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DECISION-MAKING ALGORITHM OF THE CIRCULAR ECONOMY

Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (PhD), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on March 12, 2026, at the Faculty of Natural Sciences and Technology of Riga Technical University, Āzenes iela 12 K1, 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 (PhD) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Terēza Bezručko ……………………………. (signature)
Date: ………………………

The Doctoral Thesis is written as a set of publications in Latvian, it contains an introduction, three chapters, conclusions, 40 figures, 21 tables, and eight publications in the appendices, a total of 259 pages.

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INTRODUCTION

By emphasising the need to move from a linear economy to a circular economy model, the European Union (EU) has set a clear course towards sustainable development. The traditional approach of “take-make-dispose” is no longer considered a viable solution in the context of today's resource consumption and environmental load. The circular economy offers an alternative that focuses on extending the life cycle of existing materials and products by reusing, repairing, recycling and returning them to the national economy. This approach allows to significantly reduce waste and promotes resource efficiency throughout the economic value chain.

Statistics show that every year, more than 2.2 billion tons of waste are generated in the EU. A significant proportion of it is still disposed of in landfills. Simultaneously, industrial processes and product use account for 9.1 % of total greenhouse gas (GHG) emissions at the EU level, whereas waste management accounts for 3.32 %. Up to 80 % of a product's total environmental impact is determined just at the product's developmental stage. It means that sustainable production must be based on strategic planning from an early stage; therefore, in February 2021, the European Parliament adopted a resolution on the new circular economy plan, setting ambitious targets for achieving carbon neutrality by 2050, as well as binding criteria for the use of materials by 2030.

The Thesis includes an analysis of resources (textile waste, wood processing waste, food processing by-products waste and energy waste). The author used multi-criteria decision analysis, life cycle assessment, bibliometric analysis, system dynamics, fuzzy cognitive maps and CO_2 calculations. Challenges on the way to higher value-added products were defined and taken into account.

Topicality

The European Parliament has developed and determined the need to transition from a linear economics model to a circular. The current priority is to minimise waste, lengthen the product life cycle, and, ideally, turn waste from one production process into raw materials for another production process, thereby returning it to the national economy. The resolution on the new circular economy action plan provides additional measures to achieve a carbon-neutral, ecologically sustainable, non-toxic circular economy by 2050. It also includes stricter recycling provisions and binding goals for material use and consumption by 2030; however, each Member State must find its own most effective solution for achieving targets in different areas of the national economy.

Aims and Tasks

The Thesis aims to investigate which methods can be used and how they can be combined so that production process residues or products that are at the end of their life cycle can be used as resources in the production of a new, higher added-value product. Any recycling of resources reduces the impact on the climate, provides a path to sustainable development and promotes the development of products with higher added-value.

To achieve the aim, three tasks were set:

1) select resources that are production residues or end-of-life products, focusing on the potential resources that are either available or stored in large quantities in landfills;
2) select appropriate analysis methods, define challenges on the path to high added-value products, and create a set or combination of methods as a tool system for the development of the circular economy;
3) approbate a set of methods by evaluating various production processes, assess the obtained results, and draw reasonable conclusions.

Scientific Novelty

The comprehensive and unique novelty of the Thesis is the use of various scientific methods at the same time, their sequential combination to develop and speed up the progress toward a circular economy, toward products with higher added value. The set of methods has also been used to dynamically refine the implementation steps, identifying the most significant aspects and defining potential solutions to the problems. In the Thesis, new and compatible selection criteria were developed for the scientific methods used. The strengths and weaknesses of each production process have been identified in terms of resource consumption, energy efficiency, waste reduction and emissions.

During the development of the Thesis, life cycle assessment and multi-criteria analysis methods were used repeatedly and in various combinations. System dynamics modelling, fuzzy cognitive mapping and GHG (CO_2) calculations were used. Scientific literature was analysed extensively in various sections.

Such a dynamic, multi-level and multi-dimensional analysis as a structural view is categorically necessary for the progress of the circular economy and can be considered the central scientific novelty of the Thesis.

Hypothesis

One of the main directions for the circular economy toward sustainable development is reducing product consumption.

Practical Importance

The findings and conclusions presented in the Thesis are useful for Latvia's circular economy, especially in the field of textile waste and wood utilisation, in the process of policy development and improvement, taking into account the individual efforts made so far in this sector in Latvia. The results are important for institutions of various levels and for members of society who are involved or willing to become involved in the use of industrial by-products and the creation of new businesses.

The reuse of textile waste is important for both the officials of ministries and government agencies, as well as for local governments that are seeking to attract new investors and the investors of start-ups.

The solutions offered for the full utilisation of wood are significant for potential investors in forest and wood processing.

The wide range of food production by-products is a future challenge for potential investors. An example of scientific research in this field could address and encourage the search for solutions for the use of these by-products.

The use of energy residues is relevant for all energy users.

Structure of the Thesis

The Thesis is based on a collection of eight scientific publications, which focus on resources that are residues from other production processes or products that are already at the end of their life cycle and their path to becoming products with higher added-value, by using various methods, while facing problems and challenges.

The Thesis includes a literature review, which discusses potential types of resources that are initially sorted or unsorted waste or other by-products of the production process, as well as an overview of the experience gained so far in the academic analysis of achieving the objectives.

Six research methods were used in the Thesis:

1) multi-criteria decision analysis method;
2) fuzzy cognitive maps;
3) system dynamics;
4) life cycle analysis;
5) GHG calculations;
6) bibliometric analysis.

In the Thesis, solutions for products with high added-value are evaluated and selected, assessing their highest possible potential.

The structure of the Thesis conceptually has been designed as a flower, where the pistil symbolises the central concept of the theoretical core of the circular economy. The petals represent the various aspects of the circular economy and their interrelationships, which together form a systematic view of the problem. The different colours and shapes of each petal indicate the unique contribution of a particular element to the overall concept, while the whole “flower” illustrates the vastness, integration and interdisciplinary nature of the circular economy. The structure of the Thesis is illustrated in Fig. 1.

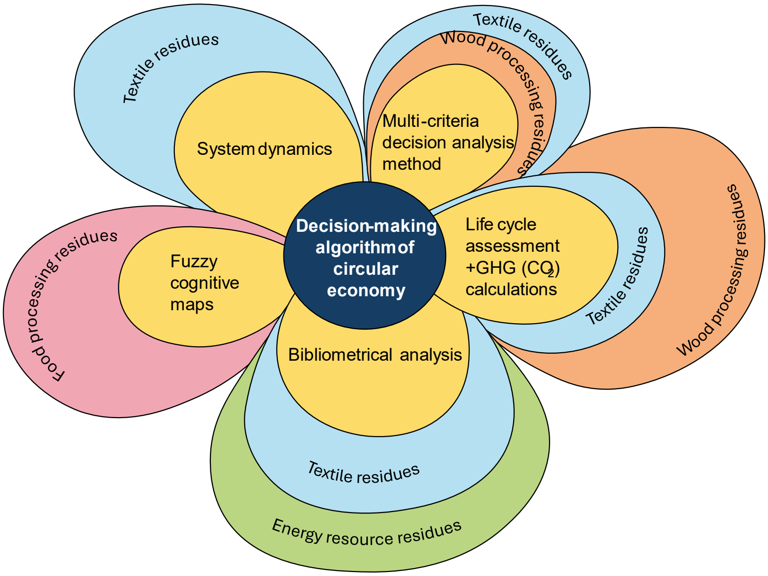

Fig. 1. The structure of the Thesis.

To ensure that the results obtained in the study are as widely applicable as possible, the resources to be evaluated were selected to be as diverse as possible, and they were analysed to see which ones have the greatest impact on the environment or whose growth trends are the most significant. The following resources were examined in the study:

1) textile residues;
2) wood processing residues;
3) food production residues;
4) energy resource residues.

The link between the research structure and the set of publications is shown in Fig. 2. The research of resources is reflected in the following publications: "Analysis of Textile Circularity Potential", "CO_2 Storage in Logging Residue Products with Analysis of Energy Production Scenarios", "Unleashing Energy Potential: Insights of Energy Audit Practices", "What Drives the Circular Economy? Textile Sorting or Consumtion Reduction", "Recycling of Mixed Post-Consumer Textiles: Opportunities for Sustainable Product Development". Research on the technology is reflected in the following publications: "CO_2 Storage in Logging Residue Products with Analysis of Energy Production Scenarios", "Bioeconomy Towards Green Deal. Case Study of Citric Acid production Through Fuzzy Cognitive Maps". The product research is reflected in the following publications: "Analysis of Textile Circularity Potential", "Recycled Cross-laminated Timber as a Low Environmental Impact Alternative to Virgin Material: Latvia Case Study", "Uncertainty of Life Cycle Assessment Studies for Blended Textiles", "Bioeconomy Towards Green Deal. Case Study of Citric Acid Production Through Fuzzy Cognitive Maps".

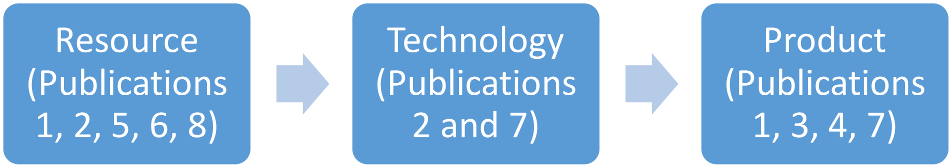

Fig. 2. The link between the research structure and the set of publications.

The selection and implementation of the technological system solution in practice, as well as the analysis of the problems, the application of methodology and the connection with the levels of analysis in the Thesis are summarised in Table 1, which lists the methods used in the publications and the results obtained for the main part of the Thesis.

Table 1

Overview of Methods and Publications Used in the Thesis

Resource	Method	Publication number	Title of publication
Textile residues	Multi-criteria decision analysis method	1	Analysis of Textile Circularity Potential.
Textile residues	Multi-criteria decision analysis method	8	Recycling of Mixed Post-Consumer Textiles: Opportunities for Sustainable Product Development.
Wood processing residues	Multi-criteria decision analysis method and GHG (CO_2) calculations	2	CO_2 Storage in Logging Residue Products with Analysis of Energy Production Scenarios.
Wood processing residues	Life cycle assessment	3	Recycled Cross-laminated Timber as a Low Environmental Impact Alternative to Virgin Material: Latvia Case Study.
Textile residues	Life cycle assessment and bibliometric analysis	4	Uncertainty of Life Cycle Assessment Studies for Blended Textiles.
Energy resource residues	Bibliometrical analysis	5	Unleashing Energy Potential: Insights into Energy Audit Practices.
Textile residues	System dynamics	6	What Drives the Circular Economy? Textile Sorting or Consumption Reduction.
Food processing residues	Fuzzy cognitive maps	7	Bioeconomy Towards Green Deal. Case Study of Citric Acid Production Through Fuzzy Cognitive Maps.

