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MIRRORING DECISION-MAKING IN THE RESOURCE VALUE CHAIN

Summary of the Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
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To be granted the scientific degree of Doctor of Engineering Science (PhD), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on October 2, 2025, at 14:00 at the Faculty of Natural Sciences and Technology of Riga Technical University, 12/1 Āzenes Street, Room 607.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Beate Zlaugotne ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction, 3 chapters, Conclusions, 32 figures and 24 tables; the total number of pages is 260, including appendices. The Bibliography contains 246 titles**.**

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Abbreviations

AHP	analytical hierarchy process
BAU	business as usual
BSF	black soldier fly
DH	district heating
DMC	domestic material consumption
EAF	electric arc furnace
EF	Environmental Footprint
EU27	27 Member States of the European Union
EU	European Union
FM	fish meal
GDP	gross domestic product
GHG	greenhouse gas emissions
IH	individual heating
iHCW	infectious healthcare waste
ISO	International Organization for Standardization
LCA	life cycle assessment
LCC	life cycle costing
MCDA	multi-criteria decision analysis
NGO	non-governmental organisation
PEFCR	Product Environmental Footprint Category Rules
QSL	*Queneau Schuman Luigi* process
RDF	refuse-derived fuel
RES	renewable energy sources
S-LCA	social life cycle assessment
SWOT	strengths, weaknesses, opportunities and threats analysis
TOPSIS	technique for order preference by similarity to ideal solution
UNEP	United Nations Environment Program
VS	valorisation scenarios

Introduction

Topicality of the Thesis

The dynamic growth of the world's population raises serious concerns about the social well-being of citizens and the increasing challenge of meeting the growing demand for resources and energy consumption. While society encourages resources through daily choices and consumption patterns, overconsumption leads to significant environmental, economic and social problems [1]. The exhaustion of natural resources, the devastation of ecosystems, and the escalation of pollution not only put pressure on the availability of resources for production – resulting in higher costs – but also exacerbate social inequality, disproportionately impacting the most vulnerable segments of society.

In response to these growing concerns, the European Green Deal was launched as a forward-looking growth strategy aimed at increasing resource efficiency, promoting a competitive and sustainable economy, and ensuring social justice – all with the overarching goal of achieving climate neutrality by 2050 [2]. While some countries are performing better than the average of the 27 Member States of the European Union (EU27), others are lagging behind the targets. One of the foremost priorities is the sustainable utilisation of resources, bolstered by the delivery of renewable and eco-friendly energy – both vital to promoting the tenets of a circular economy.

Decision-makers at international, national, municipal and sectoral levels can influence the choice of a solution for a more sustainable resource value chain. Nevertheless, the process of implementing a resource supply chain that is more sustainable in nature is fraught with challenges that must be addressed, including but not limited to technological and economic barriers, as well as regulatory and strategic hurdles, along with the complexities posed by stakeholders who may have differing interests. To successfully navigate and overcome the various challenges that hinder the creation of a sustainable resource supply chain, it is essential to have a unified approach that incorporates coordinated efforts rooted in scientific research and evidence-based practices.

In this Thesis, a methodology for decision-makers based on a framework of incremental complexity is developed and tested to support the decision-makers in the resource value chain, where resources are defined in a broader sense, i.e. material resources and energy. The framework guides decision-makers – regardless of their level and scope – through a structured decision-making process tailored to the specific problem within the resource value chain in terms of strategic relevance, sustainability, and utility fit to extend the resource value chain. This approach enables knowledgeable and context-sensitive decisions to be made consistently throughout the resource value chain.

Aim and objectives

The aim of the Thesis is to develop a comprehensive yet adaptable in scope multi-factorial decision-making methodological framework to enhance sustainable solutions within the resource value chain.

To achieve the aim of the Thesis, the following tasks were set:

1. Explore barriers in the transition of resource value chains to sustainable solutions.
2. Review existing decision-making methods according to their applicability and group them according to their complexity and the type of results obtained.
3. Develop a multifactorial decision-making methodology based on a framework of incremental complexity to support decision-making within resource value chains.
4. Test the developed multifactorial decision-making methodology by decision-making levels (strategic fit, sustainability, utility value), by resource value chain (energy, waste, agriculture, industry) and decision scope (international, national, municipal, sectoral).

Hypothesis

A multi-factorial methodology based on the incremental complexity framework can be applied to evaluate the decisions across international, national, municipal and sectoral scopes within energy, waste, industry and agriculture resource sectors while pinpointing the most appropriate and sustainable decisions in the resource value chain.

Defended theses

1. The incremental complexity framework improves decision-making by guiding decision-makers from simple, low-risk decisions to more complex assessments, improving accessibility and practical usability at international, national, local and sectoral levels in the energy, waste, industrial and agricultural resource sectors.
2. The use of qualitative and quantitative data provides the application of the methodology in various decision-making contexts and ensures effective application regardless of the type and amount of data available.
3. The application of the methodology to nine different cases confirms its adaptability and effectiveness in identifying sustainable solutions in the energy, waste, industrial and agricultural resource sectors and enabling informed, inclusive and sustainability-based decisions at international, national, local and sectoral levels that support a circular and climate-resilient economy.

Scientific novelty

The scientific novelty of this Thesis lies in the development of a new decision-making methodology based on a framework of incremental complexity, which distinctively combines three essential decision-making levels:

- *strategic fit* – strengths, weaknesses, opportunities and threats (SWOT) analysis;
- *sustainability* – life cycle assessment (LCA), life-cycle costing (LCC), social life cycle assessment (S-LCA);
- *utility value* – multi-criteria decision analysis (MCDA).

The privilege of this methodology, firstly, lies in the incremental complexity framework where the decision-making begins with straightforward, low-risk options and progressively incorporates additional variables and information, fostering clearer thought processes – while being approachable and efficient for decision-makers across all skill levels, as it is often present in resource management contexts.

Secondly, the methodology is adaptable to the needs of different decision scopes (international, national, municipal, sectoral) and various resource value chains (energy, waste, industry and agriculture), thus facilitating more multi-dimensional, holistic (technological, regulatory, environmental, social, economic), yet specific target-oriented decision-making.

Thirdly, the methodology is adjustable to accommodate and combine various forms of data, whether qualitative or quantitative, and aids in assessing solutions by considering both internal and external influences, along with strategic criteria.

These all benefits bring the developed methodology as an innovative contribution to the resource value chain assessment. Its application across diverse resource value chains, demonstrated in the Thesis, has revealed its high adaptability, as well as its value in deepening the understanding of sustainable decision-making within resource supply chains of varying complexity.

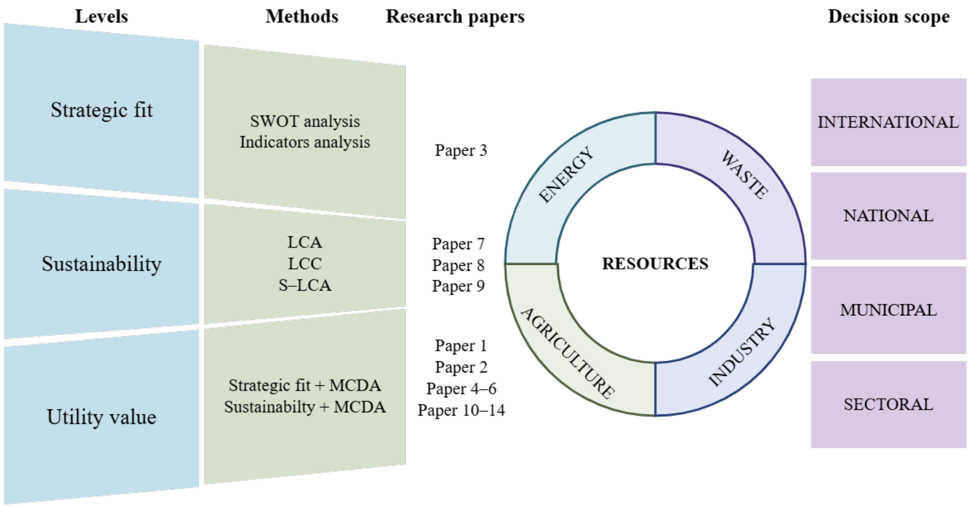

Fig. 1. Thesis research framework.

Practical relevance

This Thesis has high practical value as a developed resource value chain methodology can serve as a practical tool for decision-makers at international, national, municipal and sectoral levels and across different sectors to systematically assess solutions in the resource value chain. The structured incremental complexity approach helps overcome various obstacles that decision-makers encounter, which often hinder sustainable development and growth within the resource value chain. The multi-scope approach enhances the usefulness of the developed methodology by addressing the diverse needs of decision-makers within the resource value chain – spanning from strategic policy formulation and climate-sensitive, economically feasible, and socially advantageous planning to financial processes and sustainability reporting.

Approbation of the research results

1. **Zlaugotne, B**., Zihare, L., Balode, L., Kalnbalkite, A., Khabdullin, A., & Blumberga, D. (2020). Multi-Criteria Decision Analysis Methods Comparison. *Environmental and Climate Technologies*, 24(1), 454–471. https://doi.org/10.2478/rtuect-2020-0028
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1. Laktuka, K., Pakere, I., Kalnbalkite, A., **Zlaugotne, B**., Blumberga, D. (2023). Renewable energy project implementation: Will the Baltic States catch up with the Nordic countries? *Utilities Policy*, 2023, 82, 101577. https://doi.org/10.1016/j.jup.2023.101577

Monographs

1. Blumberga, D., Balode, L., Bumbiere, K., Dzalbs, A., Indzere, Z., Kalnbaļķīte, A., Priedniece, V., Pubule, J., Vamža, I., **Zlaugotne, B**., Žihare, L. Bioresursi ilgtspējīgai attīstībai. Rīga: RTU Izdevniecība, 2021. 483 lpp. ISBN 978-9934-22-701-1.

Approbation of the research results at scientific conferences

1. **Zlaugotne, B**., Zihare, L., Blumberga, D. Multi-criteria decision analysis methods comparison. *International Scientific Conference of Environmental and Climate Technologies CONECT 2020*, 13–15 May 2020, Riga, Latvia.
2. **Zlaugotne, B**., Pubule, J., Blumberga, D. Methodology for composite index for a sustainable assessment for fish feed. *International Scientific Conference of Environmental and Climate Technologies CONECT 2022*, 11–13 May 2022, Riga, Latvia.
3. **Zlaugotne, B**., Pubule, J., Diaz Sanchez, F. A., Blumberga, D. Assessment of the environmental impact of protein source used in fish feed production using Life Cycle Assessment. *17th Conference on Sustainable Development of Energy, Water and Environment Systems SDEWES*, 6–10 November 2022, Paphos, Cyprus.
4. **Zlaugotne, B**., Pubule, J., Diaz Sanchez, F. A., Blumberga, D. Life cycle assessment of fish feed for oil alternatives – environmental impact of microalgae, rapeseed and fish oil. *Biosystems Engineering Conference 2023*, 10–12 May, Tartu, Estonia.
5. **Zlaugotne, B**., Diaz Sanchez, F. A., Pubule, J., Blumberga, D. Environmental impact of natural and synthetic Astaxanthin pigments using Life cycle assessment. *International Scientific Conference of Environmental and Climate Technologies CONECT 2023*, 10–12 May 2023, Riga, Latvia.
6. **Zlaugotne, B**., Diaz Sanchez, F. A., Pubule, J., Blumberga, D. Environmental impact assessment of fish feed proteins from Black Soldier Fly, Yellow Mealworm and soybean using LCA. *International Scientific Conference of Environmental and Climate Technologies CONECT 2023*, 10–12 May 2023, Riga, Latvia.
7. **Zlaugotne, B**., Pubule, J. Bibliometric analysis and literature review on sustainability assessment methods in the bioeconomy. *International Scientific Conference of Environmental and Climate Technologies CONECT 2023*, 10–12 May 2023, Riga, Latvia.

