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Ilze Vamža

BIOECONOMY INNOVATIONS IN CONIFER VALUE CHAIN

Summary of the Doctoral Thesis

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

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on December 7, 2023 at 14.00 at the Faculty of Electrical and Environmental Engineering of Riga Technical University, Azenes Street, Room 212.

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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 Engineering Sciences is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Ilze Vamža …………………………… (signature)

Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction, three chapters, Conclusions, 18 figures, 15 tables, and x appendices; the total number of pages is 99. The Bibliography contains 235 titles.

TABLE OF CONTENTS

INTRODUCTION

The author investigates the relevance and implications of existing practices, product development, and carbon mitigation strategies within the wood value chain. The study aligns with the principles of biobased industries, the bioeconomy, value-added opportunities, and the global goal of achieving carbon neutrality by 2050. By adopting a comprehensive approach, this research aims to provide insights into the potential of the conifer value chain. The Thesis explores the interconnections between different aspects within the wood value chain, investigates the environmental impacts of recycling cross-laminated timber, thermal insulation packaging from forest residues, bio-based adhesives for engineered wood products, carbon storage in wood-based products, carbon dynamics in various carbon pools, and the development of 100 % bio-based particle boards from forest logging residues.

THE RELEVANCE OF THE TOPIC

The primary objective of this study is to contribute to the advancement of biobased industries by exploring the factors and technologies impacting the transition to a more resource-effective and carbon-neutral economy. The Thesis elucidates sustainable practices and innovative product development in the wood value chain. By replacing fossil-based resources with renewable biological resources, the research supports the transition toward a more sustainable and environmentally friendly economy. Additionally, the study aligns with the concept of the bioeconomy, emphasizing the sustainable utilization of biological resources. By focusing on value-added opportunities, this research investigates the enhancement of wood-based products through the development of bio-based adhesives, thermal insulation material, and 100 % bio-based particle boards. These endeavours aim to increase the value, competitiveness, and economic viability of the forest sector while concurrently reducing atmospheric carbon.

Moreover, this research addresses the urgent need to achieve carbon neutrality by 2050 and, using mathematical modelling, explores potential policies for using the forest sector as a carbon buffer. It explores carbon dynamics among carbon pools and evaluates the potential of carbon storage in wood particle boards. By developing a mathematical model, this study provides a better understanding of carbon sequestration potential within the wood value chain. The obtained insights can be utilized by policymakers in the forest sector to develop efficient policies that align with global carbon neutrality goals and facilitate the transition to a sustainable bioeconomy.

Ultimately, this research contributes to the body of knowledge surrounding sustainable practices, product development, and carbon mitigation strategies in the wood value chain. Its findings and recommendations provide a basis for practical solutions that drive the transition towards a low-carbon and sustainable future, benefiting both the forest sector and society.

THE RESEARCH AIM

To reach the primary objective of the study – to contribute to the advancement of biobased industries, the factors and technologies impacting the transition to a more resource-effective and carbon-neutral economy were explored. Sustainable practices, product development, and carbon mitigation opportunities within the wood value chain were investigated, aiming to enhance resource efficiency, promote environmentally friendly solutions, and contribute to the overall sustainability of the industry. The following tasks were set to reach the overarching goal:

1. Determine the factors impacting the bioeconomy focusing on resource efficiency.
2. Develop a bioresource utilization index to evaluate the value added to the wood biomass.
3. Propose cascade and circularity approaches to enhance wood-value chain resource efficiency and carbon storage in the economy.
4. Conduct the life cycle assessment (LCA) for innovative products developed in line with this work.
5. Conduct a literature review on bio-based adhesives from various wood residues.
6. Conduct an experimental study for a product that would increase the added value of the raw material beyond its current use.

NOVELTY OF THE RESEARCH

The research combines multiple evaluation methods and aspects of sustainability: value-added, carbon footprint, and carbon storage dynamics. The novelty of the research lies in the exploration of sustainable practices, product development, and atmospheric carbon mitigation within the wood value chain. While there may already be existing research papers and patents on specific topics within this domain, the novelty of the research lies in the comprehensive approach. The research aims to provide a comprehensive examination of multiple aspects within the wood value chain, ranging from recycling cross-laminated timber to carbon dynamics in various carbon pools. This holistic perspective adds value by considering the interconnections and potential synergies between different areas, leading to a more integrated understanding of sustainability and reduction of the carbon footprint of the wood-based industry. The Thesis seeks to address sustainability challenges and promote environmentally friendly solutions in the wood value chain by examining various topics such as bio-based adhesives, thermal insulation packaging, and 100 % bio-based particle boards. The research can potentially propose integrated solutions that combine different innovations and technologies for more sustainable wood-based products and practices. In addition, the research on carbon dynamics can serve as a basis for specific policy development, empowering forest sector policymakers with a tool for efficient policy development. The mathematical model of carbon dynamics among carbon pools can contribute to a better understanding of carbon sequestration potential and the environmental impact of wood-based products.

The research elucidates seven main factors that impact the bioeconomy and further focuses on the Forest sector, exploring the seven factors in line with the wood value chain. Therefore, the novelty of this research also stems from its practical implications and real-world applications. Examining the viability and sustainability of recycling cross-laminated timber, developing thermal insulation packaging, or creating 100 % bio-based particle boards provide insights and potential solutions that have tangible impacts on the wood industry, resource efficiency, and carbon mitigation efforts.

HYPOTHESIS

Wood value chain, despite its bio-based raw material, can be utilized not only for energy production but also for long-term carbon storage. By integrating sustainable practices, product development, and carbon mitigation strategies within the wood value chain, it is possible to enhance resource efficiency, reduce the carbon footprint of the wood-based industry, and promote environmentally friendly solutions while maintaining economic viability.

PRACTICAL RELEVANCE

According to Latvia's National Research and Innovation strategy for smart specialization – RIS3, the national economy needs to transform towards resource efficiency and social innovations in main economy areas, including forestry as one of the biggest areas. According to the National Research Ecosystem Report 2014–2018, only a small fraction of research has been devoted to innovations in wood biomass use. Therefore, the practical relevance of this research lies in multiple aspects: (1) patent of 100 % bio-based chipboard from forest residues; (2) system dynamics model for carbon flows in forest economy; (3) multiple propositions for improvements in resource efficiency of forest economy.

RESEARCH STRUCTURE

The Thesis is based on seven scientific publications with an overreaching goal to evaluate and explore opportunities to increase the resource efficiency and value of conifers in Latvia's forest economy. Multiple methods have been used in the research, covering the topic at multiple levels – national, market, enterprise, and product (as depicted in Fig. 1)

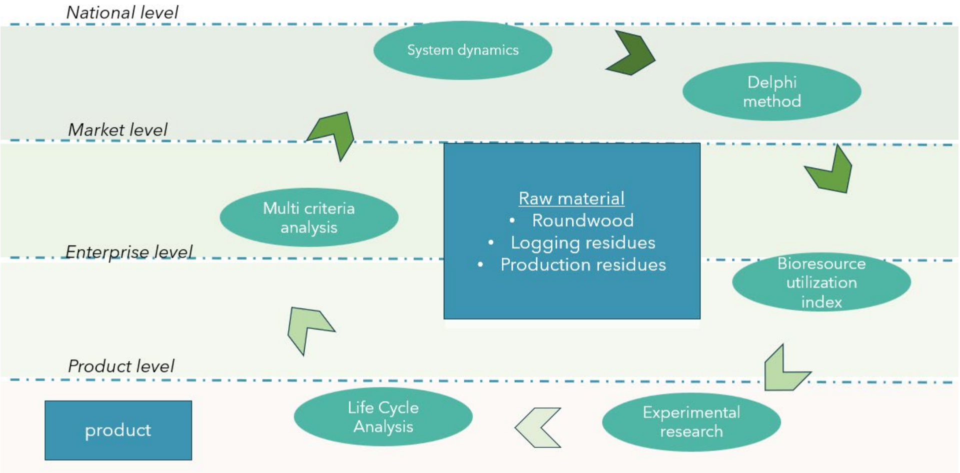

Fig. 1. Visual research structure.

Identifying the phenomenon or problem to be analysed. The first step was to clearly define the phenomenon or problem that will be the focus of the Thesis – Latvia's forest economy and the use of the Scots pine.

Data for the analysis was gathered according to the levels described above and the corresponding methodology used to reach the required milestones for further work. The main methodologies used in this work are life cycle assessment, multicriteria analysis, system dynamics modelling, Delphi method, and newly created bioresource utilization index approved in scientific publication.

APPROBATION

Publications

1. A Review of Bio-Based Adhesives from Primary and Secondary Biomass for Wood Composite Applications
Vamza, I., Krigers, G., Valters, K.
Environmental and Climate Technologies, 2022, 26(1), pp. 1350–1360

2. CO_2 Storage in Logging Residue Products with Analysis of Energy Production Scenarios
Viksne, G., Vamža, I., Terjanika, V., ...Pubule, J., Blumberga, D.
Environmental and Climate Technologies, 2022, 26(1), pp. 1158–1168

3. Bioresource utilization index – A way to quantify and compare resource efficiency in production
Vamza, I., Kubule, A., Zihare, L., Valters, K., Blumberga, D.
Journal of Cleaner Production, 2021, 320, 128791

4. Bioeconomy triple factor nexus through indicator analysis
Zihare, L., Kubule, A., Vamza, I., Muizniece, I., Blumberga, D.
New Biotechnology, 2021, 61, pp. 57–68

5. Complete Circularity in Cross-Laminated Timber Production
Vamza, I., Valters, K., Luksta, I., Resnais, P., Blumberga, D.
Environmental and Climate Technologies, 2021, 25(1), pp. 1101–1113

6. Criteria for choosing thermal packaging for temperature sensitive goods transportation
Vamza, I., Valters, K., Dzalbs, A., Kudurs, E., Blumberga, D.
Environmental and Climate Technologies, 2021, 25(1), pp. 382–391

7. Life Cycle Assessment of Reprocessed Cross Laminated Timber in Latvia
Vamza, I., Diaz, F., Resnais, P., Radziņa, A., Blumberga, D.
Environmental and Climate Technologies, 2021, 25(1), pp. 58–70

8. Forest residues towards climate neutral products
Krumins J. A., Vamza I., Dzalbs A., Blumberga, D.
Buildings (iesniegts manuskripts)

Reports at Scientific Conferences

1. System dynamics thinking to optimize carbon storage in the wood-based economy
Vamza I., Gravelsins A., Kasakovska A., Blumberga D., Prodanuks T.
European Biomass Conference EUBCE2023

Other scientific publications

1. Single Cell Oil Production from Waste Biomass: Review of Applicable Industrial By-Products
Spalvins, K., Vamza, I., Blumberga, D.
Environmental and Climate Technologies, 2019, 23(2), pp. 325–337

2. Multi-Criteria Analysis of Lignocellulose Substrate Pre-Treatment
   Vamza, I., Valters, K., Blumberga, D.
   Environmental and Climate Technologies, 2021, 24(3), pp. 483–492

3. Analysis of Bioeconomy Affecting Factors-Climate Change and Production
   Indzere, Z., Kubule, A., Zihare, L., Vamza, I., Blumberga, D.
   Environmental and Climate Technologies, 2021, 25(1), pp. 1293–1304

1. METHODS

The Thesis results are represented corresponding to the methodology.