At the end of the Thesis, the results are discussed, conclusions are drawn, and recommendations are developed for implementing the circular economy model in various sectors of the national economy.

Approbation of Research

1. Valtere, M., Bezrucko, T., Blumberga, D. Analysis of Textile Circularity Potential. Environmental and Climate Technologies, 2023, 27(1), pp. 220–232.
2. Viksne, G., Vamža, I., Terjanika, V., Bezrucko, T., Pubule, J., Blumberga, D. CO_2 Storage in Logging Residue Products with Analysis of Energy Production Scenarios. Environmental and Climate Technologies, 2022, 26(1), pp. 1158–1168.
3. Vasuks, P., Vamza, I., Valtere, M., Bezrucko, T., Blumberga, D. Recycled cross-laminated timber as a low environmental impact alternative to virgin material: Latvia case study. Case Studies in Construction Materials, 2025, 22, e04094.
4. Valtere, M., Bezrucko, T., Poberznik, M., Vamza, I., Blumberga, D. Uncertainty of Life Cycle Assessment Studies for Blended Textiles. Environmental and Climate Technologies, 2024, 28(1), pp. 794–811.
5. Liberova, V., Bremane, I., Lauka, D., Laktuka, K., Bezrucko, T., Zvirbule, K., Bezrucko, A. E., Blumberga, D. Unleashing Energy Potential: Insights into Energy Audit Practices. Energies, 2025, 18(3), 522.
6. Valtere, M., Bezrucko, T., Lauka, D., Blumberga, A., Blumberga, D. What Drives the Circular Economy? Textile Sorting or Consumption Reduction. Circular Economy and Sustainability, 2025.
7. Bezrucko, T., Lauka, D., Laktuka, K., Sniega, L., Vamza, I., Dzalbs, A., Terjanika, V., Blumberga, D. Bioeconomy towards Green Deal. Case study of citric acid production through fuzzy cognitive maps. Environmental and Climate Technologies, 2022, 26(1), pp. 684–696.
8. Valtere, M., Bezrucko, T., Liberova, V., Blumberga, D. Recycling of Mixed Post-Consumer Textiles: Opportunities for Sustainable Product Development. Environmental and Climate Technologies 2025, vol. 29, no. 1, pp. 323–343.

1. LITERATURE RESEARCH

1.1. Basic principles of the circular bio-economy

Humans keep consuming natural resources and services unsustainably, exceeding the rate at which these resources can be produced and/or renewed, thereby increasing the pressure on climate, ecosystems, habitats and biodiversity. The goal of the European Green Deal is to tackle the problems of climate change by transforming the 27-country bloc into a fair and prosperous society with a modern, resource-efficient, competitive, low-carbon economy, protecting and strengthening the EU's natural resources and improving the quality of life for current and future generations. The common goals set by the EU are:

- achieve climate neutrality by 2050;
- protect human life, animals and plants by reducing pollution;
- help businesses become global leaders in clean products and technologies;
- ensure fair and inclusive adaptation.

The EU growth strategy points to the need to rapidly change the current situation, invest finansial resources in research, promote innovations, ensure clean energy, stimulate the transition to a clean economy for industries, be energy and resource efficient, find solutions for food security and natural resource management, reduce climate change and dependance on fossil resources, increase Europe's competitiveness, create new jobs and promote bio-economy. Nowadays, the bio-economy is seen not only as an economy based on biological resources, but also as the sustainable consumption of biological resources that creates added value for society. Although EU directive 2008/98/EC stipulates that production by-products are not classified as waste, companies often treat them as such and send them to waste streams or low-value streams, to, for instance, produce biogas or solid fuel. The development of the bio-economy, based on innovation skills and investment in knowledge, is essential to achieving many of the objectives that have been set. The bio-economy is based on three principles of sustainable development: economy, society and nature. These three fundamental principles should form a closed cycle in which the by-product of one process (waste product) is the raw material for another process. This approach in bio-economy increases and improves the added value of products, replaces fossil fuels in energy production and reduces GHG emissions. The Thesis aims to create and propose circular economy opportunities by demonstrating, analysing and describing possible solutions with the help of various examples. This is an illustrative and demonstrative study on how to create possible solutions that would promote the achievement of the Green Deal objectives, develop the circular economy and be suitable for implementation in Latvia.

2. RESEARCH METHODS

2.1. Multi-criteria decision analysis (MCDA)

Multi-criteria decision analysis (MCDA) is a common method for solving decision-making problems. It is suitable for any field where one must define the problem, criteria and alternatives that have to be compared. In this study, it is used to assess the potential of textile circulation, the recycling of blended textile waste and the use of wood residues for the production of new products.

The TOPSIS analysis method used in the Thesis

To start the calculations for the multi-criteria decision analysis method, first, it is necessary to assign the importance coefficients for the criteria, which show how important each criterion is. The importance of each criterion can be determined using different methods, such as the analytical hierarchy process or the sensitivity analysis. In this case, given that the number of criteria to be analysed exceeds seven, it is not possible to use the analytical hierarchy method, as the results obtained would be inconsistent. Therefore, in this study, it is assumed that all criteria are of equal importance; that is, all were assigned the same importance coefficient.

After determining the input data and importance coefficients, the TOPSIS method was used for analysis.

Sensitivity analysis is performed to assess the impact of the criteria on the final results and to confirm their reliability.

2.1.1. Multi-criteria decision analysis method for the potential of movement of textile

Selection of criteria

The MCDA analysis begins with the selection of criteria. The selected fifteen criteria are shown in Table 2.1. The technical aspect was included to make the analysis more diverse and more relevant to the development of the circular economy.

Table 2.1

Criteria of Multi-Criteria Decision Analysis

Category of criteria	Criteria	Ideal value
Environmental aspects	Environmental impact – global warming potential of the products, $kgCO_2eq\ kg^{-1}$.	+
	Washes – the environmental impact of use-phase, determined by the average number of washes of the textile product, times.	+
	Projected lifetime – average lifetime of the product, years.	–
	Landfilled waste – ratio of landfilled waste to the total amount of waste, %.	+
	Recycled waste – ratio of recycled waste from the total amount of waste, %.	–
	Fabric origin – ratio of synthetic material, %.	+

Table 2.1 (continued)

Economic aspects	Market demand – global market size estimate, in billions of euros.	+
	Production volume – ratio of the amount of manufactured products, %.	+
	International trade – ratio of exported production amount, %.	+
	Labour productivity – gross added value per employee, thsd. EUR.	+
	Added value – share of added value in total production, %.	+
Technical aspects	Energy efficiency of productive technologies – ratio of energy consumption during the production phase to energy consumption in the whole life cycle, %.	+
	Innovation capacity – number of patents submitted from 2015 to 2019.	+
Social aspects	Employment – share of persons employed in the sector, %.	+
	Companies – share of companies in the sector, %.	+

Ideal value is depicted as "+" or "–". If the ideal value is the maximal value, then the criteria are shown with a plus sign, but if the ideal value is the minimal value, then it is the opposite symbol. In this case, the aim of the publication on the analysis of the circularity potential of tectule materials was to identify the group with the greatest potential for the development of the circular economy, rather than the sector with the highest circularity efficiency.

2.1.2. Multi-criteria decision analysis method for the blended textile waste recycling

The multi-criteria decision analysis method is quite universal and has a wide range of applications. In Publication 1, "Analysis of Textile Circularity Potential", the multi-criteria decision analysis method was used to assess the circularity of fashion textiles, while in Publication 8, "Recycling of Mixed Post-Consumer Textile: Opportunities for Sustainable Product Development", the multi-criteria decision analysis method is used with a different emphasis, focusing on the assessment of the recycling process for blended textile waste. It can be applied in any field where it is possible to formulate a problem, define criteria and comparable alternatives. There are several MCDA methods, but each has its own calculation operations; therefore, the results may differ even if the input data is identical.

In this study, the technique for order preference by similarity to ideal solution (TOPSIS) method was chosen, based on the author's previous research, which compared different products, which is also the objective of this study. The TOPSIS method offers relatively simple calculation steps, allows for an unlimited number of criteria and alternatives, and input data can be both qualitative and quantitative. The result reflects the distance from the alternative to the ideal point, which in this method is equal to "one". The closer the score is to "one", the more suitable the alternative is. TOPSIS calculations were performed using MS Excel software.

The MCDA analysis was performed following the steps developed in the author's previous study.

The identification of the product

The literature analysis aims to identify products that can be obtained from blended textile materials after use.

To select publications based on two criteria (used textile products and blended textile materials), additional qualitative analysis was required.

All products were evaluated according to these two criteria. The aim was to identify products that met both conditions.

The chosen nine criteria are shown in Table 2.2. In all cases, the ideal value is the maximum; that is, the higher the value, the better the alternative.

Table 2.2

Multi-Criteria Decision Analysis Criteria

Category of criteria	Criteria	Description
Environmental aspects	Environmental aspect	Comparison of global warming potential for the new and traditional product (times)
	Resource efficiency	Use of other waste materials in production (weight percentage, %)
	Longevity and recycling	Product lifetime and recycling potential (points)
Economic aspects	Price of the product	Comparison of prices for new and traditional products (times)
	Market demand	Global market size estimate (billion EUR)
Technical aspects	Technology readiness level	Technology readiness level (TRL 1–9)
	Research level	Number of studies on similar products (points)
	Market competitiveness	Comparison of characteristics of the new and traditional products (points)
Social aspects	Social aspects	Assessment of safety and health risks during production and the specific nature of work (points)

The assessment was carried out on a nine-point scale. Mankins' TRL description was used to ensure an in-depth understanding and evaluation.

2.1.3. Multi-criteria decision analysis method for storing CO_2 in forestry residues

The production of rigid board wood insulation material was selected for the study. The production methodology consists of stages, such as a description of the production process and the necessary raw materials, which allows for calculating the amount of CO_2 that can be stored in the final product. The energy sources used in the production of rigid were also compared in three different scenarios using a multi-criteria decision analysis method. All stages of the methodology are shown in Fig. 2.1.

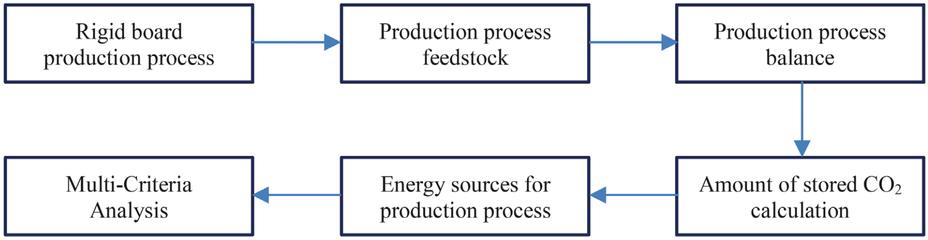

Fig. 2.1. Algorithm of the methodology.