8. **Zlaugotne, B**., Pubule, J. Review of Social Life Cycle Assessment. *18th Conference on Sustainable Development of Energy, Water and Environment Systems SDEWES*, 24–29 September 2023, Dubrovnik, Croatia.
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1. Literature review

The European Green Deal growth strategy aims to make resource consumption more efficient and foster a competitive economy in a fair and inclusive way, reaching climate neutrality by 2050 [2]. This includes ensuring clean, affordable and secure energy, transforming towards a circular and low-emission industry, improving the energy and resource efficiency of buildings, promoting sustainable and smart mobility, creating a fair and environmentally friendly food supply chain, restoring ecosystems and biodiversity, and achieving zero pollution for a non-toxic environment [2]. For Europe to achieve its goals, active participation at all levels and in all sectors is needed to jointly promote the belief in the importance of mitigating climate change while improving the efficiency and rational use of energy and resources.

The European Union economy's resource productivity has grown by 44 % between 2000 and 2024, although various crises have had a slight impact on this indicator; but overall resource productivity continues to grow [3]. Resource productivity measures the ratio between gross domestic product (GDP) and domestic material consumption (DMC) as GDP per unit of resource. In 2023, the EU27 achieved a resource productivity of 2.7 EUR/kg, up from 1.9 EUR/kg in 2014 [4]. Meanwhile, Latvia's performance was lower, with a 2023 value of 1,3 EUR/kg, showing a slight increase from 0.9 EUR/kg in 2014 [4]. However, among the EU27, the best results are for Luxembourg and the Netherlands, which share first place every year. While Luxembourg's resource productivity in 2014 was 4.3 EUR/kg and in 2023, 5.6 EUR/ kg, for the Netherlands, it was 3.9 EUR/kg in 2014 and 7 EUR/kg in 2023 [4]. The consumption of resources or products is influenced by the behaviour of residents, their economic status, as well as geographical location and the availability of products [5–7]. Generally, better economic conditions lead to higher resource consumption and increased waste generation.

Achieving the target of reducing GHG emissions by 60 % compared to 1990 by 2050 requires clean and secure energy, which can be achieved by decarbonising the energy system and relying on renewable energy sources, interconnected in Europe with smart infrastructure, ensuring clean energy at affordable prices [2]. To facilitate the transition to a secure and clean energy, it is necessary to promote the replacement of fossil fuels with renewable energy, to implement energy savings and efficient use, diversifying the import of necessary energy, as well as make an investment in the energy sector for development and to ensure energy security [8].

In 2023, the EU produced 42 % of its own energy and imported 58 % [9]. In 2023, the share of energy from renewable sources in the EU27 was 25 %, but for Latvia it was 43 % [10]. In 2023, 45 % of total electricity generation came from renewable energy sources, and 26 % of total energy consumption for heating and cooling came from renewable energy sources in the EU [11]. Meanwhile, in Latvia, 54 % of electricity was generated from renewable energy sources, and 61 % of heating and cooling was obtained from renewable energy sources in 2023 [11]. In 2023, energy consumption per capita in Latvia was 98 GJ per capita, while the EU average was 125 GJ per capita [12]. Of course, energy consumption is influenced by a variety of factors, such as the volume of manufacturing and commercial activities, weather conditions, which affect the length of the heating and cooling season and the energy efficiency of buildings, as well as the behaviour of residents and tourists. Although Latvia has relatively good results in the implementation of Green Deal targets, the set goals have not yet been achieved, due to inefficient use of resources [13], GHG emissions from industries [14], and waste recycling [15]. One of the factors slowing Latvia's progress toward its targets is the improper decision-making process [16], which acts as an obstacle: the lack of policy alignment between national and local governance arises from uncoordinated EU-level strategies and tools, coupled with inadequate political will at the national level, which collectively weaken the thoroughness and reliability of the vertical policy framework, subsequently obstructing transition processes. It is important to acknowledge that Latvia is not the sole nation encountering these obstacles [17–19].

Based on the literature review conducted within the Thesis, the primary obstacles hindering decision-makers from implementing sustainable practices in the resource supply chain are multifaceted, involving economic, regulatory, technological, organisational and even cultural challenges. These barriers are compounded by the complexity of supply chains and the diverse stakeholders involved. Despite growing awareness and commitment to sustainability, practical implementation remains challenging due to obstacles like technological barriers, economic barriers, regulatory and policy barriers, diverse stakeholder interests, supply chain and stakeholder coordination, organisational and cultural barriers and strategic barriers.

Navigating these intricate and varied obstacles demands more than just isolated measures; it necessitates a comprehensive, multi-dimensional, yet user-friendly and flexible decision-making framework that can adjust to changing circumstances to facilitate a sustainable transformation in the resource-product supply chain or resource value chain [20]. The resource value chain, as the core object throughout the decision-making process in this Doctoral Thesis, represents the transformative pathway of a resource (raw material or secondary material, including energy) into an added-value product or system. Given that the resource value chain encompasses a multitude of stakeholders and processes, strategic governance and well-planned decision-making frameworks are crucial. For resource value chains to be truly effective, they must be inclusive, interconnected, pertinent, pragmatic and adaptable. An all-encompassing approach offers a holistic perspective of all participants, processes and driving forces, allowing for strategic interventions throughout the entire chain. An interconnected viewpoint reveals the relationships within the value chain and pinpoints leverage points for meaningful transformation. By making value chains relatable, we connect resource utilisation and environmental effects to tangible economic and social contexts, ensuring their relevance. The approach must also be pragmatic, steering decision-makers toward the most significant areas for intervention. Ultimately, it should be adaptable, facilitating application across various sectors, products and regions to promote climate-resilient, sustainable, and circular transitions [21].

2. Methodology

The methodological foundation of the Thesis is grounded in the *incremental complexity framework* that is based on the approach of starting with simpler elements and gradually moving towards more complex elements [22]. The use of the incremental complexity framework improves the quality of decision-making, as well as promotes the integration of various types of information and helps to overcome uncertainty because it promotes the individual's ability to distinguish and integrate different dimensions into a decision [23]. This methodology supports an extended resource value chain, focusing on efficiency and resource circularity using strategic fit, sustainability and utility value approach.

The *strategic fit* (also called strategic alignment) framework allows for a more informed and multidimensional assessment of the problem, so that decision-makers can assess the resource chain and serves as a critical first filter for decision-makers, ensuring that the assessment considers strategies and guidelines of the appropriate level and scope. A good strategic fit indicates that the current situation is being improved and that growth and development are being strengthened. The *sustainability* framework assesses specific problems and their solutions in the environmental, economic and social dimensions and provides a holistic approach to decision-making. Good sustainability is one that reduces negative environmental impacts, continues economic growth and is socially responsible. The *utility value* framework determines the suitability of alternatives to solve the problem and meet the need. Good utility value considers multiple dimensions and builds a result based on a variety of factors.

Figure 2.1 illustrates the decision-making methodology for resource value chain assessment, following the incremental complexity decision logic.

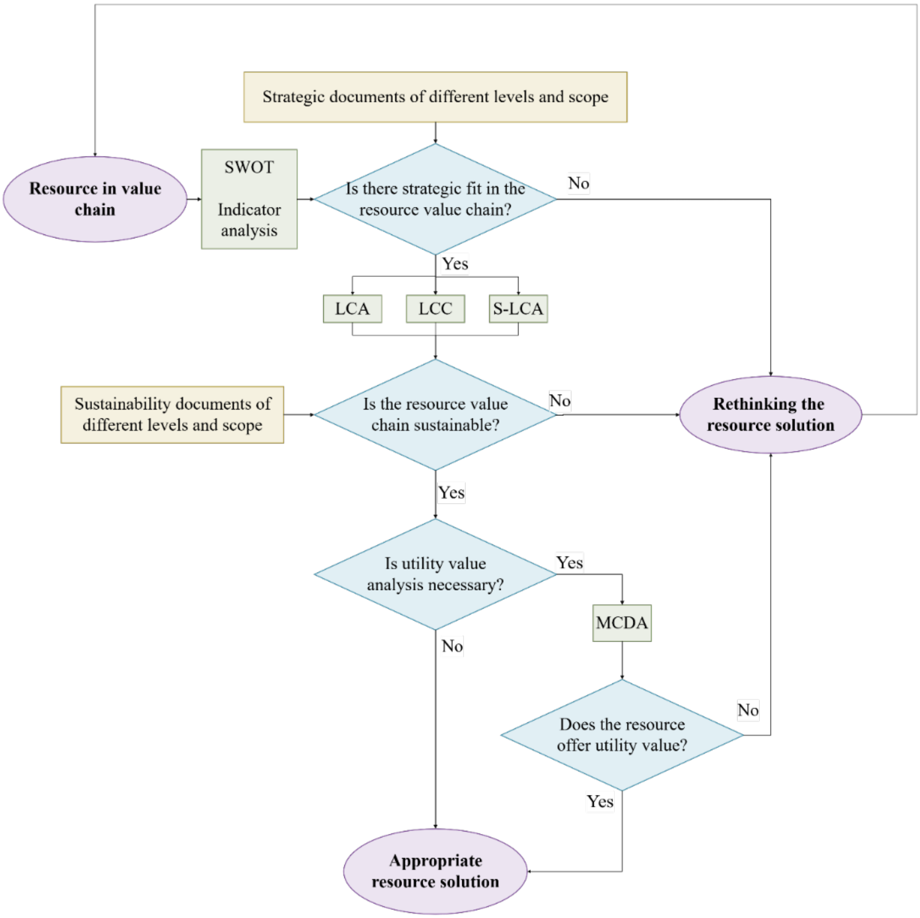

Fig. 2.1. Resource value chain decision-making methodology *via* incremental complexity theory approach.

In organisational theory, there is a mirroring hypothesis – a hypothesis that suggests that an organisation's structure tends to reflect the modular architecture of the products it develops [24]. Within the Doctoral Thesis, the author took an opportunity to mimic the mirroring hypothesis approach also to the decision-making process. A replication matrix summarising how the principles of the mirroring hypothesis are mapped onto the decision-making process is presented in Table 2.1.

Table 2.1

Mirroring Principles Reflecting the Hypothesis in the Decision-Making Process

Mirroring hypothesis in **organisational structures**	Mirroring hypothesis in **decision-making**
Change dynamics. The rate of technological change and product complexity at the component level demands flexible organisational architectures to enhance coordination, reduce complexity, and improve performance [25].	Decision-making models should be based on a modular or incremental complexity process, characterised by complex, while adaptable, criteria. Criteria or indicators-based models ensure the suitability of the decision-making models to the changing priorities of decision-makers.
Strategic priorities and value creation. Strategic priorities, such as value creation and capture, also influence the relationship between product and organisational architectures [26,27].	Just as product complexity requires flexible architectures, varying decision scopes (international, national, municipal, sectoral) and decision levels (strategic fit, sustainability, utility value) call for adaptable decision-making frameworks that adjust to the complexity and priorities of each decision level.
Industry and institutional context. The industry and institutional context also play a role in shaping the relationship between product and organisational architectures [28].	To ensure the delivery of the decision to the defined aim or values, the alignment with the strategic documents/frameworks via criteria and weights needs to be defined.
Decision-making homomorphism. The mirroring of a product's technical dependencies and organisational ties supports problem-solving by conserving cognitive resources, as real-time interdependencies require coordination within technical constraints – forming a cognitive homomorphism between technical and organisational networks [24] .	The decision-making process requires ongoing interactions between defined priorities (such as values and policy objectives), selected criteria, the opinions of various decision-makers (involved stakeholders), and the strength of these opinions as expressed through weighting. Thus, the cumulative decision-making model should be coherent with all these components.

