Field ENGINEERING AND MANAGEMENT

PhD THESIS

Research and contributions regarding the implementation of circular economy solutions in the wood industry

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CONTENTS

INTRODUCTION

Today's society faces a multitude of problems and challenges regarding the adaptation of current models of economic and social development to the challenges of the times and the environment. Today's companies are concerned more than ever about sustainability and need fast and effective solutions and tools to achieve this goal. Starting from these findings, the present doctoral thesis investigates an important sector of the manufacturing industry, the wood industry, from the perspective of adopting the circular economy paradigm, as a development model that allows reducing pressure on natural resources, while contributing to reducing carbon dioxide emissions, limiting the negative impact on the environment and forming conscious consumers.

The research effort starts from two main premises, on the one hand a critical analysis of the current stage of published research in the field of wood industry transformation and related fields towards circular economy desiderata, and on the other hand the concrete state of affairs that can be encountered in Romanian companies active in this sector. The first of these categories of support elements refers to the technical, economic, managerial and marketing aspects regarding the adoption of new methods and technologies, aligned with international, European and national strategies in the field, such as the "butterfly diagram" concept promoted by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2019) and known on a global scale. The second category takes into account the specific challenges encountered in Romania, such as: intense competition for survival in a market with low profit margins, the strong relationship formed in public opinion between the forest as a natural resource and population, the complex and dynamic legislative and regulatory landscape, difficulties in accessing finance, pressure to develop innovative solutions in the field of wood products incorporating high added value, logistical difficulties, human resources and rising costs, and so on.

STATE OF THE ART

1. GENERAL AND CONCEPTUAL ASPECTS

The wood industry in the European Union is at the crossroads of two major public policy directions, namely the Circular Economy Action Plan (European Comission, 2023) and the Bioeconomy Strategy (European Commission, Directorate-General for Research and Innovation, 2018). Romania, as a country in the process of catching up with its long-standing members of the Union, has the unique opportunity to transform many industrial sectors, including this one, with healthy economic and environmentally friendly bases, through the rapid implementation of measures, technologies and market mechanisms specific to these economic models. The focus of this paper is on companies in the wood industry that produce specific products and works and want to ensure better competitiveness at national and European level. Research aims to determine the current state of adoption and readiness for circularity approaches and practices and to propose effective and efficient implementation solutions.

The circular economy is a transformational economic model, applicable in all fields, which aims to use new technological discoveries and new ways of interaction between economic actors, in order to keep in the useful operating circuit for as long as possible the limited natural resources extracted from the environment. For this, the main concern is given by transforming the current linear approach (resource-product-landfill) into a circular one (resource-product-resource), the so-called "closing the circularity loop" or "closing the loop".

In this first sub-chapter of the literature review undertaken on the circular economy as reflected in the current literature (generally scientific articles published in the last 5 years and available in internationally recognized databases), the conceptual basis on which the circularity paradigm is based is approached. Behind these concepts lies a fundamental truth that the world economy has been facing for several decades – planet Earth's resources are limited in quantity (e.g., minerals, fossil fuels) or over time depending on the rate of renewal or growth (e.g., renewable energy, wood, flora and fauna, etc.), so economic development cannot continue indefinitely without reusing existing ones in good conditions.

2. SECTOR- AND REGION-SPECIFIC ISSUES

The current section of the literature review carried out to support doctoral research includes those specific elements that translate high-level concepts at the level of industrial practices. Those economic sectors and geographical regions of interest for companies in the Romanian wood industry were tracked, as current or potential markets for current products, as well as for the forecasted circular ones.

All authors studied and the topics they address bring through their research important contributions to the clarification and development of the field of circularity solutions with applicability in the manufacturing sector.

PERSONAL CONTRIBUTION

3. WORKING HYPOTHESIS/OBJECTIVES

The choice of the research topic entitled "Research and contributions regarding the implementation of circular economy solutions in the wood industry" for the admission colloquium and then its development within this paper was influenced by the education acquired so far, at bachelor's and master's level, respectively by the professional experience in the wood industry, where I have been working since 2007 within the IUGAN GRUP group of companies.

The aim of the undertaken doctoral research is to increase the degree of assimilation and implementation of circular economy concepts and models in the wood processing industry.

The main specific objectives are:

1. Critical analysis of current circularity practices compared to the current state of literature in the field and to the main long-term development directions promoted by the European Union through strategies on circular economy, bioeconomy, environmental protection, etc.
2. Making practical contributions regarding the design of highly circularity products and the implementation of processes / technologies with low impact on the environment, from the initial phases of studying feasibility and return on investment.
3. Development of customized models for determining, evaluating and accounting the costs associated with the implementation of circular economy models at the level of the woodworking industry.
4. Analysis of the organizational capacity to implement circular models in the wood processing sector in Romania, by investigating relevant economic actors in the field.

4. STUDY 1 – CIRCULARITY PRACTICES AND TOOLS IN THE WOOD PRODUCTS INDUSTRY

This chapter is based on the article (Tofană, Dragomir, Blagu, & Dragomir, 2022) presented at conference 4th International Scientific Conference on Circular and Bioeconomy "CIBEK 2022", organized online by Belgrade School of Engineering Management, and published in its volume of papers (proceedings), developed and expanded with the inclusion in this doctoral thesis.

4.1. INTRODUCTION

One of the most important paradigm shifts that has been taking place in the European economy for more than a decade and will continue in the near future concerns the implementation of circular economy perception in large-scale supply chains, production processes and consumer approaches that can ensure measurable environmental impact. The transformations required for this change are very diverse and complex in nature, ranging from new policies to new behaviors and technical solutions that allow companies to remain competitive while working to "close the loop."

This chapter describes a transformation of the circular economy at the level of a producer of wood products in the form of a case study that can serve as good practice for similar situations in other industries. The research approach is part of a larger effort, a doctoral project, dedicated to expanding knowledge on how to implement circular economy approaches in the Romanian wood industry in a faster, more effective and more efficient way.

4.2. STATE OF PLAY OF TIMBER PRODUCTION IN THE CIRCULAR ECONOMY

The first step taken was to conduct a survey of relevant scientific literature in recent years. As the article focuses on technological developments in circular economy implementation, the scope of the revision has been expanded to encompass a greater number of sustainability solutions applied in manufacturing. Thus, when studying the ScienceDirect and Google Scholar databases, the keywords "circular economy" were complemented by "sustainable production", "ecological production" and "environmental impact", as well as their derivatives and associated concepts. The resulting logical structure that supports the opportunity of further applied research in the field, with customization for the area of wood products, is presented below.

4.3. RESEARCH METHODOLOGY AND RESULTS

The enterprise presented in this article is based on a structured methodology for applied research, described below.

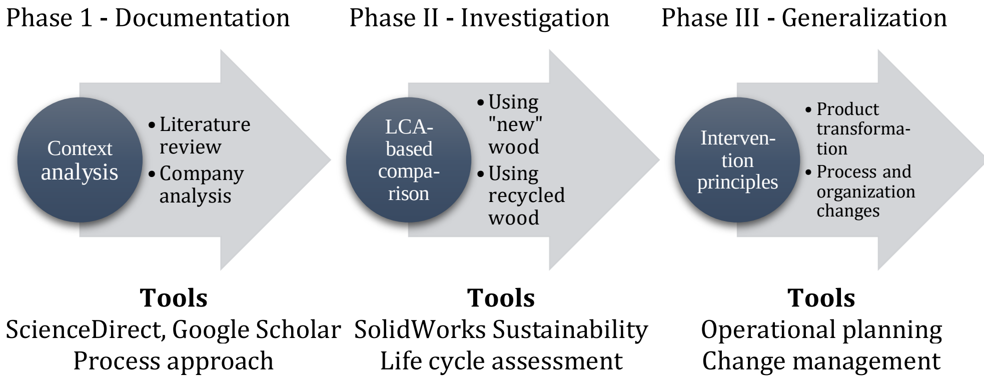

Figure 1 Research methodology and tools (and intervention)

In the first phase, an in-depth literature review was carried out, which is the basis of the previous chapter of this paper.