Rigid boards are manufactured similarly to other wood-based boards, such as MDF (medium-density fiberboard) and LDF (low-density fiberboard). After drying, the material is formed, pressed and graded.

The main raw material for the production of rigid boards is forestry residues. It is assumed that the quality of chipped wood obtained from forestry residues will be sufficient for the production of wood fibre boards.

All the other processes that require electricity, such as chipping, sawing and profiling, are grouped together.

Table 2.3

Energy Consumption for Production

Production process	**Electricity, MWh/m^3**	**Thermal energy, MWh/m^3**
Drying	0.03	0.16
Refining	0.08	0.08
Pressing	0.01	0.02
Chipping, sawing, profiling	0.01	–
Total	0.13	0.26

To calculate the potential amount of CO_2 stored in the material, eight different standards for biogenic carbon accounting in products and various technical standards for life cycle analysis (LCA) with other carbon accounting methods and approaches were reviewed and used; however, in this case, only those standards relating to forest building materials and biogenic carbon were used. The criteria selected for the analysis are shown in Table 2.4.

Table 2.4

Selected Multi-Criteria Decision Analysis Criteria

Technological criteria	**Economic criteria**	**Environmental criteria**
Fuel energy content, GJ/m^3	Capital costs, EUR/m^3	NO_x emissions, g/m^3
	Fuel costs, EUR/m^3	CO emissions, g/m^3
	O&M costs, EUR/m^3	GOS emissions, g/m^3
	Bought/sold electricity, EUR/m^3	PM emissions, g/m^3
		CO_2 emissions, kg/m^3

In order to perform a multi-criteria analysis, the importance of the criteria must be determined. They are determined using the analytical hierarchy process (AHP) method. First, the criteria are ranked according to importance, giving priority to economic and technological criteria, and then environmental criteria are ranked according to their global warming potential. The importance of each criterion is then determined according to its rank, thus comparing them with each other.

2.2. Life cycle assessment (LCA)

Just as the multi-criteria decision analysis method was examined from the perspective of the textile and woodworking sectors, life cycle analysis can also be used to study these sectors.

Reference should be made to the life cycle analysis source for the textile industry, as the bibliometric analysis was also used in Publication 4, "Uncertainty of Life Cycle Assessment Studies for Blended Textiles". A knowledge gap has been identified in LCA research on CO/PES blends. Several studies have been conducted on the environmental impact of this material; however, they do not cover a detailed life cycle inventory (LCI). Veronica Wagner has also identified this knowledge gap. A literature review is needed to develop a complete LCA for CO/PES blends. This study aims to review literature on environmental assessment studies of cotton and polyester blend production and to identify what assumptions have been made so far and how these assumptions may influence the assessment. It is known that the production and consumption of textiles contribute to environmental degradation and GHG emissions, but the actual extent of these impact remain unclear and is subject to debate; therefore, moving closer to a complete life cycle inventory can help to assess the environmental impact of textiles more accurately, consequently improving knowledge about their sustainability.

LCA is a widely recognised tool used to assess the environmental impact of all activities throughout a product's life cycle. It is used to quantitatively determine the environmental impact of a product or process. The International Organisation for Standardisation (ISO 14040) stipulates that LCA must follow a system consisting of four interrelated stages: objective and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation.

The analysis begins by defining the study aim, functional unit (FU), system boundaries, assumptions and limitations, as well as segmentation and the selected LCA method, defining objective and scope in Subsection 2.2.1. This is followed by the development of an LCI, which includes water, energy, material input and output flows, waste flows and emissions into air, water and land. In the LCIA section impact categories, their indications and characterisation models are selected. Alongside all processes, the completeness, sensitivity and consistency of the analysis are evaluated during the interpretation process, and conclusions, limitations and recommendations are determined.

2.2.1. Assessment of the cross-laminated timber life cycle

Objective and scope

A study on the impact of cross-laminated timber (CLT) waste recycling on the life cycle has been selected as an example of LCA implementation. Here, the LCA aims to determine the environmental impact of panels made from the cross-laminated timber off-cuts obtained from the recycling process and to compare it with the environmental impact of traditionally manufactured cross-laminated timber panels. In this study, the functional unit was defined as 1 m^3 of cross-laminated timber panel.

The LCA was performed in accordance with ISO 14040/14044. SimaPro software was used for the analysis. The input data set was taken from the Ecoinvent 3.8 database. The ReCiPe Midpoint (H) LCIA method was selected. The study did not include a breakdown of production processes. A gate-to-gate LCA was performed. Resource extraction, resource transportation, energy, packaging materials and equipment production were outside the technical boundaries of the production process.

2.2.2. Life cycle assessment for textile recycling

LCA data sources include both data sets containing company observations, as previously reviewed in the study on the assessment of the cross-laminated timber life cycle, and data sets obtained from literature analyses, for instance, by examining the limitations and assumptions used in the environmental assessment of cotton and polyester blends.

In this case, the LCA method was used for the literature analysis. The analysis aimed to assess the possible impact on the environmental assessments of CO/PES (cotton and polyester) blended textiles due to differences in the available data and assumptions made in the literature. The most detailed LCA was used as the baseline scenario, while the other scenarios were created by changing the overlapping data. The results will not provide quantitative data; instead, the conclusions will be used to verify the differences in LCA results, as the scenarios are based on the input data of the baseline scenario. This means that only overlapping parameters were changed, while the rest remained unchanged. It is important to note that each study on which the scenarios are based has different input data and processes with different technologies. LCA's concept "cradle-to-grave" was used, and it covers the following processes: fibre extraction, yarn production, weaving preparation (sizing), weaving, pre-treatment, continuous dyeing and fabric lining. A more detailed description of the process is provided in the study by Veronica Wagner et. al. The LCA was performed in accordance with ISO 14040/14044. SimaPro software was used for the analysis. In this study, the functional unit was defined as 1 kg of cotton and polyester blended textile product. The input data sets were taken from the Ecoinvent 3.8 database. The ReCiPe Midpoint (H) V1.08 life cycle impact assessment method was chosen because it was also used in the LCA study on similar textiles.

2.3. Bibliometric analysis

2.3.1. Bibliometric analysis of the potential for blended textile recycling

Subsection 2.2.2. examines the LCA analysis aspect of the data, assessing the limitations and assumptions used in the environmental assessment of cotton and polyester blends. These data were obtained using bibliometric analysis.

Literature review begins with a bibliometric analysis to gain an overview of the field of study and identify main keywords for further use. Bibliometric analysis is a quantitative method used to assess the current state of research by examining the interrelationship between scientific publications in the field. The analysis is based on a large number of scientific publications, which are analysed using software that employs statistical and network tools. The VOSviewer software was used in this study. The aim was to gain insight into studies on the environmental impact of blended textiles, especially CO/PES blends. The SCOPUS and Web of Science databases are recommended for bibliometric analysis. The Web of Science database was used in this study because 381 results were found while using the specific keywords, while 211 results were found in the SCOPUS database.

2.3.2. Bibliometric analysis of energy audit practices

The bibliometric analysis method was also used in the study on energy audits. The identification of relevant literature for the study on energy audit practices included an analysis of the results of documents and journal articles published between 2009 and 2024. The bibliometric analysis was performed on studies published in reliable scientific publications, found in the citation databases SCOPUS and MDPI. These databases cover a wide range of topics and provide publication metrics. The search focused on energy audit practices, energy efficiency measures and related legislation in the EU Member States.

2.4. System dynamics

Based on the literature review, three research questions were defined: (1) How much clothing will end up in landfills in the near future? (2) Will increasing sorting capacity in the EU be sufficient to achieve circular economy targets? (3) What promotes the circular economy – sorting textiles or reducing consumption? This study aims to analyse the potential of the circular economy in the fashion textile value chain at the EU level using a system dynamics model. The amount of textiles ending up in the landfills in the baseline scenario will be used to assess the circular economy potential, as it reflects the lost value that could be recovered by introducing circular practices throughout the value chain. The results will show the EU's progress towards a circular economy and sustainability, as well as whether the EU's policy objectives for textiles can be achieved by 2030. It will also answer the question of what drives the circular economy in the textile industry.

System dynamics is a research method that studies the behaviour of complex systems and the challenges they pose. The aim is to analyse the structure of systems in order to gain a deeper understanding of their behaviour and its causes. This method is commonly used in academic settings, large corporations, consulting firms and governments to improve strategy formulation, policy development and decision-making in complex and dynamic fields. It has a mathematical modelling approach. System dynamics modelling is widely used to study value/supply chains and circular economy pathways, such as reverse logistics, closed-loop supply chains, recycling systems, material flows and circular economies at multiple scales. The system dynamics modelling approach was chosen for this study to examine the value chain of fashion textiles because it is suitable for examining the structure, behaviour and interactions of elements within a system and allows for the creation of closed-loop systems. The model can be simulated over time to provide insight into the future. In addition, the policy instruments can be used to develop and test solution of value chain problems. Figure 2.2 shows the steps and sequence of the entire study.

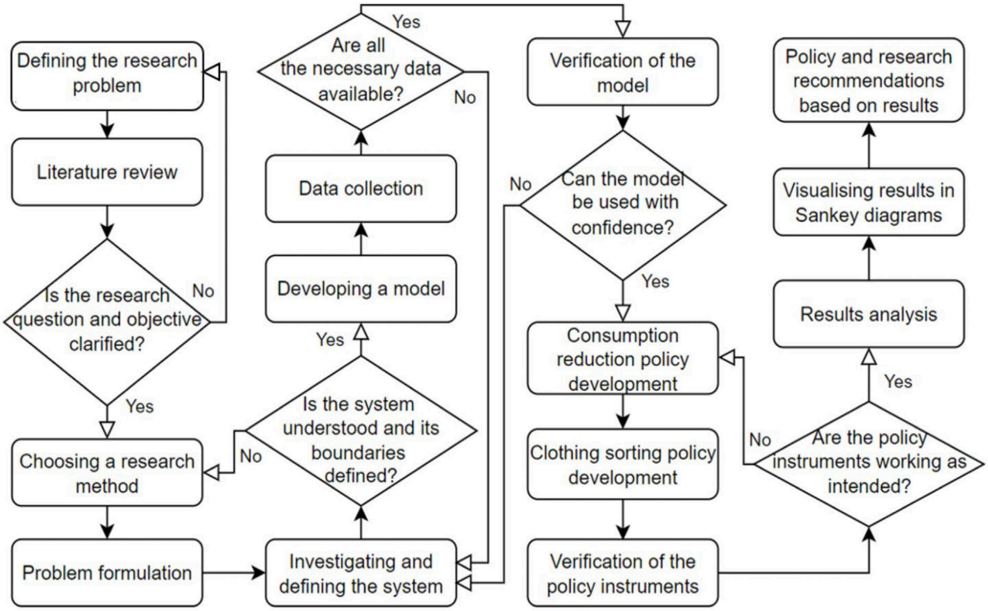

Fig. 2.2. Algorithm of study methodology.