2.1. Strategic fit level

The strategic fit approach is rooted in the idea that organisations must align their strategies with their external environment to achieve optimal performance. This alignment is critical in the context of environmental protection, where organisations must consider ecological, social, and economic factors. The key principles of the strategic fit approach are alignment of internal and external factors, integration of environmental considerations, stakeholder engagement, dynamic adaptation and performance measurement.

Strategic fit operates at multiple levels – international, national, municipal and sectoral. On the international level, it encompasses treaties, protocols, agreements, declarations, memoranda of understanding, joint statements, multilateral action plans and overarching global strategic frameworks. The national tier includes strategies, legislative structures, policy directives, action plans, development agendas and roadmaps that correspond with global commitments [29]. The local level consists of community regulations and development agendas that align with national strategies [30]. Sector-specific documents – such as targeted strategies, thematic action plans, implementation frameworks, and product category rules – guarantee consistency within fields or industries.

Strategic fit must be coherent and operate not only at the structural level, but also in the context of the linkages between sectors to ensure development. To adequately assess strategic fit, it is necessary to select appropriate methods where qualitative or quantitative data approaches or combined approaches can be applied [31].

Qualitative data analysis

One of the most recognised and extensively used tools for strategic decision-making is the SWOT analysis, which assesses strengths, weaknesses, opportunities and threats [32]. SWOT analysis is based on the analysis of qualitative or semi-qualitative data affected by internal and external factors [33]. Based on the results of the analysis, the organisation can determine the development path, reduce the impact of potential threats, adapt to various factors and assign strategies for further work, development and/or behaviour in the context of the decision being made [34]. Furthermore, SWOT analysis can serve as an approach to qualitatively evaluate a situation by examining both advantages and disadvantages for informed decision-making.

Quantitative data analysis

Indicator analysis serves as a crucial quantitative data analysis tool for decision-makers, particularly focused on assessing diverse dimensions including technological, environmental, economic, social, and others. An indicator is a variable that shows changes over time, but problems can arise with the collection of the necessary data and its interpretation [35]. This type of method allows for a better understanding of specific outcomes and helps laypeople to understand the situation more easily [36].

2.2. Sustainability assessment level

Sustainability assessment consists of environmental, economic and social dimensions, which can be assessed as individual dimensions or as an overall sustainability assessment [37]. However, to conduct an effective assessment of the environmental, economic and social sustainability of a resource value chain, it is important to define clear boundaries, assumptions, collect appropriate data and use appropriate assessment methods to obtain the desired interpretation of the data.

2.2.1. Life cycle assessment

To assess and compare products and services based on environmental impact, life cycle assessment (LCA) is used. LCA is performed according to ISO 14040 "Environmental management – Life cycle assessment – Principles and framework" and ISO 14044 "Environmental management – Life cycle assessment – Requirements and guidelines" standards [38,39].

In this Thesis, Environmental Footprint (EF) version 3.0 (European method) and ReCiPe 2016 (Global method) impact assessment methods are used. The EF 3.0 method has been developed by the European Commission and is part of efforts to harmonise environmental impact assessment [40]. The EF 3.0 method is used in the Product Environmental Footprint Category Rules (PEFCR) and the Organisation Environmental Footprint Sector Rules [41]. The updated version of the impact assessment method includes human toxicity, ecotoxicity and land use impact categories, as well as improved and expanded other impact categories [41].

The ReCiPe 2016 method is an updated and expanded version of ReCiPe 2008, which includes both midpoint (problem-oriented) with 18 impact categories and endpoint (damage-oriented) with 3 impact categories [41]. In this method, it is possible to obtain impacts expressed in terms of individualistic (I), based on short-term interest, hierarchical (H), based on the most common policy principles regarding timing and other issues, and egalitarian (E), as the most cautious perspective [41]. Approbation Paper 14 presents midpoints (H – *Hierarchist*) impact categories of the "ReCiPe 2016" method. The *Hierarchist* perspective reflects a cultural viewpoint, aiming to achieve consensus while adopting a 100-year timeframe.

2.2.2. Life cycle costing

There are several methods to assess the economic dimension of processes and products, such as technical-economic assessment *via* CAPEX and OPEX (also called conventional life cycle costing), cost-benefit analysis, environmental life cycle costing and societal life cycle costing [42].

Life cycle costing (LCC) is a multifaceted method that is divided into sub-methods with the following features [42,43]:

- Conventional LCC is used in this Thesis, which includes direct costs as acquisition and ownership costs with a reference unit to the product or project.
- Environmental LCC is used in this Thesis, which includes direct and external costs as environmental and life cycle costs with a reference unit's functional unit.
- Societal LCC, which is not used in this Thesis, includes direct and external costs, including environmental and social aspects with reference unit's functional unit.

Additionally, there exists a method for calculating environmental damage costs, which assesses the harm inflicted by environmental pollutants expressed in euros per unit of pollutant [44], which is applied in this Thesis. Since the environmental damage cost is not directly observable, it must be calculated based on LCA damage assessments and economic impact studies [44]. Environmental damage costs are updated periodically, with the latest release being from 2021 [44]. To obtain environmental prices that reflect the relevant year (for example, 2025 was relevant for this Thesis – see Papers 13–14), environmental cost inflation was adjusted using World Bank data and forecasts for that year [45,46]. The adjusted environmental damage costs by impact category are presented in Papers 13 and 14.

2.2.3. Social life cycle assessment

To analyse the social dimension – social impact or social benefit – in the decision-making processes, social life cycle assessment (S-LCA) is applied in the Thesis [47]. It is essential to promote social benefits in the evaluation of any product or service that increases the well-being of individuals and society [48]. Social assessment can be carried out using the United Nations Environment Program (UNEP) guidelines or one of the database assessment methods (e.g. Social Hotspots Database or PSILCA calculation software), with these methods being regularly updated and expanded [49,50]. Recently, the UNEP guidelines were successfully expanded and integrated in a social impact assessment standard ISO 14075:2024 "Environmental management – Principles and framework for social life cycle assessment", which sets out the basic principles, specifies requirements and provides guidelines for conducting a social life cycle assessment of a product [51].

In this Thesis, UNEP guidelines for social assessment are used. UNEP guidelines provide consistent guidance to promote context-appropriate applications to support social assessment [52]. The guidelines also include an inventory indicator with examples of data sources – databases, reports, interviews with insiders and other data sources [49]. UNEP's social assessment is divided into six main impact categories (worker, local community, value chain (excluding consumers), consumer, society, children) and 40 subcategories [49].

Social impact can be both positive and negative pressure on social parameters or the well-being of stakeholders [53]. Social category assessment can be expressed as a social reference scale or a social risk assessment [54]. In this Thesis, the scoring from +2 to –2 is applied for the S-LCA studies [54].

2.3. Utility value level

The utility value method serves as a multi-criteria decision-making framework that allocates numerical values to various outcomes, aiding in choices, especially in uncertain situations. This approach is grounded in utility theory, which offers a systematic means to assess alternatives based on their anticipated results and preferences of those making the decisions.

The utility value method is grounded on several principles:

- *Multi-attribute utility theory basis*. Based on this theory, at the utility value level, decision-makers are empowered to assess alternatives grounded in various, frequently opposing criteria. It organises choices by identifying the essential characteristics (such as environmental, economic and social factors) and allocating significance to each according to its relevance. The total utility of a choice is subsequently computed as a weighted aggregate of its performance across these characteristics [55,56].
- *Handling uncertainty.* The utility value method directly tackles the uncertainty that is a fundamental aspect of environmental decision-making. This is accomplished by employing probabilistic modelling and conducting sensitivity analysis [57,58].
- *Value of information analysis*. Value of information analysis quantifies the benefit of resolving uncertainty by collecting additional information [55,57].
- *Stakeholder participation*. The utility value approach emphasises the importance of incorporating stakeholders' preferences and values. This is particularly important in environmental decisions, where diverse stakeholders often have conflicting objectives. In the context of stakeholder engagement, aspects such as participatory process techniques are essential to guarantee transparency and robustness [58–60].

Utility values act as a numerical representation of how good or bad an option is, but it is important to use structured and sound arguments in the problem-solving and decision-making process, so multi-criteria decision analysis (MCDA) improves the quality of decision-making [61]. MCDA is a multi-step process consisting of a set of methods to structure and formalise decision-making processes in a transparent and consistent manner [62].

MCDA includes various methodologies and serves as a mechanism for evaluating related and conflicting criteria to assess options and identify the optimal solution [63]. Each MCDA method has its own calculation approach for ranking alternatives, and therefore, it cannot be assumed that the same input data will produce identical results across different methods. To understand the applicability of MCDA methods to the specific case studies addressed in this Thesis, a comprehensive review was conducted (see also Paper 1). A summary of the MCDA methods and their key characteristics is provided in Paper 1.

2.3.1. Multi-criteria decision analysis

Within the Thesis, two MCDA methods were applied: the Analytic Hierarchy Process (AHP) and Technique for Order Preference (TOPSIS).

The AHP model facilitates organising different variables at different levels of hierarchy, and it helps experts evaluate criteria [64]. AHP method calculation steps and equations are presented in Paper 1 [65].

The TOPSIS framework starts with collecting input data, then calculations of the normalised matrix and the weighted standard matrix. The next step is the distance from ideal and non-ideal solutions and calculations of closeness between each alternative to the ideal solution, and the best alternative is the one with the highest closeness [66]. The TOPSIS method equations are presented in Paper 1 [67].

3. Results

3.1. Strategic fit approach

The developed multi-factorial decision-making methodology is grounded in a framework of incremental complexity. Within this methodology, the assessment of strategic fit serves as the initial step and is applied to a case study comparing energy resource use across agricultural sub-sectors in different Latvian regions.

3.1.1. Strategic fit approach to the national energy sector

In the context of the national energy sector, the strategic fit approach is a crucial first step in assessing energy resources. It provides a basic understanding of the existing situation and helps decision-makers to identify aspects that need improvement to develop an efficient and sensible resource chain.

Agriculture in Latvia is one of the three largest sectors that emit GHG emissions [68]. To understand strategic fit, the agricultural sector was divided into subcategories based on farm size and type, and energy consumption estimates were obtained from official Latvian statistical data. Data were obtained from the public registers of the State Environmental Service, and Pollution Permits provided detailed information to more accurately assess energy consumption in different agricultural sub-sectors. Indicators such as the consumption of transport energy by different processes were obtained from the permits and based on publicly available energy balance data, and agricultural types such as crop production, dairy farming, pig and poultry farming and mixed crop and livestock production were analysed in the case of Latvia (Paper 3).