In parallel, a field investigation was conducted within the company, which served as a case study for our enterprise, to understand its characteristics and approach to market and product design and development. Silvania International is a Romanian company that relies on over 70 years of experience in the production of laminated wood and other wood-based products (Silvania International Prod - Prezentare, 2019). The company industrializes natural white wood from the forests around Lunca Ilvei, Bistrița County, and sells its products or implements construction projects in Romania or internationally.

The following determinations were made:

- The company shows a keen interest in solutions that have a positive impact on the environment of any kind, as they can be integrated into its product design paradigm and the process of continuous improvement of its integrated management system;
- The product offer is complex and is complemented by construction project implementations, which requires establishing a research foundation for a simple product, which can be extended to the entire range of solutions;
- The potential for cost savings is an important one, as the company has at its disposal a multitude of wood waste that can be used as recycled raw material for the production of laminated laminates.

The main investigation carried out during the research was related to simulating and studying the comparison between the use of 'new' wood or the use of recycled materials from previous wood-based products. The analysis was carried out using the SolidWorks 2022 sustainability software module, which uses the well-known CML 2001 method developed by the Institute of Environmental Sciences at Leiden University. The products used for the study are timber 18x75x245, paneling 12X90X300, euro-pallet 145x800x1200 and a triple layer laminate (a fixed format) with the following dimensions: 500 x 88 x 74 mm (length x width x depth).

4.3.1. CIRCULARITY ANALYSIS OF TIMBER

To study the sustainability of 18x75x245 lumber, according to SolidWorks, a 3D model of the lumber was created, reflecting its dimensions and shape. The properties of materials used in lumber have been configured in SolidWorks. Properties include wood density, coefficient of thermal expansion, hardness and other attributes specific to the material used. A detailed analysis of the life cycle of timber was carried out, taking into account the environmental impact at different stages: from obtaining wood from the forest, cutting and processing it, to using the final product and recycling or disposing of it.

The unit cost of the material used in the redesigned product is 0.2 USD/kg, compared to 2 USD/kg in the basic version, meaning a reduction of 80%. The sustainability report highlights timber made from new material as having a significant impact on the environment. The carbon footprint, energy consumption and emissions of pollutants to air and water are relatively high for this variant. End-of-life management involves a significant storage rate prior to disposal, most likely by combustion. To compare, it is also relevant to mention the sustainability report of timber from recycled material. Recycled timber has a higher durability of approx. 20 years, compared to 10 years for the original version, and a reduced environmental impact compared to new material. The carbon footprint, energy consumption and emissions are lower, and end-of-life management involves a higher recycling rate and a lower rate of landfilling and destruction. Therefore, timber from new material has a significant impact on the environment and the use of recycled materials can help reduce this impact.

4.3.2. CIRCULARITY ANALYSIS OF PANELING

In order to create sustainability reports for paneling from new and recycled material, measuring 18x75x245 mm, using SolidWorks and to compare the results obtained, the necessary information about the raw material was collected, as well as data on origin, production process, resources used and environmental impact. 3D models have been created that accurately reflect the shape and characteristics of each type of paneling and appropriate material properties have been selected (e.g., density, coefficient of thermal expansion, mechanical strength, etc.). The software enables impact analysis along different stages such as raw material extraction, processing, manufacturing, use and disposal. The relevant aspects related to circular sustainability were identified for each stage and thus the efficiency of material use was assessed, calculating the amount of material used in each type of paneling. The simulation tools in SolidWorks allow the performance and durability of the two types of paneling to be assessed throughout the life cycle starting from relevant information about the raw material, customer requirements, resource efficiency and interactions with environmental factors.

Comparing the sustainability ratio between new and recycled paneling, we can see that recycled paneling has significantly less impact on the environment. By using recycled materials and increasing service life, recycled paneling helps reduce carbon emissions and impact on air and water quality, although it achieves these results through higher utility consumption. However, other aspects, such as the quality and performance of the finished product, must also be considered before a final decision is made on the choice of materials. It is also important to evaluate and compare the advantages and disadvantages of each option according to the specific context of use and individual needs.

4.3.3. CIRCULARITY ANALYSIS OF THE EUROPALLET

In order to generate a sustainability report according to SolidWorks, relevant product information was gathered for the Euro-pallet with dimensions 145x800x1200 mm, such as materials used, production process, typical use and possibilities for recycling or reuse. Information on material sources and environmental impact at all stages of the Europallet lifecycle was obtained from the manufacturing company and applied to a SolidWorks 3D model. It accurately reflects the shape, structure and mechanical characteristics of the standard Euro-pallet, as well as the properties of the materials used. Using SolidWorks' life-cycle analysis functionalities to assess the environmental impact of the Europallet, the stages of raw material production, manufacturing, use, recycling and disposal were analyzed. The model is also useful to calculate the amount of material used in the Europallet and to assess resource efficiency. By comparing the results with relevant standards and requirements, opportunities to improve the sustainability of this type of product can be identified.

The use of recycled material in the production of Euro-pallets contributes to reducing the environmental impact, similar to the other product categories. It is also worth mentioning that a full environmental analysis of the impact of these changes is being commissioned at this time to address all aspects of making the company as environmentally friendly as possible through circularity solutions and other approaches.

4.3.4. CIRCULARITY ANALYSIS OF LAMINATED WOOD

In this sub-chapter is analyzed one of the most popular products of Silvania International Prod where the case study was performed. Also, laminated wood is considered to be among the most versatile products in this industry, having special mechanical and thermal properties, being easy to put into operation in various wood-based constructions.

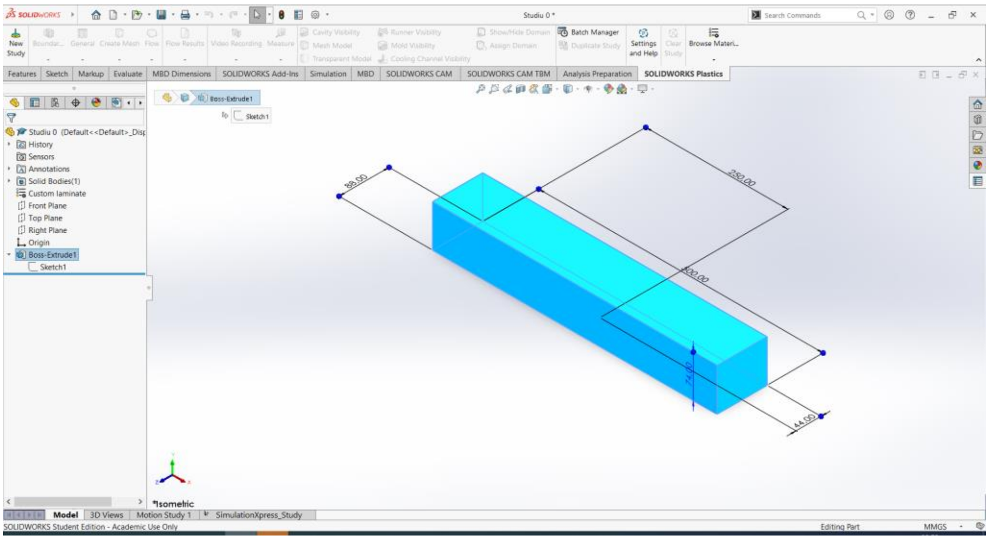

Figure 2 Simple 3D model with product dimensions in SolidWorks 2022

In the first version of the analysis ("new" wood), the material of the product was chosen to closely shape freshly harvested white wood, while in the second version (recycled wood), the characteristics were set to mimic the mixture of wood scrap commonly available in the company's production system as a result of manufacturing processes. As such, changes have been applied to:

- raw materials (as mentioned in the previous paragraph);
- energy consumption (higher for waste processing, as some breakdown of inputs is required, but lower for production and transport, as internal processes produced the waste used);
- production efficiency (lower for waste processing, as there is an increased chance of production non-compliance), and
- EOL distribution of results (it is estimated that there is a proportion of 10% lost for each circularity cycle of wood reuse).