Modelling of system dynamics

A system dynamics model was chosen in Publication 6, "What Drives the Circular Economy? Textile Sorting or Consumption Reduction", and Stella Architect was used for that. This software allows you to create a system structure and model the system over time. The main elements of the model are supplies, flows and parameters, which are interconnected. The links and interaction between the components form feedback loops. There are two types of feedback loops: positive progression and negative balancing loops.

The development of a system dynamics model involves five main steps. These are: problem formulation, dynamic hypothesis proposal, model formulation and simulation, model testing and policy development and evaluation. The complete model is shown in Fig. 2.3.

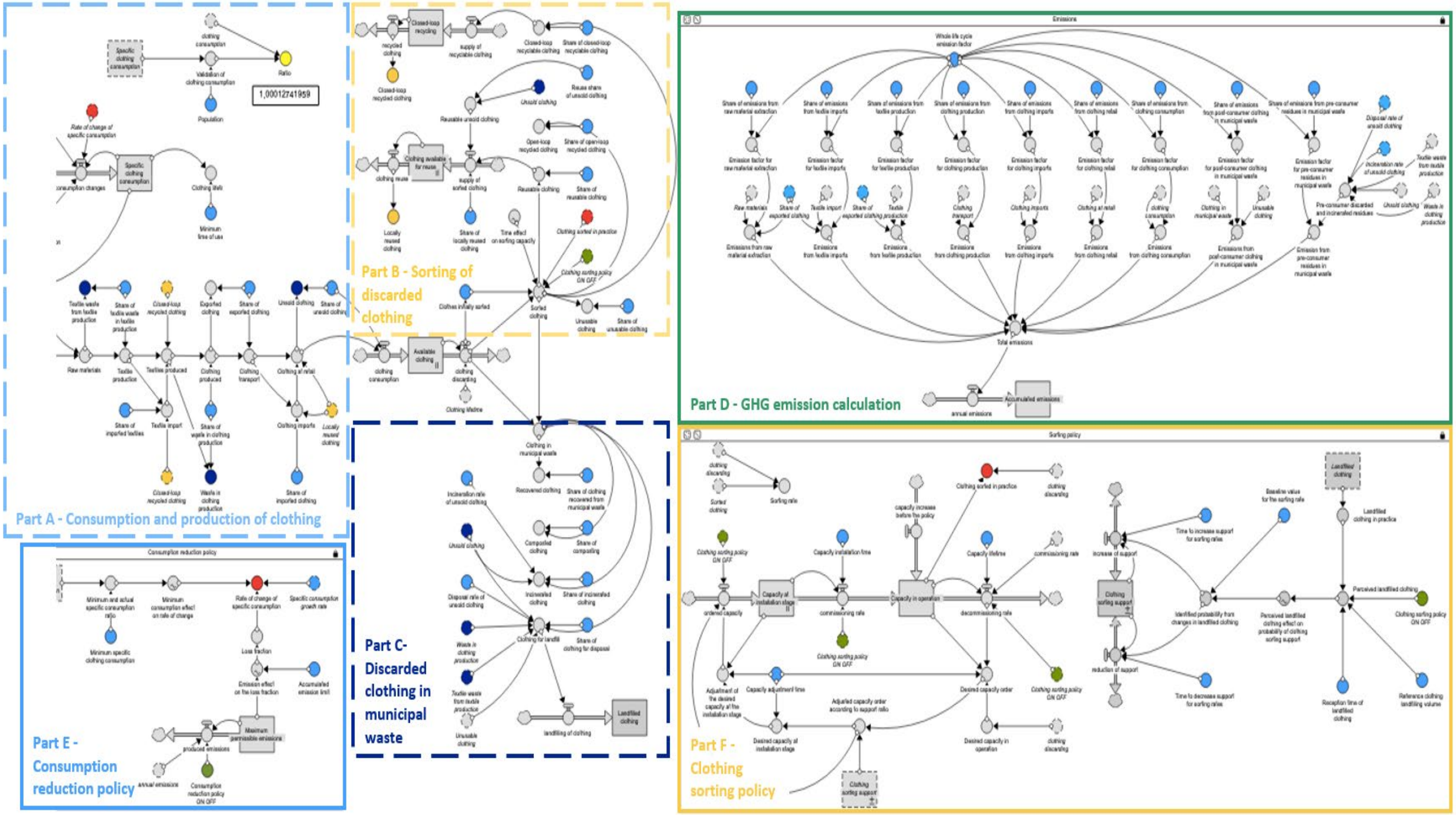

Fig 2.3. Structure of the system dynamics model of the clothing value chain.

2.5. Fuzzy cognitive maps (FCM)

Qualitative system analysis or qualitative modelling is increasingly being used to analyse complex system dynamics. Kosko introduced fuzzy cognitive maps (FCM) as a tool for dynamically perceiving and explaining the behaviour of qualitative systems. FCMs are increasingly used to model and analyse the behaviour of qualitative systems. Over the past 30 years, this approach has become increasingly popular due to its simple design and low computational needs. Two main approaches are used to model social system dynamics: deductive and inductive. The deductive approach uses knowledge gained from interviewing experts in the relevant field, while the inductive approach is an automated and semi-automated approach designed to study FCM rules based on historical data.

Overall, FCM has several advantages over traditional quantitative modelling approaches. The advantages of FCM include the ability to model data in limited environments using natural language to express knowledge, perceptions, experiences or opinions as formulated by an expert or stakeholder, often with unclear information. In addition, FCM results are easy to interpret for both specialists and the general public.

Application of the method for evaluating bioproducts

The FCM modelling method was used in the study to compare different manufacturing process methods. It will help to understand which of the methods best meets the sustainability criteria, identify potential obstacles to acquire reliable and objective results, and determine whether the use of this type of integrated analysis is appropriate for comparion the various production process alternatives examined in the study. FCM modelling is a sequential set of activities that will ensure that the research objective is achieved in a transparent and understandable manner in order to analyse sixteen manufacturing processes.

To compare all of the described production processes, the most important criteria must be defined. Several criteria are used in this process, making choices more effective, rational and clear. The analysis aims to structure processes in order to define objectives, evaluate possible alternatives and compare them from different perspectives. After evaluating the priority criteria, the following criteria were selected: environmental aspects, technological aspects, economic aspects and social aspects.

All selected criteria and sub-criteria are qualitative; therefore, they must be assigned numerical values based on the analysis of the production process carried out in the study. The qualitative approach, unlike the quantitative, makes the results obtained in the methodology validation part more subjective. However, if accurate quantitative data on the processes were available, the view of the usefullness performance would be limited.

Each sub-criterion will be assessed on a scale from –1 to 1, where 1 indicates the strongest link and will show the best, strongest possible link from a bio-economy and utility perspective. The link obtained in the sub-criteria is comparable to the highest implementation efficiency. The lowest score of –1 indicates the weakest link or results from a bio-economy and utility perspective.

Approbation of methodology for the citric acid production process

All 16 production processes have been analysed and modelled in Publication 7, "Bioeconomy Towards Green Deal. Case Study of Citric Acid Production through Fuzzy Cognitive Maps". However, one of the production processes will be presented in detail in this study, and the results of the other 15 production processes will also be evaluated in the results and discussion section, as the structure and approach are analogous for all production process models.

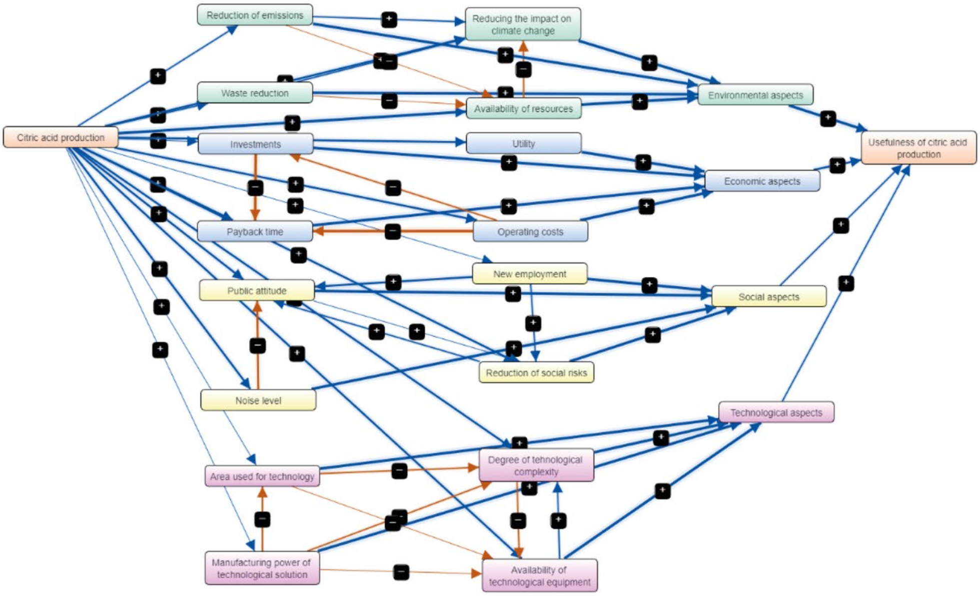

Fig. 2.4. Improved visualisation model of the citric acid production process.

For each production process, links are established for each of the sub-criteria, indicating the strength of the link on a scale from –1 to 1, based on the expert assessment. For instance, the payback period for citric acid production is relatively short; therefore, the link has a positive value of 0.7; meanwhile, the area required for the technology is approximately 1 ha, which is assessed with a positive value of 0.1.

After completing the visualisation part of the model, a quantitative result can be obtained for each model position. The values obtained are shown in Table 2.5.

Table 2.5

Quantitative Values of the Citric Acid Production Process

Component	Inner angle	Outer angle	Centrality
Citric acid	0	6.949	6.949
Environmental aspects	4	1	5
Technological aspects	4	0.48	4.48
Social aspects	4	0.2	4.2
Economic aspects	4	0.81	4.810
Waste reduction	0.47	1400	1.87
Resource availability	1.23	1.19	2.42
Reducing the impact on climate change	1.21	1	2.21
Emission reduction	0.48	1.339	1.819
Payback period	2.5	1	3.5
Usefulness	0.52	1	3.5
Operating cost	0.5	2.31	2.81
Investments	0.42	2	2.42
Social risk reduction	1.02	1.25	2.27
Noise level	0.52	1.58	2.1
Public attitude	2.08	1.16	3.24
Number of new jobs	0.09	2.09	2.179
Production capacity of the technological solution	0.09	1.680	1.770
Degree of technological complexity	1.44	1.28	2.7199
Area used for technologies	0.42	1.28	1.7
Availability of technological equipment	0.960	1.44	2.4
The usefulness of citric acid production	2.49	0	2.49

Once quantitative values have been obtained for each sub-criterion, the Mental Modeler tool can move on to the results section. The main goal is to obtain effective production process results ranging from 0 to 1.

