calculated based on relevant input/output and emission data of the biomass supply chain. Each indicator includes indirect and direct impacts (Cusenza et al., 2019, 2021; Kun-Mo et al., 2004; M.A.J. Huijbregts et al., 2016). The indicator k can be calculated by the formula (4.1).

$$I_k = \sum_{i=1}^{N} \sum_{j=1}^{Mi} CF_{kij} . m_{ij} \quad (4.1)$$

In there:

I_k - Environmental indicator k.

CF_{kij} – Specific environmental impact factor for indicator k with input or output j of stage i of the supply chain.

m_{ij} - Amount of input or output j of stage i per FU.

N - Number of supply chain stages.

M_i - Number of inputs and outputs of satge i.

The formula (1) can used to calculate indicator 1 to 18, including WTC, PEC, GWP, PAM, EUm, OZD, IORH, IORE, PHOF, AP, EUf, EUt, HUTno, Ecm, Ecfw, HUTca, LU and ADP.

Meanwhile, Indicator 19, which is about Primary renewable energy consumption in total energy use (PRec), is calculated as formula (4.2) (Rossi et al., 2020).

$$\text{PRec} = 100.\sum_{i=1}^{N}\sum_{j=1}^{Mi} Rec_{ij}\,.\,m_{ij}/(\text{PEC}) \qquad (4.2)$$

In there:

PRec – Rate of primary renewable energy use in the biomass supply chain (%)

$PRec_{ij}$ - Specific primary renewable energy use of input or output j in stage i (MJ/unit of input or output).

m_{ij} - The amount of input or output j in stage i (unit of input or output).

4.4.2. Identifying formulas for economic indicators

The economy indicators are computed by formulas as follows.

Indicator 20. Circular investment (Cin) (Rossi et al., 2020).

This metric evaluates the extent of investment dedicated to enhancing circularity in company (Rossi et al., 2020). The objective of this indicator is to express, in monetary terms, the financial resources allocated for transitioning the business model. This transition encompasses strategic and management initiatives, capacity development, as well as operational and maintenance activities. In this study, it is defined based on the relationship of amount input (for example, equipments, materials and facilities), price or investment rate, and specific relevant factors.

$$\text{Cin}=\sum_{i=1}^{Nin}(Pf_i * Cin_i * m_i) \qquad (4.3)$$

in which: Cin_i - Circular investment relevant factor of input i.

Nin-Number of inputs.

Pf_i – Price or investment rate of input i (euro/unit of input).

m_i- Amount of input i (unit of input).

Indicator 21. Internal rate of return (IRR) (Homagain et al., 2016)

IRR is the value that can make NPV equal to zero. It is defined by following equation:

$$\text{NPV} =\sum_{y=1}^{Tl}\frac{R_y-C_y}{(1+IRR)^y} - Cinitial=0. \qquad (4.4)$$

NPV - Net present value.

C_y - Total cost of company for year y.

R_y - Revenue of year y.

Cinitial - The initial cost.

Tl - Life span of the project.

The life span of a project refers to the duration or period of time during which the project remains active or relevant within the organisation (Gavaldà et al., 2022; Homagain et al., 2016; Odavic et al., 2017).

Indicator 22. Net present value (NPV)

NPV takes into account the time value of money by discounting all future cash flows back to their present value using a predetermined discount rate (Homagain et al., 2016). For a company, cash flow is determined by subtracting all yearly costs from the yearly revenue generated. (Odavic et al., 2017).

$$NPV = \sum_{y=1}^{Tl} \frac{R_y - C_y}{(1+r)^y} - Cinitial \qquad (4.5)$$

C_y - Total cost of company for year y.

R_y - Revenue of year y.

Tl - Life span of the project.

Cinitial - The initial cost.

Indicator 23. Revenue - R

Revenue refers to the total income generated by a company from its core business activities, including sales of goods or services, interest, royalties, and any other sources of income. The revenue of the company is calculated as follows:

$$R = \sum_{p=1}^{Ns} Ppro_p * Mpro_p \qquad (4.6)$$

In where: R- Revenue of company (euro).

$Ppro_p$ – Selling price of product or service p (for example, €/kWh; €/ton).

$Mpro_p$ - Amount of product or service p (kWh, ton) for yearly sales.

Ns- Number of products and services sold by the company.

Indicator 24. Total cost - TC

LCC is used to determine the total cost of company. The total cost includes initial costs, feedstock costs, production costs, and operation and maintenance costs (Gavaldà et al., 2022; Homagain et al., 2016). The costs are calculated over the entire life span of the project.

TC = Cinitial + Cmaintenance + Coperate + Creplace + Cfuel + Cdismantling – Csalvage (4.7)

in which:

1. Cinitial - The initial cost

It includes expenses such as purchasing equipment, setting up infrastructure, and acquiring technology or software. It is also related to building or modifying structures or facilities, including architectural design, engineering, permitting, labour, and materials.

$$Cinitial = \sum_{i=1}^{Nin} Pf_i * In_i * m_i \qquad (4.8)$$

in which:

Pf_i – Price or investment rate of input i (euro/unit of input).

In_i - Initial relevant factor of input i.

m_i- Amount of input i (unit of input).

Nin-Number of inputs.

2. Cmaintenance - The cost of maintenance

$$\text{Cmaintenance} = \sum_{y=1}^{Tl} \frac{\sum_{i=1}^{Nin} Pf_i * Mf_i * m_i}{(1+r)^y} \qquad (4.9)$$

in which: Mf_i - Maintenance factor of input i.

Pf_i – Price or investment rate of input i (euro/unit of input).

Tl - Life span of the project.

m_i- Amount of input i (unit of input).

Nin-Number of inputs.

r- Discount rate.

3. Coperate - Cost of operating

This cost is defined by the price of inputs directly relevant to the production process, such as energy use and labour. The rate of input initial cost or operating expense (OPEX) of the product unit can also be used to determine it.

$$\text{Coperate} = \sum_{i=y}^{Tl} \frac{\sum_{i=1}^{Nio} Pf_i * Or_i * m_i}{(1+r)^y} \qquad (4.10)$$

in which: Or_i - Operated factor of input/output i.

Pf_i – Price or investment rate of input/output i (euro/unit of input).

Tl - Life span of the project.

m_i- Amount of input/output i (unit of input/output).

Nio-Number of inputs and outputs.

r- Discount rate.

4. Creplace - Cost of replacement

Some equipment are replaced because of their life span less than life span of project. This cost is identified as following.

$$\text{Creplace} = \sum_{e=1}^{Nre} \sum_{t=1}^{Mr_e} \frac{Cinitial_e}{(1+r)^{t*Tl_e}} \qquad (4.11)$$

In which:

Nre-Number of replacements equipment’s

Mr_e – Number of replacement times of device e.

Tl_e – Life span of equipment e.

$Cintial_e$ – Initial cost of equipment e.

5. Cfuel - Cost of fuel

$$\text{Cfuel} = \sum_{y=1}^{Tl}\sum_{s=1}^{Nf}\frac{Pf_s * mf_s}{(1+r)^y} \quad (4.12)$$

in which: Pf_s- Price of fuel s (euro/fuel unit).

mf_s - Amount of fuel s (fuel unit).

Nf-Number of fuels used in company.

6. Cdismantling – Dismantling cost

This cost is defined by rate in percentage of initial cost.

7. Csalvage - Salvage value

$$\text{Csalvage} = \text{Cinitial}\,\frac{(1-d)^{Tl-1}}{(1+r)^{Tl}} \quad (4.13)$$

Here: d - Depreciation rate

Tl - Life span of the project.

4.4.3. Identifying formulas for social indicators

It is difficult to quantify the social performance and the defined social indicators/criteria, because some of the indicators, such as social acceptance and social benefits, are qualitative. In this study, some indicators are used and calculated by applying the following equations (Bouillass et al., 2021; De Luca et al., 2015; Ekener-Petersen & Finnveden, 2013; UNEP/SETAC, 2009; United Nations, 2015).

Indicator 25. Child Labour (Cl)

This indicator is identified by the number of risky hours for child labourers who directly participated in the company or indirectly participated through the use of inputs relevant to child labour.

$$\text{Cl} = \sum_{i=1}^{N_{in}} Cl_i * m_i \quad (4.14)$$

In which:

Cl – Total of risk hour of child labour (risk hour)

Cl_i – Specific risk hour of child labour factor of input i (material and child labour) (risk hour/unit of input).

N_{in}-Number of input list within company.

Indicator 26. Employee participation in the circular model (Emc) (Rossi et al., 2020)

This indicator is number of jobs related to circular economy in the company (Rossi et al., 2020).

$$\text{Emc} = \sum_{i=1}^{N_d} Emc_i \quad (4.15)$$

Emc - Total employee participation in the implementation of the CE model of the company (person).

N_d - Number of departments, units or areas within company.

Emc_i - Number of workers related to the implementation of the CE model in department or area i (person).

Indicator 27. Fair Salary (Fs)

$$Fs = \frac{Wlbc}{Wlbe} \quad (4.16) \text{ (Neugebauer et al., 2017)}$$

Fs- Fair salary

Wlbc - Average wage (cost) of company labour (which are paid to the workers) for one hour (euro/hour).

Wlbe - Average labour wage (cost) for one hour of national or regional (euro/hour).

Indicator 28. Fatal and non-fatal occupational injuries (I_{fnf})

The average number of fatal and non-fatal accident cases that occur each year in all of departments, units or function areas of a company (U.S. Bureau of labor statistics, 2022).

$$I_{fnf} = \sum_{i=1}^{N_d} I_{fnfi} \qquad (4.17)$$

I_{fnf} - Avarage number of injury and illness cases in company (case).

I_{fnfi} - Number of injury and illness cases reported in the department or area i (case).

N_d- Number of departments or areas within company.

Indicator 29. Forced Labour (Lfor)

$$Lfor = \sum_{i=1}^{N_d} Lfor_i \qquad (4.18)$$

Lfor - Total forced labors of company (person)

N_d - Number of departments, unit or areas within company.

$Lfor_i$ - Forced labours of departments, units or function areas i (person).

Indicator 30. Income generated by jobs (Inc)

This indicator measures the monetary value of the income generated by job creation in a circular business model (Rossi et al., 2020). It includes salaries, bonuses, commissions, and other forms of compensation received by employees for their work.

$$Inc = \sum_{i=1}^{T_{em}} Er_i \qquad (4.19)$$

Inc - Total income generated by jobs of company (euro)

T_{em} - Number of total employment in the company (person).

Er_i - Earnings received by the employee i (euro).

Indicator 31. Job creation (Jcre) (Thornley et al., 2008), (Llera Sastresa et al., 2010)

In the company, there are some sector production processes. Each process can create a different number of jobs due to the technology and size of the production process. For example, in the company that produces biogas from rice straw, pretreatment of biomass (processing industry) creates jobs depending on the mass of biomass produced and technology used, while collecting and harvesting biomass (agriculture activity) creates jobs depending on the type and mass of biomass.

$$\text{Jcre} = \sum_{s=1}^{N_{sp}} \text{Fcre}_s * m_s \qquad (4.20)$$ (Sooriyaarachchi et al., 2015)

Jcre - Job creation of company (man year)

$Fcre_s$ - Impact factor of job creation of sector production process s (man year/unit of input/output of production process).

m_s - Total amount of input/output of sector production process s (unit of input/output).

N_{sp} - Number of sector production processes in the company.

Indicator 32. Local employment (Elo)

$$\text{Elo} = \sum_{i=1}^{N_d} Elo_i \qquad (4.21)$$

Elo - Total local labors of company (person)

N_d - Number of departments, unit or areas within company.

Elo_i - Local labours of departments, units, or function areas i (person).

Indicator 33. Number of health workers in company (Hw)

This indicator is identified by the total number of health workers across all health-related departments or roles within the company.

$$\text{Hw} = \sum_{i=1}^{N_h} Hw_i \qquad (4.22)$$

in which:

Hw - Number of health worker within company.

N_h - Total number of health-related departments or roles within the company.

Hw_i - Number of health workers in the department or role i.

Indicator 34. Proportion of employment with education and training out of total employment (PE_{edu})

$$PE_{edu}=100*E_{edu}/T_{em} \qquad (4.23)$$

PE_{edu} - Rate of employment with education and training out of total employment (%).

E_{edu} - Number of employment with education and training degree or professional certificate in company (person).

T_{em} - Number of total employment in the company (person).

Indicator 35. Proportion of informal employment out of total employment (PI_{em})

The proportion of informal employment in total employment indicates the number of labors, who work for the company without a long time working contract. The work they do is temporary and short time. (For example, in biogas company that uses rice straw, the farmers are rented to collect straw after harvest). This indicator is define as following (United nations, 2023)

$$PI_{em}=100*I_{em}/T_{em} \qquad (4.24)$$

PI_{em} - Rate of informal employment out of total employment (%).

I_{em} - Number of informal employment in company (person).

T_{em} - Number of total employment in the company (person).

Indicator 36. Proportion of women in management positions out of total employment (PW_{em})

This indicator is expressed as the number of women in managerial positions divided by the total number of employees in a given reporting period identified by following formula (UNCTAD, 2020).

$$PW_{em}=100*W_{em}/T_{em} \qquad (4.25)$$

PW_{em} - Rate of women in management positions out total employment (%).

W_{em} - Number of women in management positions in the company (person).

T_{em} - Number of total employment in the company (person).

Indicator 37. Research and development expenditure as a proportion of revenue (E_{RD}**)** (OECD, 2015)**,**

$$E_{RD}=R_{RD}*R \qquad (4.26)$$ (UNCTAD, 2020)

E_{RD} - Expenditure of research and development (euro)

R_{RD} - Evarage of rate of cost for research and development out of revenue (%).

R- Revenue (euro).

Indicator 38. Social investment (INVso)

This index is used to evaluate the company's contribution to social sustainability within company and local communities, such as investing in improving labour working conditions, fostering positive social outcomes, and creating shared value across all stakeholders. This indicator is calculated as following equation.

$$INVso=R_{SO}*R + \sum_{i=1}^{N_d} Clb_i flb_i \qquad (4.27)$$

IVNso - Social investment (euro)

R_{SO} - Rate of social investment out of revenue (%).

R- Revenue (euro/year).

N_d - number of deparments or areas in compapy.

Clb_i - Total cost of company labour in departments or areas i (euro).

flb_i – Specific factor of cost for support labour besides salary of departments or areas i.

Indicator 39. Working Hours (Whou)

This index is used to calculate amount of yearly working hours that are paid to labourers by company. Companies can use this indicator to assess and monitor their labour costs and workforce productivity.

$$Whou=\sum_{i=1}^{T_{em}} Whou_i \qquad (4.28)$$

Whou - Total labour working hours of company (hour/year).

T_{em} - Number of total employment in the company (person).

$Whou_i$ - Working hours of employee i (hour/year).

4.4.4. Identifying formulas circularity indicators

MFA approach is employed to quantify circularity indicators. Most of the indicators are presented in forms of rate, ratio or percentage (An et al., n.d.; De Pascale et al., 2021; Kapoor et al., 2020; Kravchenko et al., 2019; Maia et al., 2019; Moraga et al., 2019; Rossi et al., 2020; Sánchez-Ortiz et al., 2020).

Indicator 40. Circular material use rate (Rcmu) (Rincón-Moreno et al., 2021)

For a company, calculating the circular material use rate involves measuring the amount of materials that are reused, recycled, or remanufactured (secondary material) within its operations relative to the total amount of materials used. The circular material use rate is calculated as follows (Rincón-Moreno et al., 2021):

$$Rcmu = \frac{m_{sem}}{m_{mu}} * 100 \qquad (4.29)$$

In which: Rcmu – Rate of circular material use (%).

m_{mu}– Total annual amount of materials used in company (ton/year).

$$m_{mu} = \sum_{i=1}^{N_{mu}} m_{mui} \qquad (4.30)$$

N_{mu} - Number of type of raw material used within company.

m_{mui} - Amount of raw material type i (ton/year)

m_{sem} – Annual amount of secondary materials of company (ton/year).

$$m_{sem} = \sum_{i=1}^{N_{sem}} m_{semi} \qquad (4.31)$$

in which:

N_{sem} - Number of types of secondary materials used by the company.

m_{semi} – Annual amount of secondary material type i (ton/year).

Indicator 41. Food waste (Fw)

Food waste is calculated by the total waste generated by food in company. It is defined by the equation follows:

$$Fw = \sum_{i=1}^{N_{fw}} Fw_i \qquad (4.32)$$

Fw - Annual amount of food waste generated (ton/year).

N_{fw} - Number of sources or categories of food waste within company.

Fw_i – Annual amount of food waste source or category i (ton/year).

Indicator 42. Generation of waste (Gw)

This indicator is identified as total waste generated from company.

$$Gw=\sum_{i=1}^{N_w} Gw_i \qquad (4.33)$$

in which:

Gw - Total annual amount of generated waste from the company (ton/year).

N_w - Total number of types or sources of waste generated.

Gw_i- Annual amount of generated waste of type or source i (kg or ton/year)

Indicator 43. Percentage of recycling rate of all waste (Pawre)

$$Pawre = (m_{repw}/Gw)100\% \qquad (4.34)$$ (Rincón-Moreno et al., 2021)

in which:

Pawre – Percentage of total packaging waste recycled annually (%)

Gw– Total annual generated waste from the company (ton/year).

m_{reaw} – Annual volume of all waste recycled annually (ton/year).

$$m_{reaw} = \sum_{i}^{N_r} m_{reawi} \qquad (4.35)$$

N_r - Total number of types or sources of waste recycled within the company.

m_{reawi} - Annual amount of waste recycled of type or source i (kg or ton/year)

Indicator 44. Percentage of recycling rate of paper and paperboard (Pwrepp)

$$Pwrepp = (m_{repp}/Gw)*100\% \qquad (4.36)$$ (Rincón-Moreno et al., 2021)

in which:

Pwrepp – Rate of total paper and paperboard waste recycled annually (%)

Gw – Annual volume of total generated waste of company (ton/year)

m_{repp} – Annual volume of recycled paper and paperboard waste (ton/year)

$$m_{repww} = \sum_{i=1}^{N_{pp}} m_{reppi} \qquad (4.37)$$

in which:

N_{pp} - Number of sources or category of recycled paper and paperboard waste within the company.

m_{reppi} – Annual volume of source or category i of recycled paper and paperboard waste (ton/year)

Indicator 45. Percentage of recycling rate of plastic waste (Prep)

$$Prepw = (m_{repwp}/Gw)*100\% \qquad (4.38)$$ (Rincón-Moreno et al., 2021)

in which:

Prepw – Rate of total plastic packaging waste recycled annually (%).

Gw– Total generated waste from the company (ton/year).

m_{repw} – Annual volume of recycled plastic waste (ton/year).

$$m_{repw} = \sum_{i=1}^{N_p} m_{repi} \qquad (4.39)$$

N_p - Number of sources or category of recycled plastic waste within the company.

m_{repi} – Annual volume of source or category i of recycled plastic waste (ton/year).

Indicator 46. Proportion of material losses in primary material cycles (Pmlo) (Sánchez-Ortiz et al., 2020).

This indicator is a measure of the efficiency of the primary material cycle and the extent of material losses incurred during production or processing. A higher material loss proportion indicates greater inefficiency and potential for improvement in resource utilization and waste reduction efforts.

$$Pmlo = (1-\prod_{i=1}^{Nc} \eta_i)*100\% \quad (4.40)$$

Pmlo-Rate of material losses in primary circular material.

Nc - Number of production processes in primary material cycles of company.

η_i - Efficiency use of production process i in primary material cycles of company.

Indicator 47. Reuse, manufacturing process (Rmp) (Rossi et al., 2020),

This indicator is used to quantify the reused materials for manufacturing processes in the company (Rossi et al., 2020). These materials are used in manufacturing processes but are not directed towards the production of products. For example, water can be used in the closed loop to cool or heat devices.

$$Rmp = \sum_{i=1}^{N_{rp}} Rmp_i \quad (4.41)$$

Rmp - Annual amount of reused material for manufacturing processes (ton/year).

N_{rp} - Number of types of reused materials for manufacturing processes in the company.

Rmp_i – Annual amount of reused material type i for manufacturing processes (ton/year).

Indicator 48. Self-sufficiency of raw materials (Ssrm)

This indicator is the rate of raw materials used in the company, but this raw materials are not imported from other countries. Therefore, this indicator reflects the level of dependence on external raw materials in the company (Rincón-Moreno et al., 2021).

$$Ssrm = 100*(m_{irm}/m_{mu}) \quad (4.42)$$

Ssrm - Self-sufficiency of raw materials (%)

m_{irm} - In-import (internal) raw material use of company (ton/year).

$$m_{irm} = \sum_{i=1}^{N_{irm}} m_{irmi} \quad (4.43)$$

N_{irm} - Number of type of internal raw material used within company.

m_{irmi} - Amount of internal raw material type i (ton/year)

m_{mu} - Total annual amount of material use of company (ton/year).

Indicator 49. Use of raw materials for producing one unit of the main product (Urm)

This index is used to assess the level of use of primary material (Sánchez-Ortiz et al., 2020). It is also to measure the reduced quantities of raw materials in the process of manufacturing when applying circular business models (Rincón-Moreno et al., 2021). For example, in the biomass company, biomass materials are considered raw materials, so this indicator is calculated by the amount of biomass to produce 1 kWh of equal electrical energy.

$$Urm = m_{rmu}/W_{mp} \quad (4.44)$$

in which: Urm – Amount of raw material to produce a unit of the main product (ton/one unit of main product).

m_{rmu} – Annual amount of raw material used per year (ton/year)

W_{mp} – Total main produced product per year of company (unit of main product/year).

4.5. Scientific literature contribution

The lack of sustainability and circularity indicators at the micro level leads to difficulty in transitioning to a CE for companies in the BSC. Besides, the difference in CE approaches and indicators is another barrier during the companies' transition to CE. To overcome this gap, this study has produced a comprehensive set of indicators to assess circularity and sustainability for biomass companies in the supply chain based on the life cycle thinking approach aligned with the United Nations SDGs and EC's guideline on the transition to a CE. 49 indicators have been selected, including 19 environmental indicators, five economic indicators, 15 social indicators and 10 circularity indicators.

Likewise, similar to Azevedo et al. (2017), these proposed indicators are suitable for assessing sustainability and circularity, offering a heightened level of comprehensiveness. First, this set of sustainability indicators is approached with a life cycle mindset and based on the United Nations SDGs. It is not only for individual companies but also usable for the BSC because the indicators are concerned with all supply chain stages. In addition, this set of indicators is also a step-by-step guide to achieving SDG 12 on responsible consumption and production and SDG 7 on affordable and clean energy.

Second, circularity indicators are based mainly on the EC guideline on transition to CE, so they are effective in assessing the performance of converting linear economy into CE at company level.

The set of indicators also shows that the selected indicators are measurable and can be calculated using the company's data. It provides valuable evidence for decision-making to apply CBMs at companies. The indicators are quantified based on the life cycle thinking approach. This approach also enables a thorough assessment of the indicators concerning their sustainability and circularity impacts.

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CHAPTER V. DEVELOPMENT OF THE DECISION SUPPORT SYSTEM FOR ENERGY ENTERPRISES FROM BIOMASS

In this chapter, the tool for making decisions is created for biomass companies in the supply chain. This decision-making tool is developed based on the use of a circular and sustainable economic model and a lifecycle thinking approach. The circular economy and sustainability are first employed to formulate a company strategy and generate circular and sustainability indicators (Chapter 4). A lifecycle thinking approach is applied to gather information on potential changes in the biomass supply chain. The result of this approach is a decision matrix that is formal for further process. The alternative then is chosen using MCDA. The methodology framework of the decision support system is constructed and the DSS tool named "Holistic Multi-Indicator Decision Support System" (HMI_DSS) is programmed by using MATLAB.

5.1. Selection of methods for weighting indicators and ranking alternatives

According to Chapter 4, a set of circularity and sustainability indicators is selected. Their values are calculated by formulas based on the LCT approach and MFA. The results of the LCT approach and MFA are employed to establish the decision matrix of alternatives and indicators.

	C1	C2	…..	Cn
A1	X_{11}	X_{12}	...	X_{1n}
A2	X_{21}	X_{22}	....	X_{2n}
…	....	....	....	...
Am	X_{m1}	X_{m2}	...	X_{mn}

In this matrix, A1 to Am are alternatives and C1 to Cn are circularity and sustainability criteria. X_{11} to X_{nm} are the values of indicators.

Moreover, Chapter 3 reveals that, with the requirement of evaluating various sustainability and circularity indicators and the potential for solving their trade-offs, MCDM methods are considered suitable choices. Techniques such as AHP, TOPSIS, ANP, PROMETHEE, and VIKOR are feasible for ranking alternatives, while AHP, expert judgement, and Entropy methods can be used for weighting indicators.

Although there are various MCDM methods for ranking alternatives, this study selected PROMETHEE II method for developing the methodology framework for some reasons:

- PROMETHEE II directly use the values of indicators for ranking alternatives. This is a strong point of these techniques compared to AHP and ANP, which transfer indicator values into the Saaty scale. The Saaty scale typically consists of values from 1 to 9, with each value representing a different level of importance or preference (Saaty, 2013), and the process of transferring indicator values into the Saaty scale is subjective. Therefore, using PROMETHEE II is easier and more advantageous for programming, as well as reducing subjectivity in decision-making.

- PROMEETHEE II method is rather simple weighting method in concept and in practice when compared with the other MCDM methods (Abedi et al., 2012).

- PROMETHEE's lack of weighting ability can be solved when combined with other methods. It facilitates the use of a variety of weighting methods for sensitivity analysis.

- PROMETHEE is considered an effective approach for prioritising and choosing among a limited set of alternative actions, taking into account multiple conflicting criteria (Abedi et al., 2012).