1.1 Experiments for chipboard production

Lab experiments were conducted for chipboard creation using conifer logging residues and bio-based binders, supporting the shift from fossil-based materials. The binders were chosen via literature review. The logging biomass was delivered in polyethylene bags as wood chips containing heartwood, sapwood, bark, needles, and more. Variables and values are listed in Table 2.1.

Table 2.1

Independent Variables and their Minimum and Maximum values

Parameter	**Min**	**Max**
Total mass, g	174	392
Particle size, mm	2.8	10
Working temperature, °C	109	180
Working pressure, bar	235	675
Pressing time, min/mm	0.36	2.4
Adhesive, % W/W	0.25	10

The experimental stand was custom-made and included a hydraulic press with a hand pump (Hansa Flex – 10 t); an analogue pressure gauge (Hansa Flex – 600 bar, ± 50 bar); a digital manometer (Hansa Flex – 1000 bar, ± 1 bar); cylindrical heating elements (alternating currents); temperature sensors; and heating metal blocks/surfaces. The experimental stand is depicted in Fig. 1.1.

Fig. 1.1. Hydraulic hot press.

Additionally, the stand included a plate drying stand, metal frames: metal frame without perforations for holding biomass, and metal frame with perforations for biomass retention and steam discharge, metal lining for steam removal; and Teflon fabric.

The different amount of moisture in the wood chips was observed under different weather conditions during the chipping and delivery of logging residues. Biomass, as received from logging sites, can be seen in Fig. 1.2.

Fig.1.2. Biomass as received from logging site.

First, wood chips were extracted from polyethylene bags and air-dried indoors to 8 %–10 % moisture. Drying took around a week, varying by initial moisture. Moisture levels were gauged using the Greisinger GMH 3830 probe. Dried chips were ground using a hammer mill for desired particle size. Initial grinding employed a two-axis chipper, sieving larger particles or using the Vibrotehnik PM-120 hammer mill for smaller ones. Particle size methods depended on requirements: (1) crushing the chips in the chipper and then by the hammer mill, or (2) sieving the crushed particles using the Retsch AS-400 sieve shaker with varied mesh sizes.

Sieving yields a particle range, not a single size, and some particles smaller in width but longer in length may pass through. The boards were produced using the prepared biomass with specified size and moisture. The formation involved a digital pressure gauge setup, temperature control, a metal frame placement with Teflon cloth, biomass forming, and pressing. Then, pressure release followed, and boards were dried.

Particle size significantly impacts the particle board strength. For the tests, the logging residue particles were divided by their size into three parts: < 2.8 mm, 2.8–8 mm, and 8.0–10.0 mm. Hot pressing was done at 600 bar at 140 °C and 160 °C. The board density and modulus of elasticity were measured.

Density was determination by European standard EN 323:1996. Calipers and scales were used to determine dimensions and mass. Modulus of elasticity and flexural strength were measured using standard EN 310:1993, the testing stand is depicted in Fig. 1.3. The modulus of elasticity was calculated from the load-deflection curve's linear region. Bending strength was calculated from the maximum bending load until mechanical collapse. Strength tests were done after marking the sawing lines, cutting the sheets, support point placement, and load application.

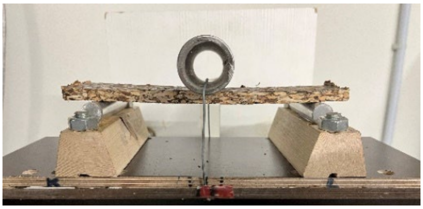

Fig. 1.3. Testing stand.

Data was analysed using the two-factor analysis of variance (ANOVA) with replications to investigate the effects of two independent variables on the observed outcomes. Particle size, temperature, and pressure were manipulated as independent variables to evaluate both their individual impacts and potential interactions. To employ the two-factor ANOVA, only two independent variables were compared at a time. This specific analysis was done of 102 samples, each representing a specific pairing of pressure, particle size, and temperature. Three replications of each sample were incorporated to enhance the robustness of the findings. Measurements were made according to the previously described methodology. Data preparation involved structuring the collected data into columns for each combination of factor levels, with rows representing replications. This data organization facilitated an effective assessment of the independent variables' effects. To conduct the two-factor ANOVA, the Microsoft Excel's Data Analysis tool was used.

ANOVA allowed for the testing of three simultaneous hypotheses:
H1 – there is no significant difference in the 1st variable's results;
H2 – there is no significant difference in the 2nd variable's results;
H3 – there are no significant interactions between both factors.

T-test was chosen as a post hoc test for the pairwise comparison of the disproven null hypothesis. Each composition and parameters were replicated at least three times and produced boards sawn in three equal parts for MoE testing, and density calculations, resulting in at least six repetitions. The calculated standard deviations are depicted in graphs, 5 % confidence P-value was used in the analysis.

1.2 Multi criteria decision making

In the Thesis, multi criteria decision analysis (MCDA) was used multiple times on various occasions, and all of the MCDA were conducted using a combination of the technique for order of preference by similarity to ideal solution (TOPSIS) and the analytical hierarchy process (AHP). The combination of these two methods is helpful for evaluating how close to the ideal solution are all the alternatives, as the TOPSIS method not only elucidates the best alternative but gives the closeness to the ideal solution coefficient. Hence, by using TOPSIS, a more detailed picture of “how ideal are all the alternatives” can be acquired. To acquire the weights for TOPSIS, AHP was used. AHP is one of the most widely used multi-criteria analysis methods because it allows to easily compare the criteria. In the Thesis, the Saaty's scale was used to compare the criteria, in which nine degrees of importance were verbally denoted, indicating the importance of one criterion over another. The scale of nine ratings starts with 1 which stands for equal importance, and ends with 9 which stands for extreme importance.

Initial criteria for all the MCDM conducted in the Thesis were identified in open interviews with representatives of companies working in the pharmaceutical and fine chemicals and the logistics field, asking the representatives to answer open questions.

1.3 Analytical hierarchy process

To determine the importance of the chosen criteria, a pairwise comparison was conducted. As it is impossible for humans to grasp the reciprocal relationships of 12 criteria at the same time, the pair analysis method was chosen. Using this approach experts were asked to compare only two criteria at a time; each expert did the total of 66 comparisons for thermal packaging. The comparison was done verbally, as suggested by Saaty et al. (2010), by determining if one criterion is equally important, less important, or more important than the other. After the verbal comparison, numerical values were assigned to each compared pair using a scale of 9. In the chosen scale, 9 was signifying a very high importance, 6 – strong to very strong importance, 3 – moderate importance, and 1 – equal importance. The values were then marked in the digital survey form.

Overall, 10 questionnaires were disseminated among the identified pharmaceutical and fine chemical industry enterprises in Latvia, including big companies like Grindex and Olainfarm. It was expected that the approached companies were heavily impacted by the global pandemic; only five responded and three were eligible to questions, as companies made their own decisions regarding temperature sensitive product logistics. Two companies outsourced this service, hence were unsuitable for multi criteria analysis and criteria comparison; nevertheless their reported practice will be discussed in the Results part of this study. The chosen companies assigned the questionnaire to logistics team experts within the company. The criteria from one MCDA exploring the market opportunity for natural thermal packaging from logging residues are shown in the digital survey presented in Table 1.2.

Table 1.2

Thermal Packaging Criteria Used for Pairwise Comparison

Criteria	Description
Odour	Material has no considerable scent.
Resistance to humidity	Material does not dissolve or get damaged to the point it loses its thermal resistance.
Vapor resistance, [m]	S_d value of thermal insulation material. Represents the resistance to water vapor taking up certain air layer thickness [m]. Mostly relevant for shipments with dry ice.
Branding opportunities	Material can be printed on.
Sustainability	Raw material of thermal packaging is renewable.
Ability to hold temperature, [hours]	Packaging can hold specific temperature for more than 24 hours. Criterion represents in situ measurements of temperature in relevant environment and packed test goods – representing goods that would be transported.
Thermal conductivity, [W/m·K]	In line with this study, 0.04 W/m·K was considered the threshold for thermal conductivity to be considered low. Thermal conductivity characterizes the material by its ability to conduct heat energy. Heat energy is always transferred down the gradient.
Reusability	Material can be re-used multiple times.
Available in multiple sizes	Multiple dimension options are available.
Price, [euros per 39l box]	Per packaging solution.
Durability	Material can be used without supportive tertiary packaging (e.g., cardboard box).
Density, [kg/m^3]	Weight to volume ratio of packaging solution.

Mathematically all the chosen criteria are plotted on a matrix, and by solving the matrix, eigenvalues were found. These values, also called eigenvectors, represent the importance of each criteria – higher value means higher importance in the final decision. Indicative eigenvalues were calculated in Microsoft Excel and used for further analysis. Consistency threshold of 0.2 was used, as done before in other research when multiple stakeholders were surveyed.

1.4 Life cycle assessment methodology

Life cycle assessment (LCA) quantifies and compares the product or process impacts, commonly used for studies like this. Each product undergoes a life cycle: design, resource extraction, production, consumption, and disposal. LCA aggregates the resource use, emissions, and exchanges to assess environmental impacts.

Conducted per ISO 14044 standard, LCA comprises four steps: goal, inventory, impact assessment, and interpretation. This study compares waste treatment scenarios. The conventional scenario waste treatment aligns with existing Environmental Product Declaration (EPD) for CLT master panels. The new scenario involves in-situ re-processing of cuttings into new CLT pieces. The study scope covers activities related to cuttings' use, irrespective of waste facility location.

An attributional model normalizes the EPD output data to scenarios using specific activities, materials, and energy flows. The results are site-specific due to varied project attributes. The baseline scenario envisions energy recovery, with impacts from Wood-Based Panel Market Report. The proposed scenario reprocesses cuttings into useful CLT units, leaving some for disposal, as in the baseline. LCA employed Simapro 9.0 with Ecoinvent 3.6. The functional unit (FU) measures performance, providing a reference for equivalence in LCA results. Here, FU is 1 m^3 of CLT used in construction. The reprocessed CLT matches virgin master panels mechanically. The Environmental Product Declaration boundaries and study boundaries led to the scheme in Fig. 2.4.

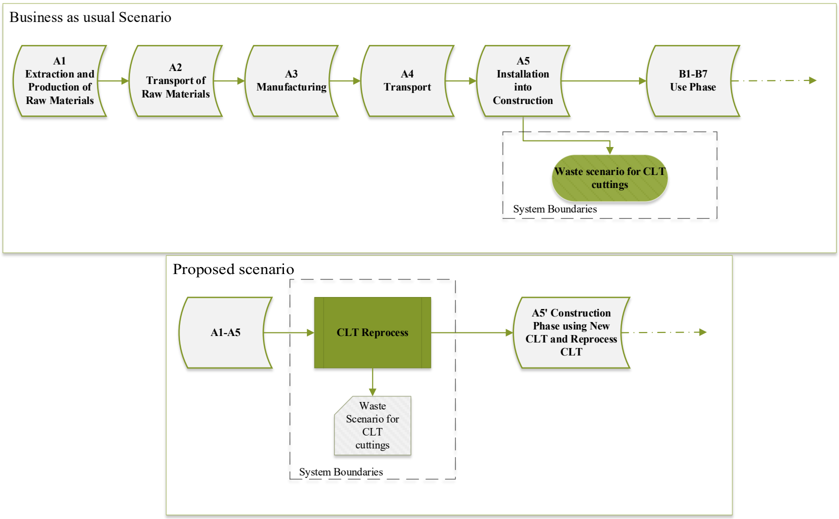

Fig. 1.4. System boundaries for the business as usual and proposed scenarios.