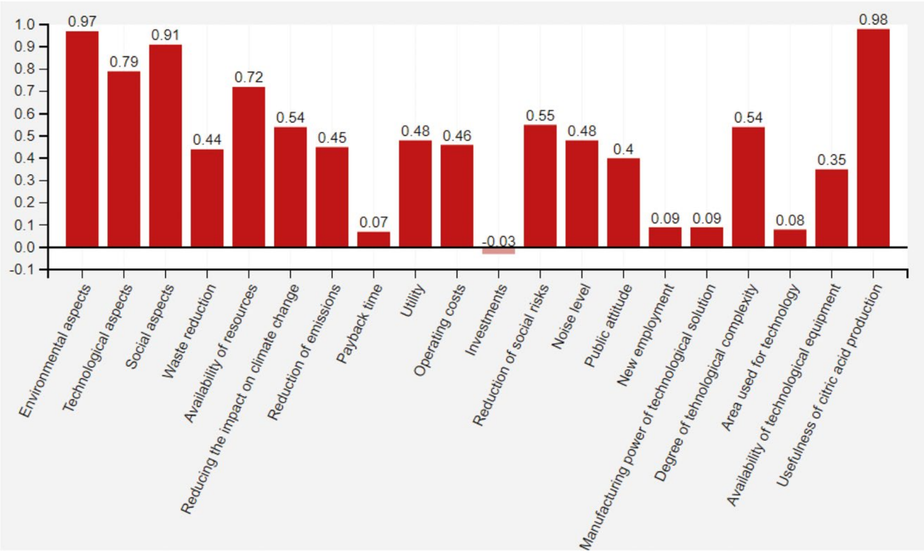

Fig. 2.5. Results of the citric acid production process.

Figure 2.5 shows the main conclusion regarding the citric acid production process, namely that the efficiency of citric acid production is 0.97. All production processes described in this paper will be compared with this endpoint. As can be seen in the graph, the citric acid production process makes the greatest contribution in environmental and social aspects, while the weakest points in setting up such a plant would be related to investment and payback. Given that the study focuses on sustainability in order to achieve the EU Green Deal objectives, the usefulness of the citric acid production process is very high – 0.97. If the modelling focused only on the economic aspects, the result of this production process would be less positive; therefore, a way to model priority changes was sought.

3. SUMMARY OF RESULTS

3.1. Multi-criteria decision analysis method (MCDA)

3.1.1. Example of an analysis of the potential for textile material circulation

Input data

All of the input data obtained from the literature review are shown in Table 3.1.

Table 3.1

Input Data of TOPSIS Analysis

Criteria	Alternatives		
	Fashion textiles	**Home textiles**	**Technical textiles**
Impact on the environment, kg CO_2 eq. kg^{-1}	30.42	5.06	81.45
Washing, cycles	30	68	63
Expected life cycle, years	3.13	4.06	6.13
Waste disposed of in landfills, %	70	68	78
Recycled waste, %	13	16	5
Origin of fabric, %	60	70	80
Market demand, EUR billion	511.39	103.31	177.53
Production volume, %	41	14	17
International trade, %	59	2	14
Productivity of labour, EUR thousand	22	29	47
Added value, %	1.01	0.28	0.37
Energy efficiency of production technologies, %	54	70	59
Innovation capacity, patents	5001	127	3440
Employment, %	72	16	12
Companies, %	75	16	9

Impact on the environment

The main source of information on fashion textiles was a review study by Gonçalves and Silva. They summarised the environmental impact of various types of clothing, such as a jacket, a t-shirt and four types of sweaters. Only the utilisation phase and the end of the life cycle were taken into account. A jacket weighs 0.9 kg and has a global warming potential (GWP) of 25.3 kg CO_2 eq. per functional unit, thus, the GWP of 1 kg of jacket is 28.1 kg CO_2 eq. For the t-shirt category, the GWP is 5.3 kg CO_2 eq kg^{-1} t-shirt. Data of four types of sweaters were used: wool, cotton, blend and acrylic. The average GWP is 57.9 kg CO_2 eq kg^{-1} sweaters.

3.1.2. Example of blended textile waste recycling analysis

The list of products obtained from the articles is shown in Table 3.2. In eight publications, the origin of textile waste was industrial, which is not relevant for further analysis, as these textile materials have not been subject to user use. Most of the publications focused on specific types of textile materials or groups of materials. In some cases, very specific textile materials were analysed, such as silk, denim, lyocell and leather.

As shown in Table 3.2, only four publications met both criteria and referred to the recycling of blended post-consumer textiles. The products obtained in the selected studies were: (1) bio-oil and terephthalic acid; (2) textile-reinforced composites for building applications; (3) textile fibres (cotton and nylon); spandex monomers and bis(2-hydroxyethyl)terephthalate; (4) a mycelium-based composite material for thermal insulation.

Table 3.2

Products Obtained from Textile Recycling

Type of textile	Industrial textile	Post-consumer textiles
Polyester	Polyurethane foams	Terephthalic acid (TPA), monomers, such as bis(2-hydroxyethyl)terephthalate (BHET) and bis(2-hydroxyethyl)terephthalamide, TPA and ethylene glycol
Cotton	Thermal insulation	Composites for industrial purposes, glucose solution, fashion accessories, vermicompost for fertiliser
Nylon	–	Fine fibrous membrane
Denim	Sound-absorbing material	Fire retarding composite dots
Silk	–	Luminescent carbon dots
Lyocell	Adsorbent for heavy metals	–
Leather	Leather-like yarn threads	–
Cotton/polyester	–	Cellulose fibres, cellulose and PET films, 3D printing filament, fungal cellulase and polyester
Viscose/polyester and viscose/polyamide	–	Synthetic fibers and lactic acid
Acrylic and wool	Thermal insulation	–
Cotton, cotton/polyester and acrylic	Biochar as fabric additives	–
Blended textiles	–	Bio-oil and TPA, textile reinforced composites for building applications, BHET crystals, spandex monomers, cotton and nylon, mycelium-based composite for thermal insulation

TOPSIS method

After defining the input data, the calculations were performed using the TOPSIS method. The results are shown in Fig. 3.1. According to the multi-criteria decision analysis evaluation, the mycelium-based material is the best alternative as it scores the highest (0.64) result; therefore, it is considered to be the most appropriate solution. This alternative met the ideal values in four criteria and at the same time achieved three anti-ideal values.

However, the other alternatives had more anti-ideal values: bio-oil and TPA – four, TRC – three, but BHET crystal, spandex monomers and cotton and nylon blend had five. Bio-oil and the TPA product group were the only alternatives that did not reach any of the ideal values and also had the lowest overall score.

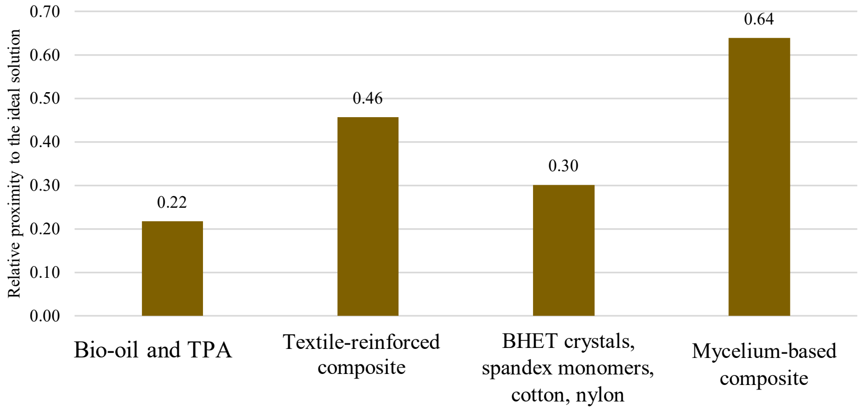

Fig. 3.1. Resulting rating of alternatives from TOPSIS analysis.

As can be seen, mycelium-based material has the greatest potential for further development as it is relatively well studied and has a simple manufacturing process. Its economic viability and market potential are very high. The material also has significant environmental advantages and can be produced from a wide range of waste and by-products. The weakness of the product lies in its characteristics compared to the products available on the market; however, only the thermal conductivity was compared in this study. In any case, further research is needed to optimise the product properties and to explore other applications.

3.1.3. Example of CO_2 storage analysis in forestry residues

The calculated criterion values and importance for the multi-criteria analysis of three different energy production scenarios are shown in Table 3.3.

Table 3.3

Criteria Values and Weights

	Wood biomass CHP	**Natural gas CHP**	**Wood biomass CP + PV panels**	**Criteria weight**
Fuel energy content, GJ/m^3	1.56	2.26	1.10	0.079
Capital costs, EUR/m^3	12.68	38.01	8.45	0.210
Fuel costs, EUR/m^3	55.17	37.75	47.80	0.288
O&M costs, EUR/m^3	1.10	0.94	0.89	0.152
Bought/sold electricity, EUR/m^3	3.84	–9.45	19.77	0.110
NO_X emissions, g/m^3	3.14	4.95	2.36	0.028
CO emissions, g/m^3	0.86	5.78	0.64	0.016
GOS emissions, g/m^3	0	4.95	0	0.020
PM emissions, g/m^3	4.7	0	3.5	0.040
CO_2 emissions, kg/m^3	0	90	0	0.057

The results of the multi-criteria decision analysis of three different energy production scenarios are shown in Fig. 3.2.

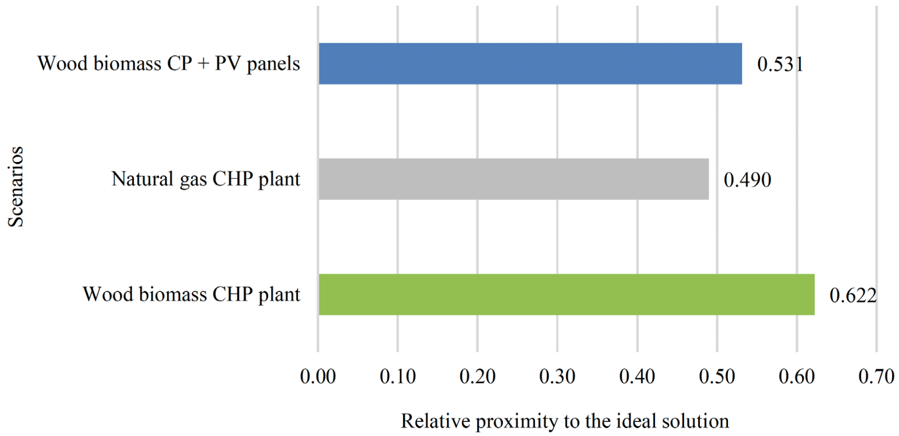

Fig. 3.2. Multi-criteria decision analysis results.