Weight selection is a significant aspect of the MCDM technique that allows for the incorporation of stakeholders' preferences into the decision-making process. It had a profound impact on the resulting decisions. In this study, Entropy method and user/decision maker definition were selected for weighting indicators based on some points:

- Entropy method is also rather simple ranking method in concept and in practice when compared with the other MCDM methods.

- Using the Entropy method promotes objectivity and reduces the risk of bias by distributing weights based on the information entropy of indicators (directly using values of indicators like PROMETHEE II).

- Choosing the Entropy method to weight the indicators can be appropriate because it does not require expert judgement, which is subjective and sometimes difficult for companies to obtain. By directly using values of indicators, the entropy method also gives objective weighting factor results.

- By using the Entropy method, decision-makers can ensure that no single indicator overly influences the decision outcome. Instead, the method promotes a balanced consideration of all indicators, leading to more robust and fair decision-making.

- Unlike the Entropy method, user definition allows decision-makers to explicitly express their subjective judgments and priorities regarding the importance of different indicators.

- If only using the Entropy method for weighting method, it is also difficult to perform sensitivity analysis by changing indicator weights. Meanwhile, user definition offers flexibility and customization, as decision-makers can tailor the weights to align with their unique decision context and objectives.

The weighting and ranking by Entropy and PROMETHEE are presented in subsections 5.1.1 and 5.1.2.

5.1.1. Weighting indicator by Entropy

The entropy method is a multi-criteria technique used to determine the weights of criteria, useful when evaluating and making decisions involving multiple factors. This method was developed based on Shannon's (1948) information entropy principle in the field of information theory (Wu et al., 2011). Entropy can be used to measure the uncertainty (or variability) of information. The Entropy method allows to determine the criteria weights without decision-makers intervention (Cao & Xu, 2022; Chen, 2021; Li et al., 2011; Shen & Liao, 2022; Wang et al., 2020). Therefore, the Entropy method is a multi-criteria technique used to determine the weights of criteria, which is useful for evaluating and making decisions involving multiple factors.

In Entropy method, m altenatives and n indicators are set in the evaluation, and the measured value of the i^{th} alternative in the j^{th} indicator is recorded as X_{ij}. In this thesis, X_{ij} is provided from decision-making matrix.

The first step is the standardization of measured values. The standardized value of the i^{th} sample in the j^{th} index is denoted as p_{ij}, and its calculation method is as follows:

$$p_{ij}=X_{ij}/\sum_{i=1}^{m}\left(X_{ij}\right) \text{ with } (j=1, 2, ..n). \quad (5.1)$$

In the entropy weighting method (EWM), the entropy value E_j of the i^{th} index is defined:

$$E_j= - (\ln(m))^{-1} \sum_{i=1}^{m} p_{ij}\ln(p_{ij}) \text{ with } (j=1, 2..., n). \quad (5.2)$$

In the actual evaluation using the EWM, E_j is generally set when $p_{ij} = 0$ for the convenience of calculation.

The range of entropy value E_j is [0, 1]. The larger the E_j is, the greater the differentiation degree of index j is, and more information can be derived. Hence, a higher weight should be given to the index. Therefore, in the EWM, the calculation method of weight is as equation like that.

$$w_j=(1-E_j)/ (n-\sum_{j=1}^{n} E_j \quad \text{ with } (j=1, 2, ..,n) \quad (5.3)$$

For example, three alternatives (A1, A2, and A3) need to be evaluated based on three criteria: Cost, Time, and Quality.

The first step is constructing the decision matrix where each row represents a project and each column represents a criterion.

Alternatives	**Cost**	**Time**	**Quality**
A1	10	6	8
A2	12	7	9
A3	8	5	7

In step 2, the decision matrix is normalised to transform different scales into comparable ones.

Alternative	Cost	Time	Quality
A1	10/30 = 0.33	6/18 = 0.33	8/24 = 0.33
A2	12/30 = 0.40	7/18 = 0.39	9/24 = 0.38
A3	8/30 = 0.27	5/18 = 0.28	7/24 = 0.29

In step 3, the entropy for each criterion is calculated:

- $E_{Cost} = -(\ln(3))^{-1} x[(0.33\ln(0.33))+(0.40\ln(0.40))+(0.27\ln(0.27))] \approx 0.996$;
- $E_{Time} = -(\ln(3))^{-1} \times [(0.33\ln(0.33))+(0.39\ln(0.39))+(0.28\ln(0.28))] \approx 0.998$;
- $E_{Quality} = -(\ln(3))^{-1}[(0.33\ln(0.33))+(0.38\ln(0.38))+(0.29\ln(0.29))] \approx 0.999$;

In step 4, the weights are calculated:

- $w_{Cost} = (1-0.996)/(3-(0.996+0.998+0.999))=0.571$;
- $w_{Time} = (1-0.998)/(3-(0.996+0.998+0.999))=0.286$;
- $w_{Quality}=(1-0.999)/(3-(0.996+0.998+0.999))=0.143$;

The weights for Cost, Time, and Quality would be approximately 0.571, 0.286 and 0.143, respectively.

5.1.2. Ranking alternatives by PROMETHEE II method

PROMETHEE II (Preference Ranking Organization Method for Enrichment Evaluations II), summarized in Figure 5.1, is an extension of the original PROMETHEE method, designed to provide a complete ranking of alternatives in multi-criteria decision-making problems (Behzadian et al., 2010; Figueira et al., 2005; Hashemkhani Zolfani et al., 2022; Macharis et al., 2004; Singh et al., 2021). Developed by Jean-Pierre Brans and Bertrand Mareschal, PROMETHEE II maintains its focus on evaluating and ranking alternatives based on multiple criteria while accounting for decision-makers preferences (Behzadian et al., 2010; Figueira et al., 2005; Hashemkhani Zolfani et al., 2022; Macharis et al., 2004; Safari et al., 2012; Singh et al., 2021). The operation of the PROMETHEE ranking is shown in Figure 5.1.

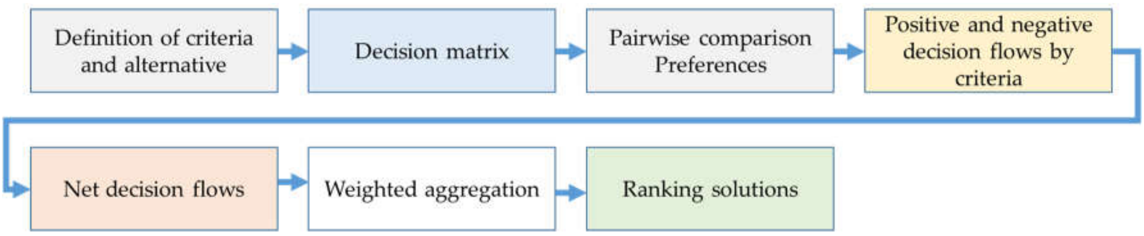


Figure 5.1 PROMETHEE II method

The ranking process includes the following steps:

Step 1 Normalize the decision matrix to range 0–1 by using

$$R_{ij} = \frac{x_{ij}-x_{ijmin}}{x_{ijmax}-x_{ij\,min}} \text{ If criteria j is positive.} \quad (5.4)$$

$$R_{ij} = \frac{X_{ijmax} - X_{ij}}{X_{ijmax} - X_{ij\,min}} \text{ If criteria j is negative.} \quad (5.5)$$

where: X_{ij} is the evaluation value, which is obtained from decision matrix.

i is the number of alternatives i =1, 2, …m; and j is the number of criteria j = 1, 2, .., n.

Step 2. This step computes each pair of possible decisions and the value of the preferred degree for each criterion. Let $g_j(a)$ be the value of criterion j for decision a (alternative a and $g_j(a)=R_{aj}$). We note d_j (a, b), the difference of the value of a criterion j for two decisions a and b.

$$d_j(a, b) = g_j(a) - g_j(b); \quad (5.6)$$

$P_j(a, b)$ is the value of the preference degree of a criterion j for two decisions a and b. The preference functions used to compute these preference degrees are defined as:

$$P_j(a, b) = F(d_j(a, b)) \text{ with } \forall x \in [-\infty, \infty],\ 0 \le F(x) \le 1 \quad (5.7)$$

There are six basic types of this preference function which were proposed by the decision maker by Brans and Vincke (1985) (usual function, U-shape function, V-shape function, level function, linear function and Gaussian function) in each case no more than two parameters (Behzadian et al., 2010).

Step 3, this step consists of aggregating all criteria preference degrees for each pair of possible decisions. For each pair of possible choices, a global preference index is computed. Let C be the set of considered criteria and w_j the weight associated with the criterion j. The multi-criteria preference index for a pair of possible decisions a and b is computed as follows:

$$\pi(a, b) = \sum_{j\epsilon C} w_j \times P_j(a, b) \quad (5.8)$$

Step 4 The fourth step, which is the first that concerns the ranking of the possible decisions, consists of computing the outranking flows. The positive outranking flow φ+(a) and negative outranking flow φ−(a) are calculated for each possible decision a. Let A be the set of possible choices and n the number of possible choices. The positive outranking flow of a possible decision a is computed by the following formula:

$$\varphi^+(a) = \frac{1}{n-1} \sum_{x\epsilon A} \pi(a, x) \quad (5.9)$$

The negative outranking flow of a possible decision a is computed by the following formula:

$$\varphi^-(a) = \frac{1}{n-1} \sum_{x\epsilon A} \pi(x, a) \quad (5.10)$$

Step 5 The last step consists of using the outranking flows to establish a complete ranking between the possible decisions. The ranking is based on the net outranking flows. These are computed for each possible decision from the positive and negative outranking flows. The net outranking flow φ(a) of a possible decision a is computed as follows:

$$\varphi(a) = \varphi^+(a) - \varphi^-(a) \quad (5.11)$$

The higher the value of the net outranking flow for a decision, the better the decision is.

5.2. Methodology framework of DSS for biomass company in supply chain

In this study, a new decision support framework has been proposed for a company in the supply chain, as shown in Figure 5.2. The goal of this methodology framework is to assess sustainability and circularity for the present situation of the supply chain, as well as identify the best sustainability and circularity supply chain alternative.

In this methodology framework, the LCT approach has been employed to collect data for determining the indicator values of alternatives. The LCA approach has been employed to determine environmental impacts for the alternatives of the supply chain, i.e. climate change, human toxicity, particulate matter formulation, land occupation, and fossil depletion (Finnveden et al., 2009; Hauschild et al., 2008; Kun-Mo Lee & Atsushi Inaba, 2004; Morales-Vera et al., 2022; Rebitzer et al., 2004; Tan et al., 2022). The LCC approach has been used to compute economic criteria aspects of supply chain alternatives, such as net present value (NPV), total cost, and internal rate of return (IRR) (Demichelis et al., 2022; Gavaldà et al., 2022; Homagain et al., 2016; Odavic et al., 2017; Tan et al., 2022; Yuan et al., 2021). The SLCA approach has been used to determine social criteria data for supply chain alternatives, i.e., fair salary, job creation, working hours and social investment (De Luca et al., 2015; Ekener-Petersen & Finnveden, 2013; Manik et al., 2013; Martínez-Blanco et al., 2015; Parent et al., 2010). Besides that, the MFA approach has been used to calculate the circularity criteria data for supply chain alternatives based on the material flows (Lenglet et al., 2017; Yana et al., 2022; Ju et al., 2017; Bauen et al., 2010, 2008). The results of these approaches are used to evaluate the sustainability and circularity of the supply chain in the present situation or to create the decision-making matrix that is used in MCDM methods for weighting indicators and ranking alternatives.

For identifying criteria (indicator) weights, the Entropy method or user/decision-maker definition has been used, while the PROMETHEE II method has been used to rank alternatives (Behzadian et al., 2010; Figueira et al., 2005; Hashemkhani Zolfani et al., 2022; Macharis et al., 2004; Singh et al., 2021). This framework shows that Entropy only uses decision-making matrix to weight indicators. Meanwhile the PROMETHEE II uses both decision-making matrix and indicator weights to ranking alternatives.

The methodology framework also shows that, before ranking alternatives by PROMETHEE II, the selection of weight values must be carried out. The value of the index weight significantly influences the decision-making outcome. When choosing objective weight values, the decision outcome will be more accurate and objective. In this methodological framework, selecting index weights involves two options. One option is to choose index weights using the entropy method for calculation; the second is to select index weights according to the decision maker.

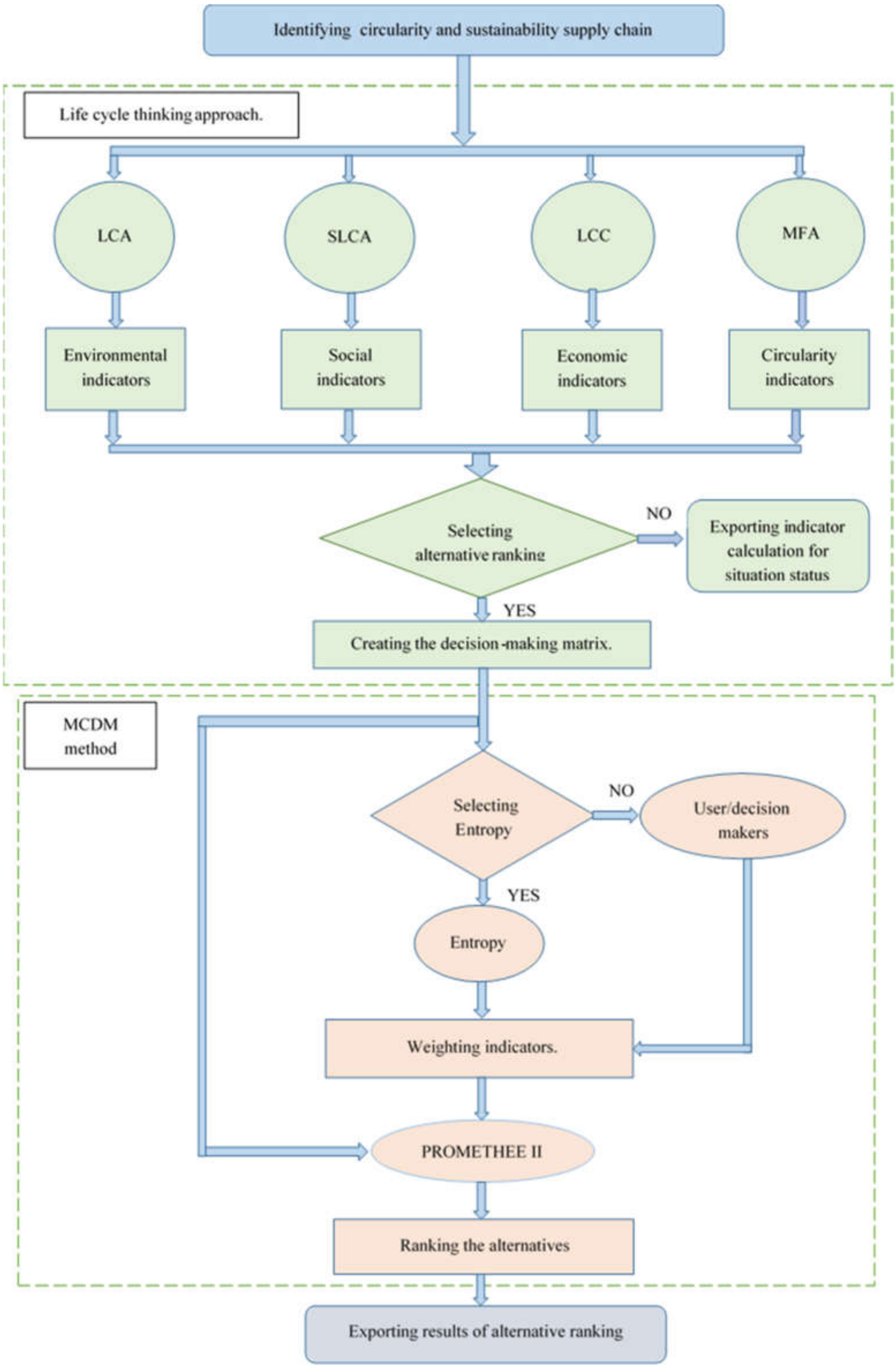


Figure 5.2. Methodology framework of DSS based on LCT approach and MFA

Abbreviation explanations: LCA: Life cycle assessment, SLCA: Social life cycle assessment, LCC: Life cycle costing, MFA: Material flow analysis, LCT: Life cycle thinking, MCDM: Multi-criteria decision making.

When selecting the entropy method to determine index weights, the value of the weights is considered objective due to the method's inherent impartiality and reliance on mathematical principles (details in subsection 5.1.1). This method objectively assigns weights to indicators based on the variability and uncertainty present in the data, rather than relying on subjective judgements or preferences of individuals. By considering the inherent characteristics of the data without bias towards any specific criteria, the entropy method ensures fairness and objectivity in the determination of indicator weights. When PROMETHEE II uses these weights for ranking alternatives, the ranking results ensure fairness in contributions from the indicators and are considered objective.

Conversely, when the second option is selected, the weights are completely defined based on the decision-maker's knowledge and preferences. Therefore, the weights of the indicators are highly subjective. In this case, the decision-maker's inclinations towards specific evaluation indicators will heavily influence and potentially skew the final decision. However, in this study, this option is mainly used for sensitivity analysis based on changes in the weights of the indicators.

Compared with Torkayesh et al. (2022) and the above studies (Section 4.1, Chapter 4), this methodology framework is suitable for assessing both sustainability and circularity, offering a heightened level of comprehensiveness. The selected MDCM methods directly take advantage of the calculation results of the LCT approach for ranking. Thus, the results of the ranking are objective and reduced depending on expert judgements. In addition, this framework allows for the selection of different weighting methods (entropy or decision-maker definition). This helps users have a more comprehensive assessment when choosing the best alternative because sensitivity analysis is easily performed by changing indicator weighting. This also allows using expert opinions or decision-maker expectations for ranking if it is necessary. Furthermore, this framework also allows not only ranking alternatives but also calculating indicators of situational status for sustainability and circularity assessment.

5.3. Programming DSS tool by MATLAB GUI and Script

To program the HMI_DSS tool, a structure of software for the DSS tool was built. The structure of a software system refers to the organisation of the system into distinct components and the relationships that exist among these components (Lorge Parnas, 2018). In this study, the structure has to cover all methods and functions used in the proposed framework. It is also organised to effectively programme and easily monitor the results of the calculated steps. This structure includes three components, including a Human interface, a Main – program and Sub-programs. The structure of the DSS tool is reported in Figure 5.3.

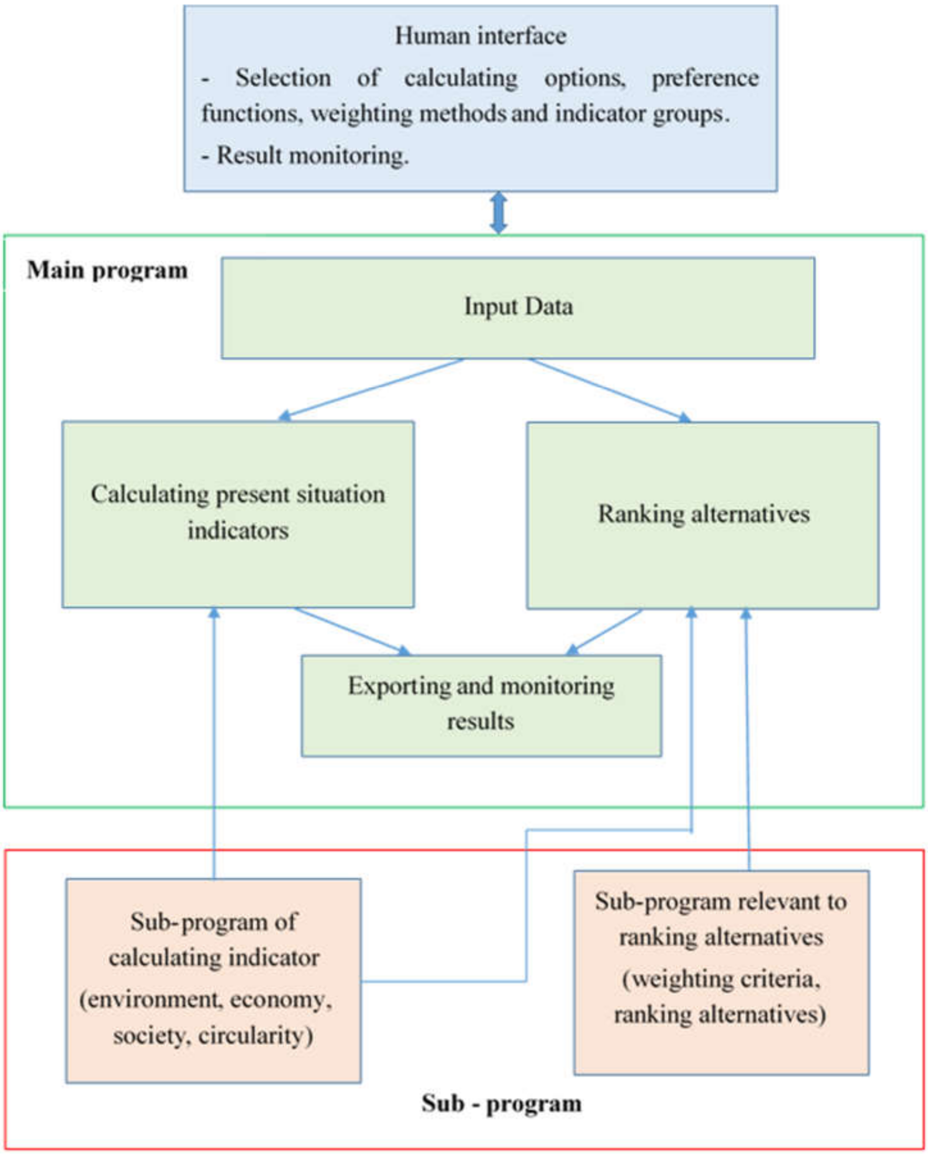


Figure 5.3. Structure of HMI_DSS software

Figure 5.3 reveals the relationship between components: The Human interface directly connects with the Main–program to perform selections and monitor calculation results; the Sub-programs link to the Main-program to perform calculations of indicators and ranking alternatives. Sub-programs are categorized into two groups, including sub-programs used to calculate indicators and sub-programs relevant to ranking alternatives. There are two calculation options in the Main-program, including the calculation of indicators for the present situation and ranking alternatives. To calculate sustainability and circularity indicators of the current situation for the supply chain, Main-program uses indicator calculation sub-programs. Meanwhile, indicator calculation and ranking sub-programs are employed by the Main-program to perform the ranking of circularity and sustainability alternatives. In addition, Figure 5.3 also shows that importing input data and exporting results are done in the Main-program.

5.3.1. Designing human interface

The term "human interface" in the context of software refers to the point of interaction between humans and computers (Human Machine Interface (HMI) Software Projects, 2019). It encompasses all the ways in which humans communicate with and control computer systems. The goal of a good human interface design is to create an intuitive, efficient, and user-friendly interaction between users and software applications. The Human Interface in this study is designed for selecting calculation options, indicator types, preference function of PROMETHEE II, weighting criteria, and result display. The Human Interface of the HMI_DSS tool is shown in Figure 5.4.

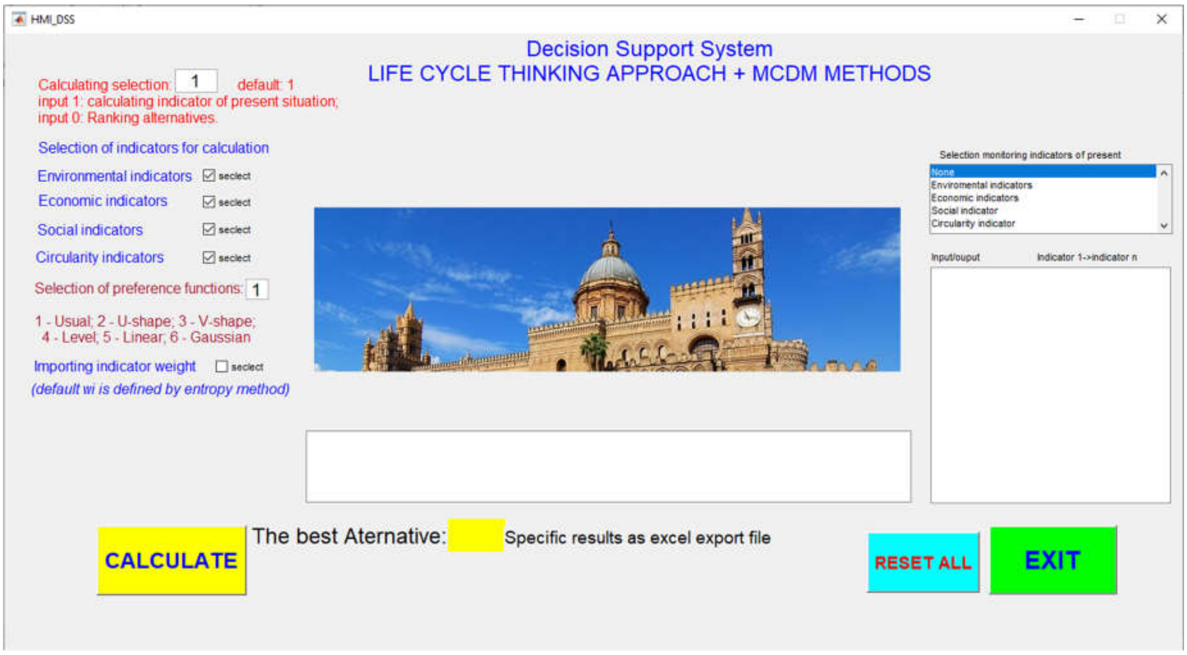


Figure 5.4 . The interface of HMI_DSS tool

The interface is structured in accordance with the graphical user interface (GUI) options of Matlab. Its architecture is tailored to cater to users with a suite of functions delineated as follows:

1) **Calculation Option Selection:** The DSS presents two options of computation: the evaluation of circularity and sustainability indices pertaining to the existing scenario (baseline) and the ranking of alternatives. There is a text box in Human Interface to choose the calculation options by typing 0 or 1. If users want to calculate present situation indicators, 1 is typed in this text box. Meanwhile, 0 is typed for ranking alternatives. The default mode upon initiation is configured for current state calculations.