Data were extracted from 46 relevant pollution permits and expressed as agricultural production units, which represent the number of livestock or arable land on specific farms. It was assumed that the energy consumption at the national level for various processes is the same as that indicated in the pollution permits of the analysed farmers. 2017 is the base year for assessment, and the results are expressed by regions – Pieriga, Vidzeme, Kurzeme, Zemgale, and Latgale, as spatial differences are considered.

The data on energy consumption shows the breakdown in 2017 in the crop production sub-sector. Zemgale (143 GWh) and Kurzeme (120 GWh) recorded the highest energy consumption, with diesel (167 GWh) and biogas (95 GWh) being the main energy sources. In the pig and poultry subsector, Zemgale (124 GWh) and Kurzeme (106 GWh) also lead in energy consumption. The main energy sources in this sub-sector are grain sieves (183 GWh) and biogas (140 GWh).

Figure 3.1 shows the total energy consumption in Latvia's agricultural sector by region. The main energy sources are diesel, biogas, electricity and fuels such as those used in grain sieves. Kurzeme and Zemgale have the highest agricultural energy consumption, due to the importance of crop and pig farming in these areas. The calculated energy consumption by sub-sector was compared with the 2017 Latvian energy balance data, confirming the consistency of the overall consumption.

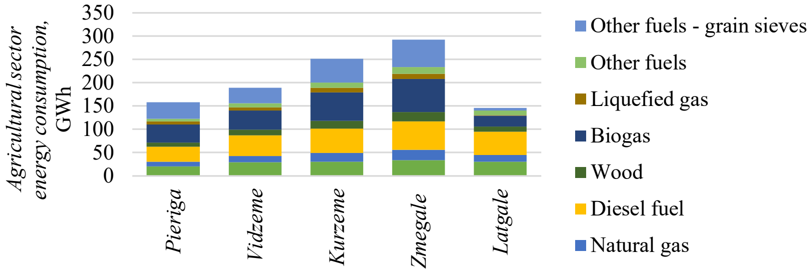

Fig. 3.1. Regional distribution of energy consumption in Latvia's agricultural sector.

The strategic fit analysis of Latvian agricultural energy consumption shows the importance of aligning energy resource planning with sector characteristics and regional realities. The results show significant differences between Latvian regions and between agricultural sub-sectors. Therefore, a regionally tailored strategy is needed to achieve the set goals, as unique approaches to energy solutions are shared by different farm types. Strategic fit provided a clearer and more detailed picture of current energy consumption in the sector, but also demonstrates that there needs to be more regional decision-makers for progress to happen.

3.2. Sustainability approach

If the resource value chain solution aligns with the *strategic fit* level requirements, decision-makers can proceed to the subsequent, more complex level of assessment – the life cycle analysis-based sustainability assessment of the proposed solution. The sustainability assessment approach is applied to two case studies:

(1) comparative assessment of healthcare waste valorisation scenarios;
(2) selection of the ideal solution for fishing waste management options.

3.2.1. Sustainability approach to the national waste sector

To support decision-makers in waste management planning, a strategic fit analysis was conducted to explore potential circular economy solutions for infectious healthcare waste (iHCW) and assess the current and a circular economy-oriented waste management system from an environmental and economic sustainability perspective.

A review of Latvia's waste management sector found that iHCW has recycling potential but is currently landfilled in Latvia. A qualitative data analysis of the potential uses of waste as a resource was carried out for strategic fit. However, an environmental and economic sustainability assessment is needed to compare recycling options with the current situation of waste landfilling, as the amount of waste increases – in 2015 it was 1754 tonnes treated iHCW and in 2023 it was 2936 tonnes [69].

This LCA examines the current situation and potential valorisation scenarios for treated iHCW. A total of seven scenarios are analysed in this study: the "business as usual" (BAU) scenario and seven treated iHCW valorisation scenarios (VS). The BAU scenario reflects a linear economy approach, where treated iHCW is disposed of in sanitary landfills. Alongside incineration, landfilling remains one of the most widely used methods for managing treated healthcare waste globally [70]. VS1–VS6 (see Table 3.1) represent circular economy approaches where six distinct products are derived from treated iHCW. These products were selected based on factors such as their added-value potential, the maturity of recovery technologies and their industrial symbiosis potential under Latvian conditions. The materials utilised in the product development (plastics, textiles or all iHCW) and their proportions in the final products vary across scenarios (see Table 3.1). A substitution approach is applied in all valorisation scenarios, where virgin raw materials are replaced with iHCW-recovered materials. According to the waste management hierarchy [71], recycling is prioritised after waste prevention and reuse, whereas energy recovery is considered a less favourable option, positioned just above landfill disposal. Building on this framework, an additional scenario (VS7) will be developed as an optimised solution. This scenario aims to maximise the use of recycling strategies with the lowest LCA results while incorporating the energy recovery strategy with the lowest LCA impact for the remaining fractions of treated iHCW (e.g. metals, wood, mixed waste and rubber) – ReCiPe 2016 midpoint method.

Table 3.1

Valorisation Scenarios and iHCW Share in the Product

Scenario	**Waste hierarchy approach**	**iHCW share used**	**iHCW material type used**
VS1: reinforced asphalt	Recycling	34 %	Plastics
VS2: reinforced cement	Recycling	31 %	Textile
VS3: RDF	Energy recovery	100 %	All iHCW
VS4: syngas	Energy recovery	100%	All iHCW
VS5: acoustic panel	Recycling	31 %	Textile
VS6: plastic components used for hydroponics	Recycling	34 %	Plastics
VS7: combination of products	Max. recycling, min. energy recovery	100 %	All iHCW

Goal and scope

The goal of this environmental LCA is to define the environmental impacts associated with the management of iHCW under both linear economy conditions (treatment and landfilling) and circular economy conditions (treatment of iHCW and its subsequent use as a raw material for the development of new products).

The data on treated iHCW (180103, 180202, 180207) in Latvia from 2015 to 2022 shows an average of 2,209 tons of treated waste per year. Since iHCW volumes have been so variable in recent years, the functional unit (FU) in this environmental LCAis 1 ton of treated iHCW.

System description

The technological system boundaries of the present environmental LCA are "gate-to-gate": from generation of the iHCW in hospitals to the end-of-life stage of the iHCW – landfilling (defined as business as usual (BAU) scenario) or one of the six valorisation scenarios (see Fig. 3.2). The time boundaries of the present LCA are October 2022 – September 2023, a period when the inventory data collection was performed. The geographical boundaries of the LCA cover Latvia.

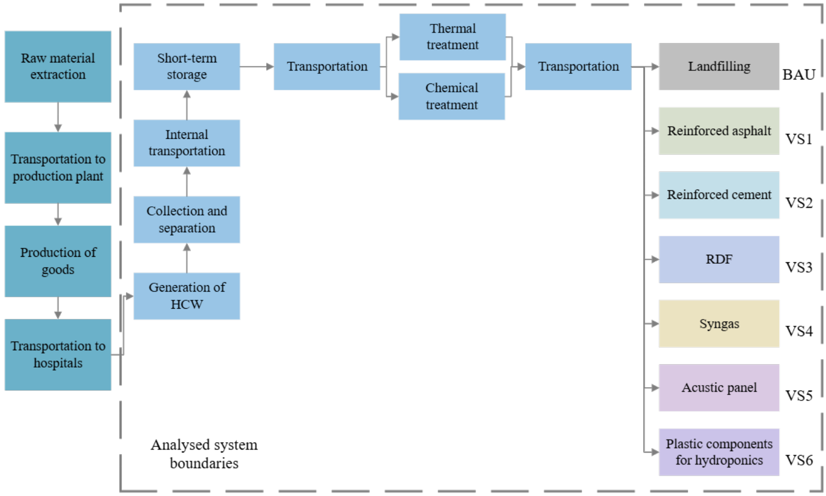

Fig. 3.2. Technological system boundaries of the analysed scenarios.

A detailed description of the valorisation scenarios is provided in the inventory section, while assumptions and limitations applied in the LCA are available in Paper 13.

Life cycle impact assessment

Life cycle assessment modelling software SimaPro v9.5 was used for the study, and ReCiPe 2016 (Midpoint, *Hierarchist* perspective) was used as an impact assessment method.

Environmental life cycle inventory

<u>iHCW generation at healthcare institutions and transportation</u>

The composition of iHCW generated in healthcare facilities varies and depends on such factors as hospital service profile, segregation practices applied in a specific facility, as well as the behaviour of medical personnel in the provision of qualitative segregation. In the current research, a levelized composition of iHCW is utilised for inventory purposes. The compositional data (refer to [72]) was obtained through experimental testing of mixed iHCW collected from various healthcare institutions across Latvia and delivered to two centralised iHCW treatment facilities in the country (detailed data in Paper 13).

<u>iHCW treatment</u>

In Latvia, treatment of iHCW is provided by two centralised iHCW treatment companies – thermal (market share based on collected iHCW mass balance is 48 %) and chemical (market share based on the treated iHCW amount is 52 %) treatment companies [69]. Lastly, in both companies, the treated iHCW is transported to the "end-of-life" or recovery site *via* specialised iHCW treatment companies' owned trucks (load capacity –15 tonnes, EURO 6 (emission limits by vehicle category and engine type)).

iHCW end-of-life

The conventional method for managing treated HCW in Latvia is landfilling, which is also applicable to the BAU scenario. The BAU scenario inventory for both Latvian companies managing iHCW is presented in Paper 13. While the processes of iHCW generation, transportation, treatment, and the transportation of treated iHCW to the end-of-life point are consistent across all analysed scenarios, the end-of-life outcomes for the treated waste vary between the scenarios, as detailed in the description of each scenario and inventory data in Paper 13.

Life cycle impact assessment results

Table 3.2 shows the results of the life cycle impact assessment using the ReCiPe 2016 midpoint (H) method, where the scenario results are indicated in numbers (a positive result indicates that the system influences the given environmental indicator, while a negative result signifies an avoided impact, thereby providing an environmental benefit). The results are also marked with colours on a scale from very low environmental impact (bright green) to very high environmental impact (orange). As seen from Table 3.2, the environmental impacts in VS3 and VS4 are entirely negative due to the high share of iHCW being recycled rather than landfilled.