The results of the multi-criteria decision analysis show that the best scenario for energy production is the wood biomass combined heat and power production plant (0.622). In second place are the wood biomass combustion plant and solar photocell scenario (0.531), barely beating out the natural gas combined heat and power production plant scenario (0.490), although the multi-criteria decision analysis currently shows that the use scenario of fossil resource of natural gas is relatively close in valuation compared to the renewable resource of wood biomass use scenario.

3.2. Life cycle assessment (LCA)

3.2.1. Recycled cross-laminated timber as a low-impact alternative to raw material: Latvia case study

Comparison of the midpoint and endpoint impact of recycled CLT

Regarding the recycled CLT, the largest impact in most categories is caused by both glueing processes. Petroleum-based adhesives are used in both processes. The third largest impact is wood chipping, which has the greatest impact on freshwater and marine eutrophication. This process consumes the most energy per functional unit (FU). The impact in the land use category shows that almost all of the impact of recycled CLT is related to the second glueing and pressing (see Fig. 3.3). This is due to the use of raw material, as in this case, primary raw materials were obtained for the production of the outer layer, ensuring identical visual quality to the new CLT.

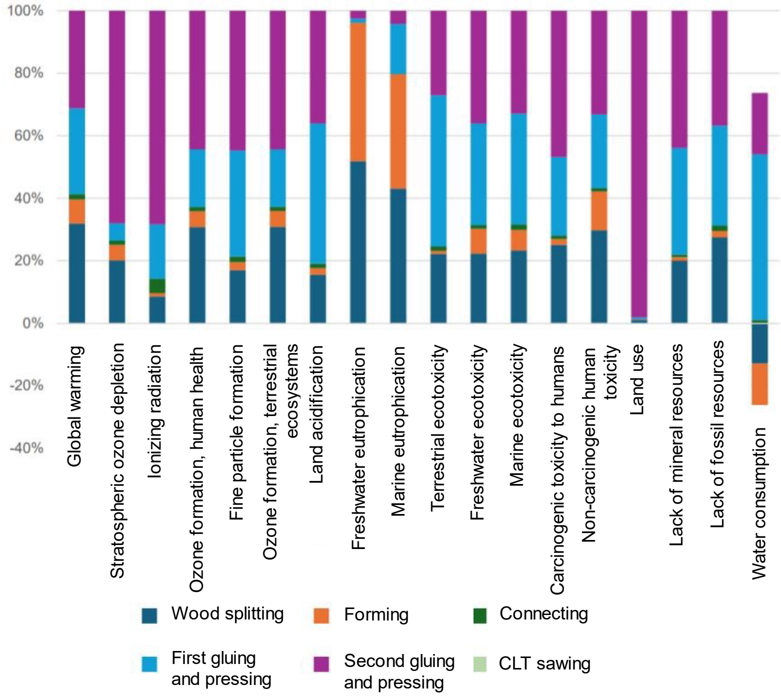

Fig. 3.3. Potential midpoint impacts of 1 m^3 recycled cross-laminated timber.

Regarding the final impact (see Fig. 3.4), three categories were assessed using the ReCiPe methodology: human health, ecosystem and resources.

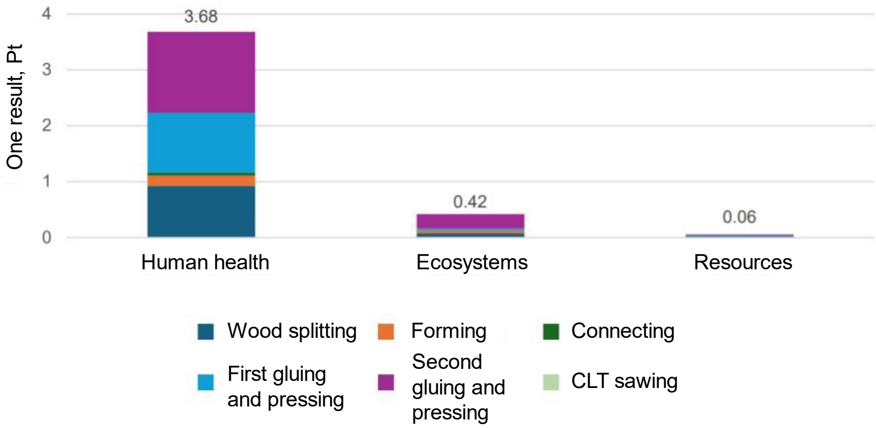

Fig. 3.4. Endpoint single score impacts of 1 m^3 of recycled cross-laminated timber.

Comparison of midpoint and endpoint impacts of recycled CLT and CLT

To truly evaluate the benefits of using recycling technology, recycled CLT was compared to CLT using midpoint and endpoint indicators that show the impact of each product, allowing for comparison. For the midpoint comparison, almost all impact categories show smaller impacts for the recycled CLT functional unit. The only exception where recycled CLT has a greater negative impact is in the eutrophication category, which causes 0.48 kg of phosphorus equivalent and 0.36 kg of nitrogen equivalent for freshwater eutrophication. This impact is related to the incorrect disposal of biomass residues; therefore, some of the impacts mentioned in this study may be related to the disposal of sawdust. The most significant improvements are in the categories of global warming, land use and terrestrial ecotoxicity impacts.

Table 3.4

Potential Midpoint Impacts of 1 m^3 of Recycled Cross-Laminated Timber and Cross-Laminated Timber

Impact category	Unit	ReCLT	CLT
Global warming	kg CO_2 eq.	82.76	151.24
Stratospheric ozone depletion	kg CFC11 eq.	0.00006	0.00017
Ionising radiation	kBq Co-60 eq.	3.96	16.73
Ozone formation, human health	kg NO_X eq.	0.23	0.87
Fine particulate matter formation	kg PM2,5 eq.	0.11	0.38
Ozone formation, terrestrial ecosystems	kg NO eq.	0.24	0.92
Terrestrial acidification	kg SO_2 eq.	0.26	0.56
Freshwater eutrophication	kg P eq	0.54	0.06
Marine eutrophication	kg N eq.	0.049	0.013
Terrestrial ecotoxicity	kg 1,4-DCB	2302.88	4243.63
Freshwater ecotoxicity	kg 1,4-DCB	3.80	6.11
Marine ecotoxicity	kg 1,4-DCB	6.82	12.93

Table 3.4 (continued)

Human carcinogenic toxicity	kg 1,4-DCB	15.35	36.44
Human non-carcinogenic toxicity	kg 1,4-DCB	94.98	153.25
Land use	m^2 a crop eq.	94.08	861.79
Mineral resource scarcity	kg Cu eq.	0.26	0.48
Fossil resource scarcity	kg oil eq.	23.33	46.78
Water consumption	m^3	0.63	1.81

Recycled CLT shows a more significant negative impact on freshwater and marine eutrophication categories, which may be related to the ammonium sulfate hardener selected for the glueing process.

3.2.2. Lack of full life cycle analysis for blended textiles

The second LCA example served to describe the limitations and assumptions used in environmental assessments of cotton and polyester blends. Two methods were used in this example: a bibliometric method with literature analysis and a life cycle assessment.

To use the life cycle assessment as a baseline model, the LCA study on medical workwear was used, which has the most detailed life cycle inventory. It is also the only study that includes all manufacturing processes. The scenarios were created without water emissions to reduce uncertainty, as this would be an additional unknown variable. In addition, a scenario was created using built-in Ecoinvent processes – the weaving of synthetic fibres, continuous dyeing of cotton fibres and finishing of cotton woven textiles. To make the scenario comparable with others, the other processes were used without water emissions, but it should be noted that emissions are included in the Ecoinvent processes.

Impact categories and production processes

First, the baseline scenario is analysed with a particular focus on the distribution of the impact of the production process. The life cycle impact assessment provides results for several impact categories. The selected method has 18 impact categories, each with a corresponding unit of measurement; however, in order to compare categories, it is necessary to convert to a common unit of measurement, which is achieved through normalisation. It is a process in which impact categories are normalised in one dimension, and the results are presented in relation to the overall impact on the environment. The normalised values for the baseline scenario are shown in Fig. 3.9. The graph includes all categories with normalised values greater than 0.0020, except for global warming (0.0016), which was also included as a widely used category in environmental impact assessments. It should be noted that the results are not original, as the model is based on existing research; however, the results are not presented and analysed in this way, therefore, these observations are original.

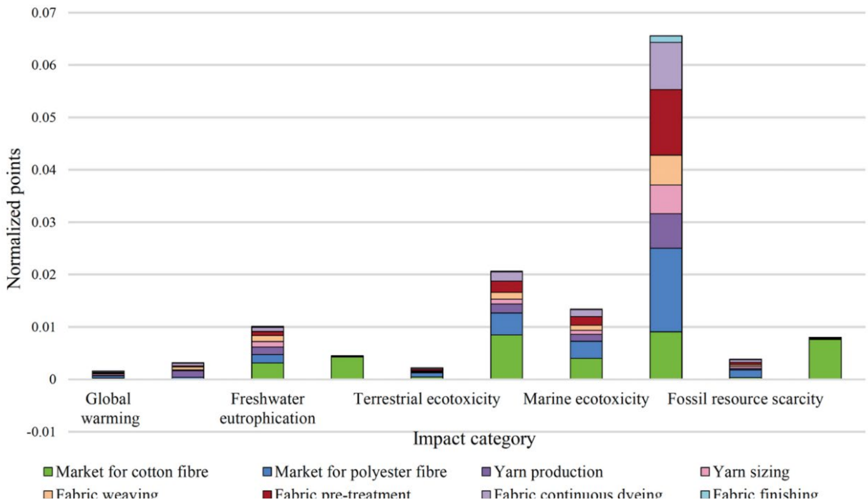

Fig. 3.5. Normalised results by impact categories for the baseline scenario of cotton and polyester blend production.

It can be observed that the main impact categories are related to toxicity (human carcinogenic toxicity, marine and water ecotoxicity), therefore, it is important to ensure a complete life cycle inventory with chemicals, as they are the main source of the toxicity. Of the input chemicals, sodium hydroxide had the greatest impact, which can be explained by the amount used, as sodium dithionite has the greatest impact in Scenario 4, based on the data company B05 included in the publication. It should also be noted that the global warming category has a relatively small impact on the overall environmental impact. This should be taken into account when analysing the ecological characteristics of textile products. Looking at the breakdown of the processes involved, the greatest impact on the environment is from the extraction of raw materials (cotton and polyester fibres), followed by pre-processing. It should be noted that this applies to the baseline scenario, as the distribution of impacts changed when looking at other scenarios. The reference study shows similar results, as the second largest impact was related to the extraction of raw materials, while the first was related to the use phase, which is not covered by this study.