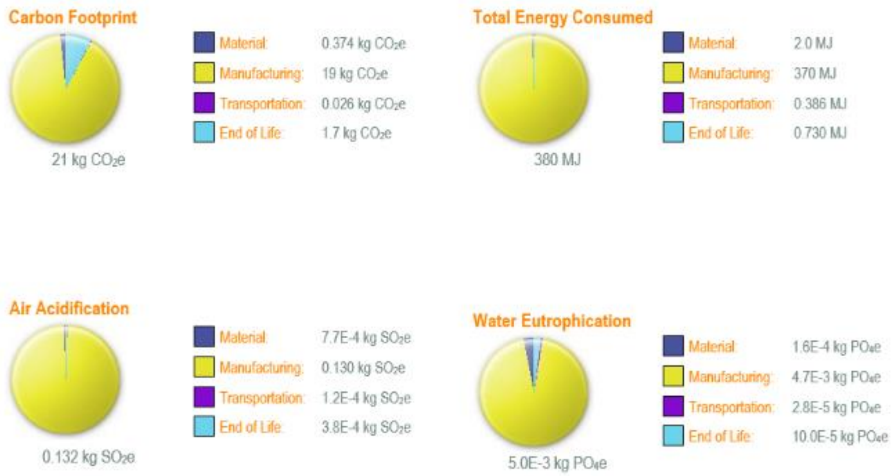

Figure 3 LCA analysis for the use of "new" wood

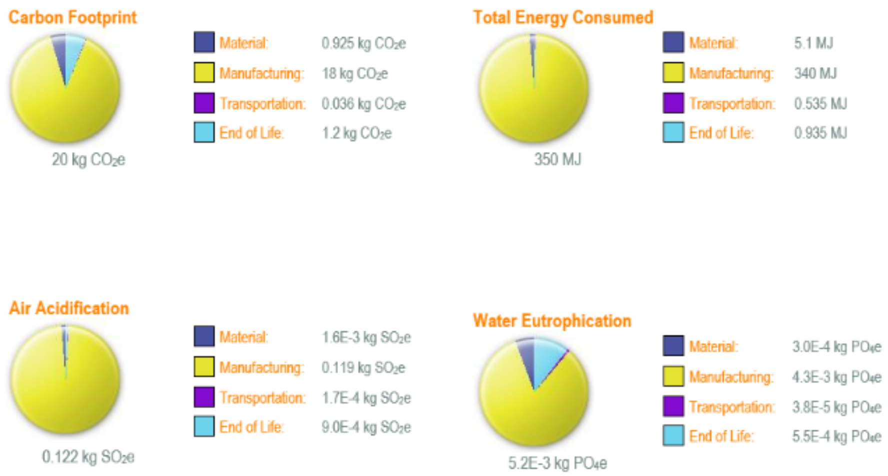

Figure 4 LCA analysis for the use of recycled wood

4.4. DISCUSSION AND CONCLUSIONS

The transformation proposed by the presented research is in the feasibility study and commercial viability analysis stage at company level, and the arguments in favor of it have been formulated and presented below with a 3-year perspective on immediate gains, to be later extended. This phased approach is necessary to enable process-level absorption of circular transformation, cost amortization and adaptation of customer and market relationships to the new realities generated by the fundamental change in operating modes. A realistic time horizon for a complete transition is estimated by the company at approx. 10 years.

Table 1 Short- and long-term changes to adopt the circularity approach

Circularity element	Short-term (current analysis)	Long-term (approx. 3 years)
Wood raw material	Use of recycled wood 10% from similar products	Using 25% recycled wood from any wood product
Chemical adhesive	Switching from solvent-based adhesives to water-based adhesives	Switching to bio-based adhesives (e.g., resins)
Cutting process	No changes are required, renewable energy and cogeneration of heat have been implemented since 2010	No changes are required, renewable energy and cogeneration of heat have been implemented since 2010
Assembly process	No change required, low environmental impact	No change required, low environmental impact
Packaging and shipping	No changes to the current adhesive used, a small amount is involved	Use of recycled wood pallets, use of electric fuel/biofuel for transport

The analysis is structured at process level, addressing the main issues that need improvement in terms of new technologies, new equipment, new practices, etc. In the first interval, the company's commitment to using recycled wood and switching to water-based adhesives is enough to produce detectable changes in results, according to the analysis presented in the previous chapter. In the second interval, the change project should significantly increase the amount of recycled waste used, should also implement new resin-based adhesives using specific techniques and should lead to similar changes to the company's logistics (renewable fuels and recycled cars for transport).

5. STUDY 2 – ASSESSMENT OF TECHNOLOGIES THAT CAN BE IMPLEMENTED FOR CIRCULARITY IN THE WOOD INDUSTRY

This chapter is based on the article (Tofană, Dragomir, Szabo, & Ţîţu, 2022) published in the Journal of Unconventional Technologies Review, completed and edited with the inclusion in this doctoral thesis.

5.1. INTRODUCTION AND BACKGROUND

This chapter aims to contribute to a better understanding of the potential of existing and predictable technologies used in the wood products industry in order to align practices and processes with the requirements of the circular economy concept. This effort is part of an ongoing scientific concern of the authors and their teams to support the digitalization (Ţîţu, Stanciu, & Ţîţu, 2018) , (Salem & Dragomir, 2022) and sustainability (Popescu, Dragomir, Pitic, & Brad, 2012), (Iliescu, Popescu, Dragomir, & Dragomir, 2013), (Popescu, Rusu, Dragomir, Popescu, & Nedelcu, 2020) efforts in various sectors. The proposed methodology can be applied at a general level to any type of company in this field, while the case study is customized for the Romanian company Silvania International Prod and its product line (Silvania International Prod - Prezentare, 2019), in accordance with their research and development approaches.

5.2. RESEARCH METHODOLOGY

To achieve the stated objectives, a four-step approach has been implemented that includes technology identification and internal observations, classification of circularity techniques, implementation across product families and critical interpretation of results. The research methodology is summarized in the figure below.