In the baseline scenario, system boundaries encompass on-site waste treatment of cuttings from the construction site. Transport to waste treatment plants is not considered due to distance uncertainty from varying geographical locations of building sites. The diagram displays phases A1–B7, contextualizing the system, but only the phases within the dashed box are within the study's scope. Extra phases offer an overview of CLT's life cycle. In the proposed scenario, re-processing happens on-site without external transport needs. Cuttings not suitable for re-processing receive the same treatment as in the baseline scenario. Transport to waste treatment facilities is again excluded due to distance uncertainty.

Both scenarios share limitations, primarily the exclusion of transport activities due to geographical uncertainty for both waste treatment facilities and construction sites. However, it is crucial to acknowledge that transporting waste incurs environmental burdens from vehicle emissions and fuel combustion. Reducing transported waste could yield environmental benefits, but this issue is beyond the Thesis research scope.

Another key assumption is that reprocessing aligns with residential house construction on the same site. This choice minimizes potential environmental burdens from transport. This consideration is crucial, as in different case studies, post-construction cuttings might need transport for re-processing elsewhere, and such additional transport could influence environmental impacts.

For the baseline scenario, the results from the energy recovery at the end of life (EoL) stage were taken directly for 1 m^3 and normalized to the amount of waste generated on the particular construction site. According to the foreground data collected, per each cubic meter of CLT used, 0.128 m^3 ends up as waste cuttings. The estimated benefits resulting from the energy recovery of 1 m^3 are 612 MJ of electricity and 4208 MJ of thermal energy for district heating. The associated environmental impact of a whole cubic meter of material disposed is shown in Table 2.3. Nevertheless, the values within the model are normalized to the actual amount of cuttings sent to waste in each scenario.

Table 1.3

Impact Assessment for 1 m^3 of CLT Disposed

Impact category	Unit	Total per m^3
Acidification potential	kg SO_2 eq	–0.1786
Eutrophication potential	kg PO_4 eq	–0.04186
Global warming potential	kg CO_2 eq	–32.51
Formation potential of tropospheric photochemical oxidants	kg C_2H_4 eq	–0.01664
Abiotic depletion potential for non-fossil resources	kg Sb eq	–0.000112
Abiotic depletion potential for fossil resources	MJ	–0.04217
Depletion potential of the stratospheric ozone layer	kg CFC-11 eq	0.000004012

For the proposed scenario where reprocess activities allow to recover part of the cuttings by making new CLT units, the inventory collection goes toward gathering impacts from 3 stages:

1) production of brand new CLT units;
2) materials and energy required for the reprocess activity itself;
3) waste treatment of the unrecoverable cuttings.

By creating new CLT units from cuttings brand new CLT units are potentially replaced on a construction site; the impact of such new reprocessed CLT units is considered as an avoided product, hence the environmental impact results from phases A1–A3 (Fig. 1.4) are normalized and mathematically treated consequently with this approach. Impacts of stages A1–A3 for 1 m^3 are shown in Table 1.4.

Table 1.4

Impact Assessment of Producing 1 m^3 of CLT (A1–A3 Stages)

Impact category	Unit	Total
Acidification potential	kg SO_2 eq	0.6272
Eutrophication potential	kg PO_4 eq	0.1116
Global warming potential	kg CO_2 eq	–0.05673
Formation potential of tropospheric photochemical oxidants	kg C_2H_4 eq	0.1144
Abiotic depletion potential for non-fossil resources	kg Sb eq	0.0002468
Abiotic depletion potential for fossil resources	MJ	1497
Depletion potential of the stratospheric ozone layer	kg CFC-11 eq	0.0000125

The inventory of material and energy required for reprocessing 0.128 m^3 of leftover cuttings (value per FU) are normalized to the following: 0.0904 kg of adhesive (polyurethane adhesive) and 0.466 kWh of electricity taken from the national grid. According to the foreground data obtained, 69.72 % of the cuttings reprocessed are successfully converted into new CLT modules, while the remaining 30.28 % are not suitable for re-process and must be left as waste material for treatment. The impact data related to such treatment is taken from Table 1.4 and normalized to the corresponding value in this scenario.

To illustrate the amount of available CLT for reprocessing, an individual house project (Fig. 1.5) was chosen. The load bearing structure is entirely created from CLT. Doors and windows are cut out creating a considerable amount of cutting waste.

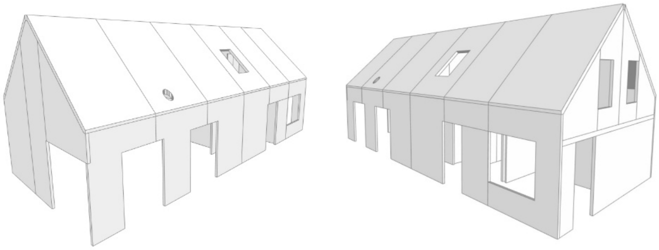

Fig. 1.5. 3D representation of the individual house CLT weight bearing construction.

Not all the cuttings were suitable for the new master panel production. Important criteria for cutting reuse was their flat surface area. Complicated geometrical shapes were sorted out, leaving the ones with reusable surface area above 1 m^2 with dimensions along the X axis (example shown in Fig. 1.6) not less than 800 mm.

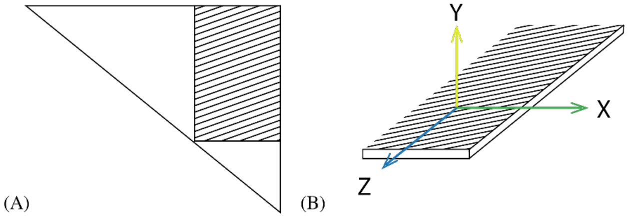

Fig. 1.6. (A) Reusable area of cutting represented with striped pattern (the reusable area is 810 mm wide and 1056 mm long); (B) schematic representation.

1.5 Delphi method

While raw material is well-defined, the pathway to stimulating bioeconomy development remains obscured by unidentified interlocking factors. This field's progression encompasses various sub-areas, including agriculture and forestry, often clashing – food versus fiber versus energy. Leveraging Muizniece et al.'s study, a 24-factor assessment and mapping using Delphi methodology were conducted to discern causal loops. The method involved academic and industry experts in two rounds. The thematic analysis organized factors into coherent patterns, guiding framework selection for theory-based analysis and nexus construction. The Delphi's strengths include Latvia-specific insights, countered by expert biases, which were mitigated by selecting experts with diverse academic backgrounds. For industry experts, interviews replaced questionnaires to address potential discrepancies in understanding factors.

1.6 Interviews

To evaluate the causal chain around bioresources, as well as explore the possibility of other factors impacting the proposed indicators and links in the academic expert surveying, qualitative interviews with managers from involved enterprises were conducted. The interview format was semi-structured, as this type of interview lets the interviewer to ask open questions and gives the possibility to go deeper into various aspects of the revealed facts. Semi-structured interviews have been already used in bioeconomy research. During the interviews, the overall attitude and motivation regarding bioresource, by-product and waste utilization was determined. The efficiency of by-product utilization was determined by collecting data from enterprises, including real consumption of raw materials as well as the produced bio-waste and by-products. The technical directors of three enterprises using the same bioresource as raw material were interviewed. Due to sensitive information interviewees were providing, the interviews were not recorded, instead, the interviewer produced comprehensive notes on the acquired information.

1.7 Algorithmic logic for nexus building

The bioresource nexus was created by analysing the information acquired in the interviews and validated by the literature analysis and by-product data from the enterprises in question. Qualitative and quantitative data were collected in interviews. The overall algorithm for building of bioresource nexus is shown in Fig. 2.7. Following the algorithm, two interviews were conducted, then as the second interview elucidated new factors, a third interview was conducted. The created algorithm demands to continue interviews until there are no new factors. In this specific case study, three interviews were sufficient, and results were published. Additional interviews afterwards have confirmed no new factors. Steps two and three represent the minimum interviews necessary to gain an overall idea of the factors impacting the specific subject. As during the second interview some new factors were identified, the third interview was conducted to see if more factors would be identified. If there are no new factors, the algorithm continues. The research was divided in smaller modules for a structured approach. While picking enterprises for this research, various production companies using the same type of biomass as a raw material were considered. An important factor in choosing the enterprises was their willingness to participate.

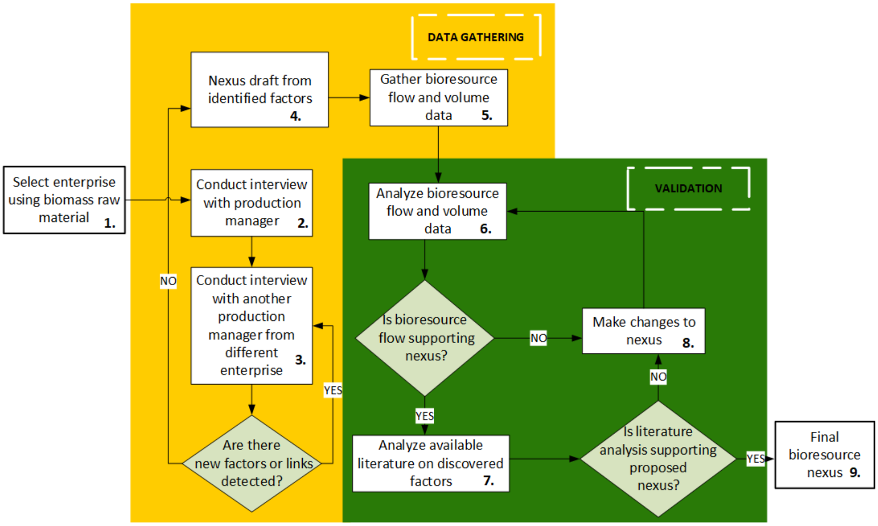

Fig. 1.7. Algorithm for bioresource nexus building.

The methodology, depicted in Fig. 1.7, can be applied for evaluation and building various nexuses using a bottom-up approach. In this study the bottom-up approach allows to analyse the factors for organic by-product flow back into bioeconomy through bioresource. Nexus provides information on factors impacting the system, but additional by-product data analysis provided information on the effectiveness of this by-product – bioresource flow.

1.8 Bioresource utilization index

The bioeconomy development impacting factor causal chain was supplemented with a more detailed bioresource utilization causal chain. In line with the theory-based analysis, heterogeneity of impact must be expected. Meaning – all actions on the same objects in causal loops will not lead to equal results. To measure the impact on bioeconomy of internally made decisions regarding the bioresource flow in an enterprise, a bioresource utilization index was developed.

The calculations were made using biomass dry weight. If there were no available data on the actual dry weight of the by-product, estimations were made using the values found in literature. The main categories analysed were production residues, damaged raw material, raw material that does not meet production standards, products that do not meet the market standards, other production leftovers, dissolved, and undissolved carbohydrates. As company managers disagreed to more detailed information disclosure, the raw material, product, or production technology could not be described in this work.

Bioresource flow in an enterprise was evaluated by comparison with waste management hierarchy and bio-based value pyramid, shown in Fig. 1.8 with the chosen coefficients from 0 – representing no value and 1 – representing the highest possible added-value to bio-based material. The bio-based value is assigned to the raw material or the by-product when it is used for the corresponding application in the bio-based pyramid.

