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Indra Muižniece

BIOTECHONOMY ANALYSIS METODOLOGY

Summary of the Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
Institute of Energy Systems and Environment

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BIOTECHONOMY ANALYSIS METODOLOGY

Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERISTY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF ENVIRONMENTAL ENGINEERING

To be granted the scientific degree of Doctor of Environmental Engineering, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 2 July 2018 at the Faculty of Power and Electrical Engineering of Riga Technical University, 12/1 Azenes Street, Room 115.

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DECLARATION OF ACADEMIC INTEGRITY

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

Indra Muižniece ……………………………….. (signature)

Date: ………………………..

The Doctoral Thesis has been written in Latvian, it consists of an introduction; five chapters; Conclusions; 47 figures; 14 tables; the total number of pages is 100. The Bibliography contains 147 titles.

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Topicality of the Doctoral Thesis

Latvia is fortunate to have various types of bioresources; however, fossil resources are not available in large volumes. Bioresources include all resources that are available and obtainable from water, land, and air, as well as those that are formed as surpluses in production processes and everyday life. Bioresources are renewable natural resources, but one must take into account that they are not inexhaustible, and the duration and amplitude of our ability to benefit from bioresource use depends on our ability to manage these resources in a sustainable manner.

The concept of bioeconomy has been widely used in recent years in regard to the use of bioresources, and it has gained an international significance [1] since the adoption of the Bioeconomy Strategy (*Innovating for Sustainable Growth: A Bioeconomy for Europe*) by European Commission in February 2012 [2]. The introduction of the bioeconomy concept within a national economy is a way to sustainably manage bioresources and to find an alternative to fossil-based products using biomass, thus, not only promoting economic and social wellbeing, but also reducing the negative environmental and climate impacts of the economy.

The European Commission has set a long-term plan to develop a competitive, resource-efficient and low-carbon economy by 2050 [3] and has incorporated the concept of the Green Economy into various EU policy documents. According to the United Nations Environment Program (2011), the green economy is defined as “low carbon, resource efficient and socially inclusive", and it aims to improve human wellbeing and social equity, while simultaneously significantly reducing environmental risks and ecological disadvantages [4]. From a broader view at the concept of the green economy, biotechonomy is focused on the use of renewable raw materials and their application in research, development, innovation and industrial technologies for such sectors as food, feed, paper and cellulose, and biofuel production. Unlike the green economy, biotechonomy focuses on new growth opportunities both in traditional and emerging bioresource-based industries.

The main focus of the European Bioeconomy strategy is science, innovation, education and training, management and dialogue with the public (Fig.1).

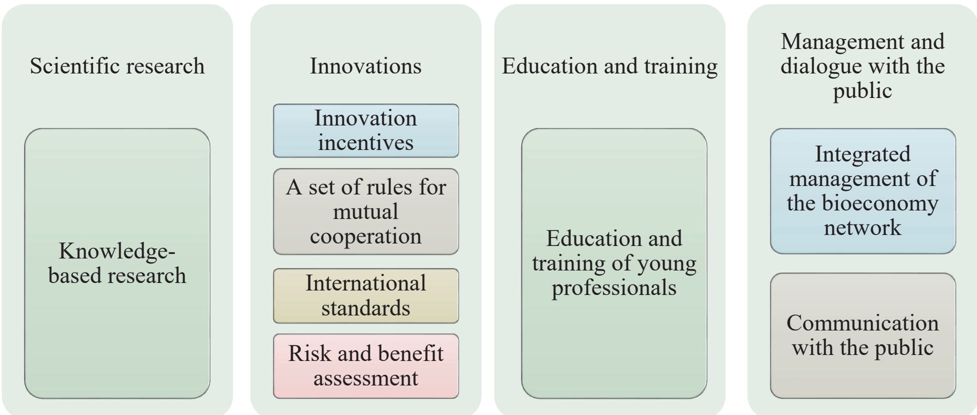

Fig. 1. European Union’s Bioeconomy Strategy.