Table 3.2

ReCiPe 2016 Midpoint (H) Results for BAU and VS1–VS6

	BAU	VS1	VS2	VS3	VS4	VS5	VS6
GW, kg CO_2 eq	1.51E+03	1.25E+03	6.03E+02	1.95E+02	2.37E+02	5.98E+02	1.18E+03
SOD, kg CFC11 eq	8.08E-05	8.21E-05	8.89E-05	2.14E-05	1.87E-04	8.73E-05	6.02E-05
IR, kBq Co-60 eq	2.77E+00	2.66E+00	2.93E+00	7.60E-01	4.33E+01	2.58E+00	1.45E+00
OFHH, kg NO_x eq	2.98E-01	1.96E-01	2.19E-01	1.65E-01	5.39E-01	2.07E-01	3.11E-02
PM, kg PM 2.5 eq	8.76E-02	7.02E-02	7.71E-02	2.80E-02	2.89E-01	6.96E-02	-4.53E-02
OFT, kg NO_x eq	3.13E-01	2.11E-01	2.37E-01	1.88E-01	5.71E-01	2.24E-01	4.18E-02
TA, kg SO_2 eq	1.91E-01	1.49E-01	1.64E-01	7.37E-02	5.68E-01	1.51E-01	–2.22E-02
FE, kg P eq	9.86E+00	4.62E+00	6.56E+00	–3.33E-03	–4.94E-02	6.55E+00	4.57E+00
ME, kg N eq	2.06E+00	6.10E-01	1.81E+00	2.35E-03	5.31E-03	1.80E+00	6.06E-01
TEC, kg 1.4-DCB	9.98E+02	1.20E+03	1.30E+03	4.02E+02	3.82E+03	1.27E+03	9.56E+02
FE_C, kg 1.4-DCB	5.18E+02	3.58E+02	4.59E+02	4.49E-01	6.52E+00	4.59E+02	3.51E+02

MEC, kg 1.4-DCB	6.87E+02	4.73E+02	6.12E+02	1.16E+00	1.20E+01	6.12E+02	4.63E+02
HCT, kg 1.4-DCB	2.04E+01	1.89E+01	2.17E+01	8.87E+00	3.23E+01	2.10E+01	1.10E+01
HNCT, kg 1,4-DCB	1.23E+04	8.07E+03	1.12E+04	2.50E+00	1.22E+02	1.12E+04	7.97E+03
LU, m^2a crop eq	5.72E+00	4.81E+00	4.70E+00	2.56E-01	2.52E+01	4.48E+00	3.68E+00
MRS, kg Cu eq	1.50E-01	1.57E-01	1.79E-01	1.05E-01	4.58E-01	1.62E-01	5.76E-02
FRS, kg oil eq	2.09E+01	2.09E+01	2.43E+01	7.43E+01	7.48E+01	2.29E+01	6.74E+00
WC, m^3	–5.67E+00	–3.11E+00	–6.07E+00	1.58E-01	2.06E+00	–6.09E+00	–3.35E+00

Colour scale: Very low | Low | High | Very high

Overall, the lower environmental impact results were achieved in the VSs, where the entire iHCW stream was recycled for energy recovery (VS3 and VS4), but this does not properly align with the circularity principles, where the focus needs to be given on re-use, recycling and recovery. To keep the focus on circularity, VS7 was created: it represents an integrated recycling and energy recovery process – plastic and textile fractions of iHCW are recycled, the remaining fraction (rubber, metals, wood and mix of fines), which cannot be yet recycled to any of the analysed recycling scenario, is transferred to energy recovery. Based on the LCA results (see Table 3.2), this includes plastics recovery *via* VS5, textiles recovery *via* VS7 and the remaining treated iHCW directed to syngas production through VS4.

For better representation of BAU and VS results, Fig. 3.3 provides the results in a single score manner, and the values are expressed in EcoPoints (Pt). The single-point results are formed from three main groups: iHCW treatment, transportation and end-of-life. As can be seen, the greatest impact is caused by landfilling iHCW, while the impact of transport and iHCW treatment has similar Pt values in all scenarios.

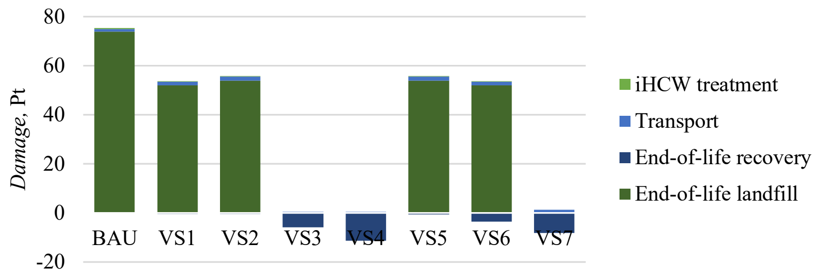

Fig. 3.3. Single score results for BAU and VS1–VS7 (ReCiPe 2016 midpoint (H) method).

Using a literature review to determine the strategic fit of the alternative and the current situation regarding the management of iHCW, several scenarios were defined. Using an environmental sustainability assessment, a more in-depth comparison of the alternatives was obtained, which shows decision-makers the alternative with the lowest impact.

3.2.2. Sustainability approach to the national waste sector

The aquatic sector presents sector-specific challenges that require sustainable management options for the generated waste. A literature review was therefore used to understand the strategic relevance of the management options, and then alternatives were compared based on environmental and economic sustainability results, enabling decision-makers to choose the most suitable alternative for waste management.

Quantification of discarded fishing nets

The methodology is based on three data collection approaches. The first is statistical data collection on import and export of fishing nets, the second is interviews with fishing net manufacturers and retailers, fishermen and association of fishermen, port authorities, waste management companies, national authorities (State Environmental Service, the Ministry of Agriculture of the Republic of Latvia Fisheries Department) and the third – extrapolation of missing data.

The interviews with fishermen revealed that fishing nets retrieved from waters, but not ghosted, are as long as possible repaired and reused directly for fishing or in other applications, such as farming, thus avoiding discarding. Waste managers also confirmed that fishing nets appear irregularly in waste sorting facilities.

The quantity and material composition of ghost nets remain unpredictable, leading to periodic fluctuations in the availability of resources for valorisation. To establish a more stable resource supply, fishing net production companies operating in Latvia could play a key role. These companies generate production scraps that are well-suited for recycling alongside discarded fishing nets, as they are made of the same material.

Methodology and methodological limitations for quantifying manufacturing scraps (pre-consumption) and discarded fishing nets (post-consumption) across all material types are presented in Paper 13. Combining both pre-consumption and post-consumption waste ensures a sufficient and stable supply of resources for recycling.

<u>Amount of discarded fishing nets and manufacturing scraps</u>

Figure 3.4 illustrates the estimates regarding the total amount of fishing net waste, which includes both discarded fishing gear and manufacturing by-products. As depicted, the annual volume remains consistent, except for the years 2021 and 2022, when a significant decrease in fishing net waste was noted. This decline is probably associated with the effects of the COVID-19 pandemic, which disrupted the activities of fishing vessels and manufacturing firms – especially in areas heavily impacted by serious outbreaks.

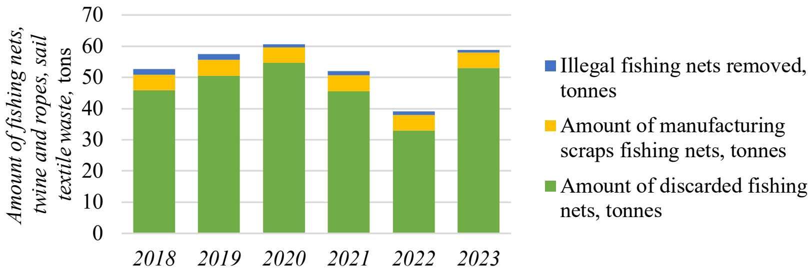

Fig. 3.4. Amount of fishing net waste in Latvia in 2018–2023.

Looking at the amount of manufacturing scraps and discarded fishing nets waste provides insight into the waste dynamics of the sector and the opportunity to assess waste management options. The amount of manufacturing scraps is important because they are off-cuts from the fishing net manufacturing processes and are therefore clean waste that can be subsequently recycled into a high-value product, and do not require a major waste treatment step. Discarded fishing nets data are not systematically recorded and are based on estimates, but the management of this waste is also important, although the amounts in Latvia are smaller than the amount of manufacturing scraps. However, Latvia generates an average of 53 tonnes of fishing net waste that needs to be managed effectively.

The strategic fit assessment of the fishing net management is followed by an environmental and economic sustainability assessment.

Goal and scope

The goal of the study is to evaluate and compare the environmental impact of management scenarios with discarded fishing nets. The functional unit selected for the LCA study is 1 ton of discarded fishing net after pre-treatment (i.e. after the separation of unnecessary fractions, such as organics, from the nets). The avoided burden approach is used to evaluate the environmental impact of different waste management scenarios for different types of fishing nets.

System boundary

The LCA system boundaries defined in the study are "cradle-to-cradle" (for S1–S3) and “cradle-to-grave” (for S4), and as the avoided burden approach is applied, it is modelled that the discarded fishing net, as a resource completely or partially replaces the traditional raw materials used in production of nylon or asphalt additive. Paper 13 presents detailed information about the system boundaries, inventory data, assumptions and limitations of the model.

Inventory

Relevant inventory data, including data on fishing net production, nylon and asphalt production, is obtained from literature review and the Ecoinvent database and is presented in Paper 14.

Impact assessment

The results from the ReCiPe 2016 midpoints method are reflected in Table 3.3. The negative values are considered as benefits to the environment, and the positive values – as negative impacts to the environment. The negative results obtained are considered a benefit to the environment, and the positive results obtained are considered an impact on the environment. The results are marked with colours on a scale from low environmental impact (bright green) to very high environmental impact (orange).

The results show that S1 is the most sustainable of the fishing net valorisation scenarios, but the results of S2 also indicate that it is a sustainable alternative. The results of S3 are moderately sustainable, but the greater environmental impact results from the S4 valorisation scenario.

Table 3.3

LCA Characterization Results

Impact category	**Unit**	**S1**	**S2**	**S3**	**S4**
Climate change	kg CO_2 eq	–7847.76	–636.36	156.10	12080.46
Ozone depletion	kg CFC-11 eq	0.000003	–0.000048	0.000003	0.000024
Terrestrial acidification	kg SO_2 eq	–26.69	–2.06	0.39	28.24
Freshwater eutrophication	kg P eq	–0.39	–0.02	0.02	1.18
Marine eutrophication	kg N eq	–8.95	–0.06	0.02	30.99
Human toxicity	kg 1.4-DB eq	–65.14	–38.04	6.37	5105.51
Photochemical oxidant formation	kg NMVOC	–19.99	–7.95	0.51	29.09
Particulate matter formation	kg PM10 eq	–8.01	–0.66	0.19	9.36
Terrestrial ecotoxicity	kg 1.4-DB eq	–0.06	–0.09	0.02	2.54
Freshwater ecotoxicity	kg 1.4-DB eq	–6.97	–1.70	2.09	1481.87
Marine ecotoxicity	kg 1.4-DB eq	–3.92	–1.84	1.85	1193.81
Ionising radiation	kBq U235 eq	43.03	32.07	42.59	128.51
Agricultural land occupation	m^2a	60.03	56.39	–443.56	1591.82
Urban land occupation	m^2a	–0.93	–7.67	–2.56	61.73
Natural land transformation	m^2	0.02	–0.48	0.01	–2.61
Water depletion	m^3	–228.18	18.07	–0.89	96.98
Metal depletion	kg Fe eq	1.10	–29.30	5.45	64.55
Fossil depletion	kg oil eq	–273.71	–9.18	4.13	322.40

Colour scale:	Low	Medium	High

The environmental damage costs per impact category are reflected in Table 3.4. The most expensive environmental damage categories are particulate matter and ozone depletion. In this case, the impact of ozone depletion and particulate matter formation is related to electricity consumption and fishing net production. Similarly, to the LCA results, some of the environmental damage costs results are negative, thus presenting economic benefits (revenues) for the environment and society.

Table 3.4

Environmental Damage Costs for Fishing Net Waste Management Scenarios Based on 2025 Monetary Values

Impact category	S1	S2	S3	S4
Climate change	–1255.64	–101.82	24.98	1932.87
Ozone depletion	0.00010	–0.00166	0.00011	0.00082
Ionising radiation	0.22	0.17	0.22	0.67
Oxidant formation, human health and terrestrial ecosystems	–65.37	–26.01	1.65	95.14
Particulate matter formation	–977.32	–81.00	23.45	1142.00
Acidification	–172.66	–13.34	2.55	182.72
Freshwater eutrophication	–1.78	–0.09	0.08	5.44
Marine eutrophication	–156.88	–1.14	0.31	543.29
Terrestrial ecotoxicity	–0.00005	–0.00007	0.00001	0.00201
Freshwater ecotoxicity	–0.18	–0.04	0.05	38.08
Marine ecotoxicity	–0.02	–0.01	0.01	4.69
Human toxicity, cancer-related and non-cancer-related	–324.85	–189.72	31.78	25462.73
Land use	7.19	5.92	–54.25	201.07
Total	**–2947**	**–407**	**31**	**29609**

The strategic relevance assessment of the problem of fishing net waste management reflected the critical point regarding the missing common methodology for determining the volume potential of waste. Consequently, a methodology was developed to determine the volume potential, followed by an environmental and economic assessment of management alternatives.