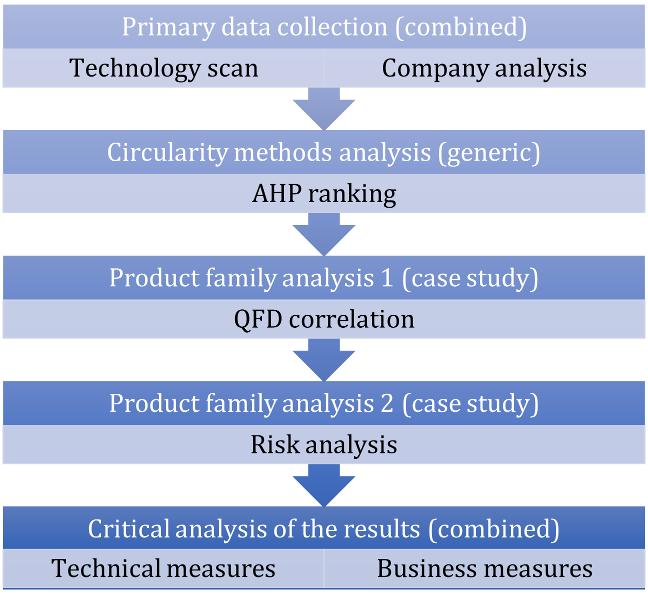

Figure 5 The concept of the implemented research approach

The structure of the approach is a classic one in innovation studies and is meant to serve as a basis for developing coherent proposals for companies in the wood products sector. By aligning product strategy with the capabilities of potential technologies, firms will be more successful in achieving circular economy goals.

5.3. RESULTS AND DISCUSSION

The study of the current processes of Silvania International Prod was completed by a technological scan of the most mature technologies used in the wood industry to "close the loop".

A list of 8 design and production technologies and methods was generated based on existing know-how and then classified using the Analytical Hierarchy Process (AHP) with the support of Qualica QFD software (see figure below) which allows fine control of the pairwise comparison mechanism.

An internal consistency index of 0.098 was calculated using CGI web software (CGI, 2005). This is below the maximum acceptable value of 0,1 and indicates correct implementation of the method.

How Important is the Left Item (Row) as Compared to the Top Item (Column) ?

Group: Top Level ITEMS — Output — Completed: ☑

AHP Toplevel Matrix

9	9,00	an order of magnitude more important
8	8,00	absolutely more important (8x as important)
7	7,00	demonstrated more important
6	6,00	demonstrated more important (6x as important)
5	5,00	essentially more important
4	4,00	essentially more important (4x as important)
3	3,00	considerably more important
2	2,00	twice as important
+	1,50	somewhat more important
○	1,00	Equally important
-	0,67	somewhat less important
½	0,50	half as important
⅓	0,33	clearly less important
¼	0,25	essentially less important (other item 4x as important)
⅕	0,20	essentially less important
⅙	0,17	demonstrated less important (other item 6x as important)
⅐	0,14	demonstrated less important
⅛	0,13	absolutely less important (other item 8x as important)
⅑	0,11	an order of magnitude less important

Input	1 Lifecycle Product Management	2 In-process wood waste collection	3 Customer wood waste collection	4 Water-based varnishing/coating	5 Biomass/pellets energy generation	6 Metalwork extraction and recycling	7 Reclaiming and refurbishing wood	8 Hot composting of wood waste	Importance in group
1 Lifecycle Product Management		3	3	2	2	4	○	4	25,1%
2 In-process wood waste collection			○	3	2	4	2	3	17,0%
3 Customer wood waste collection				3	4	4	2	4	18,8%
4 Water-based varnishing/coating					3	2	½	○	8,4%
5 Biomass/pellets energy generation						½	⅓	○	5,4%
6 Metalwork extraction and recycling							¼	2	5,8%
7 Reclaiming and refurbishing wood								2	14,3%
8 Hot composting of wood waste									5,3%

Figure 6 AHP ranking of selected circularity technologies

For the next stage of the methodology, the Quality Function Deployment (QFD) method was used with the help of Qualica QFD, starting from the 7 possible product types that make up the company's current product list (Silvania International Prod - Produse, 2019).

Figure 7 QFD implementation of technologies across product families

Finally, the QFD analysis complements these product strategy recommendations with the identification of two possible bottlenecks in frames/pallets and wood houses product lines, which are of great importance in the new configuration of the product family, but also present significant technical difficulties, identified by the research team. We believe that the former should evolve into the field of smart products, helping both customers with their businesses and the company with waste collection.

Next, a risk analysis was performed using the same software, Qualica QFD, according to the methodology implemented in this program that correlates the identified risks with the 3 levels of interest involved – technologies and products (resulting from the Quality Function Deployment analysis), respectively functions determined by functional analysis on the transition to circular economy. With the help of specialists from the company, 6 types of risk were determined: staff training and motivation, tightening regulatory conditions, unpredictability of economic changes, reliability and efficiency of equipment, difficulties in obtaining financing and communication deficiencies. The first 3 were classified as possible critical risks and the next 3 as usual level risks. Here are presented the 3 correlation matrices and the results obtained, quantified in percentages of importance or impact of unwanted events during the transformation project for circularity:

Faults	Occurrence	Severity	Critical	Detection	RN	RN Linear
1 Personnel training and motivation	6	7	☑	3	126	6,5
2 Regulatory tightening up	7	8	☑	3	168	7,5
3 Economic unpredictibility	4	9	☑	7	252	6,0
4 Equipment reliability and efficiency	7	5		3	105	5,9
5 Funding securing difficulties	9	8		1	72	8,5
6 Communication failures	6	6		3	108	6,0

Figure 8 Full assessment of risks of transition to circular economy

Using a form of visualization specific to the Qualica QFD program, it can be seen that, although 3 of the risk scores have values lower than those considered critical, they are all found in the area that requires increased attention from the firm due to the need to eliminate their possible occurrence, to the detriment of detection after the events have occurred. This fact is all the more obvious as the graphical representation places two of them (communication problems and equipment reliability issues) close to the second intervention curve, and the third close to the maximum risk curve represented graphically.

5.4. CONCLUSIONS

The current study offers two types of conclusions. First, from a methodological perspective, we can assume that, using quality management and innovation management techniques, the know-how of producers of wood products can be processed to generate useful information to address the main challenges they face when implementing circular economy models. Secondly, for the specific case study investigated, there are 4 technologies with significant impact on transformation, which have the ability to increase the environmental performance of the company, provided that a product strategy focused on 3 main types of products is implemented. However, as two of them also present complex technical problems when integrating circular friendly technologies, we believe that the company should direct its efforts towards the category with the highest potential added value.

As regards the undesirable dimension of the transition process, there is a complex package of risks of a managerial nature and stakeholder relationship, with a varied distribution compared to the main dimensions of the circular transformation. The analysis indicates the need to take preventive, highly urgent measures for critical risks and long-term plans for non-critical risks. Among these measures, following the discussion with the company's representatives, the following possibilities were outlined: periodic training programs for employees, implementation of preventive and predictive maintenance approaches, contracting consultants specialized in fundraising, marketing or operational management, subscriptions to specialized digital products in the legislative or standardization area, integration into associative structures at industry level or local and regional.

6. STUDY 3 – DEVELOPMENT OF A COST MODEL RELATED TO THE INTRODUCTION OF CIRCULARITY FOR THE TIMBER INDUSTRY

This chapter is based on the article (Dragomir, Tofană, & Dragomir, 2023) presented at conference 9th BASIQ International Conference on New Trends in Sustainable Business and Consumption, organized in hybrid format by "Ovidius" University of Constanta and the Bucharest University of Economic Studies, and published in its volume of papers (proceedings), developed and extended with the inclusion in this doctoral thesis.

6.1. INTRODUCTION

The need to transition current economic models from the existing linear and wasteful approach to a circular economy concept, where both matter and energy can be recovered and reused in one way or another, is one of today's guiding imperatives. Managing existing resources, protecting the environment and reducing the carbon footprint are concrete steps that can be derived from the circular economy paradigm and the sooner society and companies are prepared to embrace it, the better for our continued survival and sustainable development.