Europe has come to the conclusion that in order to cope with the growing population, resource depletion and increased environmental and climate impacts, a radical change is needed to the approach of production, processing, consumption and disposal of bioresources. With the Bioeconomy Strategy, the European Commission is hoping to pave the way for a more innovative, resource-efficient and competitive society capable of combining food security and industrial objectives with bioresources, while simultaneously ensuring environmental protection. The essential role of forestry is emphasized not only regarding the acquisition and use of material resources for manufacturing of products and the ecosystem services that the forest ecosystems provide, but also from the sector’s actual contribution to the economic development by providing jobs [5].

Although the term of bioeconomy is becoming more widespread, e.g. in scientific literature and in policy documents at the European level, still there may be an impression that this term is not well-defined and may be interpreted as needed. The most critical opinions even suggest that bioeconomy is just a new slogan of old ideas [1].

Bioeconomy is a knowledge-based use of bioresources that relies on innovative biological processes and principles to provide goods and services in a sustainable manner in all sectors of the economy [6].

It is recognized that so far there are no significant achievements in the European bioeconomy field. The amount of biomass that is used in the manufacture of chemicals and plastics has not significantly changed for the last ten years. Only the sectors of bioenergy and biofuels are well-developed due to rigorous legislation that is based on the Energy Directive and the Emissions Trading System [7]. In many countries, small and medium-sized enterprises are the main developers of innovative bioeconomy ideas. It would therefore be necessary to involve them in bioeconomy policy-making [6].

The development of biorefinery systems is recognized as the determining factor for the transition to bioeconomy. The most controversial issue regarding it is the high demand for biomass in order to achieve cost effectiveness, which impacts the expenses for logistics, storage and raw materials [8].

Researchers of the Institute of Energy Systems and Environment of the Riga Technical University are proposing to expand the idea of bioeconomy by introducing a new term – biotechonomy, which, unlike the well-known term of bioeconomy, focuses not only on the rational and efficient use of bioresources for the creation of innovative high added value products, but also on the technological problems of the use of bioresources [9], [10]. The term biotechonomy should be used to precisely define the sustainable use of bioresources, as it is a science-based and economical use of indigenous resources to create new, market-driven, competitive products produced with innovative and advanced biotechnology. Although it is now commonly believed in the literature that these terms are equivalent, the analysis of their nature reveals the differences. This is related to the English term *economy*, which in this case means saving of resources and assets and has little to do with the economy as a sector. The concept of biotechonomy defines the aspects of the use of bioresources most precisely as it addresses the technological challenges associated with bioresource extraction and treatment technologies, as well as the use of the new product and eco-design. Bioeconomy, in turn, analyzes the aspects of rational and efficient use of bioresources as well as saving aspects.

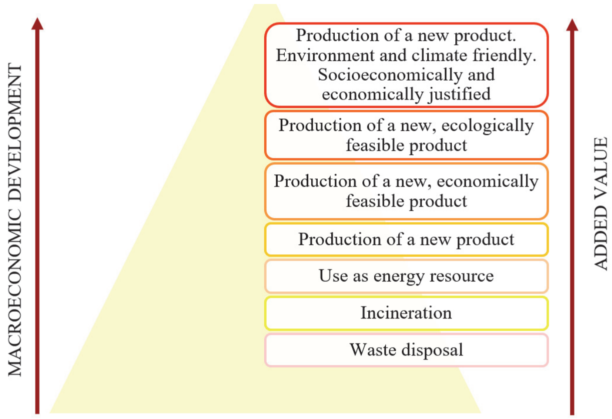

Fig. 2. The pyramid of biotechonomy with the use of bio-resources for manufacturing of new products [9].

Biotechonomy combines the use of bioresource extraction technologies and biotechnologies for treatment and processing of bioresources using innovative and advanced technologies to produce new added value products. The biotechonomy idea is most clearly explained by the pyramid at the base of which is the most simplistic treatment of a bioresource: waste that is deposited in a landfill (Fig. 2.) [9].

The use of a bioresource for energy production is the least environmentally friendly and economically cost-effective solution. If a bioresource is combusted in the furnace to produce heat which is further used in heat supply, industry, agriculture or the service sector, then the question remains: if it would be possible to use these bioresources more efficiently. Often, bioresources that are combusted in boilers may also be used for other purposes, for example, in the production of gaseous or liquid biofuels. It is possible to derive a new product from any bioresource. The questions that remain open are: what will be the application of this new product; its market demand; how much will its production cost; how will the production of this new product affect the environment and climate change and what will be its socioeconomic indicators [9].