LCA and environmental damage costs showed significant environmental benefits from recycling fishing nets. The results show the importance of avoiding landfill and instead prioritising recycled fishing nets as replacements for new nylon (S1) and asphalt reinforcement (S2) to provide the greatest environmental benefit. Although synthesis gas production (S3) has a greater impact than S1 and S2, it is still a desirable secondary waste management option.

3.3. Utility value approach

If, after completing the sustainability assessment, decision-makers require the integration of multi-dimensional factors (such as environmental, economic, social, and strategic), along with both qualitative and quantitative data to compare or rank potential resource value chain solutions, the utility value method should be applied. This method offers a holistic approach to decision-making, providing more strategic and sustainable justifications for the results.

Within the Thesis utility value approach is applied to several problem-solving areas:

1) multifactorial assessment of alternative raw materials used in fish feeds;
2) environmental and technical assessment of a metal melting furnace to obtain a comparison of possible alternatives;
3) a cross-country comparison based on GHG emission indicators.

4) the possibility for municipalities to use RES technologies for heating of public and multi-apartment buildings;
5) identifying the best use of agricultural by-products;
6) the environmental, technical and economic performance of infectious healthcare waste management technologies.

3.3.1. Utility value approach to the agriculture sector

Strategic fit assessed potential fish feed raw material alternatives, then environmental sustainability assessed potential raw material alternatives, as well as potential fish feed alternatives. Economic aspects were also assessed as conventional LCC and damage costs for fish feed alternatives, and social assessment for fish feed protein raw material alternatives. After a strategic fit, a technical assessment of fish feed alternatives was also carried out. The results obtained from the environmental, economic, social and technical assessment were entered into the TOPSIS method to be able to make a decision on the best fish feed, taking into account four dimensions as utility value.

The use of insects in fish feed production is one of the most sustainable and economically viable alternatives [73]. Also, insect meals are rich in polyunsaturated fatty acid (PUFA), which is one of the healthy fats [74]. The nutritional value and quality of the feed are essential for fish feed, and the physical properties of the feed are more important for aquatic animals than for terrestrial animals [75]. When choosing new feed ingredients, it is necessary to look at how this affects the technical properties of fish feed.

Life cycle analysis

To assess the sustainability of fish feed raw materials, ACA evaluates existing and potential alternatives for proteins, oils and pigments.

Goal and scope

The goal is to assess the environmental impact for protein (black soldier fly, yellow mealworm and soybean), oil (microalgae oil, rapeseed oil and fish oil) and pigment (natural pigments from the microalgae *Haematococcus Pluvialis* and synthetic pigments).

The boundaries of the LCA system include raw materials and energy required for production, but transport, as well as generated by-products and waste, are not taken into account. The defined functional units within the framework of the study are:

- when analysing feed alternatives for the assessment, 1 ton of animal feed produced;
- for the assessment of feed components (proteins, oils and pigments) alternatives, 1 kg of the final product (protein, oil, pigment).

System boundaries

To be able to compare different alternatives, it is defined that this LCA accounts for the product life cycle as “cradle to gate”, where the assessment is from resource extraction to factory gate. System boundaries for protein alternatives are described in Paper 7, for oil alternatives in Paper 8, and for pigment alternatives in Paper 9.

Inventory

The LCA inventory section has a complete list of raw materials to produce one functional unit for all products. Input data is taken from the literature review and Ecoinvent database, and the collected input data are expressed for 1kg of the final product.

- LCA inventory data for protein alternatives are presented in Paper 7.
- Microalgae oil, rapeseed oil, and fish oil inventory data are presented in Paper 8.
- Inventory data for pigment alternatives are presented in Paper 9.

Impact assessment

The PEFCR for food-producing animal feed defines the relevant impact assessment categories, and the EF 3.0 methodology was used to obtain the impact assessment results for the assessment of feed alternatives. The results of the full impact assessment for protein alternatives are presented in Paper 7, for oil alternatives in Paper 8, and for pigment alternatives in Paper 9.

- By climate change category, the highest impact is by yellow mealworm protein (1.7 kg CO_2 eq), followed by soybean protein (0.83 kg CO_2 eq) and black soldier fly protein (0.1 kg CO_2 eq). Black soldier fly protein has the lowest environmental impact in most categories, while yellow mealworm protein has the highest impact, particularly in land use, water use, and eutrophication. Soybean protein falls in between but generally has a higher impact than black soldier fly protein.
- By climate change category, the highest impact is by microalgae oil (9.4 kg CO_2 eq), followed by rapeseed oil (1.7 kg CO_2 eq) and fish oil (1.4 kg CO_2 eq). Microalgal oil is more intensive and has a higher environmental impact in terms of climate change, eutrophication and ecotoxicity compared to rapeseed oil and fish oil.
- By climate change category, the highest impact is by microalgae pigment (335 kg CO_2 eq), followed by synthetic pigment (7.2 kg CO_2 eq). Synthetic pigments are generally more environmentally friendly than microalgal pigments in most impact categories, including climate change, human toxicity, eutrophication, and resource use.

The protein, oil and pigment alternatives had significant differences in terms of environmental impacts. However, an important aspect in fish feed is how these potential fish feed raw materials are used in the overall fish feed production, what their proportions are and how the fish take up these new fish feed types. After several fish feed trials, five types of fish feed were defined, which were analysed according to environmental, economic and social dimensions, as well as technical aspects.

Goal and scope

The goal is to assess the environmental impact of five fish feeds, where the proportion of the other fish feed ingredients varies according to the protein source and is reflected in five alternatives:

- A1_ traditional protein – 100 % fish meal;
- A2_ traditional protein – fish meal and 5 % of traditional protein replaced by black soldier fly protein;

- A3_ traditional protein – fish meal and 10 % of traditional protein replaced by black soldier fly protein;
- A4_ traditional protein – fish meal and 15 % of traditional protein replaced by yellow mealworm protein;
- A5_ traditional protein – fish meal and 30 % of traditional protein replaced by yellow mealworm protein.

The scope is a necessary ingredient for fish feed, although required energy consumption, transport and packaging, as well as the by-products and waste generated, are not considered. The function unit for LCA is 1 tonne of animal feed based on PEFCR feed for food-producing animals [76].

System boundaries

Fish feed LCA is "cradle to gate", and system boundaries are given in Fig. 3.5. The impact of raw materials is considered.

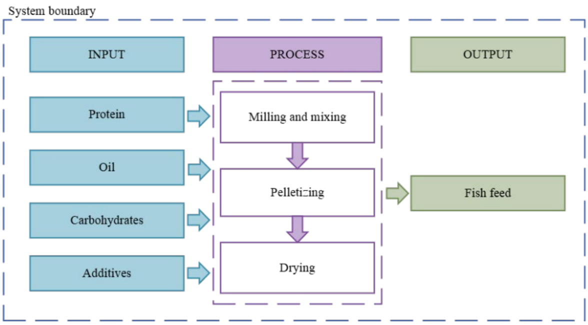

Fig. 3.5. System boundaries for fish feed.

Inventory

Table 3.5 shows the inventory data for five fish feed alternatives, with changes mainly in the form of the protein, which are partly attributed to some insect protein source.

Table 3.5

Fish Feed Alternative Inventory Data

Ingredients	**100 % fish meal**	**5 % replaced with black soldier fly larva protein**	**10 % replaced with black soldier fly larva protein**	**15 % replaced with yellow mealworm larva protein**	**30 % replaced with yellow mealworm larva protein**
Black soldier fly larvae meal	-	5	10	-	-
Mealworm meal	-	-	-	15	30
Fish meal	20	20	20	20	20
Soy protein concentrate	20	20.04	19.71	15.3	2
Wheat gluten	14.5	12.9	11.5	9.5	9.6
Vegetable raw material	18.8	18.8	18.8	18.8	18.8
Fish oil	13.3	13.3	13.3	13.4	14.2
Rapeseed oil	6.2	4.4	2.6	3.6	-
Other (incl. pigment)	7.2	5.6	4.1	4.4	5.4
Yttrium	0.05	0.05	0.05	0.05	0.05

Assumptions

Assumptions and sensitivity analysis for protein alternatives are presented in Paper 7, for oil alternatives in Paper 8, and for pigment alternatives in Paper 9.

Impact assessment

After defining the five fish feeds, LCA results were obtained for the entire feed. Table 3.6 summarises the environmental impact results per 1 ton of fish feed. Overall, the environmental impact of feeds where the protein is partly insect protein results in environmental savings, particularly in terms of climate change and eutrophication.

Table 3.6

LCA Results of Fish Feed Alternatives

Impact category, unit	**100 % fish meal**	**5 % replaced with black soldier fly larva protein**	**10 % replaced with black soldier fly larva protein**	**15 % replaced with yellow mealworm larva protein**	**30 % replaced with yellow mealworm larva protein**
Climate change, kg CO_2 eq	2708.11	2331.15	1968.55	2199.53	2346.57
Ozone depletion, kg CFC11 eq	0.00027	0.00026	0.00024	0.00025	0.00026
Human toxicity, cancer, CTUh	0.000006	0.000005	0.000005	0.000006	0.000007
Human toxicity, non-cancer, CTUh	0.000041	0.000035	0.000030	0.000043	0.000045
Particulate matter, disease inc.	0.00021	0.00018	0.00015	0.00018	0.00021
Ionising radiation, kBq U-235 eq	64.56	54.70	45.44	58.63	75.33
Photochemical ozone formation, kg NMVOC eq	8.87	8.08	7.31	8.48	9.46
Acidification, mol H+ eq	14.93	13.18	11.49	15.22	17.44
Eutrophication, terrestrial, mol N eq	44.62	38.90	33.32	48.68	56.51
Eutrophication, freshwater, kg P eq	0.53	0.45	0.38	0.44	0.51
Eutrophication, marine, kg N eq	9.30	8.23	7.14	12.31	14.89
Ecotoxicity, freshwater, CTUe	97729.89	88337.57	78714.88	87455.20	79705.46
Land use, Pt	80726.97	75247.93	69653.32	88135.89	93985.75
Water use, m^3 depriv.	1399.08	1251.31	1115.30	1551.14	2112.78
Resource use, minerals and metals, kg Sb eq	0.007	0.006	0.005	0.007	0.009
Resource use, fossils, MJ	24063.16	19112.91	14466.47	15803.78	19214.63

Colour scale: Low Medium High

Sensitivity analysis

Sensitivity analysis is performed to determine how the replacement of a specific component affects environmental performance. The results of the sensitivity analysis show that changes in the insect diet (by introducing insect larval protein) significantly affect the environmental performance results due to the impact of the insect feed type. It is also important to consider the energy used in the production of raw materials, as the type of energy resource affects the overall environmental impact of the product. Detailed results of the sensitivity analysis are presented in Papers 7, 8 and 9.