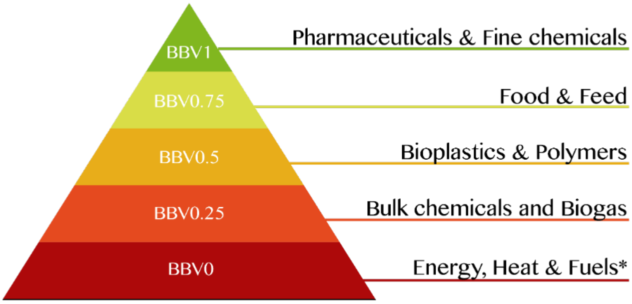

Fig. 1.8. Bio-based value pyramid. Five bioresource utilization options by categories and assigned coefficients corresponding to each group of bioresources [109] BBV – bio-based value and the corresponding coefficient, 1 representing the greatest value and 0 representing no value from the point of bioeconomy.

Each level in the bio-based value pyramid (Fig.1.8) was given a corresponding coefficient representing the value for bioresource utilization – coefficient 1 was attributed to pharmaceuticals and fine chemicals, coefficient 0.75 – to food and feed, 0.5 – to bioplastics and polymers, 0.25 – to bulk chemicals and biogas. Energy, Heat and Fuels were assigned the value of 0. The bioresource utilization index provides insight into production efficiency regardless of the product type, hence no value is assigned to the product. The calculations were conducted with various generated by-product utilization options and attributing corresponding coefficients from the previously described bio-based value pyramid.

$$B_{u_{ind.}} = (P + BP_1 \times c_1 + BP_2 \times c_2 + BP_3 \times c_3 + BP_4 \times c_4 + BP_5 \times c_5)/RM \quad (1)$$

$B_{u_{ind.}}$ – bioresource utilization index;
P – product [kg of dry weight];
BP_n – by-product [kg of dry weight];
c_n – coefficient assigned to bio-based value pyramid;
RM – used raw material [kg of dry weight].

1.9 Carbon accounting in wood-based products

To calculate the possible amount of CO_2 stored in the material, eight different standards for biogenic carbon accounting in products were reviewed and used. There are many different technical standards for LCA with other methods and approaches for carbon accounting. Still, in this case, only standards relevant to forest-based building materials and biogenic carbon were used. The standards used can be grouped into those that deal only with building materials (ISO-21930, EN-15804, CEN/TR-16970, EN-16485) and those which cover all products (PAS-2050, ISO/TS-14067, PEF). The standards can also be distinguished by geographical coverage, as some are international standards (ISO-21930, PAS-2050, ISO/TS-14067), and others are specific to Europe (EN-15804, CEN/TR-16970, EN-16485, PEF) and have stronger links to government regulation. As there currently exists no scientific consensus on which standard and method are the most appropriate for use, an average value derived from all standards was proposed.

The initial calculation for CO_2 stored in the material is assumed to be the same for all standards and is calculated as follows:

$$msq_{CO_2} = m_{dry}(timber) \times C_f \times \frac{m_{CO_2}}{m_C}, \quad (2)$$

where

msq_{CO_2}	–	mass of CO_2 sequestered, kgCO_2;
$m_{dry}(timber)$	–	dry weight of timber in the finished product, kg;
C_f	–	percentage of carbon in dry matter (for timber = 0.5);
m_{CO_2}	–	molecular mass of CO_2 = 44 g/mol;
m_C	–	molecular mass of carbon = 12 g/mol.

By substituting the masses of carbon and CO_2, Eq. (2) becomes:

$$msq_{CO_2} = m_{dry}(timber) \times 0.5 \times \frac{44}{12}, \quad (3)$$

where msq_{CO_2} is the mass of CO_2 sequestered in the finished product and $m_{dry}(timber)$ is the dry weight of timber in the finished product.

1.10 System dynamics modelling

Neutral or even negative carbon emissions is to be considered an important benefit of bioeconomy. While considering the development of bioeconomy, this needs to be part of the evaluation. Therefore, when considering the bioeconomy development in forestry, the factors need to be evaluated over long period of time. System dynamics modelling uses stocks and flows as a basis to describe the state and events of various systems. In the Thesis, system dynamics modelling was used to illustrate the carbon flow in wood-based value chain.

System dynamics uses integral calculus to determine the volume of stocks; in the Thesis the main stock is determined as carbon (C). This does not show the direct impact on global warming, as carbon has multiple forms, e.g., CO, CO_2, CH_4, that each impact global warming differently. The system dynamics approach demands the definition of dynamic hypothesis, in this case the dynamic hypothesis was defined as follows: complete utilization of logging and production residues in conifer value chain can lead to delay of carbon release into atmosphere.

The dynamic hypothesis is a theory about what existing structure runs the system. A dynamics hypothesis can be stated verbally, as a causal loop diagram, or as a stock and flow diagram.

In this research, the causal loop of carbon flow in nature was defined. Further, the dynamic hypothesis was supplemented with Bern's model of carbon sequestration involving human activity (Fig. 2.9).

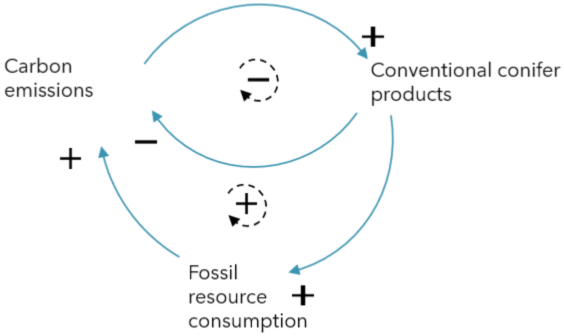

Fig. 1.9. Causal loops of carbon in the conifer value chain.

The defined dynamic hypothesis is based on the common assumption that wood products are carbon neutral as they balance the carbon in atmosphere by sequestering it during the tree growth phase. Nevertheless, the hypothesis states that there is an unintended effect of fossil resource consumption increase during the whole wood value chain. When more products are produced, more fossil resources are consumed – fossil-based adhesives, additives, fuel, and fossil energy used during the production process.

The model was built according to the identified causal loops and expanded based on the market and scientific literature analysis. Stocks represented carbon, thereby multiple calculations in the model are made to convert CO_2 emissions, product densities, biomass densities, etc. to tonnes of carbon. Density of the wood was assumed to be 420 kg/m^3.

Only national market was considered, therefore imports and exports were not considered although including trade with external markets would show additional valuable dynamics.

Atmospheric carbon was defined as 0 at the starting point of the simulation to assess the impact of explored scenarios. Three inflows and one outflow were connected to atmospheric carbon stock.

The model was divided into three sectors – forest, product production, and atmosphere. The forest sector was divided into tree stocks, assigning a biomass stock for each age decade starting from 0 to 10 years and ending with 151–160 years and, lastly, trees older than 160 years. This was due to multiple reasons, firstly due to the carbon assimilation dynamics and, secondly, to match the available statistical data to use biomass as means of model validation. For the purpose of illustrating the system dynamics approach for carbon accounting and planning, only the data regarding the Scots pine forests managed by JSC "Latvia's State Forests" were used.

The model was supplemented with the data from multiple sources – the Central Statistical Bureau of Latvia [184], the United Nations Statistics Division of the Food and Agriculture Organization, and empirical data from peer reviewed literature.

2. RESULTS

2.1 Chipboard from conifer logging residues and bio-based binders

Thorough literature review elucidated multiple promising bio-based adhesives, multiple of whom could be acquired from various biological production residues. List of adhesives and their biological sources are compiled in Table 2.1.

Table 2.1

Bio-based Adhesives and their Uses Described in Scientific Literature

Biological source	Compound	Polymer formation reaction	Primary raw material*	Uses
Penicillium oxalicum	Anhydrous citric acid	Polycondensation	Yes	Wood composites
Shrimp and other crustaceans	Chitosan (carbohydrate)	Polycondensation	No	Medicine, wood composites
Vibrio parahaemolyticus	Exopolysaccharides	Polyaddition	No	Research, low technology readiness
Flowering plants	Latex (isopropene)	Polymerization	Yes	Wood composites
Wood	Lignin (aromatic polymer)	Polycondensation	No	Wood composites, foams
Oleaginous plants	Polyols	Polyaddition	Yes	Wood composite, foams

Table 2.1 continued

Biological source	Compound	Polymer formation reaction	Primary raw material*	Uses
			No	Wood composites
Wheat	Protein	Polycondensation	Yes	Paper
Fish	Protein	Polycondensation	No	Wood composites
Rapeseed cake	Protein, carbohydrates, and other residues after oil press	Polycondensation	No	Wood composites
Potatoes	Starch (carbohydrate)	Polycondensation	Yes	Packaging
Tree bark, cork	Suberin	Polycondensation	No	Wood composites
Potato tubers		Polycondensation	No	Research, low technology readiness
Flowering plants	Tannin (polyphenol)	Polyaddition	Yes	Wood composites
Wood	Hemicellulose (carbohydrate)	Polycondensation	No	Wood composites
	Vanillin (phenol)	Polycondensation	No	High temperature environment
Vanilla planifola	Vanillin (phenol)	Polycondensation	Yes	High temperature environment
Bovine milk	Casein (protein)	Polymerization	Yes	Composites
Saccharomyces cerevisiae	Casein (protein)	Polymerization	Yes	Composites

* Biological source marked as “No” is classified as secondary or tertiary raw material.

Based on the literature review, most of the bio-based adhesives are plant-based, and more than half of the plant-based raw materials are secondary bioresources (Fig. 2.1).

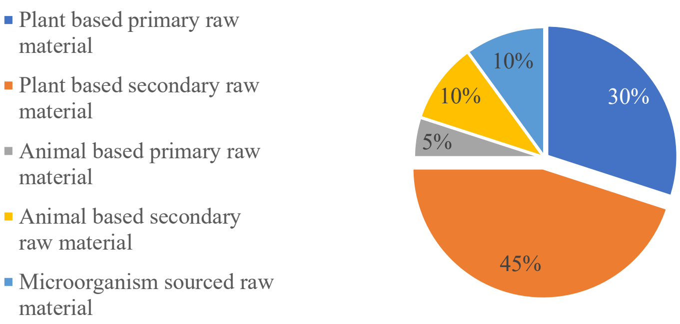

Fig. 2.1. Biological source of bio-based adhesives.

2.2 Chipboard from conifer logging residues

Analysing the strength results of the boards whose wood particles were obtained using the two-horizontally rotating axis chipper, no strong relationship between the particle size and the obtained strength result was observed.

The pressure and temperature range was chosen from literature, and initial tests narrowed down the temperature and pressure to a working range, producing valid boards after qualitative assessment. The boards produced by applying extreme variable values were burnt, crumbled, or produced cavities. Some examples are depicted in Fig. 3.2.

Fig. 2.2. The boards produced under extreme independent variable values.

For further tests, 140 °C and 160 °C temperatures and 390 bar, 590 bar, 600 bar, and 660 bar pressure were chosen; additionally, the impact of particle size was evaluated using multiple-range particle size up to 10.0 mm, separated as described in the methodology section.

The ANOVA results showed that there was no significant impact of the temperature range on material durability, but the particle size and the way particles were acquired showed a significant impact on the results.

The initial durability results for three particle size boards are depicted in Fig. 2.3. The highest strength was obtained for the plates with a particle size of 2.8 mm, and the highest inconsistency was detected under high pressure board preparation for medium particle size boards. The boards prepared from the 8.0–10.0 size fraction were generally less durable than the rest, but as seen from the statistical analysis, the difference between the MoE of 2.8–8.0 and 8.0–10.0 particle size boards in 660 bar pressure was not significant ($P = 0.27$).