Sustainable development of biotechonomy depends not only on the characteristics of the sector and the properties and potential uses of the new bioproducts, but also on other specific preconditions and aspects: financial assets, human resources, climate, environment, engineering, economic and socioeconomic aspects (Fig. 3.). It is necessary to create sectorial clusters within biotechonomy field that would combine some common features, such as a set of products with high added value derived from forest biomass.

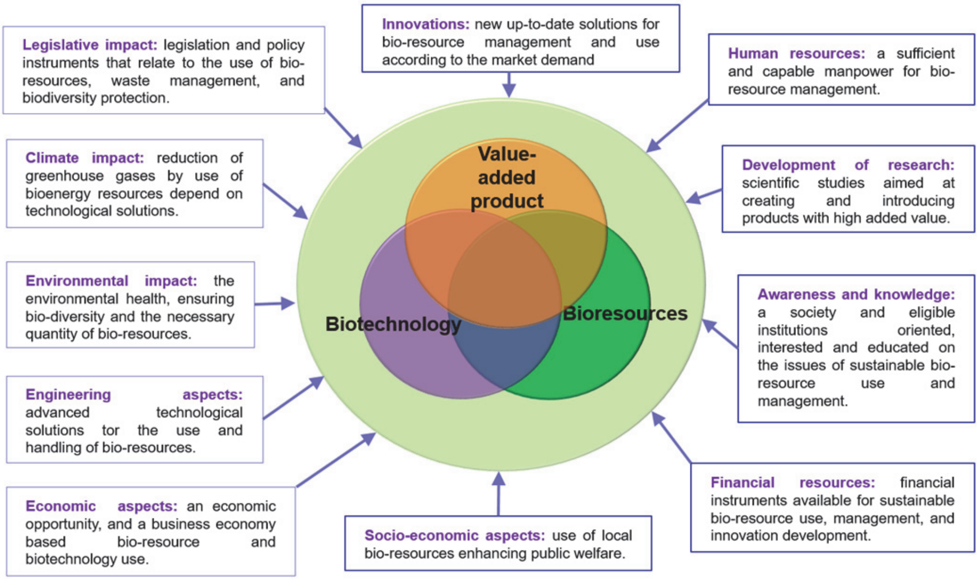

Fig. 3. The triple helix of biotechonomy and factors affecting them [10].

The main preconditions for the development of biotechonomy sector depend on the direction in which the use of bioresources will develop. It is very important that all of the above mentioned aspects are based on the following principles:

- introduction of innovative and scientifically sound biotechnologies;
- use of biotechnologies that are economically viable and based on business economy;
- development of socioeconomically sound biotechnologies that increase the level of employment and reduce imports;
- use of environmentally friendly biotechnologies and bioresources which are extracted in an ecologically sound manner;
- the concept of greenhouse gas emission reduction [9].

By considering the principles of biotechonomy within the Latvian economy and the use of bioresources for the manufacturing of products, it would be possible to gain even greater economic, social, environmental and climate benefits. Within the framework of this dissertation, detailed attention is paid to the development possibilities of Latvian forestry in the context of biotechonomy, by using those forest resources, which have previously been underestimated for the manufacturing of new products. Therefore, the following questions are raised: what is the current situation regarding the use of Latvian forest resources and in which direction it should develop? This dissertation seeks to answer these questions and proposes one of many possible ways to make use of some of the under-utilized forest resources to produce innovative products in accordance to sustainability and biotechonomy principles.

The Aim and Tasks of the Doctoral Thesis

The aim of the Doctoral Thesis is to develop a biotechonomy analysis methodology and approbate it for the Latvian forestry sector in order to find its development perspectives in the context of biotechonomy and a novel solution for the use of previously under-utilized forest resources through manufacturing of new products.

To achieve the aim of the Doctoral Thesis, five main tasks have been set:

1. to perform a biotechonomy analysis in Latvia;
2. to analyse the possibilities to abide by the principles of biotechonomy in Latvian forestry sector;
3. to evaluate the possibilities for sustainable use of low-value wood and logging residues to produce high added value products;
4. to perform a case study and evaluate the possibilities to use one under-utilized forest resource and determine the availability of this resource;
5. to carry out a case study and create an innovative product from logging residues, that corresponds to the biotechonomy concept.