2) **Indicators for Computation Selection:** Indicators are categorized into four distinct groups, affording users the flexibility to opt for one or all groups in the context of

computations. Selections are effectuated through the manipulation of checkboxes on the interface.

3) **Preference Function Selection:** Given the reliance of the DSS on the PROMETHEE II methodology, the imperative to select a preference function for the evaluation of alternative weights is underscored. The interface affords users the option to choose from six preference functions by inputting numerical designations 1 through 6, denoting: 1 - Usual; 2 - U-shape; 3 - V-shape; 4 - Level; 5 - Linear; 6 – Gaussian. The text box for selecting the preference function of the PROMETHEE II method is mounted in left corner of interface.

4) **Indicator Weight Determination:** This DSS tool allows users to determine indicator weights through two distinct methodologies. Method 1 leverages the entropy method for calculating indicator weights, while Method 2 permits users to manually input external weights based on decision-makers' anticipations. A click box in interface is used to choose the method of weighting indicators.

5) **Results Visualization:** The interface is engineered to visually convey pertinent computation results. The right side of the Human Interface is used to monitor the indicator calculation results of the current situation of company or ranking alternatives (Figure 5.5 and 5.6). The calculation results are displayed in the middle-bottom of the Human interface for both calculation options (Figure 5.5 and 5.6).

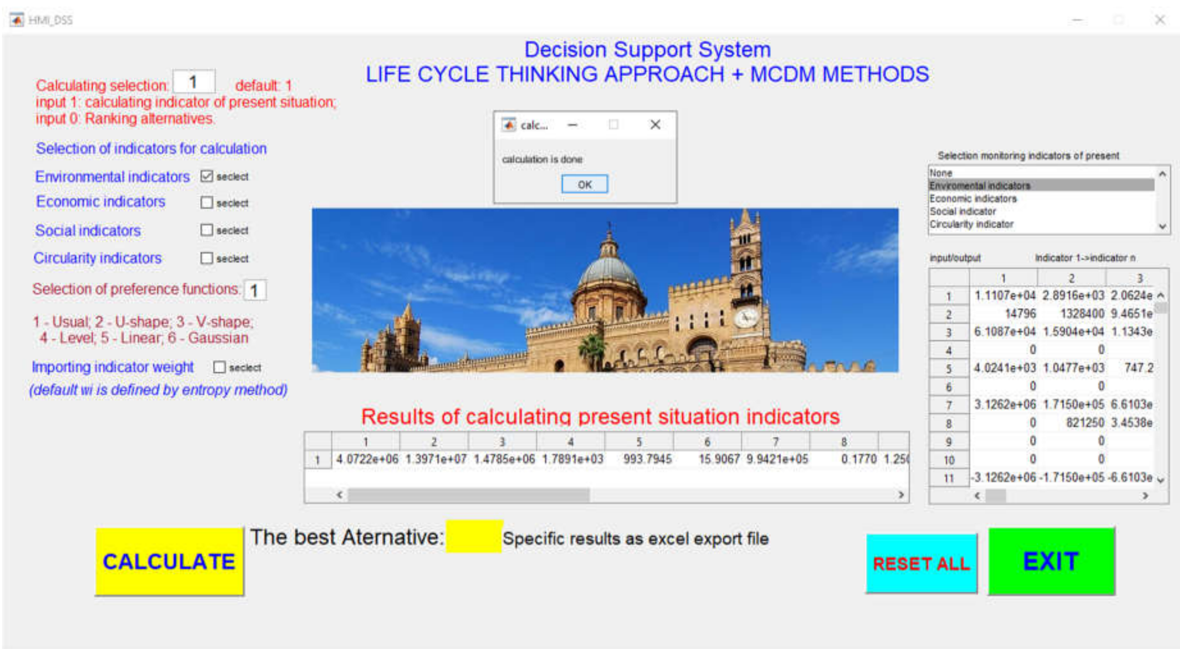


Figure 5.5. Displaying result of situation status of company in supply chain

When users calculate indicators for the current situation of a company, the results of the indicators responding to each input/output are displayed in the right corner of the

HMI_DSS interface. The indicator results are presented at the bottom of the interface (Figure 5.5). Meanwhile, when users rank alternatives, indicator results of alternatives are presented on the right of the interface, while value of the net outranking flow is displayed as a table at the bottom of the interface (Figure 5.6). Moreover, the best alternative is pointed at the bottom of the interface. The ranked results of alternatives are also presented in graphical format. Therefore, users can easily view rankings and the net outranking flow value of alternatives.

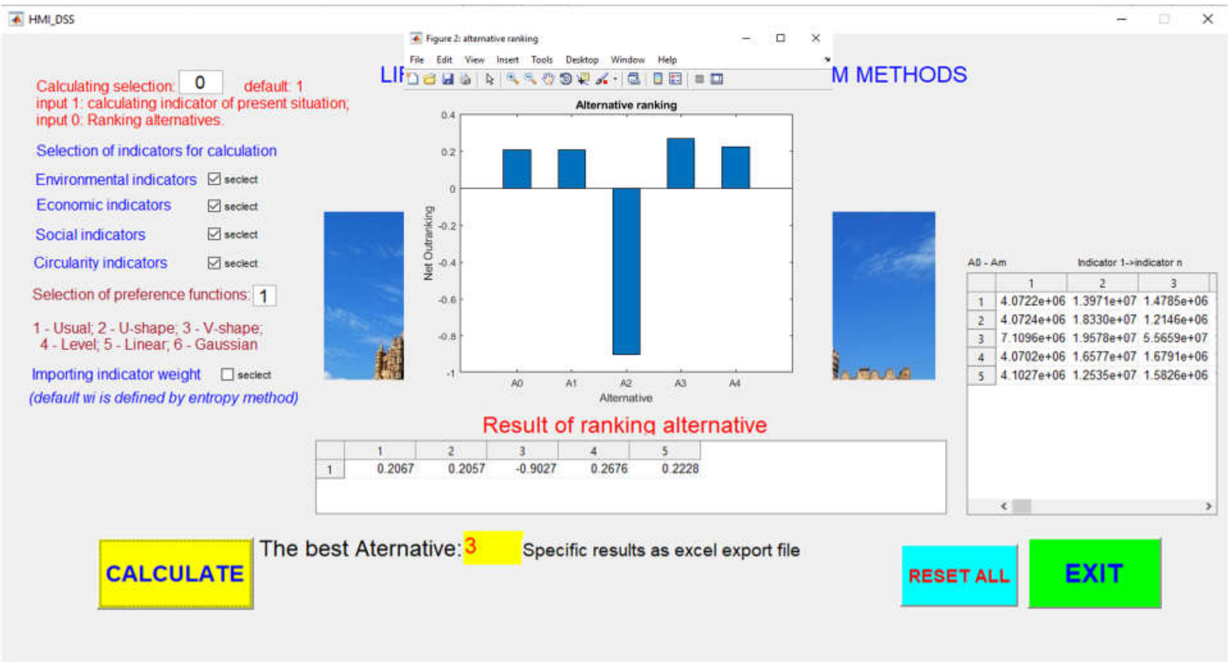


Figure 5.6. Displaying result of ranking circularity and sustainability alternatives

5.3.2. Designing main program

The main program is designed to import input data, perform calculations of indicators and ranking alternatives, as well as export results as shown in Figure 5.7. The input data, including number and text formats, is imported from Excel files. The input Excel file includes the inputs and outputs of the supply chain, and the specific impact factors of each indicator corresponding to each input and output. Besides, for calculating economic indicators, some general information must be included in the Excel file, such as life span, discount rate ...etc. Therefore, users can efficiently perform data preparation. The users can also easily select the data, they want, from an Excel sheet for importing. The imported data is used to calculate indicators and rank alternatives. After importing input data, the calculations are carried out by using sub-programs.

```
HMI_DSS.m | Fun_PROMETHEE.m | environmental_indicators.m | criteria_weighting.m | nomanlization.m
set(handles.Quang1,'string', '');
[HT,tf]=str2num(get(handles.calculating_selection,'string'));
if (tf==0)||((HT>1)||(HT<0))
    set(handles.Quang1,'string', 'ERROR in selection of calculation');
    warndlg ('ERROR in selection of calculation','Warning');
else
'*******************************************************************';
% nh?p d? li?u tinh toán chr s? môi tru?ng D1-Dn, A0
 check1= get(handles.checkbox1, 'value');
 check2= get(handles.checkbox2, 'value');
 check3= get(handles.checkbox3, 'value');
 check4= get(handles.checkbox4, 'value');
if (check1==0)&&(check2==0)&&(check3==0)&&(check4==0)
    set(handles.Quang1,'string', 'ERROR in selection of indicator for calculation');
    warndlg ('ERROR in selection of indicator for calculation','Warning');
else
 if check1 == 1
[envi,path1,~]=uigetfile('*.*','import file excel environmental_data');
run textbox1;
%msgbox('input/output environmental data','import data');
envi_data=xlsread([path1,envi],-1, 'selection of input/ouput amount');
[a,b]=size(envi_data);
for i=1:a
    for j=1:b
        if isnan(envi_data(i,j))
            envi_data(i,j)=0;
        end
    end
end
close textbox1;
run textbox2;
```

Figure 5.7. The main program in the Matlab script

The main-program also exports calculation and ranking results to an Excel file and displays them in the Human interface. For example, the resulting file of situation calculation includes five sheets, each sheet containing results of the total indicator, the environmental indicators, the economic indicators, the social indicators, and the circularity indicators. In the environmental indicator sheet, the indicator results of each input/output are stored in a row, so users can monitor and calculate impacts for stages of the life cycle. This is also like social and circularity sheets. In the economic sheet, the costs are shown in columns corresponding to each input/output and the sum of them, including initial, operation, maintenance, and fuel costs. Meanwhile, the ranking result file consists of the indicator value of the alternatives, the decision matrix, the normalisation matrix, the criterion weights, and the outranking results. Each result is presented on an individual sheet. Therefore, the users have more advantages in assessing and checking results.

5.3.3. Designing sub-program

The sub-programs in this tool are divided into two groups (Figure 5.3). One includes Sub-programs for the indicator calculation: environmental, economic, social and circularity indicators. These indicator calculation sub-programs were programmed based on the LCT approach. Another one comprises sub-programs for ranking alternatives: weighting indicators, ranking alternatives. The ranking alternative Sub-programs are created due to multi-criteria methods. All of them were programmed in Matlab Script.

1. Sub-program for calculating indicators

The DSS incorporates four distinct sub-programs dedicated to calculating indicators. These programs execute computations based on the four facets of life cycle thinking, leveraging input data to derive insightful results (Chapter 4).

a) Enviromental_indicator Sub-program (figure 5.8)

Objective: Calculate environmental and cyclic indices utilizing the Life Cycle Assessment (LCA) approach.

Methodology: The sub-programs for calculating indicators are programmed based on formulas to identify indicators' values. These results are aggregated across all stages to comprehensively evaluate the impact of each input on index values. The cumulative results contribute to the ranking of available options.

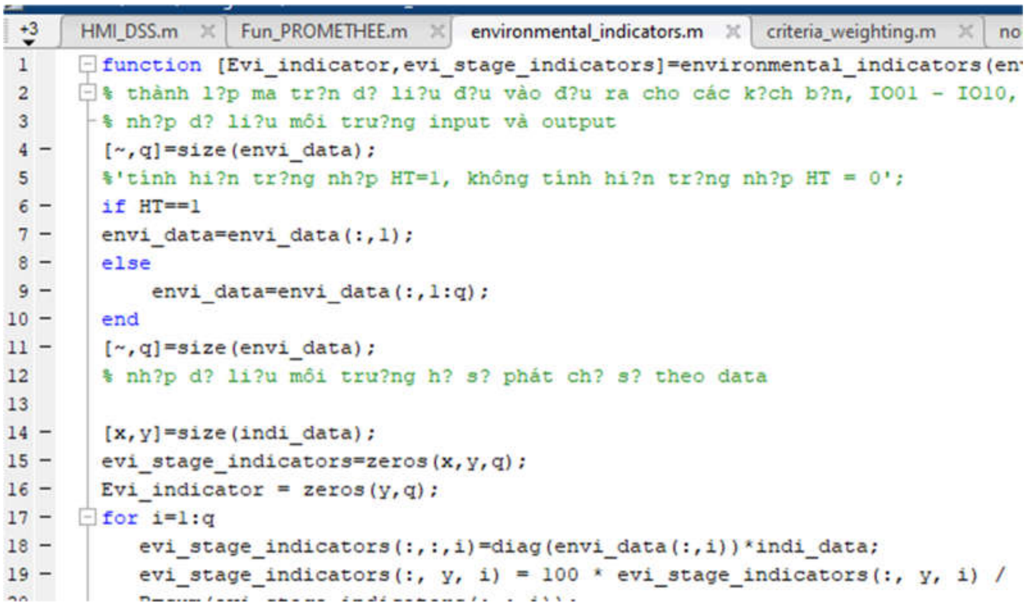


Figure 5.8. Sub-program of environmental indicator calculation in MATLAB script

b) Fun_economic Sub-program (figure 5.9)

Objective: Compute economic-related indices encompassing costs, revenue, NPV, and IRR at each stage and throughout the entire supply chain.

Methodology: Tailored calculation data accounts for diverse input/output scenarios and the nuanced relationships between different cost and revenue types. NPV and IRR are derived by considering costs and revenue over the entirety of the project cycle.

```
HMI_DSS.m | Fun_PROMETHEE.m | environmental_indicators.m | criteria_weighting.m | nomanlization.m | FUN_economic.m

function [eco_indicator, Cost]=FUN_economic(INPUT_OUTPUT,r,N,d,a1,a2,IN2,HT)
% FUN_economic computes the economic indicator and cost for given input/output data and time horizon
%
% INPUTS:
%   INPUT_OUTPUT - input/output data
%   HT - time horizon
%
% OUTPUTS:
%   eco_indicator - economic indicator
%   Cost - cost calculation
%



% II. Input/output information
% Check size of INPUT_OUTPUT and select columns
[a, b] = size(INPUT_OUTPUT);
if HT == 1
    INPUT_OUTPUT = INPUT_OUTPUT(:,1);
else
    INPUT_OUTPUT = INPUT_OUTPUT(:,1:b);
end

% Read price and relevant cost data from eco_data
[x, y] = size(IN2);
PRICE = IN2(:,1);
RELEVANT = IN2(:,3:y);

% Read time replacement of device
Timereplacement = IN2(:,2);
```

Figure 5.9. Sub-program of economic indicator calculation in MATLAB script

c) Fun_SLCA Sub-program (figure 5.10)

Objective: Determine social indicators by integrating input and output data across supply chain stages, incorporating coefficients reflecting their relationships.

Methodology: The program calculates the value of each indicator with added supplementary indicators expressed as percentages, providing a holistic perspective on social aspects.

```
function [Social_indicators,soc_stage_indicators]=Fun_SLCA(social_input_output,indi_data, HT)
% FUN_SLCA - Function to calculate social indicators
%   [Social_indicators,soc_stage_indicators]=Fun_SLCA(social_input_output, HT)
%
%   Inputs:
%   social_input_output - 2D matrix of social input/output data (p x q)
%   HT - Flag indicating which columns of the social_input_output to use (1 for 3rd column only
%
%   Outputs:
%   Social_indicators - 2D matrix of social indicators (y x q)
%   soc_stage_indicators - 3D matrix of social indicators for each stage (x x y x q)
%

% Get the dimensions of the social_input_output data
[p,q]=size(social_input_output);

% Select the columns of social_input_output data to use based on the HT flag
if HT==1
    social_input_output = social_input_output(:,1);
else
    social_input_output = social_input_output(:,1:q);
end
[p,q]=size(social_input_output);

% Read in the environmental data from an Excel file (sheet 2)
[x,y]=size(indi_data);
% Initialize matrices to store the results
A=zeros(x,y,q);
soc_stage_indicators=zeros(x,y-1,q);
Social_indicators = zeros(y-1,q);
```

Figure 5.10. Sub-program of social calculation in MATLAB script

d) Fun_Circular Sub-program (figure 5.11)

Objective: Assess the circularity degree of chain indicators.

Methodology: The program evaluates the circularity of indicators within the chain, offering insights into the sustainable and circular aspects of the supply chain.

```
function [Circular_indicators,cir_stage_indicators]=Fun_circular(Cir_input_output,indi_data, HT)
% Fun_circular: Function to calculate circular indicators
%
% Inputs:
%   Cir_input_output: matrix with p rows and q columns
%   HT: binary flag indicating whether to consider input data or not
%
% Outputs:
%   Circular_indicators: matrix with y rows and q columns, containing calculated circular indicato
%   cir_stage_indicators: 3D matrix with x rows, y columns, and q layers, containing intermediate
%

% Get the size of Cir_input_output
[p, q] = size(Cir_input_output);

% Check the value of HT
if HT == 1
    % If HT is 1, consider only the first column of Cir_input_output
    Cir_input_output = Cir_input_output(:, 1);
else
    % If HT is 0, consider all columns of Cir_input_output
    Cir_input_output = Cir_input_output(:, 1:q);
end

% Get the updated size of Cir_input_output after considering HT
[p, q] = size(Cir_input_output);

% Read the environment indicators data from the worksheet "circ_data"
% Get the size of the environment indicators data
[x, y] = size(indi_data);
```

Figure 5.11. Sub-program of circularity indicator calculation in MATLAB script

Four indicator calculation sub-programs were created for the HMI_DSS tool that correspond to environmental, economic, social, and circularity indicators. They contribute to a comprehensive assessment of the supply chain, enabling informed decision-making through the synthesis of environmental, economic, social, and circular perspectives. They also make the HMI_DSS tool more flexible in terms of indicator selection priorities in assessment. It also gives users an advantage in collecting and preparing data for calculation when each indicator category is based on an individual methodology.

2. Sub-program for weight calculation

To calculate the weights of alternatives, three sub-programs are used in succession: Normalization, Fun_promethee and Criteria_weighting. Normalization is used to convert the decision matrix into a matrix with values within the range of 0 to 1 to serve the calculation of the alternative weights using the Fun_promethee program.

HMI_DSS.m | Fun_PROMETHEE.m | environmental_indicators.m | criteria_weighting.m | nomanlization.m

```
function iV1 = nomanlization(D,MM,m,n)
    t1=min(D);      %-- min
    t2=max(D);      %-- max
    %  Max-Min
    V1 = zeros(m,n);
    for i=1:n
        if t1(i)==t2(i)
          V1(:,i)= 0;
        else
           t1_min = repmat(t1,m,1);
           t2_t1 = repmat(t2-t1,m,1);
            V1(:,i)=(D(:,i)-t1_min(:,i)) ./t2_t1(:,i) ;
        end
    end
    D1=ones(m,n);
   for j=1:n
         if MM(j)==-1
               V1(:,j)=D1(:,j)-V1(:,j);
         end
```

Figure 5.12. Sub-program of matrix normalisation in MATLAB script

Fun_promethee is used to calculate the weights of the alternatives based on the result of normalization and the weights of the indicators. The calculation result and a weight vector are obtained. This vector will be used to arrange the best level for the alternatives.

HMI_DSS.m | Fun_PROMETHEE.m* | environmental_indicators.m | criteria_weighting.m | nomanli:

```

function [Q,V]=Fun_PROMETHEE(m,n,iV1,w,cH)

    V1=zeros(n,m,m);
    V=zeros(m,m);
    Fplus=zeros(m,1);
    Fminus=zeros(1,m);

    %-- Determine Preference
    % Linear: p & q thresholds
         p=zeros(6,n); q=zeros(6,n);

         p(2,:)=((max(iV1)-min(iV1))/m);    % floor?
         p(3,:)=((max(iV1)-min(iV1))/2);
         p(4,:)=((max(iV1)-min(iV1))/m);
         p(5,:)=((max(iV1)-min(iV1))/m);
         q(4,:)=(0.5*(max(iV1)-min(iV1))/m);
         q(5,:)=(0.5*(max(iV1)-min(iV1))/m);
         p(6,:)=(p(5,:)+q(5,:))/2;
          for j=1:n
              for i=1:m
                  for s=1:m
                      %-- for each j -> Hj    ?    abs ?
                      d=iV1(i,j)-iV1(s,j);
                      H=H_app(d, cH(j), p(cH(j),j), q(cH(j),j));
                    if cH(j)==1
                      V1(j,i,s)=w(j)*H*d;
                    else
                        V1(j,i,s)= w(j)*H;
                    end
                  end
```

Figure 5.13. Sub-program of Fun_Promethee in MATLAB script

Criteria_weighting is called when users use Entropy method for weighting indicators. Normally, the entropy is selection default.

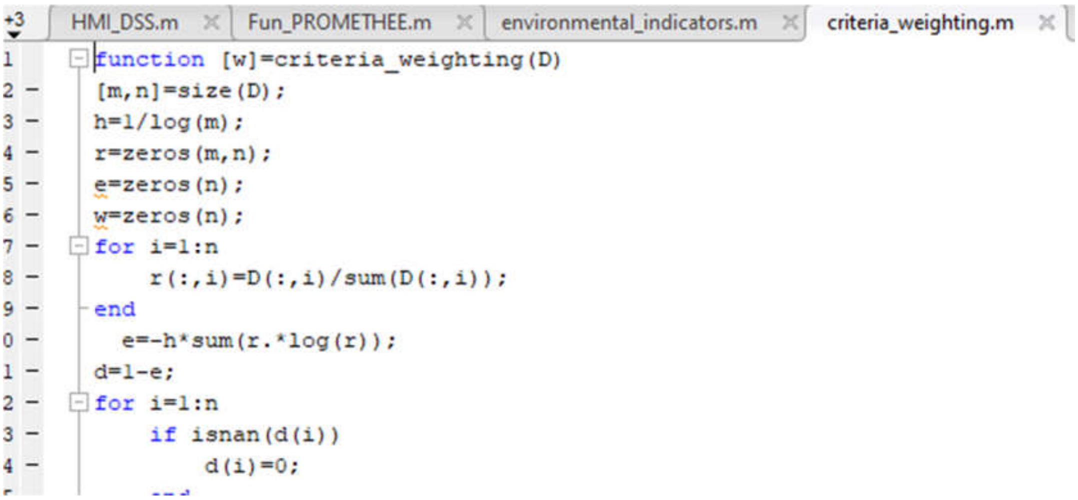
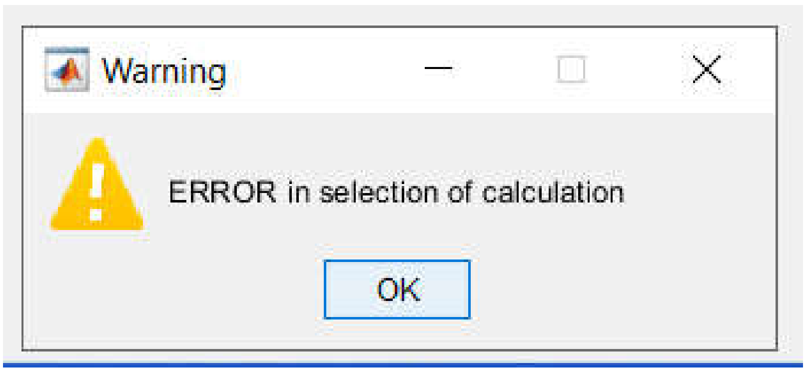


Figure 5.14. Sub-program of criteria_weighting in MATLAB script

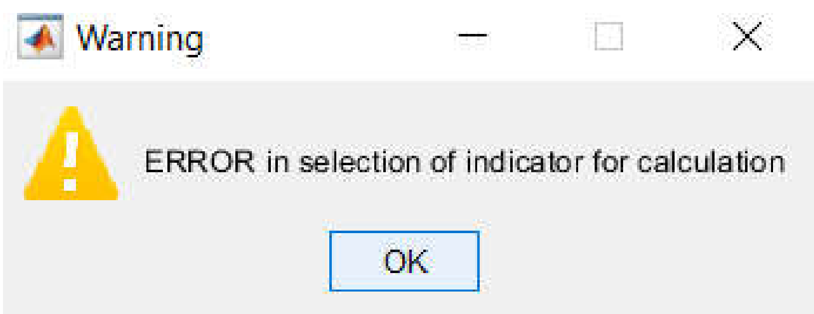
5.3.4. Designing warning error

In addition to performing functions, the tool is supplemented with an error warning function. Warnings include:

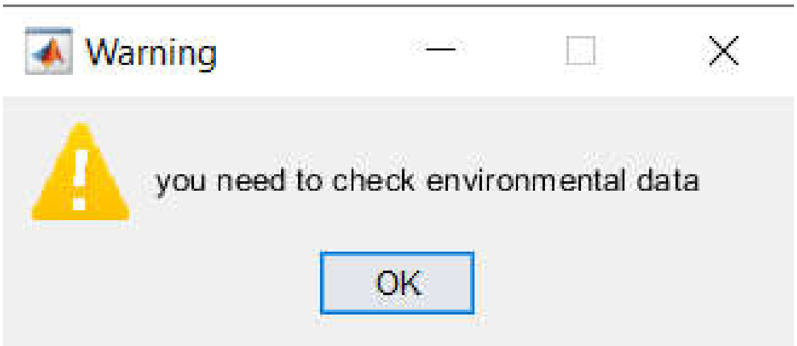
- Error due to option calculation selection: When users give a value to select option calculation, if it is not 0 or 1, the error message will be displayed as a text box.