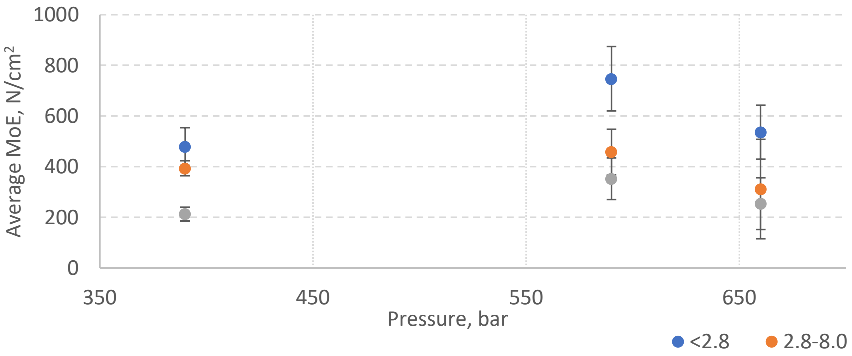

Fig. 2.3. Modulus of elasticity depending on pressure and particle size: < 2.8 mm particle size boards; 2.8–8.0 mm particle size boards; 10.0 mm particle size boards. MoE – modulus of elasticity

According to ANOVA, there are no interactions between the particle size and pressure. The T-test showed that there was no significant impact of the chosen pressure extremes on board durability ($P = 0.43$) for the < 2.8 mm particle boards; the boards produced by applying the 590 bar pressure showed a significantly higher durability compared to the 390 bar ($P = 0.002$) and 660 bar ($P = 0.01$) pressures.

For further tests, a 600-bar setting was chosen. According to the biomass tests conducted in external laboratory, some supplied biomass had a high sand content in the ash (ashing at 550 °C) showing up to 26 % and around 2 % sand content in the raw biomass. Therefore, further tests were done by using the hammer mill approach by milling the previously chipped and sifted > 1 mm fractions. Larger particles were combined to prepare boards in the range of 2.8 mm to 10 mm particle size, as initial tests did not show significant difference between these two fractions in the chosen pressure range. The boards were prepared using 140 °C and 160 °C temperature regimes to assess the temperature and particle size impact on the board mechanical properties. Initial tests for temperatures were done prior to this study, elucidating the 140 °C and 160 °C temperature range as the most suitable for further testing, as lower range temperatures produced boards that were not truly bonded, and higher temperatures produced burnt boards. The results from 140 °C and 160 °C temperature tests are depicted in Fig. 2.4.

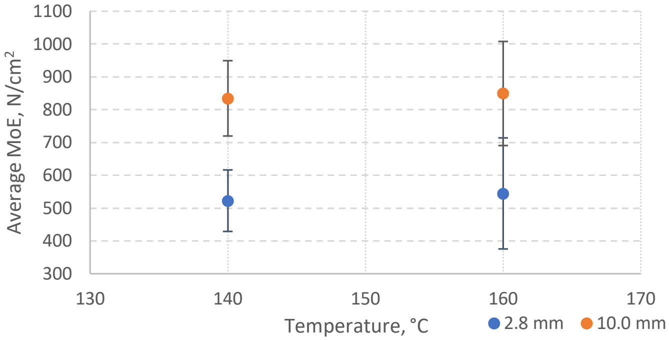

Fig. 2.4. Modulus of elasticity of < 2.8 mm particle size boards (blue), and for 2.8–10.0 mm particle size boards (orange) depending on the hot press temperature.

The results from combining the 2.8–8.0 and 8.0–10.0 fractions showed a great increase in board durability, showing better results than prior. Nevertheless, smaller fraction boards showed decrease in durability; this might be explained by bark removal from the biomass. By separating sand from the biomass, other smaller particles got removed from the raw material – including finer bark and needle particles. To explain such change, temperatures were further tested by combining the hammer milled biomass with chipped and sieved particles. The results depicted in Fig. 2.5 show that although the larger particle size boards show roughly the same results as the standard deviations overly in the same areas on the graph, the smaller particle size boards show increased results, with one outlier even reaching the minimum MoE threshold determined by European standard for wood chip materials EN 312-2:1997.

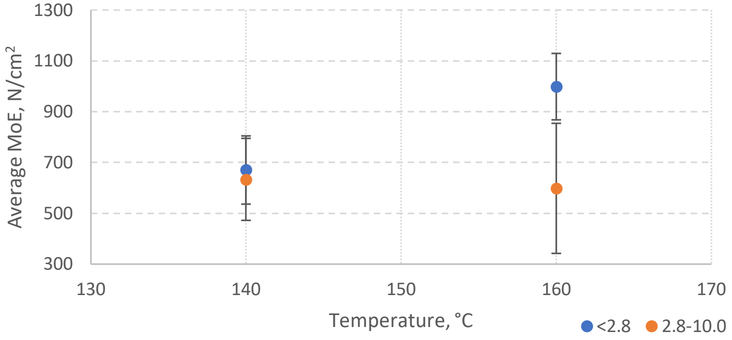

Fig. 2.5. Modulus of elasticity of < 2.8 mm particle size boards (blue), and for 2.8–10.0 particle size boards (orange) depending on the hot press temperature for combined particles.

The smaller particles pressed together make the final product denser losing the desirability of such woodchip boards. Nevertheless, there was no correlation of overall density increase and increased durability when boards from all particle sizes were compared.

Although other research groups have been testing the logging residue and pine bark applications for chipboard production, the possibility of completely excluding fossil-based adhesives have not been explored. With today's climate objectives it is crucial to completely rethink the construction and housing approaches by completely excluding fossil carbon from the market. Therefore, the scientific community and industry need to find working alternatives. This research provided insights on logging residue usefulness for chipboard production and provides a few valuable takeaways confirming previous work on logging residue potential application in chipboard production even without fossil-based adhesives. Although laboratory research has been done using particle size separation using sieves, it might be useful to consider gravimetric separation by cyclones as this would result in more even particle dimensions and therefore lead to more consistent results. It was shown that the smallest conifer logging residue particle size might have a positive impact on 100 % bio-based chipboard durability and methods for mineral separation from the bark material could be explored, perhaps by using flotation. There already is research on creating adhesives from bark extractables along other bio-based adhesives, and this research confirms the potential of chipboard transition away from fossil resources and towards completely bio-based materials.

Bio-based carbohydrate adhesive was used in this research, as in previous tests without any adhesive, the materials showed low durability and other unwanted effects like bulging and burning of the material. The chosen adhesive showed promising results, but search for more efficient adhesive is still open. The previously done literature review on adhesives elucidates multiple bio-based options, even potential adhesives from other industry residues. Successful research in this direction could potentially result in chipboards from mostly residue-based raw materials – biomass and adhesive.

2.3 Improved circularity in cross-laminated timber production

Evaluation of cross-laminated timber cutting reprocessing

The proposed case scenario where cuttings from CLT are reprocessed was modelled in *SimaPro* according to the defined functional unit FU, and the results are presented, first, in a comparative way with the business-as-usual scenario, and then, it is disaggregated by the unit process. The impact assessment is presented at midpoint level (kg of substance equivalent), as recommended by the EDP method and ISO standards in Table 2.2. The results in the business-as-usual scenario correspond to the energy recovery phase for 0.128 m^3 of CLT; on the other hand, the results in the proposed scenario correspond to the sum of the three considerations aforementioned: impact from the reprocess activity, avoided impact from putting on the market new CLT modules, and the impact related to the energy recovery of remaining cuttings not reprocessed.

Table 2.2

Comparison of Characterization Results in Scenarios

Impact category	Unit	Business-as-usual	Proposed scenario
Acidification potential	kg SO_2 eq	–0.023	–0.059
Eutrophication potential	kg PO_4 eq	–0.005	–0.011
Global warming potential	kg CO_2 eq	–4.155	–0.524
Formation potential of tropospheric photochemical oxidants	kg C_2H_4 eqv	–0.002	–0.008
Abiotic depletion potential for non-fossil resources	kg Sb eq	–1.43E–05	–2.35E–05
Abiotic depletion potential for fossil resources	MJ	–0.005	–122.457
Depletion potential of the stratospheric ozone layer	kg CFC-11 eq	5.13E–07	–920E–07

In the business-as-usual scenario, most of the impact categories show a benefit to the environment since, as it is understood that the electricity and thermal energy generated from the incineration of CLT material would replace conventional electricity production in Latvia according to the market for electricity mix in the *Ecoinvent 3.6* database. In the proposed scenario, even higher benefits to the environment are obtained due to the energy recovery of 30.28 % from the leftover cuttings and the avoided impact from new CLT modules.

Percentual changes of moving from a business-as-usual scenario towards the proposed one are easily seen in Fig. 2.6.

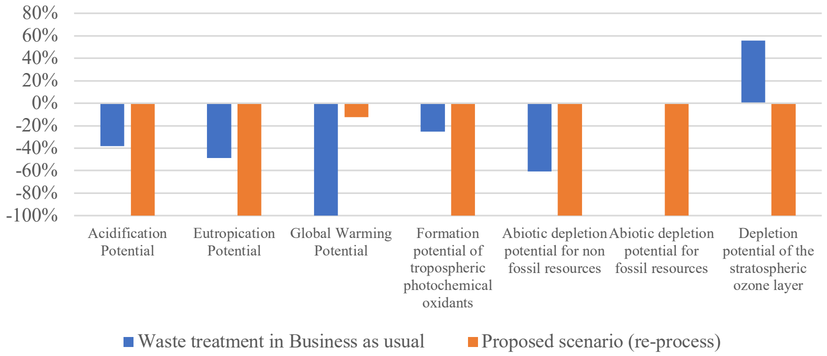

Fig. 2.6. Characterization results.

In general, the nowadays EoL stage or waste treatment of CLT delivers benefits to the environment in almost all the impact categories assessed within the EDP method, but for the ozone layer depletion one. Nevertheless, the proposed new set of activities that give birth to new CLT panels by reducing the amount of waste to be incinerated aids to increase the already delivered benefits in all areas except for the global warming potential (GWP); this as a result of lower electricity production would eventually substitute the production from conventional sources in the specific Latvian market. It is worth noticing that the GWP benefits under the business-as-usual scenario are due to substituting energy production from the local market by the energy recovery from a one hundred percent renewable source such as wood. In all other areas, benefits from the new approach surpass the original ones.

Regarding the proposed scenario of reprocessing of CLT cuttings, the adverse effects on the environment are coming from the reprocess activity, since the waste scenario is the same as for the business-as-usual scenario, thus resulting in an environmental benefit, and the new produced CLT modules are considered as an avoided product. In the evaluation of the proposed scenario, it was found that the main driver in most of the evaluated impact categories is the use of polyurethane adhesive (Fig. 2.7), except in the ozone layer depletion one.