Life cycle costing

To evaluate fish feed from an economic perspective, the conventional LCC method was used. The differences in the raw material ratios of each feed were considered, and the costs were estimated based on publicly available raw material prices in 2022. The publicly available data were for different amounts, so all aggregated raw material price data were converted to 1 kg of feedstock. The cost of protein sources is a significant factor in the overall cost of fish feed, as they make up most of the feed composition.

Using environmental sustainability fish feed models, damage cost estimates for fish feed alternatives were obtained by changing the impact assessment category. Figure 3.6 shows the total results for fish feed alternatives considering conventional LCC results and environmental damage cost results.

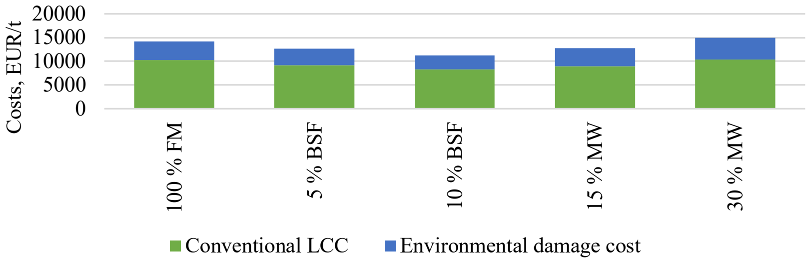

Fig. 3.6. Results of conventional LCC and environmental damage cost results of fish feed alternative.

Traditional LCC and damage cost economic valuations are in the same order of fish feed alternatives, and therefore, the total will also correspond to the individual economic valuation.

Social sustainability

To assess the social impact of protein, which is one of the main ingredients in fish feed, the UNEP Guidelines methodology was used.

The social dimension assessment considered the country of production of each protein alternative: black soldier fly protein is sourced from Denmark, yellow mealworm protein is sourced from Norway, fishmeal protein is sourced from Peru, and soybean protein is sourced from Brazil (Table 3.7).

Table 3.7

S-LCA Data and Assessment [77–84]

Category	Subcategory	Black soldier fly protein	Yellow mealworm protein	Fishmeal protein	Soybean protein
Worker	Fair salary	No national minimum wage; wages set by collective bargaining.	Minimum wages are set *via* collective bargaining, not nationally mandated.	The law sets a national minimum wage above the poverty line.	The law guarantees a minimum wage above the poverty line.
	Average weekly hours per worker	34.5	33.5	37.3	37.9
	Share of workers with 49+ weekly hours	6 %	4 %	31 %	12 %
	Forced labour	The law bans all forced and child labour, with effective enforcement.	Forced labour is criminalised and strictly enforced by the government.	The law bans "slave labour," incl. forced labour, debt bondage, long hours and degrading conditions.	"Slave labour", incl. forced work, debt bondage, long hours and abuse, is banned by law.
	Equal opportunities/ discrimination	1.3 % of workers faced discrimination, rising to 20 % among minority youth (ages 15–24) in the service sector.	Women earned 12 % less; 46 % held part-time jobs. Immigrant unemployment was higher, 7.1% among Africans.	Women earned 72 % of men's wages; pregnant workers faced bias despite equal pay laws.	78 % of men, 56 % of women employed; NGOs report bias in pay and promotion persists.
	Health and safety (workers with labour health insurance (%))	88	90	7.4	48.7
	Employment ratio (%)	60 %	63 %	69 %	57 %
Local community	Access to material resources	The company uses local food waste and organic by-products to produce insects.	It offers sustainable products that cut methane, water use and land consumption.	The company sources its product from anchovy fishing.	It employs certified advanced technology for safety, productivity and sustainability.

Table 3.7. continued

	Access to immaterial resources	Good accessibility	Good accessibility	Difficult accessibility	Difficult accessibility
Value chain actors (excl. consumers)	Promoting social responsibility/supplier relationships	Maximising resources by using local food waste and organic by-products *via* industrial synergies.	It prioritises environmental impact by producing sustainable products and reusing delivery boxes.	The company builds long-term partnerships to enhance the quality of life and supports employee growth.	It supports local communities and motivates employees with career growth and added benefits.
Society	Public commitments to sustainability issues	77.9	59.3	39.8	43.6
	Contribution to economic development (2022)	3.8 %	3.3 %	2.7 %	2.9 %
	Poverty alleviation	1.18 %	1.96 %	4.22 %	6.07 %

Evaluations scale: *+2* *+1* *0* *–1* *–2*

The results indicate that the insect-based protein alternatives have better social outcomes than the other two protein sources. In particular, the better outcomes are related to sustainability, fair wages, working conditions and resource availability. The social evaluation of fishmeal protein is more negative, especially due to the depletion of local resources, as well as the working environment. Similarly, the social evaluation of soy protein is negative, with negative social impacts on the working environment.

Utility value

The aim of utility value is to find the best fish feed alternative, considering the environmental impact of the feed, feed costs, social impact, and technical parameters of the feed. Input values for TOPSIS and sensitivity analysis are presented in Paper 12, and Fig. 3.7 shows TOPSIS results for five fish feeds of different composition. 100 % FM alternative has the lowest rating in this case, and this is the conventional fish feed composition. However, the best alternatives are 10 % BSF and 15 % YM, although slightly different proportions of ingredients and different alternative protein raw materials are used, the same result was obtained.

Fig. 3.7. Comparison of the utility value of fish feed composition alternatives, TOPSIS result.

3.3.2. Utility value approach to the national industry sector

To clarify the possibilities of using existing and more environmentally friendly metal smelting furnace technologies in Latvia, a SWOT analysis was performed to clarify the strategic fit as an analysis of the efficiency of Latvian metallurgical enterprises and to determine the utility value of 8 smelting furnaces according to 11 criteria using the TOPSIS method.

To determine strategic fit, a literature analysis was conducted regarding technological processes, as well as interviews with industry representatives [85], [86]– [87]. Now, nationwide metal processing enterprises rely on their strength and resources received from local sellers. The enterprises use natural gas as fuel instead of coke (or the amount of coke is kept to a minimum, like in Hidrolats, Evan Group and Fonekss Metals companies). In this way, the amount of CO_2 emissions from the melting process can be reduced. The enterprises have developed a system for attracting experts. The hiring of young specialists and students is stimulated to improve the skills of employees and develop new ways to improve the efficiency of the enterprise. Ways are also being considered to obtain funding from EU funds, which could contribute to the development of factories.

The *strengths* of Latvia's scrap metal smelting industry are its compact geographical location, which reduces logistics costs. Modernised equipment increases efficiency and reduces energy consumption. Close cooperation between stakeholders and direct relations with customers increase reliability. Recycling and reuse of metals support sustainability, and several collection points encourage public participation.

The industry's *weaknesses* are a lack of skilled workers and outdated technology due to limited funding for modernisation. It is highly energy-intensive, dependent on a single energy supplier and has few sustainable alternatives. A small sales market and increasing environmental demands increase financial instability and make long-term planning difficult.

The industry has the *opportunity* to attract foreign experts, partners and investors to boost technological and economic growth. Expansion into foreign markets, the introduction of CO_2 capture systems and research into alternative energy sources can improve sustainability and efficiency.

Threats include an ageing workforce, skills shortages and rising commodity prices that reduce profits and liquidity. Market and political instability, as well as volatile energy prices and changing suppliers, increase financial risks and discourage investment in modern, environmentally friendly equipment.

To assess the utility value of various scrap metal melting furnaces, eight furnaces were defined and compared according to 11 technical and environmental criteria using the MCDA method TOPSIS. Detailed input data values are presented in Paper 11. The results in Fig. 3.8 show that, based on input data and after TOPSIS method assessment, the electric arc furnace (EAF) is the most efficient. This result is consistent with the literature sources.

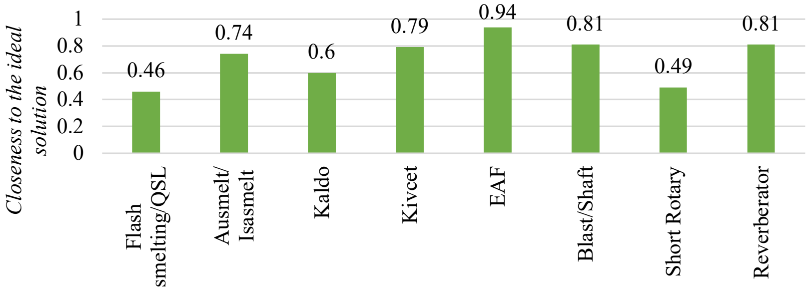

Fig. 3.8. Utility value comparison for metal melting furnaces, TOPSIS result.

The strategic fit showed that the scrap metal smelting or recycling industry in Latvia is a place for growth, directly related to the high energy intensity of the industry and that it is necessary to find solutions to more environmentally friendly technologies and the use of renewable energy resources, and that the industry also needs to expand beyond the borders of the country to ensure financial stability. It is also necessary to think about growth in the field of employees and in the technological field.

The utility value showed that half of the metal melting furnaces examined are quite close to the ideal option. The main advantage of EAF is the ability to work with a large amount of scrap metal, as well as the relatively low amount of lead produced in the waste, low SO_2 and CO_2

emissions. Due to the ability to use electricity, this furnace is also characterised by low consumption of fossil fuels and given the ability to use electricity generated from renewable energy sources, EAF can be considered the most environmentally friendly among other analysed metal melting furnaces.

3.3.3. Utility value approach to the international energy sector

Strategic fit was assessed through quantitative and qualitative data analysis for selected EU countries, which were then compared using the TOPSIS ranking method according to defined quantitative criteria to determine GHG emissions performance.

For the comparison of GHG performance, eight EU countries have been selected, ensuring that different national environmental, economic and political backgrounds are covered. The main point of reference for selecting countries for comparison was the GHG intensity of energy consumption. Latvia was chosen as the main focus of analysis, alongside Ireland and Slovenia, classified as medium GHG intensity. Estonia and Lithuania were selected as the countries with high GHG intensity, whereas Finland, Denmark and Sweden were chosen to represent countries with relatively low GHG intensity. Detailed data analysis is presented in Paper 2.

The GHG assessment considered the results of a literature review on the criteria to be used for cross-country comparisons, as well as the corresponding data from the Eurostat database for the period 2005–2015, which were normalised using the MIN-MAX method to ensure comparability of indicators.

The AHP method was used to determine the weights of the criteria, where the criteria were compared in pairs on a scale from 1 to 9, and the evaluation was done by five experts. The criteria evaluated are GHG emissions per capita (as a primary measure of emission intensity); revenues from environmental taxes (reflecting the role of environmental policy in fiscal measures); household energy consumption per capita (indicating energy demand at the housing level); investment as a share of GDP (reflecting economic progress and sustainability); solid fossil fuel consumption (as a major source of GHG emissions); and renewable energy consumption (indicating the transition to cleaner energy sources).

Figure 3.9 shows the TOPSIS results for eight EU countries, ranked by their GHG emissions over the period 2005–2015. The TOPSIS results obtained are relatively similar, but Sweden is the best performer with low emissions per capita and high renewable energy consumption, although the worst performer is solid fossil fuel consumption. Ireland came in second place, mainly due to high environmental tax revenues and low fossil fuel consumption, despite having the highest GHG emissions per capita. However, Latvia came in last place, mainly due to high household energy consumption and heavy reliance on fossil fuels.