3.3. Bibliometric analysis

3.3.1. An example of bibliometric analysis of mixed textile products

The LCA method example described the limitations and assumptions used in the environmental assessments of cotton and polyester blends. In this case, the data was obtained using bibliometric analysis.

As a result, 31 keywords that were used 12 or more times were identified. They were linked to 278 links and formed four clusters. The keywords and their links are shown in Fig. 3.12. The most popular keyword was “waste” (36 occurences), followed by “textiles” (35 occurences), then “life cycle assessment” and “wastewater” (35 occurences). Looking at the overall strength of the links, the order was similar, except for the second strongest link, which is shown by sustainability, indicating a high correlation with other words, although it occurs less frequently than other words.

An important finding is that "life cycle assessment" is not closely linked to "wastewater", as it does not relate to terms such as "wastewater", "toxicity" and "heavy metals". This suggests that existing LCA studies on blended textiles are unlikely to focus on wastewater and its toxic effects. Similarly, there are no keywords related to greenhouse gases, which means that this aspect has not been sufficiently researched or may not be relevant when considering the environmental impact of blended textiles.

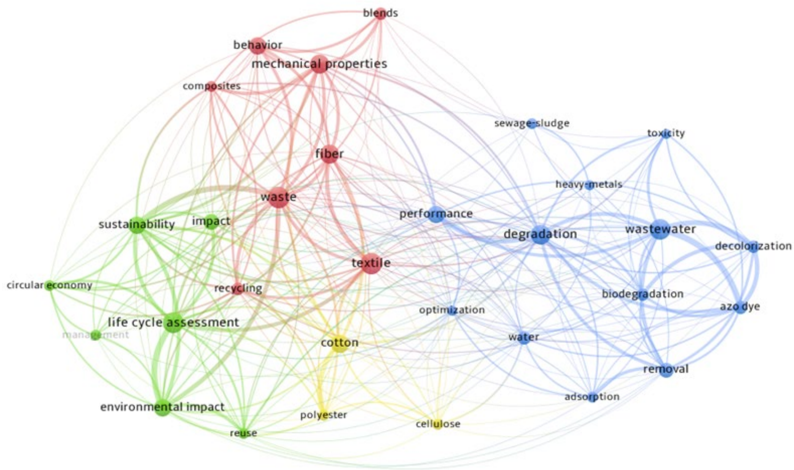

Fig. 3.6. Keyword co-occurence with a threshold of at least 12 occurences.

Environmental assessment of the production of cotton and polyester blends

Many reviews and research studies were examined before it was possible to compile studies on the environmental impact of CO/PES production relevant to this study. Most of the reviewed studies do not directly address CO/PES blend production and either use generic data, pre-built processes from databases such as Ecoinvent, or do not provide detailed input data. It was confirmed that a complete life cycle inventory for CO/PES production is not available in the literature. The most comprehensive inventory of CO/PES production was included in the study by Wagner et al. It includes data on primary raw materials such as energy and water, which are included in several reviewed studies; however, it also includes a detailed list of used chemicals and the characteristics of the wastewater from each process. To obtain complete data, information on emissions into the air is missing; nevertheless, the main problem is that all data is taken from cotton production, as the author found out that no data on CO/PES production were available in the literature.

Energy and water data were compiled in the same way as for chemicals (see Table 3.9). Once again, there are cases where the differences are minimal, such as water consumption in finishing, and there are also very significant differences, such as in water and wastewater pre-treatment. The least data is available on thermal energy. Zhang et al. included in their list the amount of coal used, which was most likely used for heating, but due to insufficient information, this was not included. The BAT report provided only general data on energy and water consumption in the textile industry, but no data on specific materials or processes, except for water consumption pre-treatment.

Table 3.5

Compilation of Overlapping Data from Selected Studies and Reports (Energy and Water)

	CO (medical workwear)	CO and CO/PES (BAT)	CO/PES (hospital uniform)	CO/PES (fabric, company B05)	CO/PES (fabric)
			Pre-treatment		
Electricity, kWh kg^{-1}	0.036	–	–	0.049	4
Water, l kg^{-1}	–	23	–	23.24	616
Wastewater, l kg^{-1}	15.10	–	–	20.40	350
Heat, kWh kg^{-1}	0.16	–	–	–	–
			Dyeing		
Electricity, kWh kg^{-1}	0.19	–	0.70	0.014	0.45
Water, l kg^{-1}	72.72	–	75	24.80	12
Wastewater, l kg^{-1}	33.35	–	–	19.50	–
Heat, kWh kg^{-1}	1.84	–	8.33	–	–
			Finishing		
Electricity, kWh kg^{-1}	0.16	–	–	–	0.31
Water, l kg^{-1}	23.30	–	–	–	22.90
Wastewater, l kg^{-1}	8.35	–	–	–	19.75
Heat, kWh kg^{-1}	0.56	–	–	–	–

The least included data in the reviewed environmental assessments are water and air emissions. This is consistent with the conclusion of the bibliometric analysis that LCA and wastewater do not show correlation. This should not be the case, as the toxicity of wastewater is a major concern when discussing the environmental impact of textile production; therefore, LCA studies should also include this aspect in order to fully assess the environmental impact of blended textiles. Only the study on medical workwear includes a detailed composition of textile wastewater, but it is taken from cotton production. Other studies include only chemical oxygen demand (COD), which is the most significant component by weight; consequently, one of the objectives of further analysis is to determine whether the exclusion of wastewater has a significant impact on the results.

It is not possible to develop a comprehensive LCI CO/PES blend for textiles using literature analysis data, as some data are not available, the differences in the available data are too great and assumptions about processes and technologies are not entirely clear; however, a LCA was performed to determine how the differences in the available data affect the environmental impact results for CO/POS blends.

3.3.2. Example of bibliometric analysis of energy management

Similar to how bibliometric analysis was applied to the study of blended-type textiles, however, with a different focus, the application of bibliometric analysis to energy management crystallised the results for this sector, which are clearly shown in Table 3.6.

Table 3.6

Query Settings and Keywords

#	Query setting	Keywords in query	Number of documents
		Query in SCOPUS	
1.	Advanced query in all fields, in all published documents in the year range of 2009–2024	ALL (“energy audit”) OR ALL (“energy auditing”) AND PUBYEAR > 2008 AND PUBYEAR < 2025	9446
2.	Advanced query in title, abstract and keywords, in all published documents in the year range 2009–2024	TITLE-ABS-KEY (“Green Deal”) OR TITLE-ABS-KEY (“fit for 55”) AND PUBYEAR > 2008 AND PUBYEAR < 2025	3441
3.	Advanced query in title, in all published documents in the year range 2009–2024	TITLE (“energy audit”) OR TITLE (“energy auditing”) AND PUBYEAR > 2008 AND PUBYEAR < 2025	631
4.	Advanced query in title, in all published documents in the year range 2009–2024	TITLE (“energy audit”) AND ALL (“energy efficiency”) AND PUBYEAR > 2008 AND PUBYEAR < 2025	366
5.	Advanced query in title, abstract and keywords, in all published documents in the year range 2009–2024	TITLE-ABS-KEY (“Green Deal”) OR TITLE-ABS-KEY (“fit for 55”) AND PUBYEAR > 2008 AND PUBYEAR < 2025	321
6.	Advanced query in title, in all published documents in the year range 2009–2024	TITLE (“energy efficiency first”) OR TITLE (“energy efficiency first principle”) AND PUBYEAR > 2008 AND PUBYEAR < 2025	17
		Query in MDPI	
7.	Advanced query in the full text field, in all published documents in the year range 2009–2024	FULLTEXT (“energy policies”) AND FULLTEXT (“energy policy”) AND “energy efficiency” Adding a search filter for years between 2009 and 2024	3448
8.	Advanced query in all fields, in all published documents in the year range 2009–2024	ALL (“energy audit”) OR ALL (“energy efficiency audit”) AND “energy efficiency” Adding a search filter for years between 2009 and 2024	821
9.	Advanced query in title, in all published documents in the year range 2009–2024	TITLE (“energy audit”) AND ALL (“energy efficiency”) Adding a search filter for years between 2009 and 2024	23
		Query in EUROPA SEARCH	
10.	Query in all fields and all formats (Web, Word, PowerPoint, Excel, PDF)	Energy efficiency	6061

3.4. System Dynamics

The base year for the model was 2018, as this was the year with the most available data. The main objective was to determine how the volume of clothing landfilled will change in the near future, so a baseline scenario was modelled until 2030. In addition, four scenarios were created to examine the impact of policy instruments on the usual business approach. The scenarios are summarised in Fig. 3.7.

Fig. 3.7. Developed and modelled scenarios and their time intervals.

Policy instruments were combined in all possible ways, resulting in four modelling scenarios. They came into effect in 2025, given that previous years cannot be influenced, and the EU has made the separate collection of textile waste mandatory starting in 2025. To enable the policy instruments to influence the behaviour of the model, the simulation was extended to 2040. Scenario 1 is the same as the baseline scenario. In Scenarios 2 and 3, only one of the policy instruments is activated, while in Scenario 4, both policy instruments are active. Table 3.07 shows the values obtained for the parameters that were initially defined as important circular economy indicators in the different scenarios. The results are described in more detail in the following subsections.

Table 3.7

Values of Key Indicators of the Circular Economy in the Textiles Sector under Different Scenarios

	Base	Business as usual in 10 years	Business as usual in 20 years	With a focus on sorting clothes	With a focus on reducing consumption
Specific clothing consumption, kg/capita/year	9.8	16.0	24.1	24.1	5.0
Clothing lifetime, years	3.3	1.7	0.9	0.9	8.6
Textile sorting rate, %	38	33	31	81	100
Landfilled clothing, million tonnes/year	3.3	5.8	8.9	5.1	0.7

Baseline scenario

The baseline scenario shows that 58 million tonnes of clothing consumed and produced in the EU will be landfilled in 2030. Not all of this ends up in landfills in the EU, as some textile waste is exported. The model showed that, in 2030, with a business-as-usual approach, clothing consumption could be 16 kg per capita, but the lifetime of clothing could be reduced to 1.66 years. Annual life-cycle GHG emissions ranged from 130 tCO_2eq/year to 212 million tCO_2eq/year. A total of 2.13 billion tCO_2eq would be generated over the period. The estimated EU textile sorting volume in 2018 was between 1.7 and 2.1 million tonnes. The initial clothing sorting model was 1.67 million tonnes. The results are consistent with the EU data, considering that the share of fashion textiles could be around 81 %. Figure 3.8 shows the results and the distribution of flows for the first year of the simulation. All flows are given in thousands of tonnes per year. Various options for textile flows in the EU have been proposed in the literature, but until now, a detailed overview of clothing flows has not been available.