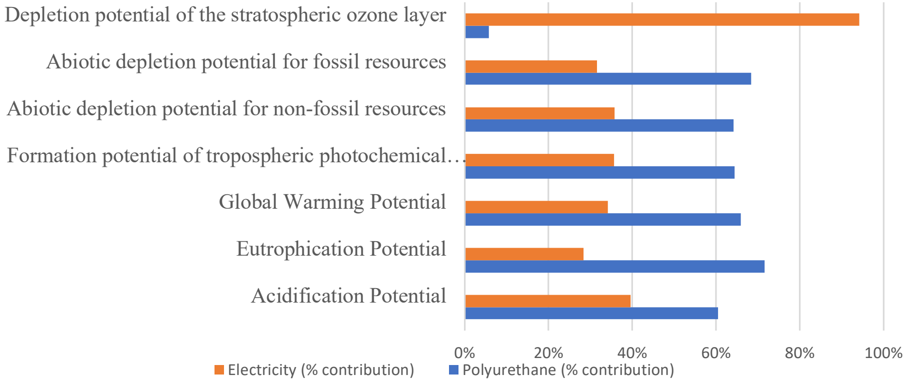

Fig. 2.7. Environmental impact contribution per reprocessing activity/flow.

Multi criteria decision-making

Based on the conducted AHP weights for criteria of wood residue, recycling was calculated and used in TOPSIS analysis to elucidate the best alternative from the companies working with CLT perspective.

According to expert evaluation, production costs are the most important when considering the potential applications of wood residue. Production costs are followed by the product market price, and wood residue to new product ratio. The results of AHP are shown in Fig. 2.8.

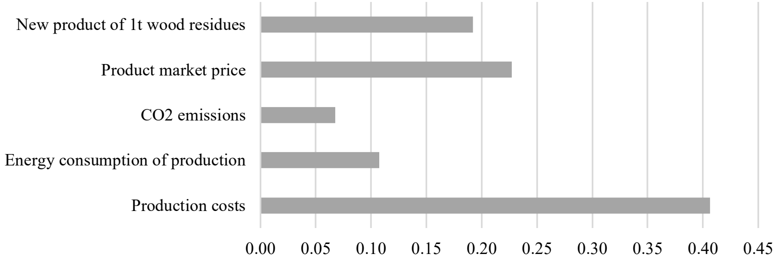

Fig. 2.8. Weighed criteria. The weights of criteria are determined using an analytical hierarchy process and input form expert interviews. The sum of all weights is equal to 1.

The calculated weights were used for the TOPSIS analysis, as described in Chapter 2. The data matrix of alternatives and their corresponding criteria are depicted in Table 2.3 along with the calculated weights.

Table 2.3

Data Matrix with Considered Alternatives (A_n) and Corresponding Data of Weighed Criteria (x_n)

	(x_1) Production costs	(x_2) Energy consumption	(x_3) CO_2 emissions	(x_4) Product market price	(x_5) New product to wood waste ratio
Criteria weights (ω)[1]	0.41	0.11	0.07	0.23	0.19
Units	€/tonne	MWh/t	Kg CO_2/t	€/tonne	t
(A_1) Medium density fibreboard	250	1.6	1088	586	0.9
(A_2) Mycelium insulation material	68	0.28	47	140	0.9
(A_3) Solid fuel	113	0.02	38	204	1
(A_4) Particle boards	147	0.77	150	350	0.9

[1] Weights calculated using analytical hierarchy process approach.

The TOPSIS approach elucidated the mycelium thermal insulation material as the most promising wood residue utilization option and MDF production as the least preferable option (Fig. 2.9). Mycelium thermal insulation gained a closeness coefficient (CC) of 0.65 to the ideal solution. According to expert evaluation and literature data, solid fuels gained CC of 0.59, showing that solid fuel production is still closer to ideal than non-ideal solution. Nevertheless, when raw material cascades are considered, burning the by-product is considered as the least preferable option, especially if the by-product could still be recycled for other purposes.

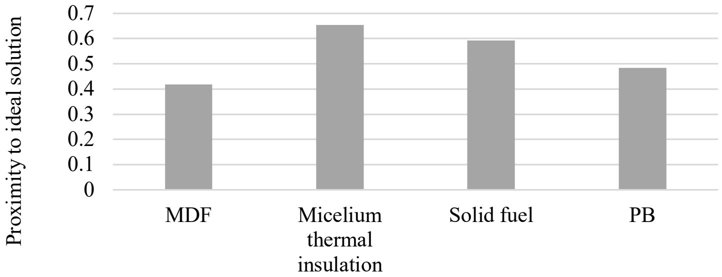

Fig. 2.9. Multi-criteria analysis results showing the options considered and their proximity to the most preferable alternative represented on y-axis (PB – particleboard; MDF – medium density fibreboard).

The sensitivity analysis of criteria weight showed the similarity of two preferable options – mycelium thermal insulation and solid fuel. By changing the weight of the product market price according to unity variation β_{pm}, the mycelium thermal insulation material and solid fuel alternatives experienced the same trend. When the weight of the product market price doubles, these two alternatives lose their positive proximity to the ideal solution. The MDF experience mirrored the trend to mycelium thermal insulation and solid fuel alternatives, but PB is the least impacted by the changes in the product market price (Fig. 2.11).

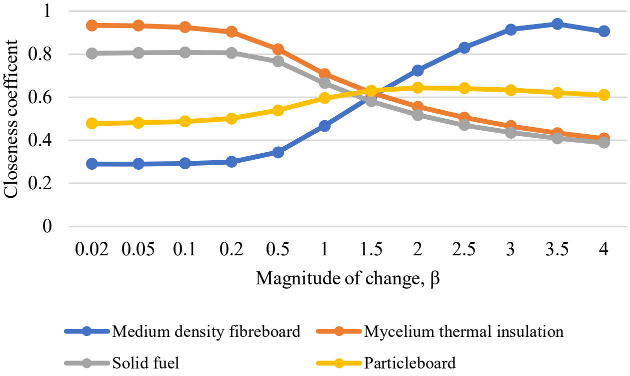

Fig. 2.11. TOPSIS results of sensitivity analysis. Sensitivity analysis is conducted by changing the weight of the product market price and re-calculating the rest of the assigned weights. X-axis depicts the magnitude (β) of change of the product market weight, and y-axis depicts the closeness coefficient of all alternatives to the ideal solution.

As the production costs were the only criterion where the mycelium thermal insulation material took the lead from the start, the sensitivity analysis was conducted to find out how big should be the changes in the mycelium thermal insulation production for the material to lose its most preferred rank. The sensitivity analysis of the mycelium thermal insulation production cost (Fig. 2.12) shows that the 60 % increase of production costs would make the mycelium alternative less desirable than the solid fuel production.

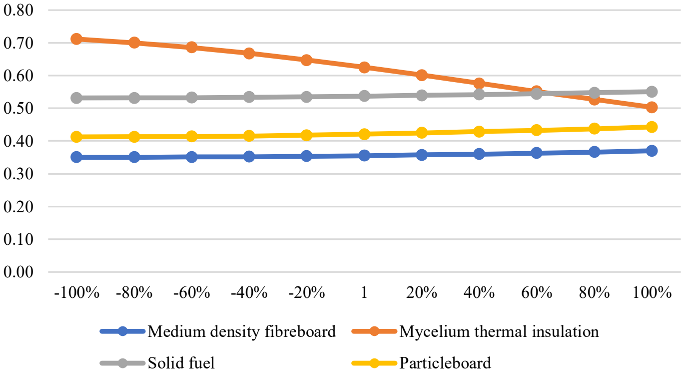

Fig. 2.12. Sensitivity analysis of mycelium thermal insulation's production cost changes.

2.4 Evaluation of natural thermal packaging market fit

For innovations to be implemented, there needs to be a market demand for them. In this case, when a completely new material is invented, it needs to be evaluated in a weighing process using pairwise comparison of all 12 criteria, which gives an overall look on the importance of each criterion in relation to the rest. The results of weighing are shown in Fig. 2.13.

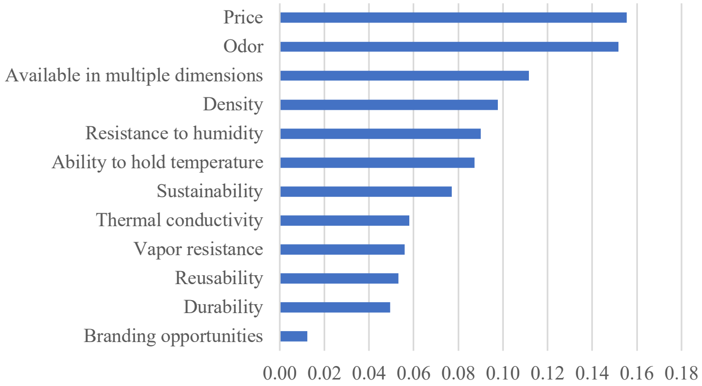

Fig. 2.13. Weighed criteria in ascending order of their importance.

Enterprises specializing in fine chemicals and those utilizing thermal packaging for internal purposes underscore the value of reusable packaging. For instance, businesses seek thermal packaging withstanding a minimum of 10 applications. Conversely, pharmaceutical companies opt for single-use packaging, given its compromised appearance after initial utilization. To evaluate available thermal packaging options, only five criteria were selected for analysis. The criterion such as neutral smell was excluded due to its universal absence. The dimension availability was not scrutinized due to varying company preferences. Water resistance was recognized as significant, encompassing aspects like water absorption, release, and material integrity. However, the criterion's importance varies depending on the context. For instance, while corn-starch foam is suitable for electronics due to shock absorption, it dissolves in water, rendering it unsuitable for humid shipments like iced products. Water resistance is less critical in electronics shipping, as cargo is usually protected, and compromised packages can be recalled.

Furthermore, the criteria for durability, vapor resistance, repeated use, and graphical identity were omitted from the analysis. Vapor resistance is tied to hazardous dry ice shipments, which companies tend to avoid. Preferences for reuse varied among companies, with some reusing packaging at least ten times, prioritizing functionality over appearance. In contrast, pharmaceutical firms opt for single-use packaging due to its compromised post-use appearance. Graphical identity, akin to scent, was excluded due to its binary nature.

In summary, businesses' preferences for thermal packaging hinge on factors such as intended use and reusability, while certain criteria like water resistance have nuanced significance based on the application contexts. The criteria chosen for further analysis were weighed, and the results are depicted in Fig. 2.14.

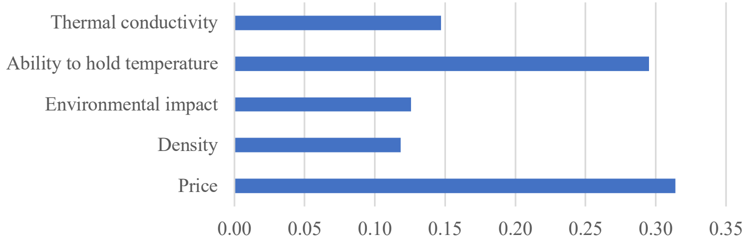

Fig. 2.14. The chosen quantitative criteria and their weights showing the importance of each criterion in the final decision-making.

As shown above, after narrowing down to five criteria, price and ability to hold temperature took a considerable lead as being the two most important criteria; they together accounted for more than a half of the impact on the final decision.

2.4.1 Most preferable material

To evaluate the most preferable "green" thermal packaging available on the market, four products were compared to polystyrene packaging. Using previously determined weights, the following thermal insulation materials were compared: non-woven feathers, non-woven wool, starch foam, mycelium, and polystyrene (Fig. 3.12).