- Error in the selection of an indicator for calculation. This error is announced if the user does not select the indicator group.

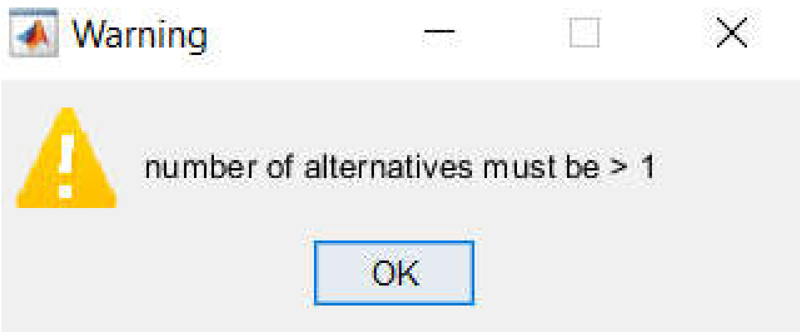


- Error entering data for environmental, economic, social, and circularity indicator calculation. This error occurs if the number of inputs or outputs is not identical to the number of specific impacts.



- Error in selection preference function: This error is done if the user types wrongly in preference function selection.

- Error when the number of alternatives is not more than 1. This error will happen if the number of alternatives is not more than 1 when ranking.



5.3.5. Creating and running software of the DSS tool

After programming with MATLAB GUI and Script, the DSS software is generated as an executable (exe) file. The DSS tool comprises several files located in the same folder, including exe files for running the tool, Excel files used for data input following a template structure, and some text files for guidance. This software can run on a PC with MATLAB runtime installed. The application process of the DSS tool involves the following steps:

Step 1: Run HMI_DSS.exe in the tool folder.

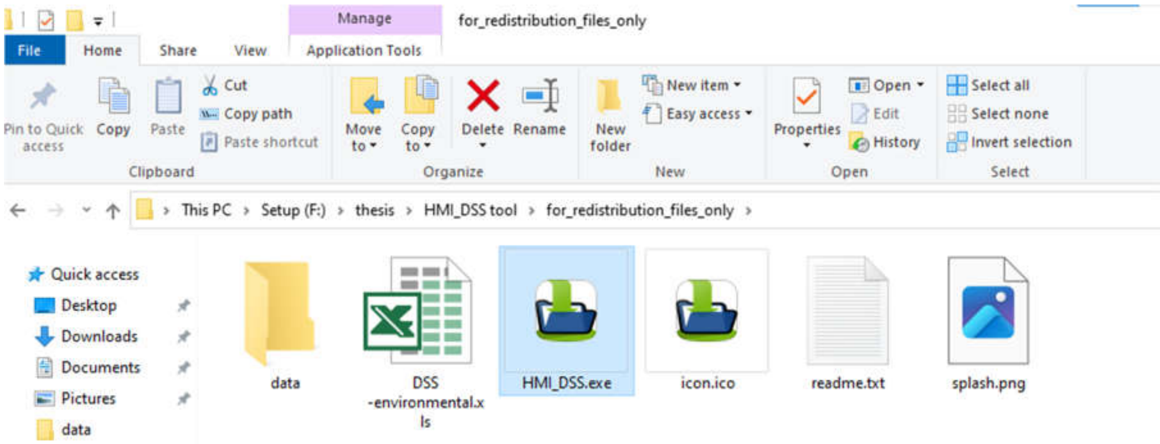


Figure 5.15. HMI_DSS.exe in the DSS tool folder

Step 2: Choosing the computation option.

On the top-left corner of the command window, type 0 or 1 to select the computation option. Typing 0 corresponds to the ranking calculation. When choosing 0, proceed to select the reference function in the bottom-left corner and input data regarding the weights of the indicators. Typing 1 corresponds to the calculation of indices in the current state. When choosing this calculation, the corresponding indices are displayed on the top-left corner: displaying environment, economy, society, and circularity indicators.

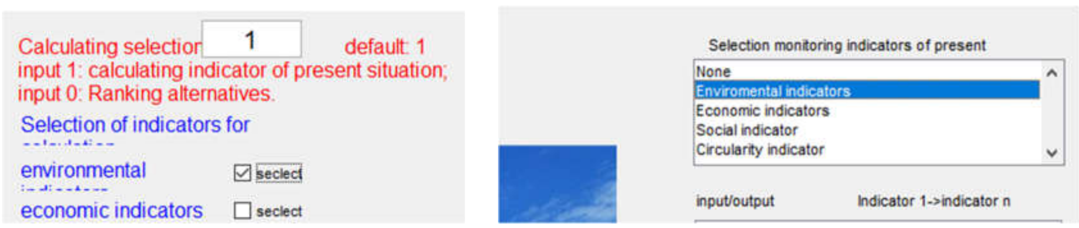


Figure 5.16. Selection for calculation option and indicator for monitoring

Step 3: Choosing indicator groups for computation and other things (figure 5.17).

After the selection of the calculation option, the selection of the indicator group is performed. The selection of the preference function of PROMETHEE II is also taken for ranking alternatives.

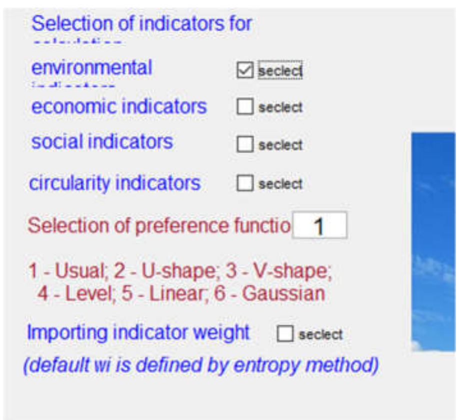


Figure 5.17. Selecting indicator groups for assessment

Step 4: Performing the calculation process.

When all selections are done, the calculate button on the human interface is clicked. After pressing this button, command windows appear for selecting Excel data files and data regions in the Excel file for the calculation process (figure 5.18 and 5.19).

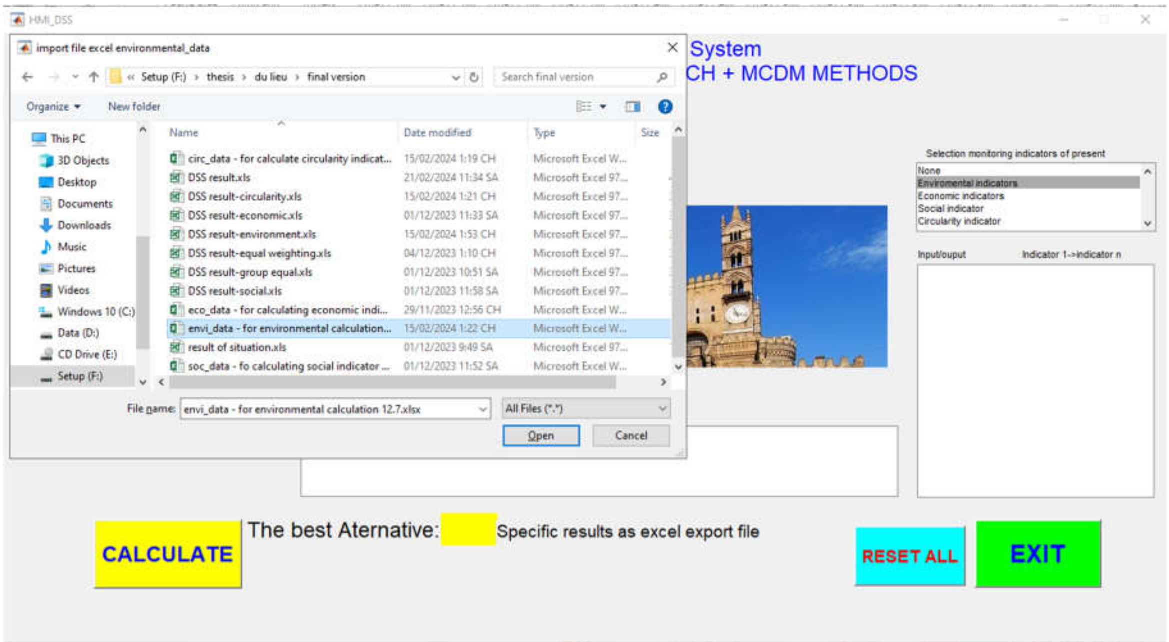


Figure 5.18. Selecting excel file to import data

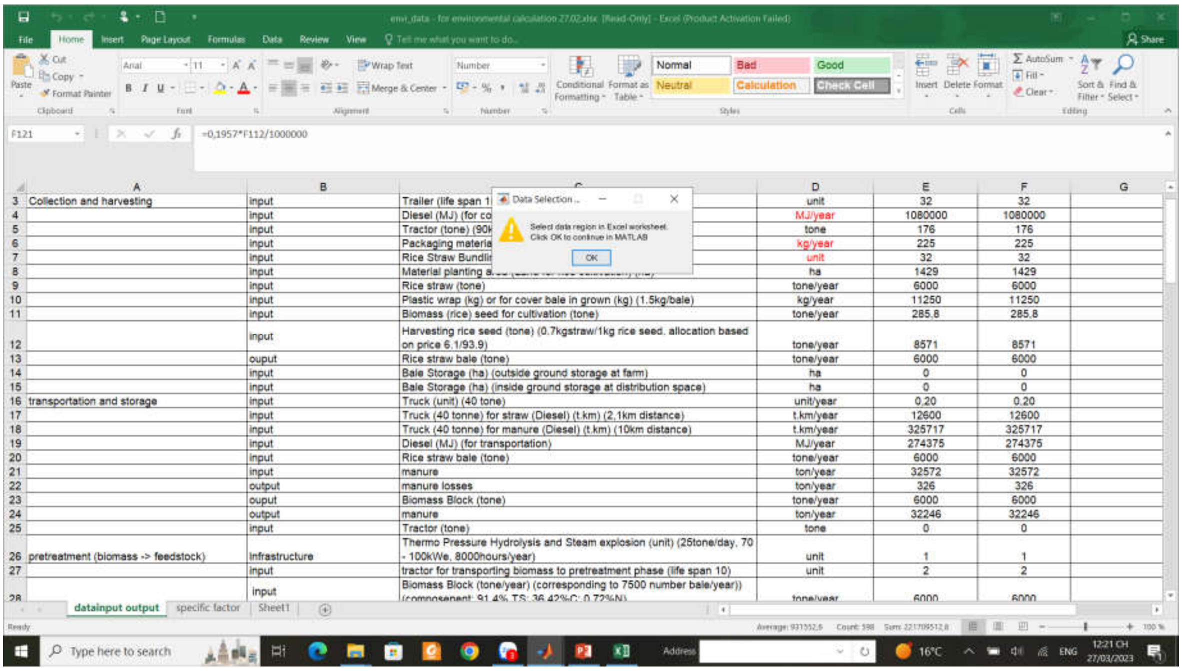


Figure 5.19. Selecting data region in Excel file for importing

After completion, a command window will prompt the input of the link and file name of the Excel file to save the calculation and ranking results as Figure 5.20. The results are displayed on the command window and exported as an Excel file.

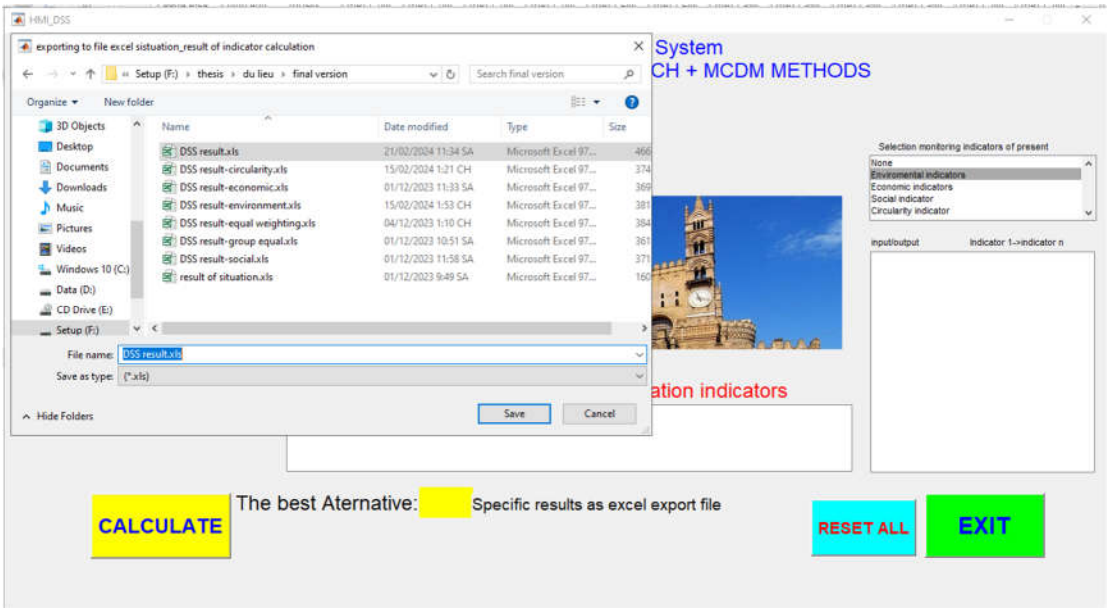


Figure 5. 20. Exporting results to Excel file

When the calculation is completed, an announcement text box message appears to confirm (figure 5.21).

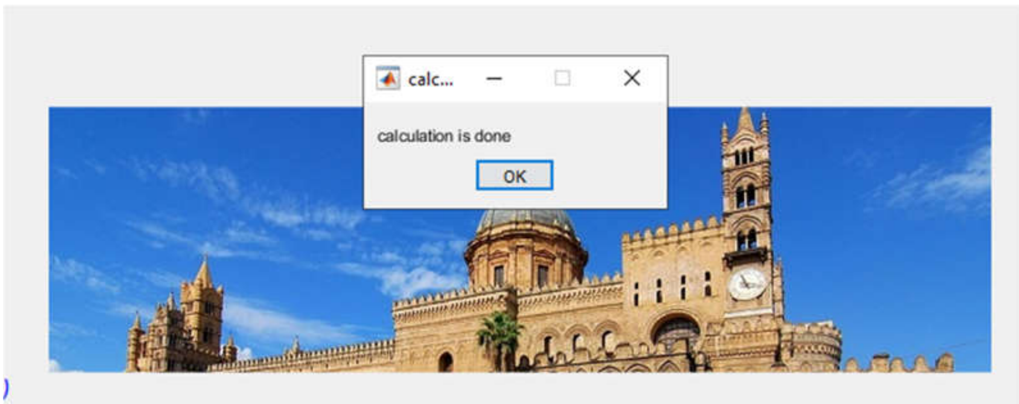


Figure 5.21. The completed announcement text box message

During the selection of functions on the interface, if an inappropriate choice is made, a warning screen about the selection errors appears on the interface.

5.4. Scientific contribution

This Chapter shows that the HMI_DSS tool is comprehensive and flexible software designed to evaluate sustainability and circularity indicators within supply chain enterprises. This tool employs a comprehensive set of 49 indicators, arranged hierarchically based on LCT approach and MFA, to evaluate environmental, economic, social, and circularity factors. It provides a robust decision support methodology framework for decision-makers, utilising techniques such as Entropy and PROMETHEE II for indicator weighting and alternative ranking. The structure of this tool consists of an intuitive Human Interface, a Main program for importing data and performing calculations, and Sub-Programs for indicator calculation and alternative classification. It allows for both the evaluation of the current state of the supply chain and the classification of circularity and sustainability alternatives.

The HMI_DSS tool stands as an effective means for assessing sustainability and circularity indicators for the company within the supply chain, offering several noteworthy advantages. It provides a comprehensive array of indicators, enabling the evaluation of these businesses based on circular economy models and sustainable development principles. One of its key strengths lies in its simultaneous assessment of sustainability and circularity indicators, aided by the integration of the PROMETHEE II method, which facilitates the appraisal of alternatives across various supply chain stages. Unlike decision support systems that use other MDCM techniques (AHP, ANP and MAVT), HMI_DSS can yield objective results because it directly uses indicator results obtained from the LCT approach. This approach is also to decrease dependence on subject matter experts for decision-making. Furthermore, its adaptability to company-specific conditions allows for its implementation using data from individual companies. By utilizing MFA and life cycle tool results as input for MCDM methods, the tool equips decision-makers with valuable information for making informed choices in complex scenarios involving multiple criteria and trade-offs. Presenting results according to each stage of the life cycle and each step of the calculation process in Excel format also helps users effectively observe hotspots in the life cycle and data errors during the calculation process.

Despite the advantages of PROMETHEE II and Entropy methods, they have inherent limitations. If certain indicators share identical values across all alternatives, it's impossible to normalize the decision matrix by PROMETHEE and Entropy methods. Consequently, ranking the alternatives becomes unfeasible. However, the HMI_DSS tool has addressed these issues by giving zero value for these indicators, so the result ranking is still performed. This tool also provides two distinct quantification techniques for indicator weighting: entropy-based quantification and decision-maker-determined weights, so it can help users make better decisions according to their priority aspect. These approaches not only help mitigate potential drawbacks but also enhance the tool's usability and reliability in the assessment of sustainability and circularity for company in the supply chain.

However, the HMI_DSS tool requires users to collect impact factor values for inputs and outputs, because they are not available in the tool. Therefore, it is an issue for companies to approach and collect these data due to the level of their available databases. When the input and output list is large, it can take a lot of effort to collect data on impact factors. This lack of data on specific impact factors should be solved in the next research to make this tool more user-friendly. In addition, circularity indicators of HMI_DSS tool are used for the general supply chain. However, some specific fields such as electronics or construction need to add more CE indicators which are important for these fields, for example, the recycling rate of electronic waste or the recycling rate of construction and demolition waste or the proportion of ecologically certified materials in material use (Rincón-Moreno et al., 2021; Sánchez-Ortiz et al., 2020). Thus, further expansion of circularity indicators for specific fields needs to be further researched. Despite these limits highlighted, the advantages considered above render the HMI_DSS a promising tool for effectively evaluating sustainability and circularity for company in the supply chain.

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CHAPTER VI. APPLICATION OF HMI_DSS TOOL FOR RICE STRAW SUPPLY CHAIN - CASE STUDY

6.1. Introduction

Integrating CE principles into the current economic system is considered a feasible solution to achieving sustainable development goals. For companies in the supply chain, adopting a CBM is the practical implementation of the CE. Although both CE and sustainability comprehensively consider different stages of the supply chain and related partners, there are fundamental differences between evaluating circularity and sustainability. The CE focuses on material flows without considering the nature of those materials, whereas sustainability emphasises the consequences based on its three pillars: environment, economy and society. Accordingly, a more sustainable solution might not necessarily be better in terms of circularity as shown by Zeller et al. This study showed that an environmentally superior solution might not be more circular (Zeller et al., 2020). For example, the circularity alternative has global warming potential at 4953ton CO_2/year higher than the baseline at 1485tonCO_2/year, while resource use of the circularity alternative is at 205E+3 USD/year lower than 460E+3 USD/year of the baseline alternative. Similar trade-offs exist within the pillars of sustainability. Zhang et al. demonstrated that different biomass energy production processes from algae have contrasting environmental and economic benefits (Zhang et al., 2013).

In the energy sector, bioenergy and biofuels derived from biomass are considered sustainable renewable alternatives to fossil fuels, mitigating greenhouse gas emissions. Biomass involves various processes within the biomass supply chain (BSC), including harvesting, collection, transportation, pre-treatment, storage, and end-use (Whittaker & Shield, 2018). A waste-free biorefinery-based BSC maximises all biomass components to create products and energy, aligning with CE principles (Kapoor et al., 2020; Kumar & Verma, 2021; Sherwood, 2020). Biomass encompasses diverse types and sources, and the energy conversion can employ various technologies like pyrolysis, anaerobic digestion, and hydrothermal methods (Archer & Steinberger-Wilckens, 2018; Chung, 2013; Verma et al., 2012; Zabed et al., 2019). Thus, enhancing circularity and sustainability in the BSC involves different stages, technology alternatives, and CBMs.

According to Oliveira Pavan et al., suitable CBMs for the BSC include recycling, cascading, repurposing, and organic feedstock models (Oliveira Pavan et al., 2021). Oliveira Pavan et al. study also proposed two CBM approaches: a centralized and a decentralized AD plant model. These models are applied to energy production from industrial waste. Other research emphasises the application of CE principles, like recovery and recycling, to create closed-loop systems in biomass supply chains (Allegue et al., 2020; Fuentes-Grünewald et al., 2021; Zabaniotou et al., 2018). For example, Allegue et al. (2020) suggested an integrated biorefinery for resource recovery and value-added product manufacturing. Based on these insights, the study outlines several sustainability and circularity enhancement options, leveraging CBMs and CE principles. Four improvement options were proposed. Given the trade-offs between sustainability and circularity, DSS based on LCT are valuable tools for selecting optimal supply chain strategies.

This Chapter aims to evaluate the potential of the application HMI_DSS tool for the biomass supply chain in the assessment of the level of sustainability and circularity and selection of the best alternative. The rice straw supply chain in the north of Italy is selected as a case study, specifically the power plant's biomass supply chain in Ferrera Erbognone, Italy. The HMI_DSS is used for evaluating environmental impacts, economic performances, social implications, and circularity levels across the supply chain's present situation. Subsequently, four sustainability and circularity alternatives are created according to the application of CBMs to improve the sustainability and circularity of the rice straw supply chain. The application of the HMI_DSS tool for ranking is also performed. Furthermore, this application also provides information on the possibility of applying CBMs to BSCs. Related assessment of CBMs will also be made in this chapter.

6.2. Rice straw in Italy

6.2.1. Characterization of rice straw

Straw has a low nutritional value. The typical components of this biomass are wet cellulose, hemicellulose, lignin, lipids, proteins, simple sugars, starches, water, hydrocarbons, ash, and other compounds. The concentrations of these compounds depend on the plant species, the stage of growth, and the growing conditions. Rice straw is generally considered a lignocellulosic biomass containing 38% cellulose, 25% hemicellulose, and 12% lignin (Van Hung et al., 2020).

These components could be fractionated through pretreatment, as shown in Figure 6.1 (Klass, 1998; Rapone et al., 2022). Cellulose and hemicelluloses are organic fibers, while lignin is the cell wall (Klass, 1998; Rapone et al., 2022).

Rice straw has a very high Silica (SiO_2), making it unusable for animal feed, and as regards energy use, some systems must be set up in the plants to avoid the formation of low-melting ashes. Unlike other cereals, however, the chlorine (Cl) content is slightly lower.

The specific weight of uncompressed rice straw is around 70–80 kg/m^3, with a moisture content of about 15–18%. The properties of rice straw and its ash composition are summarized in Tables 6.1 and 6.2 (Rapone et al., 2022), respectively.

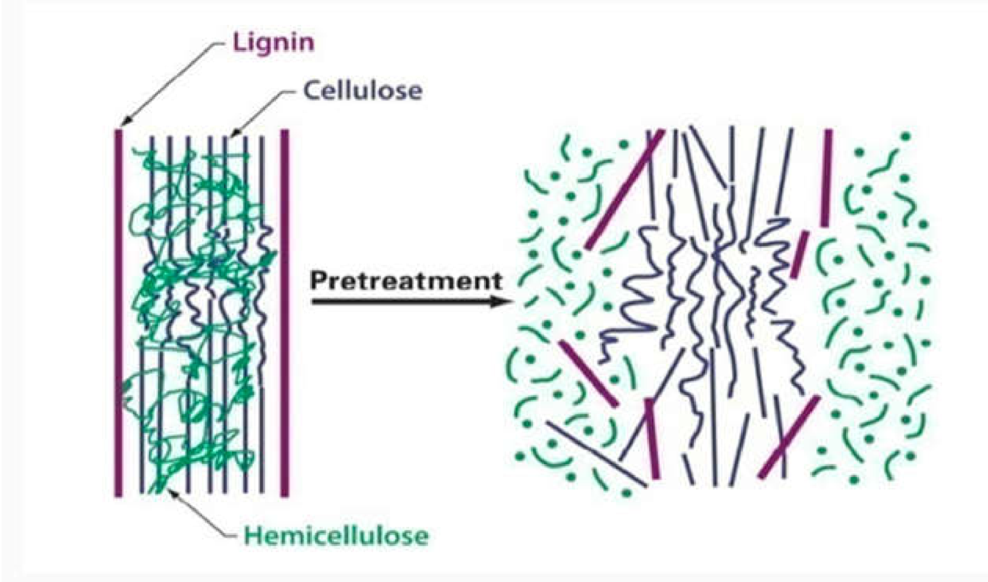


Figure 6.1. Main components of lignocellulosic biomass (Klass, 1998; Rapone et al., 2022)

Table 6.1. Rice straw properties

HHT MJ kg-1	Proximate analysis			Ultimate analysis (% weight - dry fuel)					
	Fix C	Volatile	Ash	C	H	N	S	Cl	Ash
15.09	15.86	65.47	18.67	38.2	5.2		0.87	0.12	20.26
14.57				35.94		1.18			22.00
14.08				33.7	4.0	1.71	0.16	0.32	29.1

Table 6.2. Properties of ash from rice straw

SiO_2	Al_2O_3	TiO_2	Fe_2O_3	CaO	MgO	Na_2O	K_2O_3	SO_3	P_2O_5
74.67	1.04	0.09	0.85	3.01	1.75	0.96	12.3	1.24	1.41
82.6	1.1		1.0	3.3	1.7	0.3	6.3	0.9	1.7

Furthermore, it is known that rice straw has a high C/N ratio (Table 6.3). Therefore, if you want to use it as a feedstock in AD to aid digestion, it would be necessary to add a matrix, such as animal manure, which contains a high amount of nitrogen to achieve an optimal C/N ratio between 25 and 35 (Darwin et al., 2014)

Table 6.3. Rice straw characteristics (wet basis)

Parameters	Unit	Rice straw
Total solids	%	91.4
Volatile solids	%	84.4
Moisture content	%	8.6
Organic matter	%	72.82
Carbon content	%	36.42
Nitrogen content	%	0.71
Chemical oxygen demand (COD)	mg/L	1 950.48
C:N ratio	-	51.3

The characteristics of rice straw compared to other solid fuels can be summarised as follows:

- The high silica content consumes the components of the machines for its processing, such as conveyors or shredders, and does not make it suitable as feed for livestock. The content of volatile substances in rice straws is higher than that of wood and much higher than that of coal. In contrast, fixed carbon is much lower than that of coal. Furthermore, the ash content in rice straw is much higher than that of wood and coal, making it difficult to use for energy production.
- The high content of ash, alkali, and potassium causes agglomeration, fouling, and melting in the components of combustors or boilers.