In Romania, steps are being taken in this direction, as industrial sectors struggle to stay in line with European guidelines and strategies, while other difficulties arise all the time. One of the most visible areas where this solution can be of great value is wood exploitation and processing, including many other subfields such as forestry, timber and timber production, MDL/chipboard production, wood-based products, furniture, etc.

6.2. LITERATURE REVIEW

Although the circular economy has become an important policy orientation and requirement in the last decade in manufacturing, the focus of most companies, like many scientific studies, is based on the technical (Silva, et al., 2021) and operational (Gigli, Landi, & Germani, 2019) aspects of the transition from current models or on the overall assessment of investment opportunity (Kravchenko, Pigosso, & McAloone, 2019).

By focusing on a profound transformation of the business model (Nastase, et al., 2022) as part of a holistic approach at national (Ungerman & Dědková, 2020), supply chain or sectoral level (Pitti, Espinoza, & Smith, 2020), the prognosis of success can be significantly increased. Unnecessary limiting factors and costs (e.g., bureaucracy, administration, protection, etc.) can be overcome more easily if target markets can be persuaded through economic efficiency (Mellquist, Boyer, & Williander, 2022) arguments or public policy interventions (Sikkema, Styles, Jonsson, Tobin, & Byrne, 2023) to facilitate the establishment of the circular economy.

6.3 CONCEPTUAL FRAMEWORK

In order to correctly distinguish the cost categories of the transition from a classical approach to a circular approach in the wood products industry, we propose the following methodical framework that takes into account the necessary transformations before, during and after the completion of the process. This model is based on an understanding of the specificity of each of the paradigms that generate both costs and savings between them (see figure and table below).

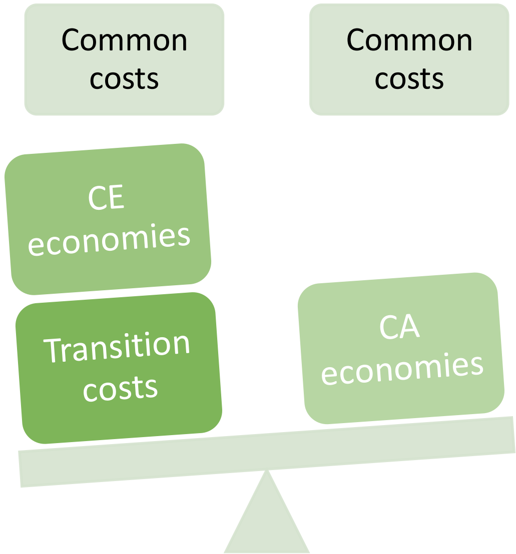

Figure 9 CECACM (Circular Economy – Classical Approach – Cost Model)

Table 2 Details of cost categories

Cost category	Cost items (examples)
Common costs	Overhead costs related to location, management, administration, etc. Production costs associated with design and manufacture Marketing/distribution costs for promoting and selling new products Costs of financial and business services necessary for the company Personnel costs related to the workforce employed by the company
Transition costs (temporary and permanent)	Change of production equipment/software to adapt to CE Retraining of staff to use new equipment/software Additional logistical costs for the use of the new type of recycled materials Cost of new consumables used in specific CE processes
CE savings	Reduced raw material costs through reuse/recycling Reduced costs of compliance with environmental legislation Increase sales of current product lines Sales of new types of products and solutions
CA Savings	Use of existing infrastructure, knowledge and solutions

In turn, if we study the accounting approach used by most Romanian companies, there are several elements that show the possible links between CECACM and the records that are usually kept (Table 3). The symbols in the tabular matrix below show the degree of correlation between the analyzed categories, ranging from very low to very high and using five steps.

Table 3 Determination of the relationship between CECACM and accounting practices

	Salaries and contributions	Raw	Energy & Utilities	Transport & Services	Depreciation and interest	Various
Common costs	❺	❺	❹	❸	❷	❶
Transition costs	❸	❹	❶	❺	❺	❶
CA Savings		❶	❶	❶		
CE savings		❹	❸	❸		❺

Legend (relationship intensity): 1 - very low, 2 - low, 3 - medium, 4 - high , 5 - very high

6.4. RESULTS AND DISCUSSION

When analyzing the cost categories proposed in the above model, one should recognize the following important aspects in relation to their definition and possible means of data collection:

- Both approaches will generate costs related to the use of equipment and labor, as well as capital and services for the creation and sale of products, but the technical and competence content of these elements could vary considerably (e.g., replacing tree trunk cleaner with a painting machine, replacing a primary saw worker with a CNC specialist worker, etc.);
- The transition costs incurred for the conversion from classic to circular are either temporary or one-off (e.g., purchase of new machinery, establishment of a collection system) or may become permanent in the new production system (e.g., use of

enzymes to break down lignin or water-based coatings instead of solvent-based coatings);

- The savings generated by the EC approach are either easily quantifiable (e.g., amount of timber replaced) or difficult and vague to assess (e.g., image impact on market niches of becoming a circular producer);
- AC economies are mostly linked to well-known economic effects related to scale, know-how or common externalities.

The classical approach above is explained and modified at the level of the proposed cost model by implementing the following approach:

Total costs (T) = Common costs (CC) + Transition costs (CT) + Savings from circular practices (CEE) - Savings from usual practices (CAE)

Common costs (CC) include general and recurring costs that arise during the entire transition process to the circular economy in the timber industry. An initial investment in research and development is needed to adopt circular practices and develop innovative solutions in the timber industry. The implementation of circular practices may require the purchase of specific equipment and technologies, such as recycling machines, woodworking machinery and other advanced technologies. To ensure an effective transition to the circular economy, employees need to be trained and trained to understand and implement new practices and technologies.

Transition costs (CT) include expenses associated with planning, monitoring and implementing circular practices at all stages of the production and distribution process. The use of recycled or renewable materials may involve higher costs compared to the purchase of new raw materials. These costs can be offset by the long-term benefits of the circular economy.

As regards CEE (economies of circular practices) and CAE (economies of usual practices), these can be assessed by specifically identifying potential savings in each cost category mentioned above. Common savings may include reduced raw material consumption through recycling or reuse, energy savings through energy efficiency or transport savings through route optimization, as well as effects from high production volumes, mature know-how and industry-wide standardization. On the other hand, circular economies can be assessed by identifying new business opportunities, increasing sales of recycled or renewable products, capitalizing on waste by generating additional revenues and other economic benefits specific to the circular economy.

Based on these premises, the circular cost model was simulated to analyze the change in profit and production price of the product in the first half of 2023. The model combines different components of the cost of production determined according to accounting practices and assigns weightings to them to calculate total circular costs. These weightings reflect the relative importance of each component in the timber, paneling, Europallet and layering production process.

$$CC=50\%SC+50\%MP+70\%EU+50\%TS+30\%AD+10\%DIV$$

$$CT=50\%SC+70\%MP+10\%EU+90\%TS+90\%AD+10\%DIV$$

$$CEE=70\%MP+50\%EU+50\%TS+90\%DIV$$

$$CAE=10\%MP+10\%EU+10\%TS$$

$$T=CC+CT+CEE-CAE$$

Total circular costs

$$T=1.4*SC+1*MP+0.4*EU+1*TS+1.2*AD-0.6*DIV$$

By using the weights assigned to each component in the circular cost model formula and monitoring their variation over time, it is possible to estimate how the output price changes in the same month from one year to the next. This model can be used as a cost analysis and planning tool to identify and evaluate factors influencing prices in the timber industry and to make informed decisions regarding production strategies and sales prices. According to the data obtained from accounting, the following graphs were made regarding the total classic cost of products, with the classic profit, respectively the circular cost of products, with the circular profit of products for the first six months of

2023 (the graphs presented are numerically depersonalized for data privacy reasons).