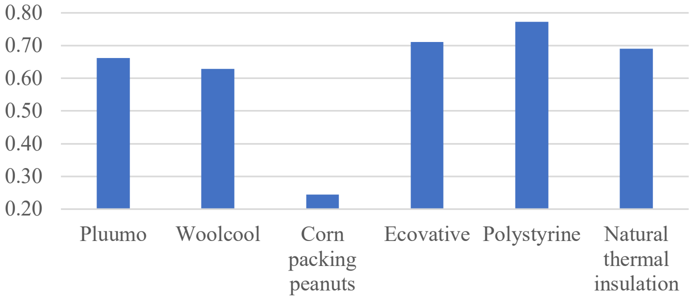

Fig. 2.11. Order of preference by similarity for ideal solution ranking of thermal packaging materials. The Y-axis represents the proximity to ideal solution 1.

Among the thermal packaging options the closest proximity to ideal solution (represented by 1 on the Y-axis in Fig. 3) by applying the TOPSIS method was assigned to non-woven wool followed by feathers and polystyrene, the lowest rank was assigned to starch foam, and mycelium was second-to-last in the ranking.

2.5 CO_2 storage in wood-based panels

The amount of stored biogenic CO_2 in the new fibreboard insulation material for the eight different accounting standards is shown in Table 2.5. The stored amount has been calculated for one cubic meter of the new fibreboard insulation material.

Table 2.5

Stored Biogenic CO_2 Depending on the Accounting Standard

Technical standard	Stored CO2, kg/m3	Source
EN-15804 (2012)	359	[18]
ISO/DIS-21930 (2015)	251	[29]
EN-15804 (2012) +A1:2013	359	[18]
CEN/TR-16970 (2016)	359	[18]
EN-16485 (2014)	359	[18]
ISO/TS-14067 (2013)	90	[30]
PEF v2.2 (2016)	90	[30]
PAS-2050 (2011)	291	[31]

For standards EN-15804 (2012), EN-15804 (2012) +A1:2013, CEN/TR-16970 (2016) and EN-16485 (2014), the calculated amount of stored CO_2 is the same, as they are all based on the same standard of EN-15804 (2012), and it is assumed that the amount is calculated with the formula shown in Eq. (7), with no further elaboration. ISO/TS-14067 (2013) and PEF v2.2 (2016) standards are based on the previous ISO-14040/44 standard for LCA and do not differ when calculating the stored CO_2.

The standards based on the EN-15804 standard offer the highest amount of CO_2 stored in one cubic meter of the product – 359 $kgCO_2/m^3$, while the lowest amount of CO_2 stored can be attributed to the standards based on the previous ISO-14040/44 LCA standard – 90 $kgCO_2/m^3$. Considering all standards, an average value of 270 $kgCO_2/m^3$ stored can be assumed as the result if no single carbon accounting method is chosen.

2.6 Carbon in forest economy

Carbon dynamics in forest economy was estimated using the system dynamics modelling. The model's forest sector was validated using the data from the national forest bioresource monitoring. The forest biomass validation is depicted in Fig. 2.13.

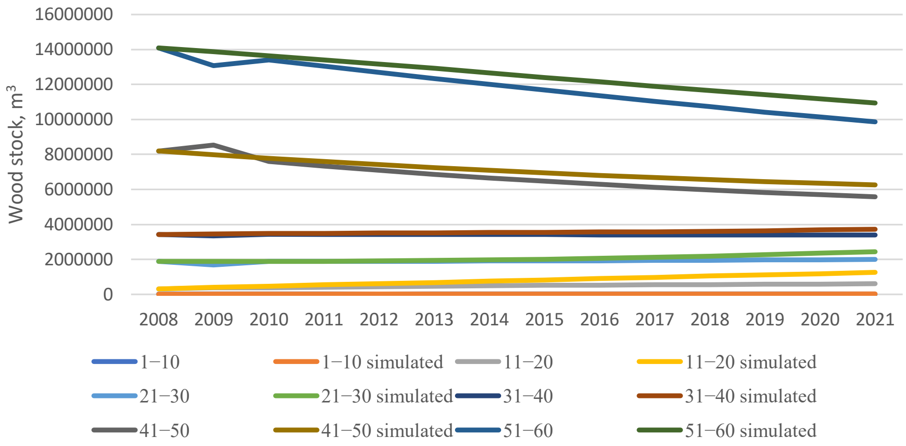

Fig. 2.12. The model's validation using 1 to 60-year-old Scots pine forest stands in Latvia's forests.

The forest biomass data was available in the time frame from 2008 to 2021, therefore, to assess the carbon flow in the future, the model was run up to 2160. As forest management is out of this research scope, relative harvesting values were used – static rates in % for each forest age group. Although this is not the most beneficial way to harvest timber, it provided some stability. The statistical data showed that some age groups had a decreasing trend, and using a stable harvest rate allowed for them to recover. The Scots pine biomass forecast in the territories managed by JSC "Latvia's State Forests" is shown in Fig. 2.13.

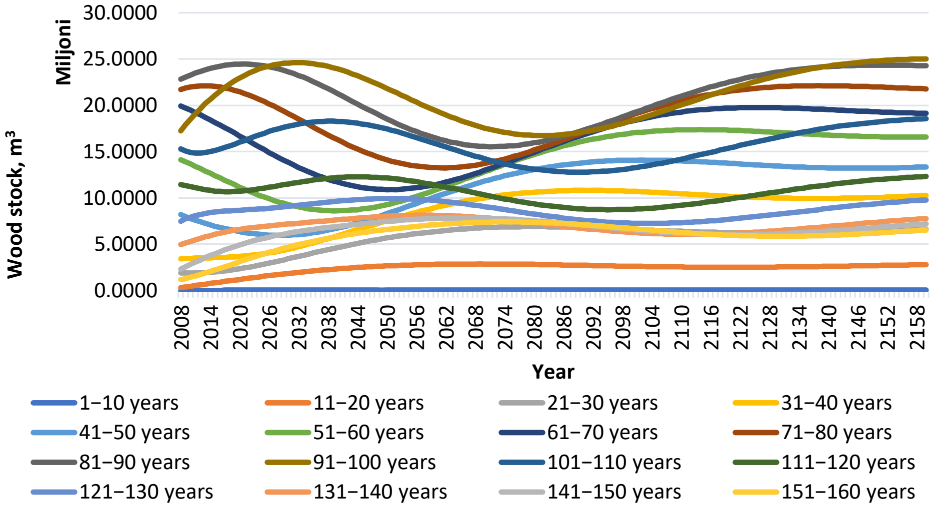

Fig. 2.13. The model's forecast of the Scots pine biomass stock in Latvia's state forests.

The chosen scenarios for the product sector include CLT and thermal insulation material for packaging and building insulation. The results depict carbon stock in atmosphere over 152-year period (Fig. 2.14.).

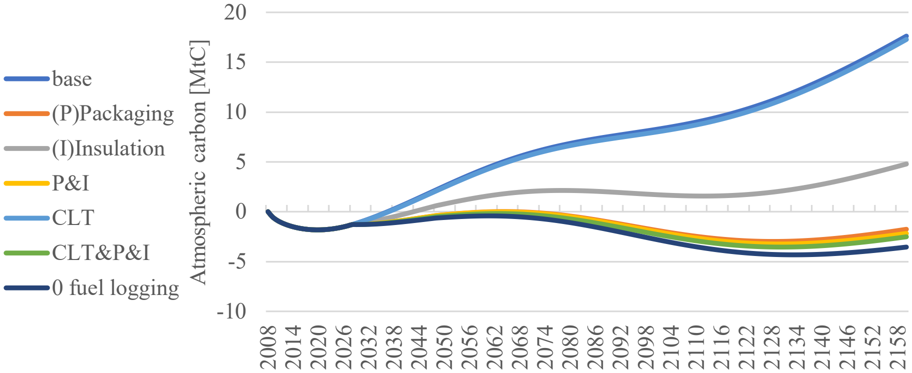

Fig. 2.14. Atmospheric carbon stock depending on chosen scenarios: base – base scenario; (P)Packaging – partial logging residue utilization for thermal packaging; (I)Insulation – partial logging residue utilization for building thermal insulation; P&I – partial logging residue utilization for thermal packaging and building thermal insulation; CLT – CLT cutting reprocessing in new panels; CLT&P&I – combined CLT, P, and I scenarios; 0 fuel logging – no fuel is accounted for logging.

2.7 Bioeconomy impacting factors and indicators

2.7.1 Top-down approach

After expert evaluations and application of the Delphi method, seven primary bioeconomy-affecting factors and their linkages were identified (Fig. 2.15). The discussed linkages discussed based on scientific literature and are described as direct or indirect based on how they affect the narrowed down factors.

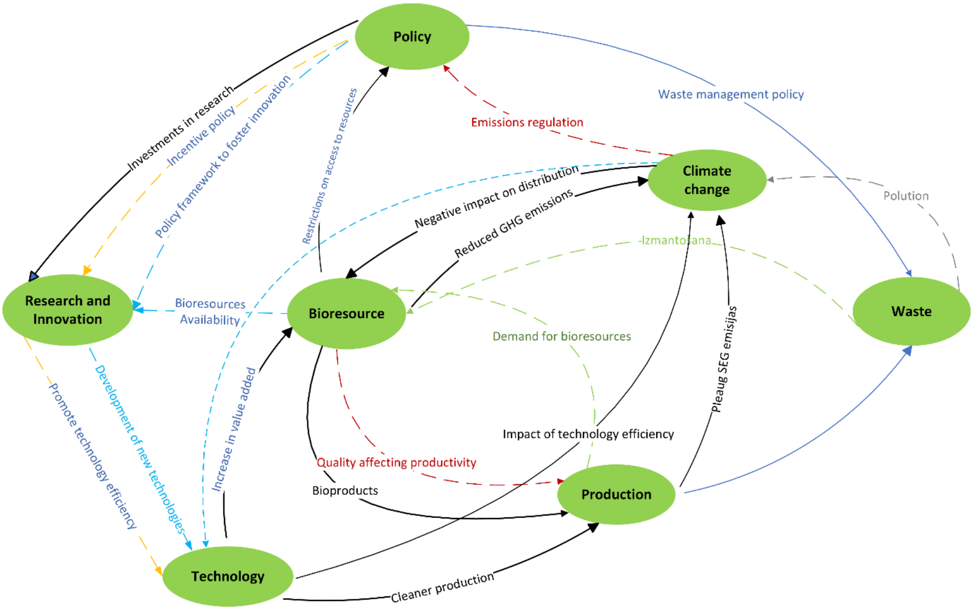

Fig. 2.15. Graphical representation of seven bioeconomy influencing factors and their interlinkages.

The main nexus identified from graphical representation linkages in Fig. 2.15. are: (1) Policy – Research and Innovations – Technology; (2) Production – Waste – Climate change; (3) Production – Waste – Bioresources; (4) Policy – Production – Bioresources; (5) Technology – Production – Climate change; (6) Climate change – Policy – Production; (7) Policy – Technology – Production – Bioresources; (8) Climate change – Bioresources – Production. Factors like Consumption and Economic growth did not make it to the final cut of 7 factors from the top-down approach. According to theory-based analysis, when causal chains are detected, heterogeneity should be expected. It was predictable that the analysis from one dimension will not show the full causal chain, therefore top-down approach was added, experts from industry were chosen for another focus group, and Delphi methodology was used to refine the causal chain. A few new factors were detected using the bottom-up approach. Factors like behaviour were elucidated only when the bottom-up approach was used. Previously, the financial resources factor was left out using the top-down approach, and now this factor resurfaced as important.