6.2.2. Usage of rice straw in Italy

As the previous paragraph explains, rice straw consists mainly of cellulose, lignin, minerals, and silicates. The very high silica content makes it unsuitable for animal feed. In Italy, only a percentage that varies between 15% and 30% is used on farms as litter for livestock. Therefore, there is no organized collection system. Often companies give straws to those who request them (Rapone et al., 2022).

In the recent past and partly even today, rice straw is considered a waste and used directly in the field or burned in the areas themselves, causing greenhouse gas emissions, contamination, and pollution. Using available technologies, rice residues can be processed and managed using best practices, as shown in Figure 6.2 (Klass, 1998). The management options for rice straw can be classified as in-field and off-field management.

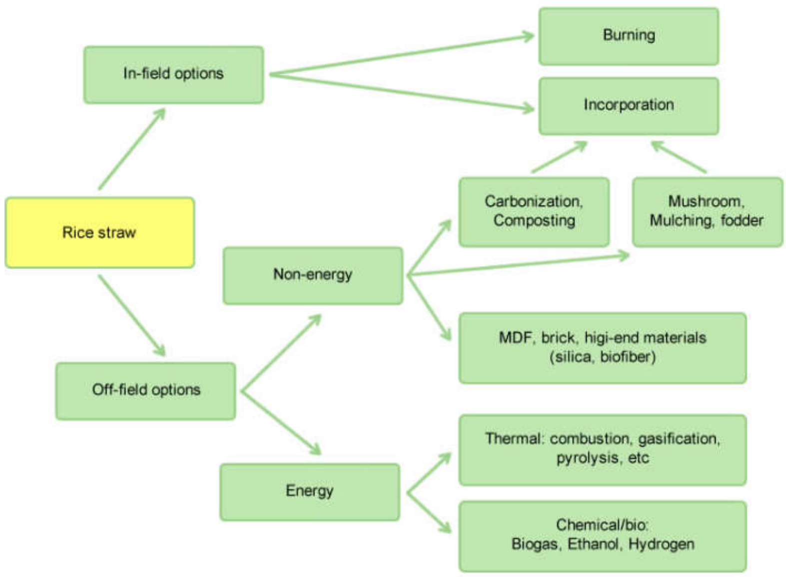


Figure 6.2. Options for rice straw management and use.

Worth mentioning is the initiative of the Piedmontese startup RiceHouse10, founded in Biella in 2016 (Rapone et al., 2022), which works everything that cannot be eaten with rice and obtains plasters, paints, and insulating panels, following the idea of a regenerative architecture (Figure 6.3). In the last five years, it has transformed rice straw into an opportunity in the field of green building based on some of its characteristics (insulating capacity, breathability, sound insulation, biodegradable material) (Rapone et al., 2022).

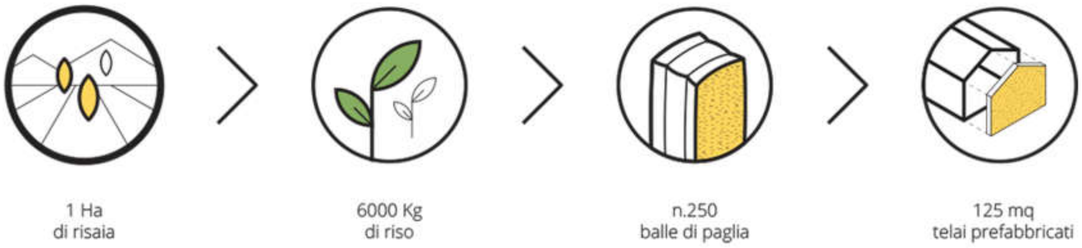


Figure 6.3. The idea of a regenerative architecture

6.2.3. Production of rice straw in Pavia - Italy

In 2019, the area cultivated with rice in Italy was about 220,000 hectares, with an increase of 1.3% compared to 2018. The average yield in 2019, equal to 6 ton/ha, resulted in a production of 1,502,682 tons. Lombardy and Piedmont cover 93% of the rice produced in Italy (Rapone et al., 2022). Piedmont is the rice-growing region of Italy with 50% of the national rice area and includes about 70,000 hectares in the Province of Vercelli, over 30,000 in the province of Novara, 8,000 in the region of Alessandria, 4,000 in the section of Biella and some small crops in the area of Cuneo and Turin.

Lombardy is the second most rice-growing region in Italy. It includes about 84,000 hectares in the province of Pavia, 14,000 in Milan, 2,000 in Lodi, and just over 1,200 hectares in Mantua. From the above numbers, it emerges that Lombardy and Piedmont together represent 93% of the rice in Italy. Furthermore, it should be emphasized that Lombardy, the province of Pavia with the most extensive rice in Italy, is further subdivided into other areas, including Lomellina and Pavese.

In Figure 6.4, the rice-growing areas in Italy are shown in green (Rapone et al., 2022).

Figure 6.4. The rice-growing areas in Italy

Focusing on the province of Pavia (Figure 6.5), the theoretical availability of rice straw was determined based on the local rice production (cultivated hectares).

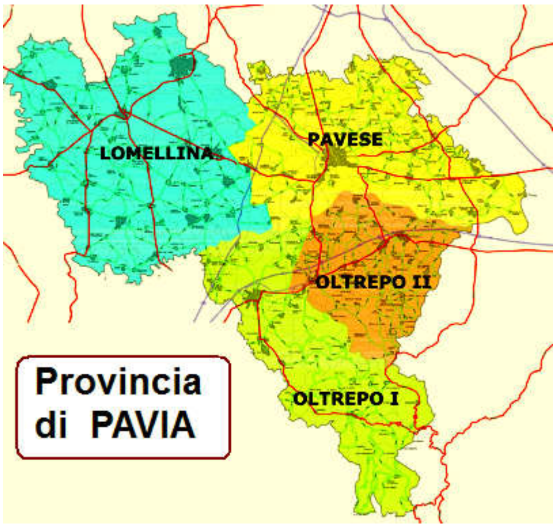


Figure 6.5. Rice straw production in Pavia, Italy

Generally, every kg of milled rice produced translates into about 0.7–1.4 kg of rice straw, an amount linked to the variety, stubble height of the cut, and moisture content during harvest. Adopting the more conservative hypothesis, 0.7kg rice straw/kg of rice produced, Table 6.4 shows the potential straw production in Pavia's province. It is essential to underline that theoretically determined the 351 ton/year indicated.

To date, there is no organized and centralized collection system, and the composition of the rice straw, particularly the considerable silica content, makes it unsuitable for animal feed. Only a percentage that varies between 15% and 30 % in Italy is used on farms as litter for livestock.

Table 6.4. The potential straw production in Pavia's province

Pavia Province	83625 ha
White rice	1ton
Rice straw	0.7ton
rice productivity	6 ton/ha
Pavia rice productivity	501750 ton/year
Pavia rice straw productivity	351225 ton/year
Theoretical availability	351kt/year

6.3. Description of case study

Particular attention is given to the availability and production in Lombardy and the province of Pavia, where the Ferrera Erbognone power plant is located, considering that this work aims to evaluate the production of biogas/biomethane from rice straw for a partial decarbonization of the electricity produced. The rice straw supply chain stages are shown in Figure 6.6.

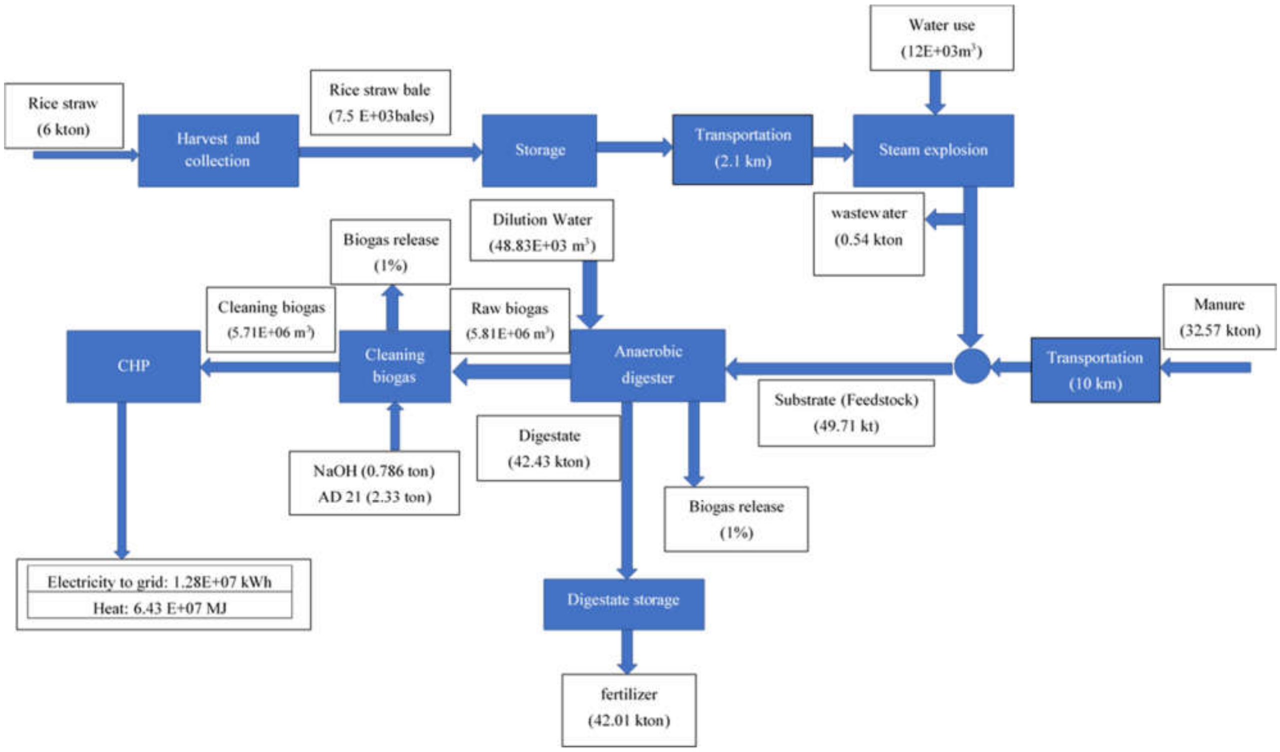


Figure 6.6. Rice straw supply chain of case study

Harvesting: The straw collection is carried out immediately after the rice harvest. The ranchers carry out this process. Tractors are used in the group and collection of straw. The baler is fitted to the tractor during the collection period. The collection area is selected around the plant. The collection area is 1429 ha. The collection time is 10-15 days. After collecting the straw, the tractor is transported to the above-ground storage located on the farm. This area is rented from a farm.

Transport and storage: Straw stored in aboveground warehouses on farms is transported to the AD factory for further processing. Transportation is carried out by a 40-ton truck. The average payload is 27 tons, and the average travel distance is 2.1 km. The shipping volume a year is 6000 tons. Loading is done by the farmers who own the farm. Unloading and collection prices are included in the price of straw bales.

Pretreatment: The rice straw, with 91.4% total solid (TS), is pretreated in a steam explosion (SE) unit to partially deconstruct the biomass thus increasing the potential of biogas production up to 450 m^3/ton-of straw with a methane content of 53% by volume. After the SE treatment, the straw, with 37.86% TS, is mixed with animal manure (29%TS) to reach the optimal C/N ratio required for AD plant feeding (Salangsang et al., 2022). Water is also added to the digester to reduce the TS content of the slurry down to 15%.

Biogas production - AD plant: The AD factory can consume 18 tons of straw daily, equivalent to 6kton a year, 96.54 tons of manure per day and 146 m^3/day of water. The factory working time is 8000 hours (approximately 334 days). Straw, after heat treatment, is mixed with manure to create a mixture for the digester. After 20 days of fermentation, the digestate is transferred to the storage tank for further processing. The amount of biogas obtained per h is about 670 m^3. The total capacity of the digester is about 10,600m^3.

Cleaning pure biogas: The raw biogas is then cleaned by sodium hydroxide scrubbing for sulfur removal and used to produce electricity and heat in a Combined Heat and Power (CHP) plant.

Energy production: Biogas, after cleaning treatment, is used to produce electricity and heat. The plant has a capacity of 1500 kW—factory specifications. The energy production efficiency of the plant is 90%, of which the electricity production is 37%, and the heat production efficiency is 51.8%. The electricity generated is partly used for self-consumption in the AD and CHP sections and the excess is supplied to the local power grid.

Digestate management: The digestate co-produced in the AD section is extracted from the bottom of the digester using a centrifugal shredder pump (4kW) and sent to a separator at the rate of 116 tons/day. The output is a solid fraction (15% w/w) separated from the liquid one (85% w/w). Both fractions of the digestate are stored in open concrete tanks which have a useful lifetime of 20 years. After storing, digestate is used as a bio-fertilizer.

6.4. Calculating sustainability and circularity indicators for the present situation

6.4.1. Goal and scope

The study aims to estimate rice straw's life cycle environmental impacts for electricity and heat co-generated in a CHP plant using biogas produced in an AD reactor. The AD is fed a combination of rice straw comprising manure. Rice straw is collected in Lomellina, Pavia, Italy. The system boundary is from the cradle to the grave. The impact indicators are calculated for one year of supply chain production, corresponding to a functional unit of 6,000 tons of rice straw per year. The impact assessment is based on circularity and environmental indicators selected in Chapter IV.

6.4.2. Data input import

The sustainability and circularity calculation data for importing to HMI_DSS was collected from the plant site, Encoinvent database, and literature. The collection data includes data about material and energy input or output of the supply chain and data about specific impact factors of indicators corresponding to each input or output. The data collection process started with collecting documents describing the technological processes of the plant in the supply chain. Technical specifications were taken from the plant introduction and Ecoinvent, while data on production process parameters was taken directly from the plant. The data was gathered at all stages of the rice straw supply chain. For instance, with environmental data, the data on the input or output amount of each supply chain stage were mainly collected from the plant site database. According to these documents, the data was listed as input or output data suitable for calculating indicator groups. Next, data about specific impact factors for each input or output was collected from Ecoinvent and the literature. For example, impact factors for environmental indicators at havesting and collecting stages were collected from Ecoinvent (Ecoinvent, 2010) and literature (Fusi et al., 2016; Giuliana et al., 2022; Lijó et al., 2017; Bressan et al., 2022).

For the calculation of economic indicators such as total cost, the impact factors are the integration of price, capex and opex with the contact coefficient of input/output with types of cost. For example, the Capex of the AD plant is 3,350 euros/kWel (Rapone et al., 2022), while the cost of maintenance is 2.5% of the investment cost. Thus, the impact factor of maintenance cost is 0.025x3350 = 83.75 euro/kWel. Furthermore, the data on prices were updated to match the economic situation in 2023. The source of the database is described for each stage of the supply chain as follows.

1. Harvesting and collection

In this study, data source of input/output rice straw is collected from the plant owner database. For example, collection farms of rice straw are around the AD plant. The collection area is about 1429 ha, and the volume of rice straw is 6000 ton/year. The yield of rice straw is 0,7 ton/1ton rice seed, and they are harvested in the form of bales. 1700 bales are created in the collecting process. Rice Straw Bundling Machine takes the collecting process. The time for collecting is 10 to 15 days in September/October and is conducted by the farmer. The rice straw is removed when the moisture content has dropped from 50% (typical value for biomass just after harvesting) to about 20% since a low moisture content prevents the activation of harmful fermentation processes. The straw, baled in a cylindrical or polygonal shape, is wrapped in a nylon film, loaded onto a trailer, and transferred to the storage area inside the farm (Bressan et al., 2022) as figure 6.7. In addition, the price of rice straw, cost and labour data are also collected from plant site.

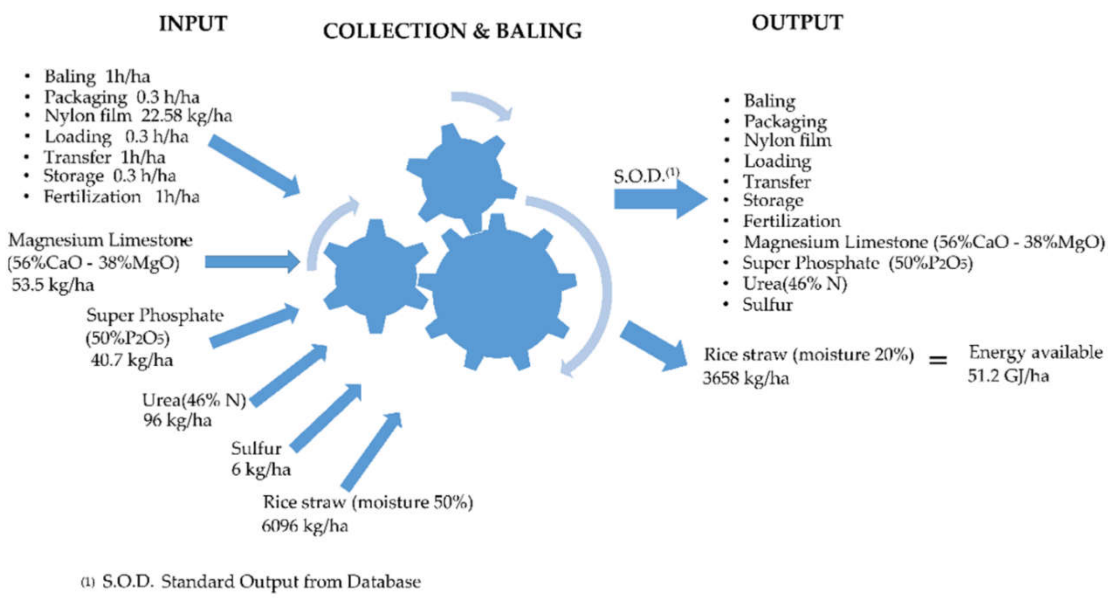


Figure 6.7. Data on rice straw collection and baling and additional fertilization operation (Bressan et al., 2022).

Moreover, rice straw is considered agricultural waste and a by-product of rice chain production. Therefore, data sources of rice cultivation are also taken from literature. For example, data on rice production for examining the environmental impacts are collected from Giuliana et al. for the North of Italy (Giuliana et al., 2022) and Bacenetti et al. for the Pavia region (Bacenetti et al., 2016), as shown in Table 6.5. The rice grain and straw price defines the allocation (grain/straw = 93.9/6.1).

Table 6.5. Data of input/output for rice production (Giuliana et al., 2022)

Phases	Input	Typology	Unit/ha
Soil preparation			
Plowing			55.43 l
Harrowing	Farming diesel	Fuel	18.47 l
Leveling			11.08 l
Sowing			
Farming diesel		Fuel	9.24 l
Rice seeds		Production input	200 kg
Crop management			
	Farming diesel	Fuel	17.15 l
	Organic NPK 10–5-15 mix		400 kg
Fertilization	UREA 46%	Fertilizer	160 kg
	Potassium Chloride (KCL)		160 kg
	Farming diesel	Fuel	12.01 l
	Lambda-cyhalothrin	Insecticide	0.5 l
	Cycloxydim pure (HRAC-A)		2.5 l
Weeding	Imazamox (× 2) (HRAC-B)	Herbicide	2 l
	Profoxydim (HRAC-A)		0.5 l

	Florpyrauxifen-benzyl (HRAC-O)		1 l
Irrigation			
Water		Production input	39,000 m^3
Harvest			
Farming diesel		Fuel	38.79 l
Output			
Rice			7000 kg
Emissions to air			
Carbon dioxide			7435.9 kg CO_2 eq
Methane			683 kg CO_2 eq
Dinitrogen monoxide			159 kg CO_2 eq
Sulfur hexafluoride			43.7 kg CO_2 eq
Emissions to water (freshwater)			
Phosphate			0.755 kg P eq
Phosphorus			0.0533 kg P eq
Emissions to water (marine)			
Ammonium, ion			0.0403specific kg N eq
Nitrate			0.56 kg N eq
Nitrite			0.0001 kg N eq
Nitrogen			0.0236 kg N eq

To facilitate the anaerobic digester process, nutrients are added. In this supply chain, manure was selected for inclusion. The amount of manure added is based on the C/N ratio. The ratio C/N is from 25 to 35 (Haryanto et al., 2018; Labatut & Pronto, 2018; Rapone et al., 2022; Shahbaz et al., 2020). The ratio C/N is identified by equation 6.1 (Haryanto et al., 2018).

$$C/N = \frac{m_r.C_r + m_m.C_m}{m_r.N_r + m_m.N_m} \qquad (6.1)$$

where m is dry mass and subscripts, r and m denote rice straw and manure, respectively.

In this study, the ratio is 30, amount and components of manure (Table 6.6) are gathered from the Plant owner (Haryanto et al., 2018). Manure is collected from livestock farms, with an average distance of 10 km to the AD plant. Data on manure production is not available.

The amount of input/output of the harvesting and collection stage are shown in Table 6.7.

Table 6.6. Manure characteristic.

Characteristic	Manure
Water content (%, wet basis)	71.0
Total solid (TS) (%, wet basis)	29.0
Ash (% TS)	26.04
Volatile solid (VS) (% TS)	74.96
C (%)	39.87
N (%)	1.42
C/N Ratio	28.08

Table 6.7. Amount of input/output of harvesting and collection stage

	Input, output	unit	Amount
input	Trailer (life span 10years)	unit	3.20E+01
input	Diesel (for collection rice straw)	MJ/year	1.08E+06
input	Tractor	ton	1.76E+02
input	Packaging materials	kg/year	2.25E+02
input	Rice Straw Bundling Machine	unit	3.20E+01
input	Material planting area (Land for rice cultivation)	ha	1.43E+03
input	Rice straw	ton/year	6.00E+03
input	Plastic wrap	kg/year	1.13E+04
input	Biomass (rice) seed for cultivation	ton/year	2.86E+02
input	Harvesting rice seed	ton/year	8.57E+03
output	Rice straw bale	ton/year	6.00E+03

For each input and output, the impact factors for it are also gathered. The data on environmental impact factors are collected from literature and the OpenLCA database. For example, rice straw GWP impact factors were collected from Bacenetti et al. (Bacenetti et al., 2016) and Bressan et al. (Bressan et al., 2022), diesel, tractor and trailer, plastic were collected from the OpenLCA database as shown in Table 6.8.

Table 6.8. GWP impact factor of harvesting and collection

	Input, ouput\indicators	GWP ($kgCO_2eq$/unit of input/output)
input	Trailer	6.44E+01
input	Diesel	8.76E-02
input	Tractor	6.44E+01
input	Rice Straw Bundling Machine	2.34E+01
reference input	Rice straw	1.10E+02
input	Plastic wrap or for cover bale in ground	3.07E+00
reference output	Rice straw bale	1.10E+02

2. Transportation and storage

The residual biomasses are transported from the farm to the AD plant. The transport distances based on a single trip for each residual biomass and the average composition of feedstock entering each AD plant are primary data (Table 6.9). The source of transport data is reached from ENI's documents (cost and labour data), and the specific impact factors are gathered from the plant site, literature and OpenLCA database (Table 6.10).

Table 6.9. Residual biomass transport distances and average composition of the AD feedstock.

Type of biomass	Distance (km)	Amount (ton/year)	Source
Rice straw	2.1	6000	ENI and owner AD plant
Manure	10	32246	ENI and owner AD plant
Total biomass		38246	

Table 6.10. Life cycle inventory of transportation

Input/output		unit	Amount
input	Truck (40 ton)	unit/year	2.00E-01
input	Truck (40 ton) for straw	t.km/year	1.26E+04
input	Truck (40 ton) for manure	t.km/year	3.26E+05
input	Diesel (MJ) (for transportation)	MJ/year	2.74E+05
input	Rice straw bale	ton/year	6.00E+03
input	Manure	ton/year	3.26E+04
output	manure losses	ton/year	3.26E+02
output	Biomass Block	ton/year	6.00E+03
output	Manure	ton/year	3.22E+04

3. Pretreatment process

Before being sent to the AD, the biomass is pre-treated. The rice straw is treated in the steam explosion process. Subsequently, it is sent to a mixing tank with manure. They aim to simplify the complex structure of the organic substance and improve its biodegradability.

The analysis by Panigrahi and Dubey (2019) establishes that an effective pre-treatment should (Panigrahi & Dubey, 2019):

• Preserve the organic substance in the biomass.

• Develop the progress of beneficial substances to the hydrolysis stage.

• Avoid the formation of toxic compounds or inhibitors.

• Be sustainable from an environmental point of view.

• Be economically feasible.

The pre-treatments used are mainly physical, chemical, biological, and hybrids. In this case study, pretreatment is conducted by a steam explosion (SE).

SE is a widely used technology for the pretreatment of lignocellulosic biomass because it has the advantage of deconstructing the lignin and thus favouring the action of microorganisms inside the digester, with the ultimate aim of maximizing the production of biogas/biomethane.