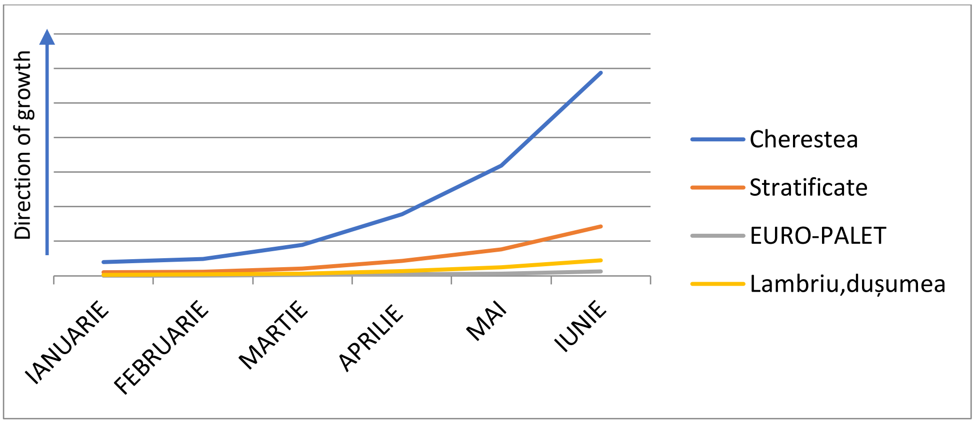

Figure 10 Classic cost model chart

As can be seen in the graphical representation of the classic cost model, the expenses for timber production are very high, compared to the expenses of other products in production. For this reason, for the circular transformation process, in continuation of the transition:

- recycling and reuse has been encouraged by identifying and separating wood waste generated in production processes;
- opportunities have been identified to recycle wood waste into new products or to reuse it in processes;
- savings from using recycled or reused waste instead of new raw materials have been calculated;
- an energy audit has been carried out to identify potential areas for energy efficiency improvement in energy production and use processes;
- the implementation of energy-saving technologies and practices, efficient lighting, low-consumption equipment and monitoring of energy consumption was encouraged;
- the savings achieved by reducing energy consumption and associated costs have been calculated;
- Optimal resource management has been promoted by identifying alternative raw materials or composite materials that can replace traditional wood.

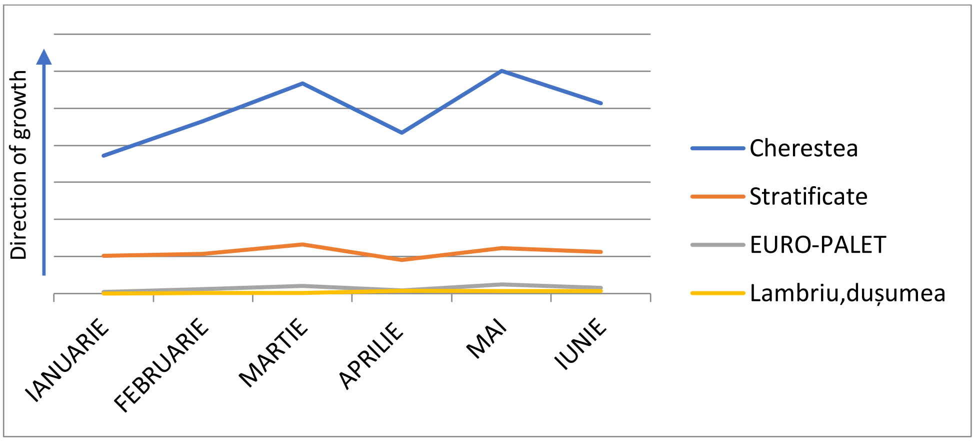

Figure 11 Circular Cost Model Graph (CECACM)

By applying the circular cost model from the beginning, the expenses of the timber product are more tempered, even reduced compared to the classic production cost model, which allows a better adaptation of the measures within the company to the requirements of the circular economy:

- effective stock planning and management has been created to reduce waste and maximize the use of raw materials;
- savings achieved by using alternative materials and reducing waste have been calculated;
- partnerships have been established with suppliers and customers to share resources and create closed supply and recovery cycles;
- opportunities for waste recovery and collaboration in waste recovery in production processes have been identified;
- The savings and values generated by collaborating in the supply chain were calculated.

6.5 CONCLUSIONS

Based on the investigation, we can conclude that Romanian producers of wood products are in the early stages of planning and implementing circular economy models, as they get to assess the scale of the necessary changes from an operational and economic point of view. The focus is often on the necessary investments in equipment and software, but we have concluded that the long-term operation of the approach entails other significant costs, which should nevertheless be offset by the magnitude of the savings generated by the possibility of using reclaimed wood.

However, the classical approach also has some important savings for which there is no substitute yet, including the use of existing business channels, the learning effect produced by wood production generation and the possibility to capitalize on current infrastructure (e.g., production facilities, pollutant treatment plants, classic transport options, etc.). It is also worth noting that the transition is difficult if it does not happen as part of a coherent ecosystem whereas many partners in the value creation chain as possible go through the same process, thus indicating the need to support this conversion through appropriate incentives and funding.

7. STUDY 4 – STUDY ON THE CAPABILITY OF ORGANIZATIONS IN THE WOOD INDUSTRY TO ADOPT THE CIRCULAR ECONOMY

This chapter is based on the article (Dragomir M. , Tofană, Dragomir, Țîțu, & Popescu, 2023) published in the journal Forests, Clarivate Analytics Web of Science rated, with an impact factor (2022) of 2.9 and classified in quartile Q1 (JIF) – red area, completed and edited with the inclusion in this doctoral thesis.

7.1. INTRODUCTION

To this end, this approach aims to develop a circular economy conformity assessment model customized for use in the wood products industry, which is operationalized as a circularity audit tool and is then implemented on a significant sample of companies in the wood industry in Romania.

7.2. MATERIALS AND METHODS

For the development of the proposed approach, the research method included 6 stages (figure below):

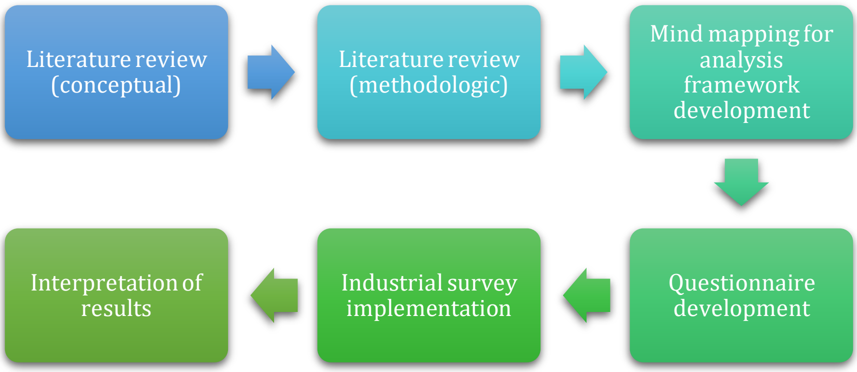

Figure 12 Research methodology applied in the study

The methodology is built around the objective of developing and administering a questionnaire appropriate to the situation of companies in the wood industry in Romania. Based on this foundation, a literature survey was conducted that includes two stages, one dedicated to the implementation of circular economy approaches in the manufacturing sector in general and in the wood sector in particular, and the second dedicated to methodological aspects related to identifying and measuring innovation, technology management and circularity capacity at organizational level (which is significantly different from product/process and national economy levels). The literature was selected using the ScienceDirect database and the Google Scholar search engine that links to other important databases, while the time period considered includes the period 2018-2023.