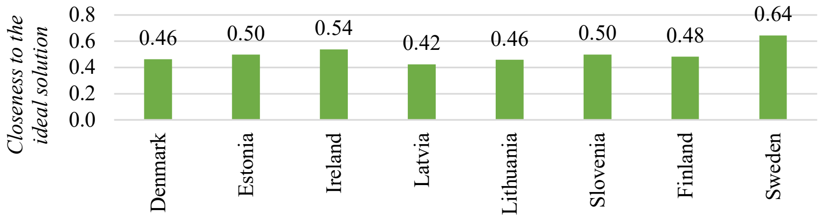

Fig. 3.9. Comparison of utility values for countries according to GHG indicators, TOPSIS result.

Although countries were selected based on strategic fit, with different environmental, economic and political backgrounds, the resulting utility values are in a relatively similar range. This means that countries can learn from each other some criteria that can improve their overall national GHG emissions performance.

3.3.4. Utility value approach to the municipal energy sector

Strategic feasibility and utility value of the use of renewable energy resources in one of the Latvian municipalities were determined, possible RES technologies were compared, as well as district (DH) and individual (IH) heating alternatives.

The Carnikava DH system consists of six interconnected boiler houses and heating networks. The total length of the heating networks is 2,837 m, of which 1,156 m is industrially insulated. All boiler houses have *Viessmann* natural gas boilers with different capacities, from 520 kW to 1,500 kW. Losses in heating networks range from 15 % to 17 %. The loss value indicates that the heat transmission infrastructure is inferior. The main reason is the preparation of hot water outside the heating season. As summer consumption is meagre, the percentage of heat losses is very high in the summer months.

According to 2019 data, the municipality has a population of more than 9,500 inhabitants, and six municipal buildings were analysed. Therefore, municipal buildings vary greatly in their functionality and building characteristics, and they are not connected to a centralised heating system. Based on the average monthly heat and electricity consumption from 2019 to 2021, the largest energy consumers are the primary school, the preschool educational institution and the office building. The highest heat consumption is during the heating season, especially in winter. In summer, heat consumption is for hot water preparation.

Various RES alternatives were analysed for 28 residential, six municipal, and five commercial buildings in the municipality to promote the use of RES resources and replace the use of natural gas.

DH1_Wood chip boiler with flue gas condenser
DH2_Wood chip boiler + PV panels + heat pump solution
DH3_Wood chip boiler + solar collectors with thermal energy storage
DH4_ Pellet boiler
DH5_Pellet boiler + PV panels + heat pump solution
DH6_Pellet boiler + solar collectors with thermal energy storage

IH1_Pellet boiler
IH2_Heat pump solution + PV panels
IH3_Solar collectors with thermal energy storage natural gas boiler
IH4_Solar collectors with thermal energy storage pellet boiler

Figure 3.10 the TOPSIS results on the utility value are shown. The best alternatives to DH are a wood chip boiler with solar panels and a heat pump, as well as a wood chip boiler with solar panels and thermal energy storage. The best IH are a heat pump with solar panels, as well as solar collectors with thermal energy storage and a natural gas boiler.

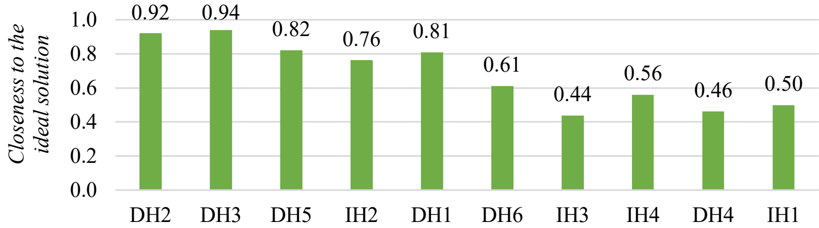

Fig. 3.10. Comparison of the utility value of RES technology in heating supply in municipal, public and residential buildings, TOPSIS result.

Taking into account the analysis of the case study and the strategic relevance of promoting the use of renewable energy sources in heating, as well as evaluating alternatives according to utility value, where environmental, economic and social criteria were taken into account, a relatively broad assessment of alternatives was obtained, which will help decision-makers understand in which direction to continue and implement the initiated plan.

3.3.5. Utility value approach to the agriculture sector

Traditionally, bran by-products from agriculture are used as waste or added to livestock feed. However, they can be used as a resource for analysis. With strategic relevance, product groups are obtained from the literature review with qualitative data analysis, where various wheat by-products are used. However, with the utility value TOPSIS method, the possibilities of using bran by-products are compared according to environmental, social, economic and technical criteria.

By reviewing the available scientific literature, strategic fit was determined, and around 30 products were obtained where wheat by-products can be used. Products were obtained from four wheat by-products: bran, straw, husk, and dust. Wheat is also the most common type of cereal in Latvia and the world [88,89]. Of these by-products, bran is the most widely used, while dust is used to produce only one product, bio-based packaging [90]. Products were divided into six groups: packaging materials, building materials, adsorbents, fuels, thermal insulation materials and chemicals.

The TOPSIS method compared seven products, which were compared according to their commercialisation potential based on environmental, social, economic and technical criteria. The criteria were assessed by experts according to a 5-point scale: 1 – does not meet the requirements; 5 – meets the requirements, except for the criterion of product price comparison, which is evaluated as a percentage. Using the TOPSIS method a comparison of potential products was performed according to environmental, economic, social and technical criteria; the input data is presented in Paper 5.

The TOPSIS results in Fig. 3.11 show that the most sustainable option for bran by-products is bio-composite production due to the favourable product price. However, if price were excluded as a criterion, single-cell oil would be ranked highest. Another good result was achieved by producing an absorbent from a bran by-product due to its lower cost and environmental impact compared to conventional adsorbents.

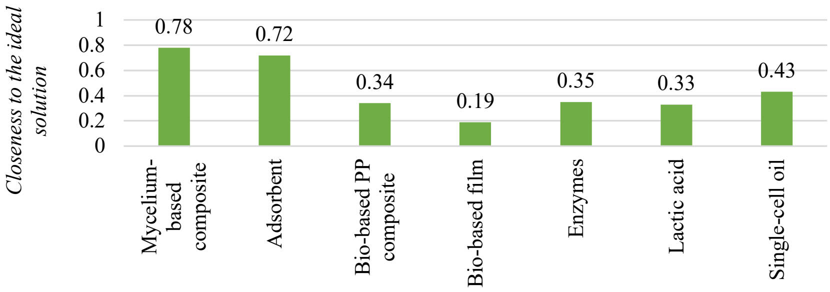

Fig. 3.11. Comparison of utility value for the use of bran by-products, TOPSIS result.

As can be seen from the strategic fit, there are several sectors where it is possible to sell wheat by-products from agriculture, and these products can then be used in various sectors. However, after determining the utility value, a large difference is shown between the analysed options, which, of course, makes decision-making easier.

3.3.6. Utility value approach to the international industry sector

The increase in the amount of infectious healthcare waste and the requirement to reduce the amount of waste deposited in landfills, and the move towards a circular economy, create a need for effective management of this type of waste. Consequently, the strategic fit of treatment technology was examined, so that infectious healthcare waste could then be recycled, and management technologies were compared according to environmental, technical and social criteria using a cost-benefit approach.

Indicators are delineated as data from technology and as evaluation from literature analysis, as seen in Paper 4.

In Fig. 3.12 the utility value results from the MCDA method TOPSIS are shown, and the highest evaluations has an autoclave with integrated shredding waste treatment technology, with a value 0.82, and the second best technology after the criterion is chemical treatment technology – sodium hypochlorite-based technology with a value of 0.73.

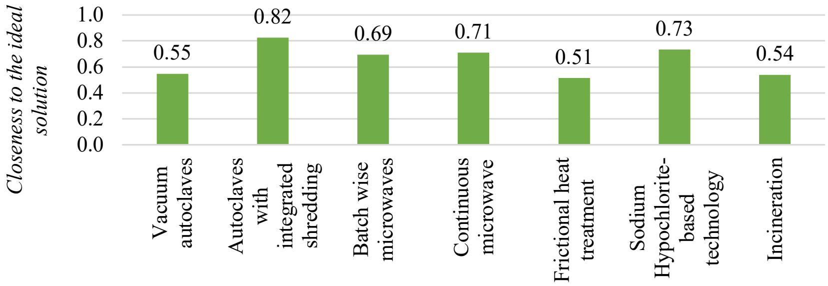

Fig. 3.12. Utility value comparison for iHCW technologies, TOPSIS result.

Technology assessment is an essential first step in decision-making, but strategic fit from an economic perspective can be one of the determining factors in technology selection.

4. CONCLUSIONS

This Doctoral Thesis introduces a thorough, yet flexible, multi-factorial decision-making methodological framework aimed at improving sustainable decision-making within resource value chains. The formulated methodology is based on an incremental complexity framework that merges three vital decision-making levels – strategic fit, sustainability assessment, and utility value – and is relevant at international, national, municipal and sectoral levels in the energy, waste, industry and agriculture domains.

This methodology allows multi-factor analysis using both qualitative and quantitative data, ensuring that decisions are consistent with environmental, economic and social standards. It supports consistent, sustainable results at all levels of governance and allows both the independent use and integration of cross-sectoral data, linking international and local objectives without complicating decision-making.

The methodology was adapted to nine varied case studies, each requiring the identification of the most sustainable solutions across different segments of the resource value chain. These applications substantiated the Thesis hypothesis: a multi-factorial methodology founded on incremental complexity can successfully steer decision-making across multiple governance levels and resource sectors while pinpointing the most suitable sustainable outcomes.

At the strategic fit level, the methodology facilitates initial evaluation of possible solutions – either qualitatively or quantitatively – based on their alignment with strategic objectives. For example, case studies on energy consumption in Latvian agricultural sub-sectors highlighted the necessity for the development of region- and sector-specific development and action strategies to achieve sustainability goals.

The sustainability assessment level offers a deeper analysis of environmental, economic or social impacts, tailored to the specific context. This was adapted in case studies from the national waste sector for infectious healthcare waste, as well as used fishing nets and fishing nets production scraps solution were evaluated using life cycle assessment, environmental damage cost assessment and social life cycle assessment, providing a robust foundation for sustainability-oriented decision-making.

The utility value level expands the decision-making viewpoint by facilitating unidimensional or multidimensional evaluations tailored to specific contextual needs *via* multi-criteria decision-making analysis. This phase is crucial for comparing alternative solutions and ensuring well-rounded decisions. In the fish feed case study, the complete methodology was employed – from the strategic relevance of agricultural by-products to environmental, economic, and social evaluations (*via* LCA, LCCA, S-LCA) and technical assessment – resulting in a comprehensive utility value judgment. Utility value evaluations were also implemented in other case studies, such as prioritization of scrap metal melting technologies in Latvia, comparative ranking of eight European countries based on GHG emission metrics, assessment of RES technologies in municipal infrastructures, evaluation of bran by-product utilization and global comparisons of iHCW treatment technologies – in all highlighting the adaptability of the multi-criteria decision making analysis to various resource value chain problems and decision scopes (international, national, municipal and sectoral).

In summary, the developed methodology makes a significant contribution to sustainable and intelligent resource value chain management. It empowers stakeholders (policymakers, municipality officers, company owners, investors, etc.) to make strategic, sustainability-focused and value-driven decisions, facilitating the systemic transformation of resource value chains. This aligns with and propels the objectives of the European Green Deal, fostering a circular, inclusive and climate-resilient economy.

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