Methodology

This dissertation is based on the analysis of the theoretical biotechonomy concept and assessment of opportunities at four levels: national, sectorial, resource and product. The resource level will include approbation of biotechonomy principles through a case study by creating and testing in laboratory conditions an innovative product made from biomass. Therefore, both theoretical research methods (literature and data analysis, data processing and modeling) and practical research methods (planning and conducting of experiments) are used for the development of the dissertation (Fig. 4.).

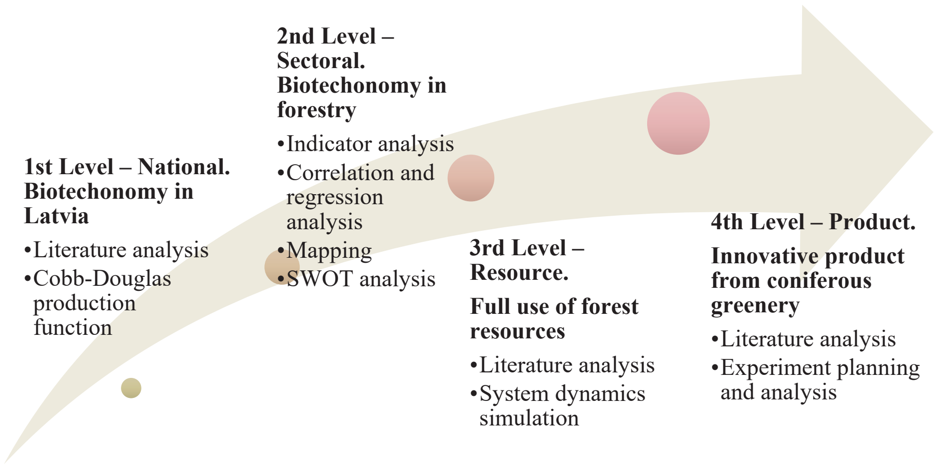

Fig. 4. Methods applied within the doctoral thesis.

Data analysis is performed by correlation and regression analysis, multi criteria analysis TOPSIS (*Technique for Order Preference by Similarity to Ideal Solution*) method, Cobb-Douglas production function and experiment analysis. Literature analysis, system dynamics modeling, mapping, indicator analysis and SWOT (strengths, weaknesses, opportunities and threats) analysis are used for understanding and analysing information and processes. The methods are used both individually and in combination with each other to formulate complex algorithms of methods.

The Doctoral Thesis focuses on biotechonomy in forestry, but the applied methodology can be adapted and used for analysis of other biotechonomy related sectors.

Scientific Significance

The biotechonomy analysis methodology developed within this doctoral thesis includes a systematic approach to the development of the national economy in the context of biotechonomy, including environmental, climate, economic and social aspects. Only by considering and solving problems as a unified system, a more sustainable outcome can be achieved.

The multi-level methodology developed within the Doctoral Thesis has been approbated for the situation in Latvia – from biotechonomy analysis at the national level to the development of an innovative biotechonomy-based product.

This Doctoral Thesis is scientifically significant as it includes:

- development of a new methodology for evaluation of biotechonomy in the context of the national economy;
- development of system dynamics model to determine the available volumes of coniferous greenery depending on various forestry development scenarios in Latvia;
- development of new methodology for determination of bioproduct's commercial potential;
- development of a new methodology for the spatial planning of biotechonomy;
- invention of an innovative product from under-utilized biomass according to the principles of biotechonomy, as evidenced by two patents registered at the Patent Office of the Republic of Latvia;
- development of methodology for further transdisciplinary studies of biotechonomy.

Approbation of the developed set of methodologies and the obtained results prove that the methodology is correct and it can be adapted and used for the analysis of sustainability in the context of biotechonomy for various countries, sectors of the economy, bioresources and bioproducts.

Practical Significance

The biotechonomy analysis methodology developed within this Doctoral Thesis can be adapted and used for analysis of other sectors of the economy or other bioresources in the context of biotechonomy in order to continue the research and to identify scientifically based and practically applicable solutions for promoting sustainable development at the national and sectorial level.

The obtained results for the assessment of biotechonomy in Latvia and Latvian forestry sector in the context of the biotechonomy concept may be used by policy makers and decision-makers to promote sustainable future development of forestry and use of forest resources.