Data collection using this questionnaire was done by e-mail or telephone interviews using a relevant database of companies in the wood industry in Romania, respectively the one managed by the Association of Foresters in Romania (Asociația Forestierilor din Romania - ASFOR, 2023). The database contains a total of 5201 companies and has been sorted in reverse order of approved operating quantities. A total of 60 responses were collected, selected and then processed to develop findings and conclusions, as well as recommendations for firms pursuing the circular economy paradigm. Statistically, this sample size was calculated using a 10% margin of error, 90% confidence level and 66.66% response distribution, leaning towards a positive approach to circularity adoption (Raosoft, 2004).

7.3. RESULTS

7.3.1. LITERATURE REVIEW

For the first step of the current study, a literature review was conducted on the most relevant topics related to the development and implementation of tools that assess the capacity of manufacturing companies to adopt circular economy models and practices. As mentioned in the section above, the focus was on issues in line with the objective of the proposed study, namely the creation of innovation audit mechanisms and company-wide circularity frameworks proposed and published over the past five years.

7.3.1.1. CONCEPTUAL ASPECTS OF CIRCULARITY IN THE TIMBER INDUSTRY

Today's studies show the critical role played by developing an enterprise's innovation potential. For example, (Hanaysha, Al-Shaikh, Joghee, & Alzoubi, 2022) conducted a survey in Saudi Arabia with 171 SME employees exploring 5 dimensions of innovation and concluded that the long-term viability of the business is positively influenced by all of them, with a special focus on process innovation. This school of thought can also be applied to the circular economy in the new economic, social and climate context, business sustainability depending on achieving a high level of circularity. Another study, from China, concludes that environmental strategy driven by external factors leads to improved innovation capacity by involving persuasive managers (Yang D. , Wang, Zhou, & Jiang, 2019), further strengthening the conceptual unity on which the approach proposed in this article is based. Innovation capacity is a complex issue to which many of the characteristics, practices and processes of companies contribute, but in the long run a very positive effect has been observed for absorption capacity in a knowledge-rich environment (Liu, Shan, & Li, 2023). This should also be the case for the transition towards circular practices, as the socio-economic environment is even more saturated with free and accessible know-how, policies and best practices in this area.

However, there are disseminated results demonstrating that while radical innovation depends significantly on the development of firm framework conditions for innovation capacity, they do not significantly influence either incremental innovation or the translation of innovations into business outcomes (Yusof, Kamal, Lou, & Kamaruddeen, 2023). As circular approaches usually start small-scale and evolve towards a major impact (Stahel, 2016), the literature consulted discusses solutions to the problem of targeting innovation capacity, for example through continuous and integrated updating of digital solutions and individual creativity used, as mentioned in (Bansal, Panchal, Jabeen, Mangla, & Singh, 2023). Another study in this direction, using as a sample 181 Chinese companies involved in production clusters, determined that radical innovation is also negatively affected by the interaction between cooperation and constructive conflict within the associative structure, but incremental innovation is positively affected by the same problem (Xu, Wu, Gu, & Raza-Ullah, 2023).

7.3.1.2. METHODOLOGICAL ASPECTS FOR CIRCULARITY ASSESSMENT

Innovation audit, as a tool to determine and improve capacity, served as a guide for the approach outlined in this article. This is based on the assumption that circularity and innovation, as multiple transformations affecting organizations, products, processes and stakeholders, can be measured in similar ways. The connections and similarity of the two fields are also documented in the literature by (Hysa, Kruja, Rehman, & Laurenti, 2020) , (Sehnem, de Quizeros, Pereira, Correia, & Kuzma, 2022) and (Pichlak & Szromek, 2022). The areas of capacity assessment and auditing are also undergoing significant changes to cope with the innovation processes of modern companies characterized by transparency, intelligent solutions and servitization (Frishammar, Richtnér, Brattström, Magnusson, & Björk, 2019), or the elaborate and dynamic requirements of industries that rely heavily on advanced patented knowledge (Li, Zou, & Li, 2022).

7.3.2. DEVELOPMENT AND CONTENT OF THE QUESTIONNAIRE

The research team established a number of 7 evaluation directions starting from the considerations of literature analysis and its own work experience in the wood industry, manufacturing sector and in quality, environment, technology and innovation audit. Each of the main directions was elucidated in a number of 4 items detailing the most important aspects related to the respective topic. The method used to reach this result was the mental mapping technique applied by the team in three successive stages to refine the final result. For each element of the questionnaire, a rating scale from 1 to 5 is used, ranging from complete disagreement to complete agreement. Thus, the total assessment score can vary from 28 to 140 (Table 5). Also, each assessment is complemented by a spider chart that shows a graphical interpretation of the result and allows further identification of opportunities for benchmarking and improvement.

Table 4 Questionnaire and elements used to assess the circular economy.

Circular economy compliance audit		
Company data:	Score	Contact person:
Email and phone:		Date of investigation:
Range: from 1 - strongly disagree to 5 - strongly agree		Answer/Details
Organizational approach to circularity		
Does the organization use dedicated organizational structures for circularity?		
Does the company implement specific circularity policies/measures?		
Does the organization carry out an assessment of circularity performance?		
Is the supplier selection process based on circularity issues?		
Product-related circular features		
Do products have the ability to recycle components (e.g., unmixed materials)?		
Are the products easy to repair, reuse, refurbish by the customer / company?		
Do products have modularity and/or ease of (dis)assembly?		
Are there ongoing efforts to minimize the environmental footprint?		
Circular process-related features		

Circular economy compliance audit		
Company data:	Score	Contact person:
Email and phone:		Date of investigation:
Range: from 1 - strongly disagree to 5 - strongly agree		Answer/Details
Is waste/scrap recycled and reused in production processes?		
Does the company use renewable energy and/or energy recovery?		
Are there biotechnologies implemented to mitigate environmental impact?		
Does the company use carbon capture and sequestration technologies?		
Education and training on circularity		
Does the organization provide/reward formal education related to circularity?		
Are specific issues addressed through in-house or tailor-made training?		
Can the company gain access to circular solution databases?		
Does the organization pursue partnerships with education providers?		
Circular technologies, mechanisms and partnerships		
Can customers access the possibilities of returning and collecting products?		
Does the company use validated circularity standards and frameworks?		
Does the organization benefit from expertise from professional bodies and/or NGOs?		
Can the company reprocess its internal materials for new/different products?		
External support, know-how and funding		
Does the organization use fiscal and operational incentives for circularity?		
Has the organization accessed public funds for investments in technology?		
Does the company contribute to the dissemination/exchange of good practices?		
Does the organization pursue partnerships with RDI suppliers?		
Adoption by customers and society		
Are customers involved in solution development/management?		
Does the organization cooperate with (local) authorities for circularity?		
Is the company actively involved in associations/networks?		
Does the company use digital tools to promote/implement circularity?		
TOTAL		

7.3.3. SURVEY RESULTS

The questionnaire was applied to 60 Romanian companies active in the wood industry, by email and telephone interviews, between November 2022 and January 2023. These companies were sampled to provide a generic picture of the entire sector in the country, with the size of enterprises ranging from small and medium-sized enterprises to large enterprises or groups of firms, as well as the geographical distribution covering the most important logging areas.