The data on steam explosions are provided by ENI's and Leona's plants (Rapone et al., 2022). The number of steam explosions is identified by the volume of rice straw fed to the digester per day (18 tons/day). The parameter of steam explosion equipment is based on Leona's data (Rapone et al., 2022). The cereal straw pretreatment technology installed in the Leona farm was provided by Economizer GmbH (Figure 6.8), in which the combination of Thermo Pressure Hydrolysis and Steam explosion was found. During the pre-treatment, 2 kg of water is added per kg straw. 0.6 kg of water is introduced during the initial shredding, which works in the T and P environments.

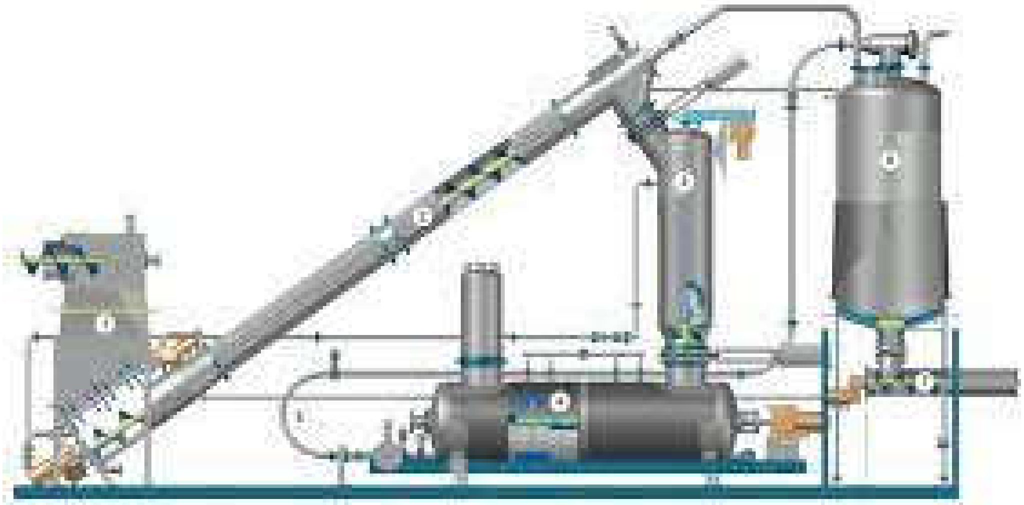


Figure 6.8. Thermo Pressure Hydrolysis and Steam explosion of Leona farm

Besides that, SE data is also can be found in the Teofipol plant in Ukraine (Rapone et al., 2022). This plant, built by Zorg Biogas, has 6 SE units (Figure 6.9). Every single module process 25 tons of straw per day. The total capacity of all modules is 54,000 tons of straw per year. The heat required for the SE is supplied from the exhaust gases of the connectors via an oil system. The prepared straw is fermented in reactors equipped with inclined agitators. The biogas production is 450 m^3/ton-straw, with a methane content of 53% by volume. The electrical power generated is 6 MW. The cost of the straw pretreatment section is 8 million euros.

Figure 6.9. SE of the Teofipol plant in Ukraine

After pretreating, rice straw has a moisture content of about 31,10%. They are combined with manure in a mixing tank to make a substrate for digestion. Water for dilution is added to create a mixture feed before pumping to the digester. The amount of water is defined based on the concentration of TS in the mixture feed. In this study, the TS in the feed is 15% (Rapone et al., 2022) (Table 6.11). The amount of input/output of the pretreatment stage is shown in Table 6.12.

Table 6.11. Characteristics of mixture feed.

Characteristic	mixture feed
Water content (%, wet basis)	85.00
Total solid (TS) (%, wet basis)	15.00
Volatile solid (VS) (% TS)	78.54
C/N Ratio	30.00

Table 6.12. Amount of input/output of pretreatment stage

Input/output	List of input/output	Unit	Amount
Infrastructure	Thermo Pressure Hydrolysis and Steam explosion (25ton/day, 70 - 100kWe, 8000hours/year)	unit	1.00E+00
Input	Tractor for transporting biomass to the pretreatment	unit	2.00E+00
input	Biomass Block	ton/year	6.00E+03
input	Electricity (for Thermo Pressure Hydrolysis and Steam explosion)	kWh/year	6.31E+05
input	Water for pretreatment	ton/year	1.20E+04
input	Diesel	MJ/year	6.55E+05
output	Rice straw after pretreatment (ton)	ton/year	1.75E+04

Input/output	List of input/output	Unit	Amount
output	Packaging material waste	ton/year	2.25E-01
output	Loss of biomass	ton/year	6.00E+01
output	Plastic waste (used for wrapping bale)	ton/year	1.13E+01
output	Wastewater	ton/year	5.40E+02
output	Water recycle	ton/year	5.40E+02

The specific impacts are also collected from literature and OpenLCA, the Ecoinvent database.

4. Anaerobic digestion process

The anaerobic digestion process starts with the biomass entering the digester. The mixture feed is fed to the digester and rests in it for 20 days. The data source of the mixture feed is based on the ENI database and the owner's AD plants. The main product of the anaerobic digestion process is biogas, while the digestate is the co-product. Biogas and digestate require further treatments before being used in other unit processes.

According to data collection, the AD factory can consume 18 tons of straw daily, equivalent to 6kton a year. The factory working time is 8000 hours (approximately 334 days). The AD has a volume of about 10,600m^3, including two reactors. Each reactor has a diameter of 32.10m with a height of about 6.6m. It is made of reinforced concrete and has a polystyrene external insulation layer. The technical design of the ENI study inferred data about the digester dimension (Rapone et al., 2022). The AD volume has been calculated according to the organic load rate (OLR) and the capacity of mixture feed with retention time (RT) (ENERGYPEDIA, 2015).

$$V_d = M_f . R_t \quad [m^3 = m^3/day \times number\ of\ days] \qquad (6.2)$$

Where M_f is the quantity of mixture feed, V_d is the volume of the digester, and Rt is retention time.

$$OLR = \frac{VS/day}{V_d} \quad [kg/(m^3.day)] \qquad (6.3)$$

Where OLR is the organic load rate, VS/day is the amount of VS fed to the digester per day.

The volume of the digester is identified according to the ORL value from 2 to 5 (Sun et al., 2017). In the case study, the volume has been designed based on the max value of calculating OLR and RT-based (Rapone et al., 2022). The OLR is used for computing at 4. The number and dimension of reactors are selected based on the limit dimension, with a maximum diameter (d) of about 36m, a maximum height (h) of about 8m, and d/2h of about 2.45 (plant owner).

Data about the construction materials are inferred from the Ecoinvent Database and the literature on the AD – CHP plant as Table 6.13 (Ecoinvent, 2010; Whiting & Azapagic, 2014). Since AD - CHP plants in literature are different from AD - CHP plants in this study. The approach scale-up based on the capacity of the CHP plant is considered (formula (4)).

The useful lifetime of the AD plant is assumed to be 20 years. Within the AD, the biomass is mixed and heated. The mixing system consists of 3 mechanical stirrers positioned at different heights.

The data about energy consumption, labour, CAPEX, OPEX and other costs is collected from the AD plants and literature (BERNARD, 2017; Ecoinvent, 2010; Whiting & Azapagic, 2014).

Table 6.13. LCI of AD plants with a capacity of 170 kW_{el} AD - CHP.

Input AD	Amount	Ref.
Concrete	8.5 dm3/MWh	(Ecoinvent, 2010)
Reinforced steel	0.71 kg/MWh	(Ecoinvent, 2010)
Chromium steel	85 g/MWh	(Ecoinvent, 2010)
Copper	8 g/MWh	(Ecoinvent, 2010)
Laminated timber	0.6 dm3/MWh	(Ecoinvent, 2010)
High-density polyethylene	3 g/MWh	(Ecoinvent, 2010)
High-impact polystyrene	37 g/MWh	(Ecoinvent, 2010)
Polyvinyl chloride	5 g/MWh	(Ecoinvent, 2010)
Synthetic rubber	20 g/MWh	(Ecoinvent, 2010)

The heating system uses a concentric tube heat exchanger that uses the CHP's thermal energy. The biomass, extracted from the digester through a centrifugal pump, circulates in the internal pipes; hot water from the heat recovery circuit of the CHP, taken using a pump, circulates in the cavity. The thermal energy required for maintaining the mesophilic temperature condition in the digester at 35^0C. The electricity consumption is estimated based on the required electrical energy per one MWh production of the AD - CHP plant (Whiting & Azapagic, 2014). The thermal consumption is calculated according to the quantity of feedstock and biogas in the digester, as well as the volume of reactors.

The daily biogas is estimated according to the average anaerobic biogas production potential of each feedstock (m^3 biogas/ton feedstock) provided by the ENI study. Specifically, the estimated daily biogas production is 1607 m^3.

During the operation phase of an anaerobic digestion plant, excess pressure might occur, and consequently, pressure valves might release some biogas resulting in emissions to the air of CH_4, CO_2, H_2S, O_2, and NH_3. Thus, according to the literature, a release equal to 1% of the biogas produced from the digestion plant and 1-2% of the biogas purified is considered.

The specific impacts of each input/output are identified from the literature, OpenLCA and ReCiPe2016.

The amount of input/output of AD conversion stage are shown in Table 6.14.

Table 6.14. Amount of input/output of AD conversion stage

Input/output	List of input/output	Unit	Amount
Infrastructure	AD plant	unit	1.00E+00
Infrastructure	Cleaning biogas	unit	1.00E+00
Infrastructure	Waste storage	unit	1.00E+00
Infrastructure	Land use for factory	ha	5.63E-01
construction materials	Cement	ton/20year	5.73E+03
construction materials	Reinforced steel	ton/20year	1.70E+03
construction materials	Chromium steel	ton/20year	2.04E+02
construction materials	Copper	ton/20year	1.92E+01
construction materials	Laminated timber	ton/20year	1.44E+00
construction materials	High-density polyethylene	ton/20year	7.19E+00
construction materials	High-impact polystyrene	ton/20year	8.86E+01
construction materials	Polyvinyl chloride	ton/20year	1.20E+01
construction materials	Synthetic rubber	ton/20year	4.79E+01
Input	Rice straw after pretreatment	ton/year	1.75E+04
Input	Manure	ton/year	3.22E+04
Input	Self-consumption electric energy	MWh/year	1.50E+03
Input	Self-use heat energy	MWh/year	5.77E+03
Input	Water use for dilution	m3/year	4.88E+04
Output	Raw Biogas	m3/year	5.87E+06
Output	Biogas release (1% emssion)	m3/year	5.87E+04
Output	CH_4 emission (from biogas release)	ton/year	1.81E+01
Output	CO_2 emission (from biogas release)	ton/year	4.87E+01
Output	H_2S emission (from biogas release)	ton/year	4.65E-01
Output	O_2 emission (from biogas release)	ton/year	6.79E+00
Output	NH_3 emission (from biogas release)	ton/year	1.51E-01
Output	Digestate production (generating waste)	ton/year	4.24E+04
Output	Solid digestate	ton/year	6.36E+03
Output	Wet digestate	ton/year	3.61E+04
Output	Waste water	m^3/year	2.73E+04
Output	Water recycle	ton/year	3.35E+04

5. Cleaning biogas

In order to remove suspended solids, hydrogen sulphide, water the biogas is subjected to cleaning treatment before feeding the CHP. These cleaning is performed by physical filtration, desulfurisation (chelated iron) and dehumidification.

The desulphurisation process takes place inside the AD and consists in a biological desulphurisation by air injection into the gasholder dome. It is operated by specialized microorganisms (sulpho bacteria) which degrade hydrogen sulphide to elemental sulphur and sulphates, which fall within the liquid mass in digestion. The data of this process is gathered from ENI database and literature (Adnan et al., 2019; Ardolino et al., 2021; Niesner J. et al., 2013) while specific impact factor data are defined by literature, OpenLCA and ReCiPe2016.

The inventory data for the biogas treatment process modelling in both the examined perspectives are shown in table 6.15.

Table 6.15. The inventory data for the biogas treatment process

Input/output	List of input/output	Unit	Amount
reference input	Raw raw biogas	m3/year	5.81E+06
input	Electricity for biogas treatment	kWh/year	1.02E+05
input	Desulfurization agent (AD21. EC3)	ton/year	2.33E+00
input	NaOH	ton/year	8.76E-01
reference output	cleaning biofuel (purebiogas)	m^3/year	5.71E+06
output	biogas release	m^3/year	5.81E+04
output	CO_2 collection	ton/year	0.00E+00
output	CH_4 emission (from biogas release)	ton/year	1.80E+01
output	CO_2 emission (from biogas release)	ton/year	4.82E+01
output	H_2S emission (from biogas release)	ton/year	4.60E-01
output	O_2 emission (from biogas release)	ton/year	1.38E-02
output	NH_3 emission (from biogas release)	ton/year	1.49E-01

6. Digestate management

The digestate is extracted from the bottom of the digester in a rate of 109 tonne/day, by means of a 4 kW centrifugal shredder pump. Afterwards, it is sent to a separator in which the solid fraction (15%) is separated from the liquid one (85%). The solid-liquid separating machine is based on screw conveyor technology. Both fractions of the digestate are stored in open concrete tanks for which a useful lifetime of 20 years is assumed.

The data of input/output, labour, CAPEX, OPEX and other costs of this stage is collected from Plant site, Ecoinvent and literature. For example, the emission from digestate is based on literature database (Cusenza et al., 2021; Fusi et al., 2016; Lijó et al., 2017). Data about the construction materials are inferred from the technical design report of the AD – CHP plant (Whiting & Azapagic, 2014). Specific impact factor data is defined by literature, OpenLCA and ReCiPe2016 (Huijbregts et al., 2017). The useful lifetime of both the storage tanks plant is assumed to be 20 years. The amount of waste management stage are shown in Table 6.16.

Table 6.16. The data of input/output of waste management stage

Input/output	List of input/output	Unit	Amount
reference input	solid digestate (15%)	ton/year	6.36E+03
reference input	Liquid digestate (85%)	ton/year	3.61E+04
	Volum of digestate storage (detention 120 day)	m^3	1.40E+04
construction materials	land use for storage	ha	1.74E-01
construction materials	Ciments	ton/lifespan	2.80E+02
output reference	digestate for fertiliser	ton/year	4.20E+04
	Avoided Mineral fertiliser	ton/year	3.53E+02
output	CO_2 emission	ton/year	1.64E+02
output	NO emission	ton/year	1.66E+00
output	N_2O emission	ton/year	1.15E+00
output	NH_3 emissions from digestate storage	ton/year	3.67E+00

7. Energy production process

Biomethane is burned in the CHP internal combustion engine, consisting of four-stroke internal combustion engine and an electric generator. The thermal and electrical energy generated are calculated based on the thermal and electrical efficiency of the engine (sub-section 6.3.8) and assuming an average low heating value of about 6kWh/m^3 biogas or 10.52kWh/m^3 biomethane.

The data of the CHP plant construction and disposal are inferred from Ecoinvent 2.2 Database and literature (Table 6.17) (Ecoinvent, 2010; Whiting & Azapagic, 2014). Since the CHP plant in Ecoinvent corresponds to a different electrical and thermal power (170 kW_{el} and 200 kW_{th}), the LCI of its manufacture process is scaled up to match the power of the examined CHP (1500 kW_{el} and 2100 kW_{th}). For this purpose, the approach used in scaling up process plants has been carried out as formula (6.4), follows (Fusi et al., 2016):

$$E_2 = E_1 . (\frac{C_2}{C_1})^{0.6} \qquad (6.4)$$

where:

E_2 environmental impacts of the larger plant

E_1 environmental impacts of the smaller plant

C_2 capacity of the larger plant

C_1 capacity of the smaller plant

0.6 scaling factor.

Table 6.17. LCI of CHP plants with capacity of 170 kW_{el} AD - CHP.

Material	Amount	Ref.
Lubricating oil	168 g/MWh	(Ecoinvent, 2010)
Reinforced steel	185 g/MWh	(Ecoinvent, 2010)
Low-alloyed steel	13 g/MWh	(Ecoinvent, 2010)
Chromium steel	10 g/MWh	(Ecoinvent, 2010)
Cast iron	56 g/MWh	(Ecoinvent, 2010)
Copper	9.4 g/MWh	(Ecoinvent, 2010)
Polyethylene	3.5 g/MWh	(Ecoinvent, 2010)
Polyvinyl chloride	0.34 g/MWh	(Ecoinvent, 2010)
Synthetic rubber	0.28 g/MWh	(Ecoinvent, 2010)

The data of CAPEX, OPEX, other costs and specific impact factors are defined by literature, OpenLCA and ReCiPe2016. Factors of CHP emissions is inferred literature about emission of CHP plant with difference fuel used as Nielsen et al. in Table 6.18 (Nielsen et al., 2010).

The amount of input/output of energy production are shown in Table 6.19.

Table 6.18. Extract of the revised 2006 emission factors for Danish decentralised CHP plants < 25Mwe (Nielsen et al., 2010)

	Unit	Natural gas fuelled engines	Biogas fuelled engines	Natural gas fuelled gas turbines	Gas oil fuelled engines	Gas oil fuelled gas turbines	Fuel oil, steam turbines	Biomass producer gas, engines	MSW incineration	Straw	Wood
SOA	g per GJ								<8.3	49	<1.9
NO	g per GJ	135	202	48	942	83	136	173	102	125	81
UHC (C)	g per GJ	435	333	2.5)	-46		(1.6)	12	< 0.68	< 0.94	< 6.1
NMVOC	g per GJ	92	10	1.6	37		(0.8)	2.3	< 0.56	< 0.78	< 5.1
CHP	g per GJ	481	434	1.7)	24		<1.3	13	<0.34	<0.47	<3.1
CO	g per GJ	58	310	4.8	130	2.6	2.8	586	<3.9	67	90
NGO	g per GJ	0.58	1.6	1.0	2.1		5.0	2.7	1.2	1.1	0.83
NHS	g per GJ								< 0.29		
TSP	g per GJ						9.5		< 0.29	< 2.3	10
As	mg per GJ	< 0.045	< 0.042		< 0.055			0.116	< 0.59		
Cd	mg per GJ	< 0.003	0.002		< 0.011			< 0.009	< 0.44	< 0.32	0.27
Co	mg per GJ	< 0.20	< 0.21		< 0.28			< 0.22	< 0.56		
Cr	mg per GJ	0.048	0.18		0.20			0.029	< 1.6		
Cu	mg per GJ	0.015	0.31		0.30			< 0.045	< 1.3		
Hg	mg per GJ	< 0.098	< 0.12		< 0.11			0.54	< 1.8	< 0.31	< 0.40
Mn	mg per GJ	< 0.046	0.19		0.009			0.008	< 2.1		
Ni	mg per GJ	0.045	0.23		0.013			0.014	< 2.1		
Pb	mg per GJ	0.043	0.005		0.15			0.022	< 5.5		
Sb	mg per GJ	< 0.049	0.12		< 0.055			< 0.045	< 1.1		
Se	mg per GJ	(0.01)	< 0.21		< 0.22			< 0.18	< 1.1		
TI	mg per GJ	< 0.20	< 0.21		< 0.22			< 0.18	< 0.45[3])		
V	mg per GJ	< 0.048	< 0.042		0.007			< 0.045	< 0.33		
Zn	mg per GJ	2.9	4.0		58			0.058	2.3	0.41	2.3
PCDD/-F	ng per GJ	< 0.57	< 0.96'*		< 0.99			< 1.7	< 5.0	< 19	< 14

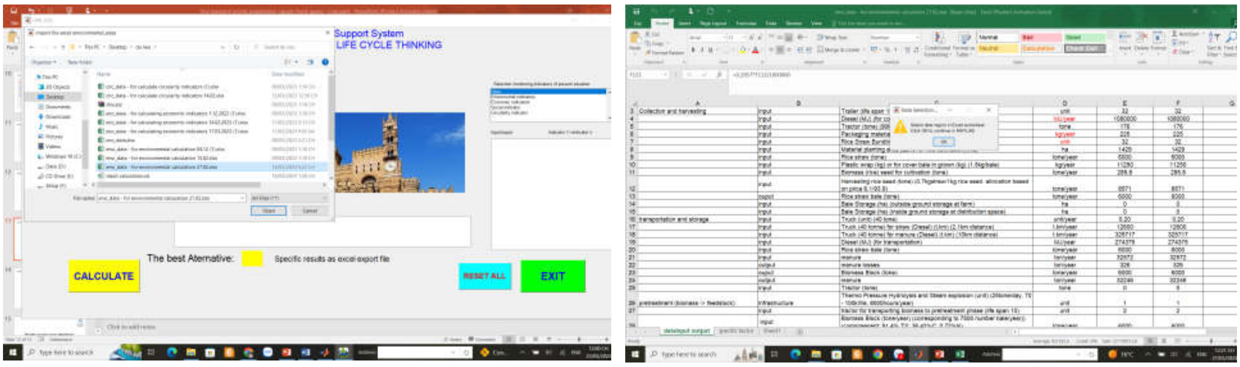
	Unit	Natural gas fuelled engines	Biogas fuelled engines	Natural gas fuelled gas turbines	Gas oil fuelled engines	Gas oil fuelled gas turbines	Fuel oil, steam turbines	Biomass producer gas, engines	MSW incineration	Straw	Wood
PBDD/-F	ng per GJ		< 5.0’)					< 7.2	< 6.3’)		
PAH (BaP)	pg per GJ	< 13	< 4.2		< 33			< 4.9	< 2	< 125	< 13
ZPAH	pg per GJ	< 1025	< 606		< 8988			< 181	< 37	< 5946	< 664
Naphthalene	pg per GJ	2452	4577		17642			8492	< 129	12088	2314
HCB	gg per GJ		0.19		< 0.22			0.80	< 4.3	< 0.11	
PCB	ng per GJ		< 0.19		< 0.13			< 0.24	< 0.32		
Formalde- hyde	g per GJ	14.1	8.7		1.3		< 0.002	1.5			
HCI	g per GJ								< 1.14	56	
HF	g per GJ	-	-	-	-	-	-	-	< 0.14		

Table 6.19. Life cycle inventory of energy production process

Input/output	List of input/output	Unit	Amount
Infrastructure	CHP plant (life span 10 years)	unit	1.00E+00
construction materials	Land use for factory	ha	1.00E-01
construction materials	Lubricating oil	ton/lifespan	4.02E+02
construction materials	Reinforced steel	ton/lifespan	4.43E+02
construction materials	Low-alloyed steel	ton/lifespan	3.11E+01
construction materials	Chromium steel	ton/lifespan	2.40E+01
construction materials	Cast iron	ton/lifespan	1.34E+02
construction materials	Copper	ton/lifespan	2.25E+01
construction materials	Polyethylene	ton/lifespan	8.38E+00
construction materials	Polyvinyl chloride	ton/lifespan	8.14E-01
construction materials	Synthetic rubber	ton/lifespan	6.71E-01
reference input	cleaning biofuel (purebiogas)	m3/year	5.71E+06
Input	Self-consumption electric energy	kWh/year	7.84E+05
Input	Self-use heat energy	MJ/year	3.39E+06
reference output	electricity to grid	kWh/year	1.13E+07
reference output	electricity (37%)	kWh/year	1.28E+07
reference output	Heat (51,8%)	MJ/year	6.43E+07
Output	CO_2 emission	ton/year	8.34E+03
Output	Unburned hydrocarbons - UHC	ton/year	3.07E-01
Output	CO emission	ton/year	4.79E+00
Output	Non Methane Volatile Organic Compounds	ton/year	1.99E-01
Output	CH_4 emission	ton/year	2.30E+00
Output	NOx emission	ton/year	1.50E+00
Output	N_2O emission	ton/year	2.50E-01
Output	SO_2	ton/year	2.50E+00

6.4.3. Examination of sustainability and circularity of rice straw supply chain by DSS_HMI tool

To calculate the indicators, the data is imported from an Excel file as shown in Fig.6.10.



a b

Figure 6.10. a. Selecting Excel file for importing; b. Selecting data for importing.

The calculation of the present situation is shown in Table 2. The results of the baseline situation indicate 49 indicators of environmental, economic, social aspects and circularity rate. For example, the GWP of the supply chain is 1.48E+06 $kgCO_2eq$/year or 130 gCO_2eq per kWh of electricity. Meanwhile, the acidification potential (AP) of rice straw in this study is 9.66E+03 kg SO_2 eq per year (0.797 gSO_2 eq per kWh). The economic indicator results show that the IRR of the rice straw supply chain is 7.57%. In addition, the NPV of the case study is 1.86 million euros. The IRR and NPV have not very high value because the investment cost of the steam explosion unit and cost of labour for operation are high. Furthermore, the results of the social indicator also show that the rate of informal labour is high (82.10%) because most of them are farmers who plant and harvest biomass. The results also show that the child labour is zero, because there is no data recorded (Child labour is prohibited by law Legge 17 Ottobre 67). The circularity indicators results show that the percentage of recycling rate out of all waste is 97.4% because the digestate of AD plant is used as biofertiliser. On the other hand, the circular material use is at 72.4%, and the proportion of material losses in primary material is 14.61%.