2.7.2 Bottom-up approach

A significant portion of biomass labelled as waste is, in fact, by-products as per EU definitions. However, production managers might categorize by-products as waste due to technological limitations – such as spoilage from improper storage or retrieval complexities, like sugars from blanched waste. Yet, behaviour and awareness play an important role in the by-product-to-waste transition. When the management avoids exploring new uses or buyers for by-products, biomass is often labelled waste. Secrecy slows innovation as there is no information exchange among enterprises adhering to closed innovation.

Waste reduction is the favoured management approach. The nexus reveals waste's negative financial impact and positive effect on bioresource availability. For instance, in vegetable production, adopting more efficient peeling technologies reduces peel waste. Many by-products, when appropriately managed, would not become waste, thereby reducing relative waste proportions.

Indicators for these links could be economic or technological. They may reflect the by-product value, technology energy efficiency, or production efficacy. Financial incentives spur research and development, incentivizing cleaner technologies. Fines discourage pollution. The existing technologies affecting production efficiency also impact waste generation. Increased waste raises pollution and climate change risks, driving policy changes. Mandates encourage cleaner production, leading to R&D investment to avoid taxes or fines. Waste-reducing and bioresource-extracting technologies emerge. Employing waste for pharmaceuticals and fine chemicals is viable. Redirecting by-products to produce different product groups fosters value cascading, extending resource circulation.

The enterprise nexus was expanded to include additional factors. Behaviour and knowledge are pivotal, driving new, eco-friendly technology implementation. Enterprise finances significantly impact environmental innovations, but behaviour and culture are often overlooked. Local policies, production, knowledge, and decision-makers influence waste-bioresource links. Climate change and pollution, although outside enterprise scope (shown in grey in Fig. 2.16), exert pressure on operations. Long-term factors like fiscal policy have discernible impacts. A core bioresource-production-waste nexus emerged for bioeconomy evaluation. Efficient by-product use leads back to bioresources, while waste signifies lost resources, offering value cascading and another product's production.

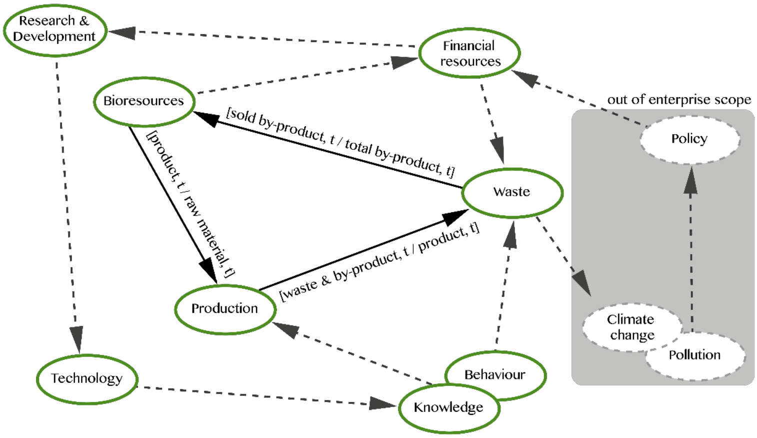

Fig. 2.16. The proposed nexus of bioresources flow in an enterprise showing all the relevant factors. Green – primary factors; grey dashed – secondary factors; arrows represent the direction

factors' impact. Central arrows represent the bioresource-production-waste-bioresource factor cluster used for the proposed bioresource utilization index calculations.

Assessment of the impact from changes in production-waste-bioresources

To evaluate a company's added value to circular bioeconomy, a bioresource utilization index was calculated using the approach described in the Methods section. For this analysis, two enterprises of the three interviewed before were chosen. An overall bioresource utilization state in an enterprise was estimated – a bioresource utilization index closer to 1 shows bioresource utilization. The constructed scenarios with corresponding biomass utilization indexes are represented in Table 2.6.

Two cases were studied and four alternative scenarios for each case. RM – raw material, BBV 1 to 0 represents bio-based value pyramid levels starting from the top. Percentages in the table represent the amounts of dry biomass sent to a specific product, waste, or by-product stream. Scenarios represent by-product use for pharmaceuticals and fine chemicals BBV1, food and feed BBV0.75, bioplastics and polymers BBV0.5, bulk chemicals and biogas BBV0.25, energy and heat BBV0. Waste is dry mass of wasted organic by-products and waste as rotten raw material. BU$_{\text{ind}}$ is the calculated bioresource utilization index. Actual situations in respective two enterprises are: II $_{\text{base}}$ – the base scenario for the first enterprise, IX$_{\text{base}}$ – the base scenario for the second enterprise.

Table 2.6

Alternative Scenario Representation by Biomass Allocation

Scenario		RM	BBV 1	BBV 0.75	BBV0 .5	BBV 0.25	BBV0	Waste	Product
Enterprise No. 1	I	100 %	0 %	0 %	0 %	0 %	0 %	34 %	66 %
	II $_{\text{case}}$	100 %	0 %	0 %	0 %	34 %	0 %	0 %	66 %
	III	100 %	0 %	5 %	0 %	12 %	0 %	17 %	66 %
	IV	100 %	0 %	0 %	0 %	12 %	7 %	16 %	66 %
	V	100 %	9 %	6 %	7 %	12 %	0 %	0 %	66 %
Enterprise No. 2	VI	100 %	0 %	0 %	0 %	0 %	8 %	32 %	59 %
	VII	100 %	0 %	0 %	0 %	0 %	0 %	41 %	59 %
	VIII	100 %	0 %	0 %	0 %	37 %	0 %	3 %	59 %
	IX $_{\text{case}}$	100 %	0 %	5 %	0 %	32 %	0 %	3 %	59 %
	X	100 %	9 %	32 %	0 %	0 %	0 %	0 %	59 %

By-product flows by dry weight. RM – raw material; BBV – bio-based value represents the added valueof biomass. Added value is represented with corresponding coefficient: 1 – high value, 0.75 – moderately high value, 0.5 – medium value, 0.25 – low value, and 0 – no value. The table represents the allocation of biomass by dry weight in the constructed scenarios (I, III to VIII and X) and detected scenarios (II$_{\text{case}}$ and IX$_{\text{case}}$) for Enterprise No. 1 and Enterprise No. 2.

Each company is represented by five scenarios, I to V and VI to X for each company, respectively, with base scenarios II for the first and IX for the second. For each enterprise, in the worst-case scenario II and VII, it is assumed that damaged raw material and all generated by-products, products that do not meet market standards, and other production leftovers are sent to waste, and sugars along with starches that are not retrieved from water or used in any other way. By calculating the worst-case scenario, it is possible to evaluate the general efficiency of production process, as the index shows the amount of product that can be acquired from a certain amount of raw material.

CONCLUSIONS

Despite almost century old records of concerns that Latvia exports low value timber, the topic is still relevant today. The Thesis unearths transformative insights into the bioeconomy and conifer value chain innovations. All explored innovations are aimed towards resource efficiency and production residue stream redirection towards value added products. Research encompassed the potential of logging residues in 100 % bio-based chipboards, thermal insulation packaging, and assessments of residue management strategies.

Although scientific literature covers logging residue and pine bark applications for chipboard production, the possibility of completely excluding fossil-based adhesives is not sufficiently explored. With today's climate objectives it is crucial to completely rethink construction and housing approaches by completely excluding fossil carbon from the market. Therefore, scientific community and industry need to find working alternatives. The Thesis provided insights on logging residue usefulness for chipboard production and a few useful takeaways confirming previous work on logging residue potential application in chipboard production even without fossil-based adhesives. Although laboratory research has been done using particle size separation using sieves, it might be useful to consider gravimetric separation by cyclones, as this would result in more even particle dimensions and therefore lead to more consistent results. It was shown that the smallest conifer logging residue particle size might have a positive impact on 100 % bio-based chipboard durability, and methods for mineral separation from the bark material could be explored, perhaps by using flotation. At the same time, there is already research on creating adhesives from bark extractables along other bio-based adhesives, and this research confirms the potential of chipboard transition away from fossil resources and towards completely bio-based materials.

The chosen adhesive showed promising results, but search for more efficient adhesive is still open. The literature review on adhesives elucidates multiple bio-based options, even potential adhesives from other industry residues. Successful research in this direction could potentially result in chipboards from mostly residue-based raw materials – biomass and adhesive.

The results of experimental studies, market research, and overall bioeconomy assessment showed that conifers as a dominant group of Latvia's forest species harbour a great potential for increasing the added value forest economy. It is possible to improve the resource efficiency of the conventional conifer value chain by introducing innovative products and technologies for more efficient residue use, e.g., CLT cutting reprocessing. Therefore, it is possible to add value to conifer value chain without significant reorientation of primary raw material use.

Currently, the implementation of resource efficiency measures in companies depends on subjective viewpoints of decision-makers. In order to stimulate the utilization of residual materials from conventional conifer processing streams for higher value-added products, regulatory measures from policymakers are necessary. This conclusion arises from the theory-based analysis on bioeconomy development. As the bottom-up approach showed – the enterprise resource efficiency is dependent on the decision-maker's knowledge and subjective attitude towards the issue. If there is no internal knowledge of the potential for production residues, the residues will be directed towards energy, as this path is well known although adds the least value. Although outside of the scope of this research – information on potential value-added products of wood and wood residues circles the economy, leading to conclude that there is a stronger impact of behaviour than knowledge factors on the development of the Conifer value chain.

Another aspect that would benefit from the policy-makers' involvement is carbon accounting. In this research, multiple methods were compared. Methodologies clearly state the boundaries and underlying calculations, and consequentially show varying results. The significant number of accounting methods lead to situations where the results can only be used for specific cases, the same as life cycle assessments. Tailor-made analysis can provide answers to very specific questions. Nevertheless, it is important to agree on a single accounting method that would allow the current situation of national and international economy level to be assessed and future scenarios to be modelled. The Thesis provided system dynamics as a comprehensive approach for carbon accounting and modelling. In the scope of this work system dynamics modelling approach was used to illustrate the concept of dynamic carbon accounting. Initial modelling results showed that the popular assumption of net zero emissions from wood-based products need to be reconsidered, as the model shows carbon accumulation in atmosphere from the activity in forest economy. Therefore, sustainability of wood products needs to be evaluated in the long term and in conjunction with the possibilities of the energy sector. It is only by addressing the issue of fossil fuel dependency and product longevity, that carbon can be effectively stored in wood and its products. Bio-based products have the capacity to buffer carbon release into atmosphere even when fossil fuel is used; nevertheless it is important to balance the product lifespan with the time the carbon takes to assimilate into the biomass.

Despite the plans outlined in the Green Deal to recover resource consumption from economic growth, the market anticipates an increase in demand for material volume. Therefore, additional alternatives need to be explored for the innovative products discussed in this study. Increasing the production volume of cross-laminated timber (CLT) and replacing concrete in multi-story buildings would significantly enhance the long-term carbon storage capacity in Latvia's economy.

Finally, the bottom-up approach enhances the importance of waste reduction and search for new technologies that would enhance the resource efficiency leading to financial savings. The Thesis illustrates the importance of production residue redirection towards the use in products that could store the assimilated carbon for longer periods.

Ilze Vamža was born in 1989 in Riga. She obtained a Bachelor's degree in Biology in 2016 and a Master's degree in Environmental Sciences in 2019 from the University of Latvia. Since 2019, she has been a researcher with the Institute of Energy Systems and Environment of Riga Technical University. Her scientific interests are related to bioeconomy and bioresource value chains.