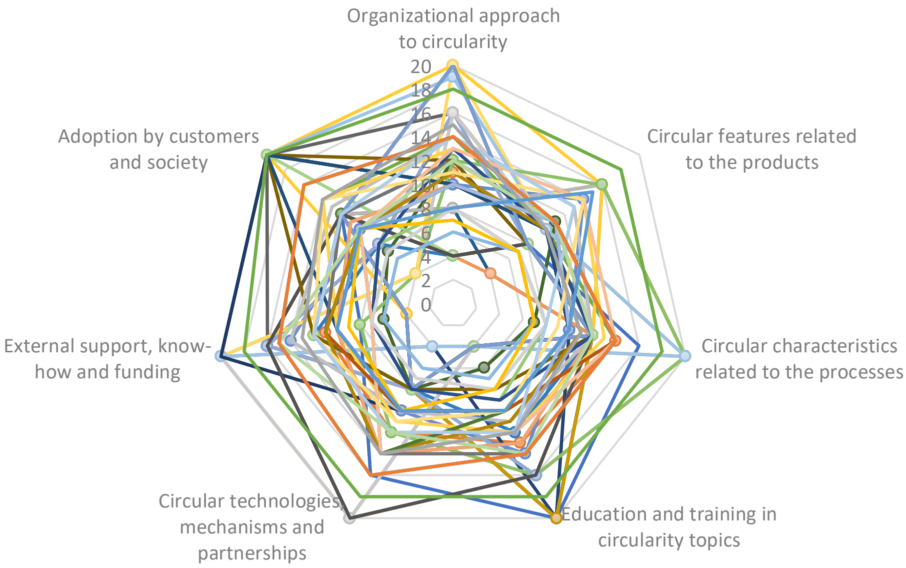

Figure 13 Concatenated spider diagram of the 60 questionnaire responses

A quick visual analysis of the results in the figure shows us that there are some companies reporting very good results (7 firms scored over 95 points) and also a small number of companies reporting modest results (5 firms scored below 55 points), while the vast majority are in the middle of the defined range (48 companies).

The descriptive statistical analysis of the questionnaire results on the 7 main categories investigated and of the totals obtained for each respondent company reveals the structure of the field.

Table 5 Descriptive statistics applied to aggregate survey results

Statistical size	***Value***
Amount	80,4667
Standard error	2,0209
Median	82,5000
Manner	92,0000
Standard deviation	15,6535
Sample variance	245,0328
Kurtosis	0,6129
Asymmetry	-0,2118
Amplitude	83,0000
Minimum	45,0000
Maximum	128,0000
Amount	4828,0000
Count	60,0000

In the case of single-factor ANOVA (Table 7), the 60 response columns are analyzed, and the F-value and P-value are generated. Since F is higher than critical F and P is considerably below the alpha level of 0.05, we can consider, on the principle of rejecting the null hypothesis, that the implementation of circular economy approaches transforms wood products companies in Romania based on their individual efforts.

When performing two-factor ANOVA without replication, F is less than critical F and the P-value is above alpha, which means that at the sectoral level, the null hypothesis must be accepted, at least partially.

Table 6 One-factor ANOVA of collected responses

Source of variation	**SS**	**Df**	**MS**	**F**	**wave, p**	**F crit**
Between groups	2015,74	59	34,16509	2,146177	1.12E-05	1,358639
Within groups	5730,857	360	15,91905			
Total	7746,598	419				

Table 7 Two-factor ANOVA without replication of collected and cross-sectoral responses

Source of variation	**SS**	**Df**	**MS**	**F**	**wave, p**	**F crit**
Rows	185,4143	6	30,90238	1,972691	0,068808	2,12421
Columns	2015,74	59	34,16509	2,18097	7.56E-06	1,35927
Error	5545,443	354	15,66509			
Total	7746,598	419				

7.4. DISCUSSIONS AND CONCLUSIONS

Based on the results of the survey and discussions with the companies involved, the following set of main recommendations can be formulated in relation to the published literature:

- circularity performance must be tracked starting from the current baseline and regularly setting concrete targets using dedicated software or platforms (Al-Obaidy, Courard, & Attia, 2022);
- product modularity is a mature approach in many industries and could be easily adopted for the wood products industry through the use of advanced PLM software and methods (Giddaluru & Gao, 2019);
- in-process reuse of wood scrap for green biomass energy generation is technically feasible and financially incentivized by existing government programmes (Marinescu, 2020);
- a high level of training in circularity areas can be achieved through partnerships with secondary and tertiary education institutions and using a diversified approach (Kirchherr & Piscicelli, 2019);
- by actively engaging in industry associations and clusters and networks, timber companies could be able to set up end-of-life product collection centres to enable rapid and quasi-complete reuse of materials (Kalra & Hara, 2022);
- Many research funding and support programmes are available at national and European level and should be accessed as a priority (Alberich, Pansera, & Hartley, 2023);
- Customers, whether businesses or end-users, should be involved in circularity implementation systems to increase the level of return and reuse of products as described (Soh & Wong, 2021).

8. FINAL CONCLUSIONS

8.1. GENERAL CONCLUSIONS

Taking into account the previously presented content of the doctoral thesis, it can be concluded overall that the transition of the wood and wood products industry towards the circular economy paradigm is a complex process, which has the potential to bring significant benefits to the companies involved, but also presents numerous challenges that need to be acknowledged and addressed in a preventive manner. Also, building the circular economy is not an individual phenomenon that can be analyzed or carried out by a single company, but requires a wide support network in which law-making and regulatory entities, firms and their associations, civil society, individual and legal customers, but also markets as a whole, as representatives of trends in society, intervene as actors. At all stages and situations specific to this transformation process, it is to the benefit of companies to resort to mature solutions that are based on scientific investigations and specific technical contributions, in order to increase the impact of changes, reduce the time required for their implementation and allow a faster diffusion of environmental benefits, first of all, but also on the costs and lifecycle life of the products concerned.

In each of the studies, specific conclusions were indicated on the four dimensions addressed: design practices for circularity, appropriate technologies for circular manufacturing, identification of costs for transition and operation in this paradigm, respectively complex assessment of transformation capability in the wood industry in Romania. The structure of the thesis follows a bottom-up process, starting from the concrete experience of the PhD student in the field and evolving towards synthesis aspects at the level of processes and organizations, offering those interested in the subject a perspective close to the way of working and conceptualization in the industrial environment.

8.2. ORIGINAL CONTRIBUTIONS

The following is a summary of the most important scientific contributions made by this paper:

- Critical analysis of literature on several dimensions (circular products, technologies and approaches supporting circularity, general and specific costs, organizational capability for the transition to circularity, innovations that can support the process, case studies in various sub-sectors or regions, etc.) to support methodologically designed research;
- Analysis of "what-if" scenarios made in SolidWorks for four products made by this industry (timber, paneling, euro-pallet and laminated wood) for which the introduction of circularity mechanisms by using recycled wood is designed, with consequences on lifespan, performance and customer satisfaction;
- Study with the help of AHP, QFD and Risk analysis tools available in Qualica QFD software to analyze the potential for implementing specific technologies and operational approaches necessary to achieve circular production, focusing on the benefits and risks of the company;
- Propose and validate a specific cost model for timber companies transitioning to a circular work model, taking into account data available in current accounting records and taking into account cost savings but also additional expenses required;
- Designing and implementing a complex questionnaire study regarding the ability of companies to adopt 7 specific dimensions of the circular economy (products, processes, training, financing, support, etc.) in which 60 organizations from the wood industry participated and which led to highlighting the current situation in the field in Romania, allowing the design of a package of support measures.

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