Table 6.20. The result of calculating alternative indicators

No	Indicators	Unit	A0
1	Water consumption	m^3	4.07E+06
2	Primary energy consumption	MJ	1.40E+07
3	Global warming potential	$kgCO_2eq$	1.48E+06
4	Particulate Matter	kg PM2.5 eq	1.79E+03
5	Eutrophication, marine	kg N eq	9.94E+02
6	Ozone depletion	kg CFC11 eq	1.59E+01
7	Ionising radiation human health	kg U235 eq	9.94E+05

No	Indicators	Unit	A0
8	Ionising radiation ecosystem	kg CTU eq	1.77E-01
9	Photochemical ozone formation	kg NOx eq	1.25E+05
10	Acidification	kg SO_2 eq	9.66E+03
11	Eutrophication, freshwater	kg P eq	5.86E+02
12	Eutrophication, terrestrial	mol N eq	1.13E+05
13	Human toxicity, non-cancer	kg 1,4 DCB	1.04E+07
14	Ecotoxicity, marine	kg 1,4 DCB	4.52E+04
15	Ecotoxicity, freshwater	kg 1,4 DCB	3.61E+04
16	Human toxicity, cancer	kg 1,4 DCB	1.82E+03
17	Land use/transformation	m^2a	5.11E+04
18	Abiotic depletion potential	kg Sb eq	2.22E+04
19	Primary renewable energy consumption sharing in total primary energy consumption	%	4.96E+01
20	Total cost	Euro	2.73E+07
21	Revenue	Euro	2.33E+06
22	NPV	Euro	1.76E+06
23	IRR	%	7.57E+00
24	Circular investment	Euro	1.42E+06
25	The proportion of employees with education and training out of total employment	%	2.18E+01
26	The proportion of women in managerial positions out of total employment	%	1.41E+01
27	The proportion of informal employment out of total employment	%	8.21E+01
28	Fair Salary	times	1.17E+00
29	Child Labour	risk hour	0.00E+00
30	Fatal and non-fatal occupational injuries	case	5.60E+00
31	Research and development expenditure as a proportion of revenue	Euro	2.39E-02
32	Social investment	million Euro	4.17E-01
33	Number of health workers in company	person	1.00E+00
34	Forced Labour	person	8.00E+00
35	Local employment	person	7.80E+01
36	Job creation	man year	2.15E+01
37	Income generated by jobs	Euro	5.06E+05
38	Working Hours	hour	5.27E+04
39	Employee participation in the circular model	person	7.40E+01
40	Self-sufficiency of raw materials	ton	9.91E+01
41	Generation of waste	ton	4.33E+04
42	Percentage of recycling rate of all waste	%	9.74E+01
43	Percentage of recycling rate of plastic waste	%	2.02E-02
44	Percentage of recycling rate of paper and paperboard	%	1.66E-04
45	Circular material use rate	%	7.24E+01
46	The proportion of material losses in primary material cycles.	%	1.46E+01
47	Use of raw materials for producing one unit of the main product	ton per kWh	5.29E-01
48	Reuse - manufacturing process	ton	3.40E+04
49	Food waste	ton	0.00E+00

Furthermore, the result calculation is exported to an Excel file, which allows users to monitor indicator values for all life cycle stages. For example, GWP can be calculated for each stage as Table 1. The results show that the hotspot point of the GWP indicator is pretreatment (45.92%) because this stage uses a lot of water and energy for processing. Comparing the existing reference with a similar process system (AD - CHP) (Fusi et al., 2016; Pasciucco et al., 2023), the value of indicators calculated by the HMI_DSS tool is reliable to assess for supply chain and provide helpful evidence for decision-making. For example, the GWP of this supply chain is 130 gCO_2eq per kWh of electricity, while this one is in the range of -39 to 408 gCO_2eq per kWh calculated for AD-CHP systems using agricultural residue as feedstocks (Fusi et al., 2016). The IRR of this rice straw supply chain is 7.57%, while the AD-CHP system carried out by Pasciucco et al. (2023) is 5.94%.

Table 6.21. The value of the GWP indicator in life cycle stages

Life cycle stage	Amount	Unit	Rate	Note
Collection and harvesting	1.43E+05	kgCO_2eq/year	9.83%	
Transportation and storage	3.51E+04	kgCO_2eq/year	2.39%	
Pretreatment (SE)	6.70E+05	kgCO_2eq/year	45.92%	
Conversion (AD plant)	2.84E+05	kgCO_2eq/year	19.46%	
Cleaning biofuel	2.00E+00	kgCO_2eq/year	1E-04%	
Waste management	-1.64E+05	kgCO_2eq/year	-11.21%	Negative value by fertilizer avoided
Energy production (CHP plant)	4.90E+05	kgCO_2eq/year	33.61%	
Total	1.48E+06	kgCO_2eq/year	100.00%	

6.5. Application DSS tool for ranking alternative

6.5.1. Defining sustainability and circularity alternatives

There are 4 alternative situations, A1 to A4, that aim to improve circular economy and sustainability (Fig. 6.11). These alternatives are proposed by applying CBMs, which are the results of literature review in Chapter 3, as shown in Table 6.22. The changes in supply chain in alternatives are proposed based on options which are considered in literature (Barzee et al., 2022; Elshamy & Rösch, 2022; Fabbri & Torri, 2016; Mohammadi et al., 2019; Singh et al., 2022; Tawfik et al., 2022).

Table 6.22. CBMs application in alternatives

CBM / Alte.	Organic feedstock	Cascading and repurposing	Recycle and recovery	extension life use of the product
A1	x	x	x	
A2	x		x	x
A3	x		x	x
A4	x		x	x

1. Alternative A1

In this alternative, the CO_2 in raw biogas from the AD plant is captured and liquefied for sale in the market. In this alternative, the upgrading process is added to the treatment of raw biogas. CO_2 is separated and collected, then converted into liquid CO_2. Methane is supplied to the CHP plant.

Upgrading

Biomethane is a gaseous mixture mainly containing methane (CH_4); it derives from biogas purification until it reaches natural gas quality.

The purification process is divided into two distinct phases:

• Biogas purification involves dehydration, desulphurization, and, where necessary, removal of gaseous ammonia, mercaptans, and dust.

• Upgrading consists of removing carbon dioxide and is aimed at making it suitable for the regulatory qualification of biomethane.

The purification phase is essential and preparatory to the subsequent stages of the process: it eliminates unwanted molecules both for the final composition of the biomethane and for the operation of the upgrading plants, which the presence of specific pollutants could damage (e.g., sulfur for membranes).

Recovery and production of liquid CO_2

The off-gas leaving the biogas upgrading is conveyed to the CO_2 recovery plant, which is first purified (up to food grade) and then liquefied. The pure liquid CO2 is then sent to the cryogenic storage tank, where it is stored.

Liquefaction takes place downstream of a CO_2 pre-treatment to remove pollutants, thus increasing the degree of purity.

This can be achieved through a multi-step process as described below:

• Compression: CO_2 is compressed to 18-19 bar.

• Filtration: the CO_2 leaving the compressor passes through an activated carbon bed. This step is intended as protection against odorous compounds/impurities.

• Drying: the filtered gas passes through a dehydration system to remove moisture altogether. The CO_2 is dehydrated to eliminate the operational problems associated with water vapor and the low operating temperatures of liquefaction condensers.

• Condensation: the purified gas is sent to the CO_2 liquefaction section; traces of non-condensable gases still contained in the stream remain in gaseous form while the CO_2 is liquefied.

• Stripping: any incondensable such as oxygen, methane, and nitrogen are effectively removed in the stripping tower.

• Storage: pure liquid CO_2 is stored in a cryogenic tank.

CO2 liquid is sold in the market.

2. Alternative A2

This alternative is based on alternative A1. However, CO_2 from the upgrading stage and liquid digestate is used to cultivate microalgae. Biomass algae are used to produce bioenergy and animal feeding for farms. The cultivated microalgae are harvested, partially dried, and post-treated as animal feed.

3. Alternative A3

This alternative replaces pretreatment steam explosion for a mechanical process and the digestate is not used as fertilizer. The rice straw is transported to the AD plant after harvesting and collecting. In the AD plant it is treated by mechanical treatment. Then it is mixed with manure to create AD feedstock. The biogas is cleaned and then fed to the CHP plant for energy production. The digestate from AD plant is dried. Then, it is used as feedstock for a pyrolysis process to produce biochar. The biochar is sold in the market for water treatment (Mohammadi et al., 2019) (Singh et al., 2022).

4. Alternative A4

This alternative is similar to A3, the steam explosion is replaced by a mechanical process and the solid digestate is not used as fertilizer. The rice straw is transported to AD plant after harvesting and collecting. In the AD plant it is treated by mechanical treatment. Then it is mixed with manure to create AD feedstock. The biogas is cleaned and then fed to the CHP plant for energy production. In this case, the solid digestate from AD plant is used as feedstock for hydrothermal carbonization process for producing hydrochar. The hydrochar is sold in the market for water treatment.

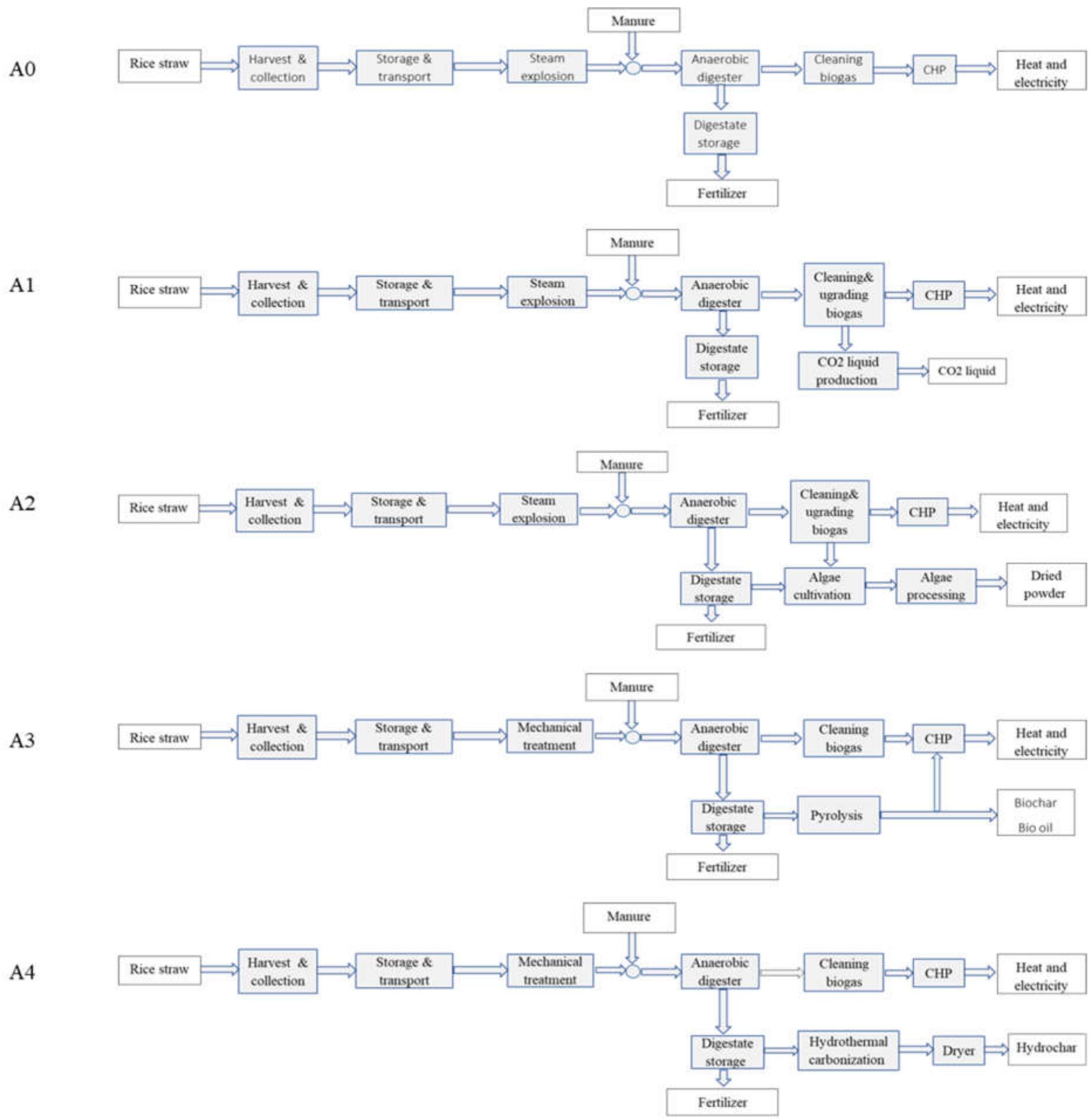


Figure 6.11. Alternatives of the rice straw supply chain

To ranking alternatives, besides the data of baseline alternative, other alternatives are collected from the Ecoinvent database and literature, as well as simulation by Aspen plus$^{@}$ at IMDEA Energy Institute. For example, for calculating environmental indicators, data of input/output amount of biogas production stage are gathered in Table 6.23.

Table 6.23. Environmental data of input/output of biogas production stage in AD plant

Input/output	Input/output	Unit	A0	A1	A2	A3	A4
Infrastructure	AD plant	unit	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Infrastructure	upgrade biofuel	unit	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Infrastructure	waste storage	unit	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Infrastructure	Land use for factory	ha	5.63E-01	5.63E-01	5.63E-01	5.63E-01	5.63E-01
construction materials	Cements	ton/20years	5.73E+03	5.73E+03	5.73E+03	5.73E+03	5.73E+03
construction materials	Reinforced steel	ton/20year	1.70E+03	1.70E+03	1.70E+03	1.70E+03	1.70E+03
construction materials	Chromium steel	ton/20year	2.04E+02	2.04E+02	2.04E+02	2.04E+02	2.04E+02
construction materials	Copper	ton/20year	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01
construction materials	Laminated timber	ton/20year	1.44E+00	1.44E+00	1.44E+00	1.44E+00	1.44E+00
construction materials	High-density polyethylene	ton/20year	7.19E+00	7.19E+00	7.19E+00	7.19E+00	7.19E+00
construction materials	High-impact polystyrene	ton/20year	8.86E+01	8.86E+01	8.86E+01	8.86E+01	8.86E+01
construction materials	Polyvinyl chloride	ton/20year	1.20E+01	1.20E+01	1.20E+01	1.20E+01	1.20E+01
construction materials	Synthetic rubber	ton/20year	4.79E+01	4.79E+01	4.79E+01	4.79E+01	4.79E+01
input	rice straw after pretreatment	ton/year	1.75E+04	1.75E+04	1.75E+04	1.92E+04	1.92E+04
input	manure	ton/year	3.22E+04	3.22E+04	3.22E+04	3.23E+04	3.23E+04
input	Self-consumption electric energy	MWh/year	1.50E+03	1.50E+03	1.50E+03	1.50E+03	1.50E+03
input	Self-use heat energy	MWh/year	5.77E+03	5.77E+03	5.77E+03	5.77E+03	5.77E+03
input	Electrical from grid	MWh/year	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
input	Water use for dilution	m3/year	4.88E+04	4.88E+04	4.88E+04	4.72E+04	4.72E+04
output	Raw Bio-fuel (biogas)	m3/year	5.87E+06	5.87E+06	5.87E+06	5.47E+06	5.47E+06
output	biogas release	m3/year	5.87E+04	5.87E+04	5.87E+04	5.47E+04	5.47E+04
output	CH4 emission (from biogas release)	ton/year	1.81E+01	1.81E+01	1.81E+01	1.69E+01	1.69E+01
output	CO2 emission (from biogas release)	ton/year	4.87E+01	4.87E+01	4.87E+01	4.54E+01	4.54E+01

Input/output	Input/output	Unit	A0	A1	A2	A3	A4
output	H2S emission (from biogas release)	ton/year	4.65E-01	4.65E-01	4.65E-01	4.33E-01	4.33E-01
output	O2 emission (from biogas release)	ton/year	6.79E+00	1.39E-02	1.39E-02	1.30E-02	1.30E-02
output	NH3 emission (from biogas release)	ton/year	1.51E-01	1.51E-01	1.51E-01	1.41E-01	1.40E-01
output	digestate production (generating waste)	ton/year	4.24E+04	4.24E+04	4.24E+04	4.47E+04	4.47E+04
output	solid digestate	ton/year	6.36E+03	6.36E+03	6.36E+03	6.71E+03	6.71E+03
output	wet digestate	ton/year	3.61E+04	3.61E+04	3.61E+04	3.80E+04	3.80E+04
output	Waste water	m^3/year	2.73E+04	2.73E+04	2.73E+04	2.83E+04	2.83E+04
output	Water recycle	ton/year	3.35E+04	3.35E+04	3.35E+04	3.26E+04	3.26E+04

6.5.2. Ranking alternative results with indicator weighting by Entropy

To rank alternatives, the data is also imported from Excel files. The results of the ranking process (case 0) are shown in Tables 6.23 to 6.25, and Figure 6.24. The ranking results show that A3 (0.267595) is the best choice considering all criteria while A2 (-0.90272) is the worst alternative.

Table 6.24. Results of indicator calculation for all alternatives

Indicator	Criteria	Unit	A0	A1	A2	A3	A4
Water consumption	C1	m^3	4.07E+06	4.07E+06	7.11E+06	4.07E+06	4.10E+06
Primary energy consumption	C2	MJ	1.40E+07	1.83E+07	1.96E+07	1.66E+07	1.25E+07
Global warming potential	C3	kg CO_2eq	1.48E+06	1.20E+06	5.57E+07	1.68E+06	1.57E+06
Particulate Matter	C4	kg PM 2.5eq	1.79E+03	1.81E+03	1.09E+05	1.85E+03	1.72E+03
Eutrophication, marine	C5	kg N eq	9.94E+02	1.02E+03	1.87E+04	1.12E+03	1.03E+03
Ozone depletion	C6	kg CFC 11 eq	1.59E+01	1.58E+01	6.47E+01	1.71E+01	1.49E+01
Ionising radiation human health	C7	kg U235 eq	9.94E+05	9.94E+05	1.59E+06	9.99E+05	9.99E+05
Ionising radiation ecosystem	C8	kg CTUeq	1.77E-01	1.77E-01	2.69E-01	1.95E-01	1.95E-01
Photochemical ozone formation	C9	kg NOx eq	1.25E+05	1.25E+05	2.02E+05	1.26E+05	1.25E+05
Acidification	C10	kg SO_2 eq	9.66E+03	9.83E+03	5.69E+05	1.05E+04	9.74E+03
Eutrophication, freshwater	C11	kg P eq	5.86E+02	5.86E+02	1.14E+04	6.16E+02	6.16E+02
Eutrophication, terrestrial	C12	Mol Neq	1.13E+05	1.14E+05	1.56E+06	1.15E+05	1.08E+05
Human toxicity, non-cancer	C13	kg 1,4 DCB	1.04E+07	1.04E+07	4.24E+07	1.13E+07	1.13E+07
Ecotoxicity, marine	C14	kg 1,4 DCB	4.52E+04	4.61E+04	1.55E+06	4.51E+04	4.50E+04
Ecotoxicity, freshwater	C15	kg 1,4 DCB	3.61E+04	3.61E+04	1.08E+06	3.69E+04	3.69E+04
Human toxicity, cancer	C16	kg 1,4 DCB	1.82E+03	1.82E+03	2.60E+06	5.24E+04	2.98E+04
Land use	C17	(m^2a)	5.11E+04	5.11E+04	1.78E+05	6.91E+04	5.11E+04
Abiotic depletion potential	C18	kg Sbeq	2.22E+04	2.22E+04	2.32E+04	2.22E+04	2.22E+04
Primary renewable energy consumption sharing in the total primary energy consumption	C19	%	4.96E+01	6.16E+01	6.44E+01	5.85E+01	4.38E+01
Total cost	C20	Euro	2.73E+07	3.03E+07	3.12E+07	3.41E+07	3.42E+07
Revenue	C21	Euro	2.33E+06	2.49E+06	2.67E+06	3.20E+06	2.94E+06
NPV	C22	Euro	1.76E+06	7.18E+05	2.03E+06	5.79E+06	2.40E+06
IRR	C23	%	7.57E+00	5.92E+00	7.20E+00	1.13E+01	7.12E+00
Circular investment	C24	Euro	1.42E+06	2.69E+06	4.10E+06	3.41E+06	6.43E+06

Indicator	Criteria	Unit	A0	A1	A2	A3	A4
The proportion of employees with education and training out of total employment	C25	%	2.18E+01	2.47E+01	3.15E+01	2.75E+01	2.79E+01
The proportion of women in managerial positions out of total employment	C26	%	1.41E+01	1.36E+01	1.35E+01	1.50E+01	1.52E+01
The proportion of informal employment out of total employment	C27	%	8.21E+01	7.90E+01	7.19E+01	8.00E+01	8.10E+01
Fair Salary	C28	Times	1.17E+00	1.22E+00	1.23E+00	1.27E+00	1.26E+00
Child Labour	C29	risk hour	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Fatal and non-fatal occupational injuries (case)	C30	Case	5.60E+00	6.76E+00	9.84E+00	7.53E+00	7.14E+00
Research and development expenditure as a proportion of revenue	C31	M.euro	2.39E-02	2.54E-02	2.89E-02	2.90E-02	2.90E-02
Social investment	C32	M.euro	4.17E-01	4.84E-01	6.53E-01	4.76E-01	4.52E-01
number of health workers in company	C33	Person	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Forced Labour	C34	Person	8.00E+00	1.10E+01	1.90E+01	1.30E+01	1.20E+01
Local employment	C35	Person	7.80E+01	8.10E+01	8.90E+01	8.00E+01	7.90E+01
Job creation	C36	man year	2.15E+01	2.41E+01	3.03E+01	2.65E+01	2.33E+01
Income generated by jobs	C37	Euro	5.06E+05	5.87E+05	8.62E+05	6.37E+05	5.97E+05
Working Hours	C38	Hour	5.27E+04	6.07E+04	8.20E+04	5.80E+04	5.54E+04
Employee participation in the circular model	C39	Person	7.40E+01	7.70E+01	8.50E+01	7.60E+01	7.50E+01
Self-sufficiency of raw materials	C40	%	9.91E+01	9.91E+01	9.99E+01	9.92E+01	9.95E+01
Generation of waste	C41	Ton	4.33E+04	4.33E+04	4.37E+04	4.57E+04	4.56E+04
Percentage of recycling rate out of all waste	C42	%	9.74E+01	9.74E+01	9.92E+01	9.61E+01	9.61E+01
Percentage of recycling rate of plastic waste	C43	%	2.02E-02	2.02E-02	9.53E-02	1.68E-01	1.92E-02

Indicator	Criteria	Unit	A0	A1	A2	A3	A4
Percentage of recycling rate of paper and paperboard	C44	%	1.66E-04	1.66E-04	2.56E-04	1.57E-04	1.58E-04
Circular material use	C45	%	7.24E+01	7.24E+01	8.82E+01	7.15E+01	5.48E+01
The proportion of material losses in primary material cycles.	C46	%	1.46E+01	1.55E+01	1.55E+01	1.62E+01	1.72E+01
Use of raw materials for producing one function unit of main product	C47	ton/kWhel	5.29E-01	5.34E-01	5.34E-01	5.38E-01	5.73E-01
Reuse - manufacturing process	C48	Ton	3.40E+04	3.92E+04	3.92E+04	3.57E+04	6.40E+04
Food waste	C49	Ton	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table 6.25. Transpose of normalization of decision matrix and criteria weight

	A0	A1	A2	A3	A4	Criteria weight by entropy
C1	0.999336	0.999279	0	1	0.989291	0.00260
C2	0.796156	0.177247	0	0.426185	1	0.00115
C3	0.994943	1	0	0.99126	0.993209	0.10018
C4	0.999381	0.999217	0	0.998773	1	0.11163
C5	1	0.99876	0	0.992837	0.998125	0.07629
C6	0.979112	0.982232	0	0.955934	1	0.01984
C7	1	1	0	0.991594	0.991594	0.00178
C8	1	1	0	0.801472	0.801472	0.00114
C9	0.999219	1	0	0.990104	0.996896	0.00189
C10	1	0.999687	0	0.998464	0.99985	0.11038
C11	1	1	0	0.997239	0.997239	0.07810
C12	0.997096	0.996017	0	0.995403	1	0.06634
C13	1	1	0	0.970996	0.971703	0.01864
C14	0.999912	0.999283	0	0.999995	1	0.09745
C15	1	1	0	0.999269	0.999269	0.09331
C16	1	1	0	0.980543	0.989246	0.12453
C17	1	1	0	0.857574	0.999983	0.01358
C18	1	0.999902	0	0.998102	0.978956	0.00001
C19	0.284637	0.865815	1	0.713425	0	0.00085
C20	1	0.563215	0.431817	0.020692	0	0.00030
C21	0	0.183565	0.388832	1	0.699924	0.00056
C22	0.206078	0	0.258268	1	0.331188	0.01789
C23	0.306083	0	0.23688	1	0.221864	0.00220
C24	0	0.254233	0.53636	0.398171	1	0.00921
C25	0	0.299663	1	0.590278	0.626306	0.00064
C26	0.362927	0.056893	0	0.88875	1	0.00011
C27	1	0.700337	0	0.797727	0.897583	0.00009
C28	1	0.546006	0.434125	0	0.033184	0.00003
C29	1	1	1	1	1	0.00000
C30	1	0.727273	0	0.545455	0.636364	0.00149
C31	0	0.285946	0.970143	1	0.992134	0.00027
C32	0	0.282081	1	0.249719	0.146089	0.00111
C33	0	0	0	0	0	0.00000
C34	0	0.272727	1	0.454545	0.363636	0.00342
C35	0	0.272727	1	0.181818	0.090909	0.00010
C36	0	0.30063	1	0.57143	0.206939	0.00062
C37	0	0.227209	1	0.367461	0.255259	0.00146
C38	1	0.727669	0	0.817266	0.908224	0.00117
C39	0	0.272727	1	0.181818	0.090909	0.00011
C40	0	0.001882	1	0.179776	0.438827	0.00000
C41	1	1	0.864405	0	0.046551	0.00003
C42	0.408135	0.408135	1	0	0.029276	0.00001
C43	0.006859	0.006859	0.512362	1	0	0.03400
C44	0.088039	0.088039	1	0	0.003892	0.00176
C45	0.525293	0.526728	1	0.500947	0	0.00095
C46	1	0.664407	0.664407	0.366179	0	0.00013
C47	1	0.878668	0.878668	0.786417	0	0.00004