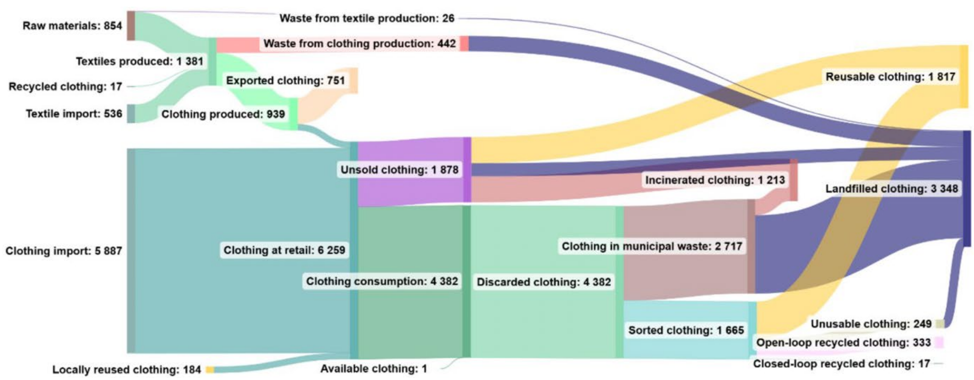

Fig. 3.8. Material flows in the EU fashion textiles value chain in 2018 (thousand tonnes/year).

Material flows in the fashion textile value chain in the EU in 2030 are shown in Fig. 3.15. It is clear that the values of all flows have increased, which is in line with the projection. Since the baseline scenario included an increase in sorting capacity, it was projected that the proportion of clothing would increase. As can be seen in Figs. 3.8 and 3.9, the visual ratio of flows has not changed significantly. This is also confirmed by the numerical value of the sorting rate. In 2018, the clothing sorting rate was 38 %, while the resulting sorting rate for 2030 was 33 %. The sorting rate has decreased because the observed increase in sorting capacity is proportionally smaller than the increase in consumption and discarded clothing.

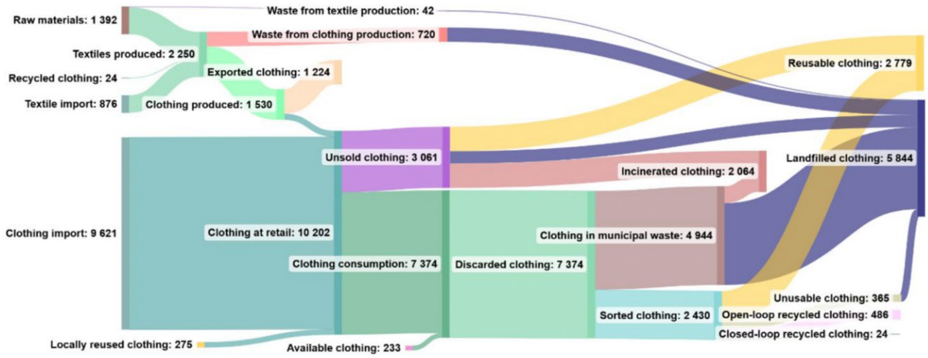

Fig. 3.9. Material flows in the EU fashion textiles value chain in 2030 (thousand tonnes/year).

The flows in 2040 resulting from Scenario 4 are shown in Fig. 3.10. There are no municipal waste flows, but landfilling of clothing still occurs. The most significant flow at the end of the value chain is reused clothing. The Sankey diagram also points to other pressing issues that need attention, such as the export of second-hand clothing and its lack of domestic use, landfilling of industrial and commercial waste and a very low rate of closed-loop recycling. As before, the flows are presented in thousands of tonnes per year.

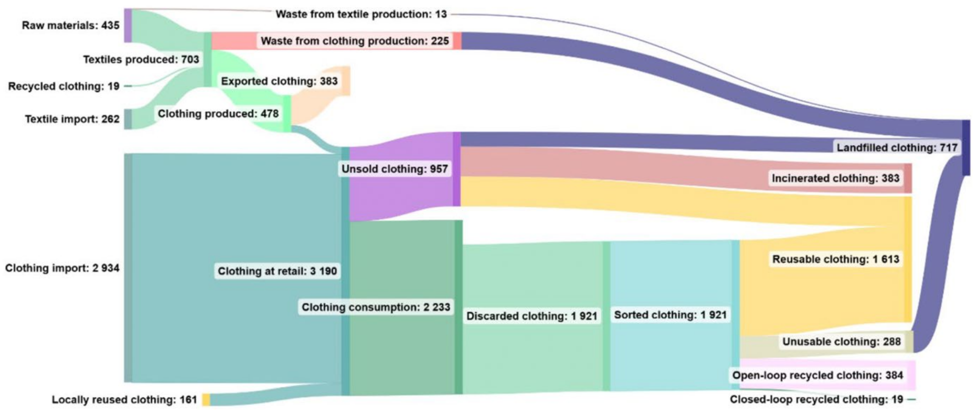

Fig. 3.10. Material flows in the EU fashion textiles value chain in 2040 from Scenarios 3 and 4 (thousand tonnes/year).

3.5. Fuzzy cognitive maps

Publication 7, “Bioeconomy Towards Green Deal. Case Study of Citric Acid Production Through Fuzzy Cognitive Maps”, described the citric acid production process model and the results obtained. All 16 production processes were analysed in the same way, using an analogous modelling method and identical criteria; however, as mentioned above, the main objective of the study is to obtain data in order to select the most promising production processes from those described and rank them, thus determining which of the proposed solutions is the most effective and demonstrates added-value from a bioeconomic perspect in terms of achieving the Green Deal objectives and developing the circular economy. To obtain such a result, the results of each production process in the category "production process efficiency" are compared with each other on a quantitative scale of “1”. The listed results are shown in a bar chart in Fig. 3.11.

The bar chart (Fig. 3.20) shows the quantitative results obtained from 16 manufacturing processes in terms of usefulness comparison. The results show that the most efficient production process is the manufacture of composite materials. This result is based on the availability of raw materials for composite materials, which are mainly by-products of other production processes: low-quality wood residues and recycled plastic. Similarly, the demand for such composites is growing rapidly in the market due to their physical properties, and the production technologies are relatively simple and accessible without excessive investment. Without delving into the positive characteristics of each production process that have contributed to the high results achieved, we conclude that 11 of the 16 production processes described have achieved very high values in the range from 0.9 to 1, and all 11 production processes correspond to high bioeconomic efficiency for achieving the Green Deal goals, thus these production processes are very valuable and should be primarily implemented into the economy by investing in production equipment.

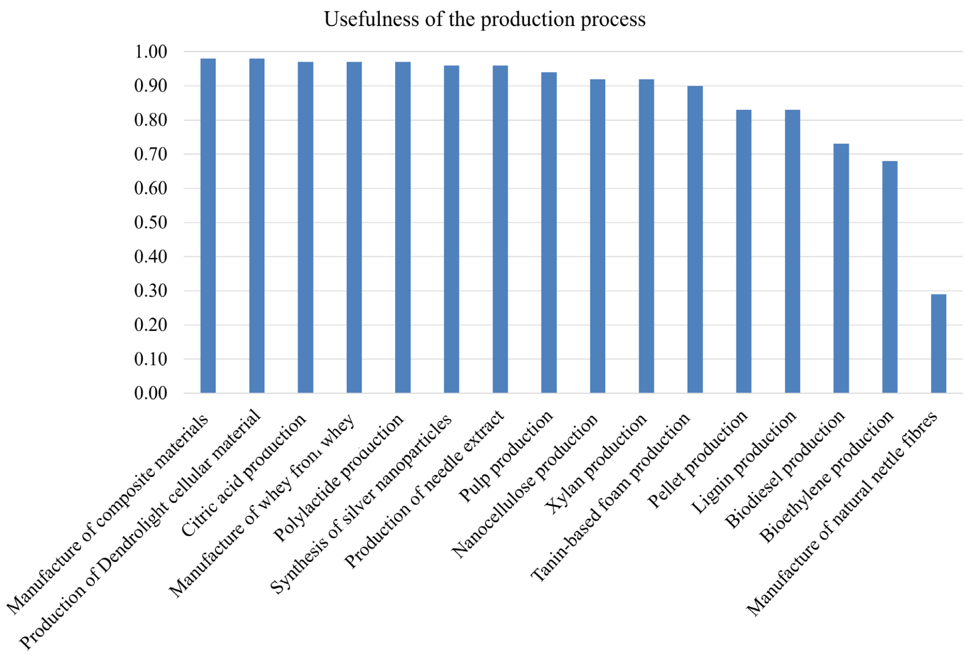

Fig. 3.11. Summary of the efficiency of production processes.

In contrast, the processes for producing biodiesel and bioethanol, although highly valuable for replacing fossil fuelds and increasing dependance of non-oil-producing countries from fossil resources, are still very technologically complex and require huge investments in production, which currently reduces their economic viability; however, rapid advances in science and technology will inevitably bring the production of biodiesel and bioethanol closer in the coming decade.

The weakest result (0.29 out of 1) was obtained in the production of natural nettle fibre. This result is related to the competition between this production process and the food industry for agricultural land and the low competitiveness of the product obtained in the textile industry, as it would be very difficult to justify the large-scale production of nettles and their processing into textiles from an environmental and economic point of view.

Considering the objectives of the study, the results obtained are reliable and objectively reflect the validity of the FCM method, and the use of this type of integrated analysis is appropriate for comparing the various alternative production processes discussed in the paper.

CONCLUSIONS

1. Although the Thesis evaluates a wide range of waste recycling and higher value-added product manufacturing processes, evidence from several studies, in particular the findings of Publication 6, "What Drives the Circular Economy? Textile Sorting or Consumption Reduction", indicates that the primary and consistently indispensable step towards a circular economy is a consumption-reduction policy, thereby confirming the hypothesis advanced in the Thesis.
2. By using scientific research methods in the decision-making process, it is possible to comprehensively evaluate the best possible scenarios and sustainable choices for implementing the circular economy, as not all aspects can be evaluated using a single method. By creating a set or combination of methods as a tool system, it is possible to comprehensively and based on data assess the potential of each production or recycling process for the development of the circular economy.
3. The system dynamics analysis conducted in the course of this research, which facilitates strategy formulation, policy design, and decision-making in complex and dynamic domains, led to the conclusion that it is currently essential for policymakers in Latvia, as well as in other countries, to evaluate the effectiveness of existing and proposed circular economy strategies to develop short- and long-term action plans that not only promote the transition towards a circular economy model, but also ensure reasonable practical solutions, including policy support and additional financial instruments, thereby incentivising enterprises to invest in sustainable circular-economy industries.
4. Considering the objectives of the study, the results obtained are reliable and objectively reflect the significance of combining the scientific methods used. The use of this type of integrated analysis is appropriate for comparing the various alternative production processes discussed in the Thesis.
5. The results obtained in the Thesis confirm that recycling any waste, residues, or by-products reduces the impact on the climate, paves the way for sustainable development and promotes the development of products with higher added value.

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