	A0	A1	A2	A3	A4	Criteria weight by entropy
C48	0	0.174477	0.174477	0.057417	1	0.00261
C49	1	1	1	1	1	0.00000

Table 6.26. Multi-criteria preference indices

	A0	A1	A2	A3	A4
A0	0	0.006332	0.920598	0.00912	0.005243
A1	0.006059	0	0.919045	0.008706	0.005482
A2	0.034131	0.032851	0	0.008584	0.026427
A3	0.057722	0.05758	0.943652	0	0.049878
A4	0.018037	0.01855	0.925688	0.014071	0

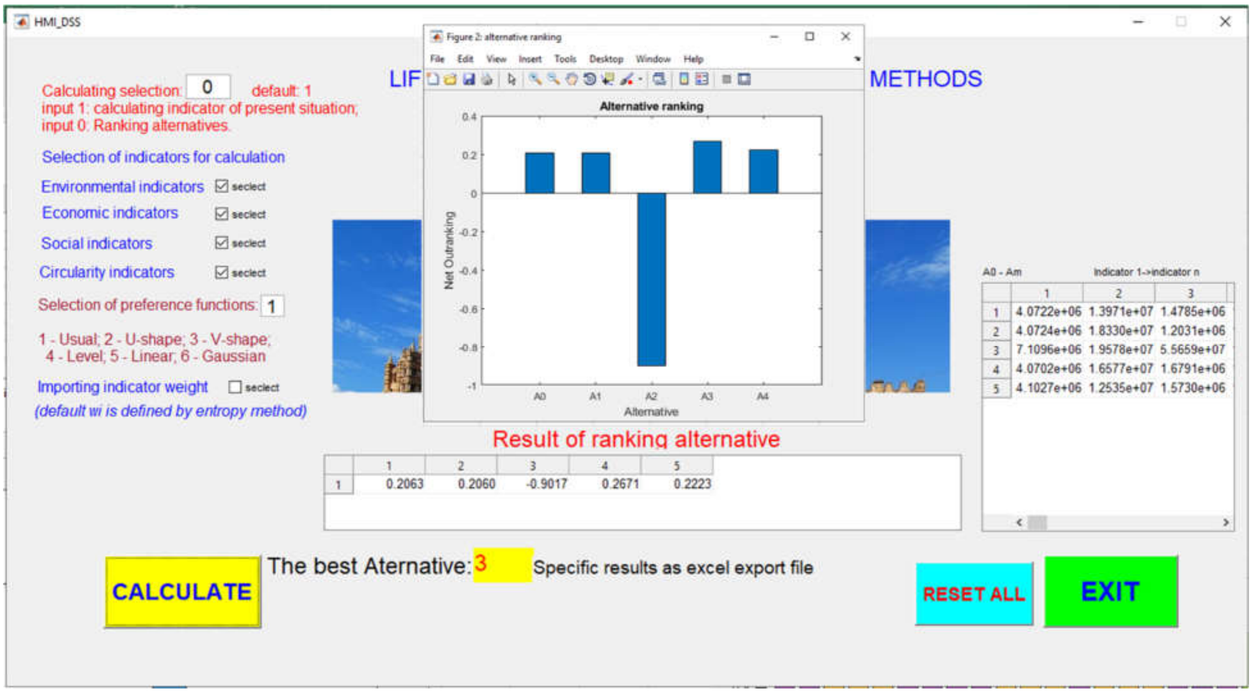


Figure 6.12. Alternative ranking results with indicator weights defined by entropy method

6.5.3. Sensitivity analysis

To assess the reliability and robustness of the final ranking, it is necessary to examine how sensitive each of the criteria weights is. The weights assigned to each criterion play a significant role in determining the priority of alternatives. Minor fluctuations in these relative weights can lead to substantial shifts in the ultimate ranking. Consequently, a sensitivity analysis was undertaken, exploring six cases in which criteria weights were altered to assess their impact on the final ranking of alternatives. Here, weight criteria are defined by both users/decision-makers and the Entropy method. The six cases are examined as follows:

- Case 1: Equal importance: assigning an equal weight of 1/49 to each of the eight criteria.

- Case 2: Equal importance of each aspect: The environment, social, economic and circularity aspects have the same weight of 0.25. The indicators of each aspect have the same weight. For example, environmental indicators have a value of 0.0132, while economic indicators weigh 0.05.
- Case 3 to Case 6: High priority on environmental, economic, societal and circularity aspects. Each aspect has a value of 1 in each case, while the remaining aspects have a value of 0. The indicators of priority aspect have a value defined by the entropy method.

The results of the cases are presented in Table 6.27 and Figure 6.13. In Table 6.27, Case 0 corresponds to weighting by entropy method in subsection 6.5.3. This case represents an objective arrangement of options based on data collected from the chain and does not represent the expectations of the decision maker or the owner.

Table 6.27. Net outranking flow values of different weighting cases

Alternative	Case 0	case 1	case 2	case 3	case 4	case 5	case 6
A0	0.206336	0.035548	0.012799	0.251722	-0.28809	-0.24406	-0.34934
A1	0.205995	0.04039	-0.0179	0.251819	-0.3729	-0.09257	-0.3364
A2	-0.90175	-0.21189	-0.09074	-0.99435	-0.04891	0.320874	0.272213
A3	0.267088	0.103452	0.120973	0.241914	0.527213	0.038939	0.714179
A4	0.222329	0.032499	-0.02513	0.248896	0.182691	-0.02319	-0.30065

The results show that case 0 has the same ranking result A3>A4>A0>A1>A2. The best alternative is A3. In this case, the ranking result is A3>A1>A0>A4>A2. Case 2 shows that A3 is the best alternative and A2 is the worst one. The ranking in this case is A3>A0>A1>A4>A2. Case 3: A1 is the best sustainability and circularity alternative; however, the difference between A1 and A0 is slight. The ranking is A1>A0>A4>A3>A2. Case 4, only focused on the economy, has the best selection of A3. The ranking follows: A3 >A4>A2>A0>A1. Case 5, which chooses an alternative based on the preference of social impact as the best alternative, has results on A2. The results of Case 5 are as follows: A2>A3>A4>A1>A0. The remaining case still has the best choice in A3. The ranking results in this case are as follows: A3>A2>A4>A2>A0. Therefore, A3 is considered the most sustainable and circular alternative.

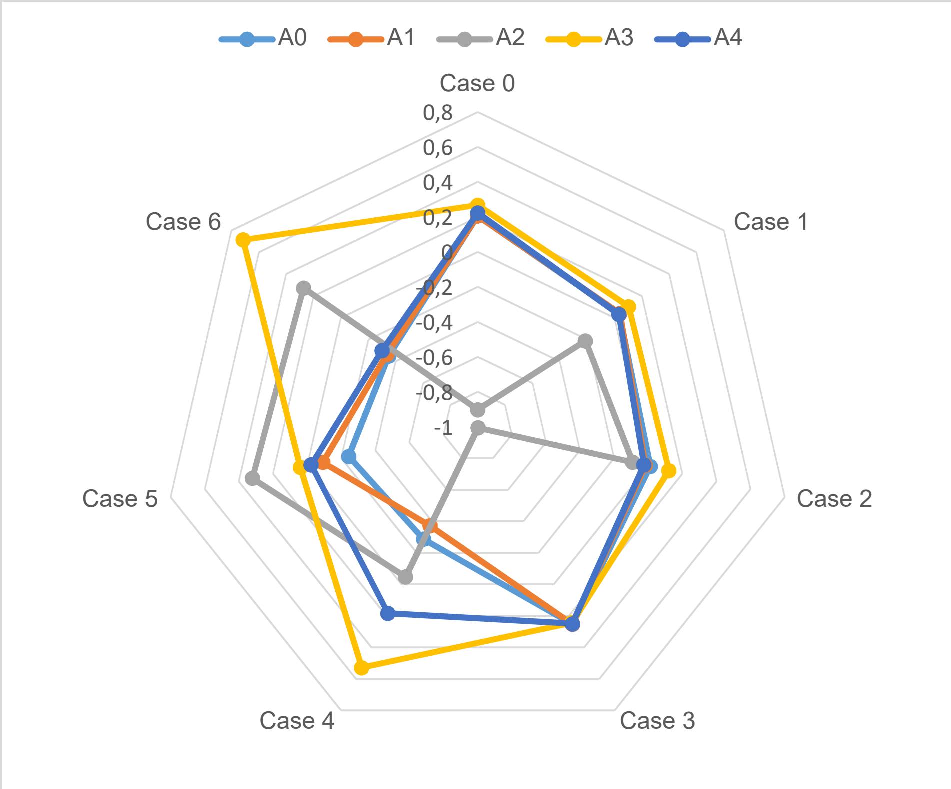


Figure 6.13. Ranking alternatives for different weighting cases

6.6. Discussion HMI_DSS tool and application results

The case study shows that assessing the potential of a DSS based on the life cycle thinking approach applied to the rice straw biomass supply chain has provided valuable insights into the complexities of integrating circularity and sustainability considerations. The evaluation of five alternatives using a range of sustainable and circular indicators has shed light on the trade-offs and synergies that exist within the context of achieving both circular economy objectives and sustainable development goals.

The results show that alternatives have changed with trade-offs in sustainability and circularity aspects. The A1 has the lowest GWP, but it also has the lowest IRR. The A2 has significantly more environmental impact than the remaining alternatives. The use of liquid digestate in A2 for producing algae products creates a new supply chain with new stages such as cultivating algae, harvesting, extracting, and producing the last product. This new supply chain has significant environmental impacts in GWP, Eutrophication - marine, and Particulate Matter impact. It also makes the A2 alternative use more resources such as water and energy. A positive aspect of this alternative, however, is that it promotes the highest job creation. Meanwhile, the remaining alternatives have fewer processes and need fewer employees. However, regarding economic aspects, A3 has the highest IRR and revenue and the lowest total cost because the process of recycling uses fewer employees while the price of biochar is high.

The analysis presented in this chapter explores four alternative scenarios (A1 to A4) aimed at improving the circular economy and sustainability of the power plant's biomass supply chain in Ferrera Erbognone, Italy. These alternatives are assessed using a comprehensive set of environmental, economic, social, and circular indicators. The results indicate that the environmental impact varies significantly across the proposed alternatives. The global warming potential (GWP) ranges from 1.21 kt CO_2eq/yr. to 55.7 kt CO_2eq/yr., demonstrating which specific alternatives significantly reduce greenhouse gas emissions compared to the baseline (A0). This reduction is likely due to the improved treatment of biogas and digestate in A1, A2, A3, and A4. Alternative A3, which avoids steam explosions and uses digestate for biochar production, stands out as a promising option for reducing environmental impact. The economic indicators, including the internal rate of return (IRR) and net present value (NPV), reflect the financial performance of each alternative. It is observed that the cost associated with the steam explosion process in A0 has a significant impact on the economic viability of the supply chain, leading to relatively low IRR and NPV values. However, A3 and A4, which replace steam explosion with mechanical treatment and utilise digestate for value-added products, show improved economic prospects. This suggests that these alternatives offer better economic sustainability. The social indicators reveal the employment and labour aspects of each alternative. The high rate of informal labour, primarily comprised of farmers involved in biomass cultivation, underscores the importance of the supply chain to the local community. Furthermore, the absence of child labour is a positive social aspect. The social impact is relatively consistent across the alternatives, with no significant differences observed. The circularity indicators, such as recycling rates and material use, provide insights into the sustainability of resource utilization and waste management. All alternatives exhibit a substantial recycling rate due to the reuse of digestate in various processes. However, A2, which incorporates microalgae cultivation, has high material losses in the primary material, indicating potential inefficiencies.

Furthermore, the integration of circularity indicators within the DSS framework has highlighted the need for a holistic approach that considers the environmental and economic aspects and the circularity of materials and processes. This comprehensive evaluation has revealed that circularity indicators play a critical role in guiding decision-making, enabling the identification of solutions that not only minimize waste but also contribute positively to the overall circular economy vision. The rice straw biomass supply chain case study has provided a practical illustration of the challenges and opportunities in implementing circular business models. The ranking of alternatives based on sustainable and circular indicators offers stakeholders a clear understanding of each option's potential benefits and drawbacks. This transparency in decision-making is essential for fostering informed discussions among various stakeholders, including policymakers, businesses, and environmental advocates.

However, the indicator importance is always subjective depending on the involved stakeholder, this is not explored in this study. The indicators used in this research are based on quantity and collection data, which are easy to get from the company. The methods used in this decision support are not hard to understand and apply, which is important when considering industrial implementation. In addition, the indicators in decision support are also general character, so they can be used for supply chain in another field without challenge.

Furthermore, in this study, the application of the new tool is conducted for a case study in Italy. Although the results completely and comprehensively reflect the circularity and sustainability of the rice straw supply chain, it does not fully reflect the entire potential of application tool for all of biomass energy production chains. Therefore, to be able to apply it widely, it is necessary to conduct more experimental calculations as well as to get opinions on its application to other companies in the supply chain in many different areas in other countries. The results of the case study application show that with a large biomass chain involving many regions and countries, collecting data for assessment is also a challenge when the volume of data to be collected is large. In addition, different policies in each country can affect the evaluation results and selection of the final optimal solution. This needs to be done in future research.

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CHAPTER VII. CONCLUSIONS

7.1. Main contents

The work described in this PhD thesis proposes a methodological framework for DSS to assess and rank the sustainability and circularity of a company in BSC. The driving force behind the development of this project is the inclusion of the LCT approach and MFA in the DSS for transferring companies in the BSC into the sustainability and circular economy model. Companies should always apply the LCT approach in their decision to select the best change in activities, which can consider circularity and sustainability. This is to ensure the company achieves its sustainable development goals.

This thesis includes the development of sustainability and circularity indicators for companies in the BSC, which is the lack of sustainability and circularity assessment for biomass companies. This work proposed a set of 49 indicators covering both circularity and sustainability. It is not only for individual companies but also usable for the biomass supply chain because the indicators are concerned with all supply chain stages. In addition, this indicator set aligns with the United Nations SDGs and EC's guidelines on the transition to the circular economy. These indicators are also easily identified with value with the company's data.

The methodology framework of the DSS integrated the LCT approach and MFA with MCDM methods. The integration in this thesis is based on the results of the LCT approach and MFA, which are inputations of the MCDM method. With the LCT approach, LCA, SLCA and LCC were selected to evaluate sustainability, while MFA was employed to examine circularity. This approach comprehensively provides for companies and decision-makers in the assessment of sustainability and circularity. Meanwhile, due to the MCDM methods, PROMETHEE II and Entropy were chosen for ranking alternatives and weighting indicators. These techniques directly use results of the LCT approach and MFA for ranking and weighting. In addition, the sustainability and circularity indicators are quantity, so the outranking technique of PROMETHEE is simple to understand and not so complex. The calculation of PROMETHEE and Entropy quickly gets results. Because of using the external indicator weighting of PROMETHEE II, the developed methodology framework allows users to import indicator weighting with user aspects.

The HMI_DSS tool was developed in this thesis. It was programmed by MATLAB GUI and Script. The tool has a friendly human interface to perform selection calculations. The data calculations are imported from an Excel file, which includes the amount of input/output and specific impact factors. The imported data was individually designed files of sustainability and circularity indicators. This helps users advantage in preparing and collecting data. In addition, data for this tool is feasibly gathered from companies and literature or open databases such as OpenLCA. That reduces time and cost in the collection of data.

The developed HMI_DSS tool was tested and applied to the case study, that is rice straw supply chain. The selected supply chain is in the North of Italy. The calculation for baseline was individually performed to assess circularity and sustainability. The hotspots of sustainability and circularity in the life stages of the supply chain are shown. According to this assessment, alternatives were created to improve sustainability and circularity based on circular business models such as recycling and recovery, extension life use of the product, cascading and repurposing, as well as organic feedstock. The results of ranking alternatives provide the best to worst alternatives. The sensitivity of analysis was performed with different indicator weighting to completely show.

7.2. Advancements in the state-of-the-art

The methodology framework illustrated in this thesis incorporates and harmonises several existing features and techniques usually employed in the analysis of sustainability and circularity, as well as choosing the best sustainability and circularity alternative. The main benefits deriving from the application of this approach are summarised below:

- Applying LCA, LCC, and SLCA to the identification of sustainability indicators contributes more of the work that lies in the simultaneous employment of all of them in the biomass supply chain, which is rarely performed in existing research.
- Applying the LCT tools and MFA in the calculation of circularity indicators provides confidence in the potential consideration of simulation of both circularity and sustainability that was not noticed in the existing literature.
- The development of sustainability and circularity contributes a standard set of indicators as guidelines step by step to get SDGs and transfer to a CE according to the EC's clear roadmap. This is not considered in the existing literature. These indicators can be useful for policymakers, and researchers in taking their work to develop a CE and sustainability for companies.
- The development of the DSS methodology framework first presents the corporation of circularity and sustainability in one DSS framework for biomass companies in the supply chain with a LCT approach. This framework is not only used for biomass companies, but also for general companies. The PROMETHEE II and Entropy used in this framework use results of the life cycle approach, so it improves the reliability of results and reduces the amount of calculation. In addition, the cooperation of Entropy and PROMETHEE II has fixed the limitations of PROMETHEE in weighting indicators that make this framework more powerful. Besides that, the multiple-criteria decision-making method helps this framework solve the trade-off issue in sustainability and circularity alternatives.
- The software in this study provides a more feasible and powerful DSS tool for ranking alternatives. In addition, it can be used to calculate sustainability and circularity indicators for one alternative by employing LCT tools and MFA.

Moreover, flexibility in the selection of indicator groups and methods for weighting indicators can provide for users to assess in many cases.

- The literature review in Chapter 3 show provides helpful information about CE principles and CBMs, which were applied to the biomass supply chain. This is the scientific reference for companies in application to their companies.

7.3. Limitations of the research

Although the HMI_DSS tool has significant strengths in assessing and selecting the best sustainability and circularity alternatives, it presents several limitations. One major challenge is the requirement for users to collect impact factor values for inputs and outputs, which are not inherently provided by the tool. When the input and output list is extensive, gathering data on these impact factors can be labour-intensive and challenging for companies. Additionally, the circularity indicators within the HMI_DSS tool are designed for general supply chains, but specific sectors, such as electronics or construction, require additional CE indicators. Examples include the recycling rate of electronic waste or construction and demolition waste and the proportion of ecologically certified materials in use. Further research is needed to expand circularity indicators tailored to specific industries.

Moreover, the potential for commercialising the HMI_DSS tool has not been explored in this research, and the importance of indicators, which is subjective and varies depending on stakeholders, has not been examined. The research focuses on indicators based on quantitative and easily collectable data from companies, potentially overlooking qualitative and stakeholder-specific factors. Additionally, the decision methods utilised in the HMI_DSS tool are limited. Incorporating a broader range of decision-making methods or techniques could enhance the accuracy and robustness of the decision-making process. Future research should explore the integration of additional methods to improve decision-making.

Furthermore, the new tool has been applied to a case study in Italy, and to further evaluate and validate the tool, research should be conducted across multiple companies in various regions and countries. This would help assess the tool's applicability and effectiveness in different contexts. Biomass fuels have diverse origins and production technologies, yet the application of the HMI_DSS tool to biomass chains other than rice straw has not been considered in this thesis. Future research should examine the tool's applicability to other types of biomass. Additionally, consultation with companies that could potentially use this tool and with policymakers on how to implement the tool in applying CE and sustainable models has not been conducted. These steps should be taken in future research to enhance the tool's practical application and policy integration.

7.4. Results of the case study and guidelines

7.4.1. Result of case study

The results of the baseline situation indicate 49 indicators of environmental, economic, and social aspects and circularity rate. For example, the GWP of the supply chain is 1.48E+06 kgCO_2eq/year or 130 gCO_2eq per kWh of electricity. Meanwhile, the acidification potential (AP) of rice straw in this study is 9.66E+03 kg SO_2 eq per year (0.797 gSO_2 eq per kWh). The economic indicator results show that the IRR of the rice straw supply chain is 7.57%. In addition, the NPV of the case study is 1.76 million euros. These economic indicators have a low value because the cost of installing the SE system and labour is high. Furthermore, the results of the social indicator also show that the rate of informal labour is high (82.10%) because most of them are farmers who plant and harvest biomass. The results also show that the child labour is zero, because there is no data recorded (Child labour is prohibited by law Legge 17 Ottobre 67). The circularity indicators results show that the percentage of recycling rate out of all waste is 97.40% because the digestate of AD plant is used as fertiliser. On the other hand, the circular material use is at 72.4%, and the proportion of material losses in primary material is 14.61%.

Furthermore, the result calculation allows users to monitor indicator values for all life cycle stages. For example, GWP can be calculated for each stage. The results show that the hotspot point of the GWP indicator is pretreatment (45.92%) because this stage uses a lot of water and energy for processing. Comparing the existing reference with a similar process system (AD - CHP) the value of indicators calculated by the HMI_DSS tool is trustful to assess for supply chain and provide helpful evidence for decision-making.

Five alternatives have been considered to select the best choice in sustainability and circularity aspects. The ranking results indicate that the digestate pyrolysis option has the best sustainability and circularity points than the other options. The results of calculating indicators for all indicators show that GWP is 1.21E+03 ton CO_2eq/yr to 55.7E+03 tons CO_2eq/yr. Meanwhile, rice straw's acidification potential (AP) in this study is 9.66 ton SO_2 eq/yr to 563 ton SO_2 eq/yr. The IRR of the rice straw supply chain is from 5.92% to 11.30%. In addition, the NPV of the case study is from 0.72 to 5.79 mil. euro. Furthermore, the rate of informal labour is from 71.9% to 82.10%, while the percentage of recycling rate out of all waste is from 96.61% to 99.2%, the circular material use is from 54.80% to 88.20%, and the proportion of material losses in primary material is from 14.61% to 15.50%.

The following points highlight the assessment of the four alternatives for improving the circular economy and sustainability of the Power plant's biomass supply chain:

- which avoids steam explosion and utilizes digestate for biochar production, is the most environmentally sustainable option, significantly reducing negative environmental impacts compared to the baseline.
- which replace steam explosion with mechanical treatment and convert digestate into value-added products, show improved economic viability compared to the baseline. These alternatives have the potential for better financial sustainability when using waste for producing value-adding products.
- which involves microalgae cultivation, raises questions about material efficiency due to high material losses, but it also has the highest social benefits such as job

creation. However, all alternatives demonstrate a strong emphasis on recycling and resource utilization.

7.4.2. Generic guidelines

It is important to stress the fact that the DSS study performed in this thesis was illustrated to provide the readers and the international scientific community with a useful and powerful method that should be applied to companies in different types of supply chains to transfer to a CE with sustainable development aspects, namely the combination of the LCT approach with multi MCDM methods. The results related to the evaluation and ranking of sustainability and circularity case study alternatives. Thus, as generic guidelines, the results recommend the best choice of the alternative that has the best environmental, economic, social and circularity performance in 49 indicators. These indicators were used to cover all the sustainability and circularity aspects.

The results show that the hotspot of environmental impact of the supply chain is clearly shown, for example, the GWP hotspot is pretreatment. The results also show the trade-off between sustainability and circularity aspects. This trade-off can lead to the final decision based on the weight of each indicator which is given by users or decision makers. The sensitivity of sustainability and circularity allows users to comprehend selection. The calculation process in this thesis reveals that technologies applied in the supply chain can be assessed as alternatives to select the pathway with the best sustainability and circularity aspects.

As future developments of the research illustrated in this thesis, further aspects might be included among the objective indicators, as additional social impacts or technology affect indicators. Besides that, adding more ranking methods can provide more complete insight into supply chain alternatives. Moreover, the CE indicators are gathered only to focus on the EC concept, so the extension of the number of circularity indicators based on the other CE concept should be considered. In addition, different policies in each country can affect the evaluation results and selection of the final optimal solution. This needs to be done in future research. The ability of commercial HMI_DSS tools and group users are also issues that need to be studied in the next research.

As a final remark, I hope that the content of this thesis, where the outcomes of a three-year-long path was illustrated, helping future researchers investigating CE and sustainable issues in the development of their studies, pursuing the target of driving mankind to the next step, where societies are based on respect for the planet as well as for others.

List of publications

- Article: Sonia Longo, Maurizio Cellura, Le Quyen Luu, Thanh Quang Nguyen, Roberta Rincione, Francesco Guarino, Circular economy and life cycle thinking applied to the biomass supply chain: A review, Renewable Energy, Volume 220, 2024, 119598, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2023.119598.
- Article: Quang, N. T., Quyen, L. L., Cellura, M., & Longo, S. (2023). Developing the Circularity and Sustainability Indicator Set for Companies in the Biomass Supply Chain. 2023 Asia Meeting on Environment and Electrical Engineering (EEE-AM), 01–05. https://doi.org/10.1109/EEE-AM58328.2023.10395470.
- Article: Luu, L. Q., Cellura, M., Nguyen, T. Q., Nguyen, H. N., & Nguyen, Q. N. (2023). The aggregation issue in quantifying sectorial and national GHG emissions using H-MRIO models. 2023 Asia Meeting on Environment and Electrical Engineering (EEE-AM), 1–7. https://doi.org/10.1109/EEE-AM58328.2023.10395611.
- Article: Nguyen Thanh Quang, Maurizio Cellura, Sonia Longo, Luu Le Quyen, Quynh T. Tran, Roberta Rincione. The decision support system framework based on Multi-Criteria Decision Making in the context of sustainability: A review - To be submitted.
- Article: Thanh Quang Nguyen, Le Quyen Luu, Nicolás Martínez-Ramónc, Sonia Longoa, Maurizio Cellura, Javier Dufour. Sustainability and circularity assessment of biomass-based energy supply chain - To be submitted.