This Doctoral Thesis would also be useful to industrial producers and investors, to notice the available resources and acknowledge the opportunities to use them more sustainably and gain higher economic benefits from a single resource flow.

It is possible to further evolve the developed coniferous greenery thermal insulation material and its production technology, invented within the Doctoral Thesis, in order to start its production in accordance with the biotechonomy concept, in order to ensure sustainable use of forestry residues for the production of products with higher added value, thus gaining economic, social, environmental and climate benefits at the national level.

Approbation of the Study

The results of the Doctoral Thesis have been presented at 8 conferences, published in 17 scientific publications and 3 monographs. Throughout the Thesis research 2 patents have been registered at the Patent Office of the Republic of Latvia.

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Thesis Outline

In order to implement the aim and tasks set for the Dctoral Thesis, the structure of the dissertation was developed at four levels of biotechonomy: national, sectorial, resource and product (Fig. 5.). Thus, gradually assessing biotechonomy implementation opportunities from the national level to the production of a real product.

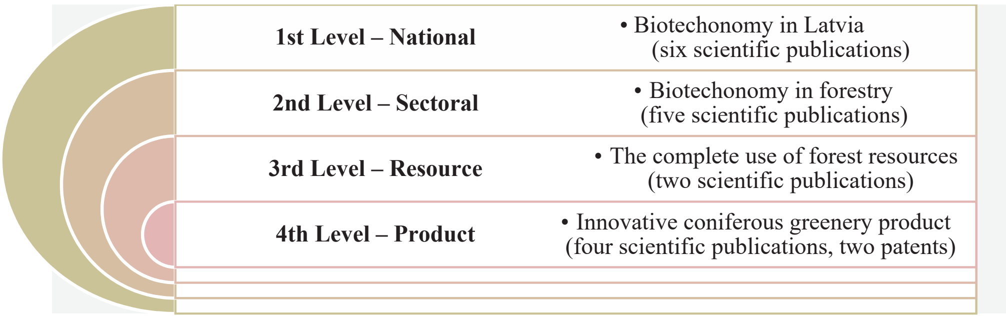

Fig. 5. The structure of the Doctoral Thesis.

At the second level, the sectorial level, one of the bioeconomy sectors – forestry – is analysed. The evaluation of Latvian forestry and logging sector has been carried out and the possibilities of using low-value wood and logging residues for the manufacturing of various products in accordance with the principles of biotechonomy have been evaluated. At the third level, the resource level, detailed attention is given to one of the forest resources – coniferous greenery, an under-utilized, widely available and underestimated resource in Latvia. Literature analysis allowed to identify which products are being produced or researched for potential production from coniferous greenery. With the help of system dynamics modeling, the current and future availability of coniferous greenery resources was identified depending on different scenarios of forestry development in Latvia. At the fourth, the product level, a case study was conducted to create an innovative product from the coniferous greenery. During this phase of doctoral research, an experimental study was carried out to develop thermal insulation material from coniferous greenery and the potential for commercialization of such a product was assessed.

At the end of the Doctoral Thesis (Chapter 5), suggestions are presented on how the further research on the development of biotechonomy should be accomplished by looking at this as a transdisciplinary cross-sectorial issue, which is influenced by a system of various consolidated factors.

Each of the stages of the thesis includes the use of several research methods and their mutual combinations, which can be adapted and approbated for the assessment of other countries, sectors of the economy and the perspective development of bioresource biotechonomy individually by a single stage or by combining several stages together.

The Dctoral Thesis consists of 100 pages, 47 images, 14 tables, 14 mathematical formulas and a reference list with 147 literature sources.

1. FIRST LEVEL – NATIONAL. BIOTECHONOMY IN LATVIA

1.1. Assessment of biotechonomy in Latvia

Within the framework of the Doctoral Thesis, an assessment of the sectors of the economy of Latvia was made in order to determine their current roles and the efficiency of sectors that are most closely related to biotechonomy in comparison with other sectors of the Latvian economy. Two indicators were used to obtain objective results: capital productivity (investments (EUR) in relation to value added (EUR)) and labour productivity through the modified production function of Cobb-Douglas (number of employees attributed to value added (EUR)).

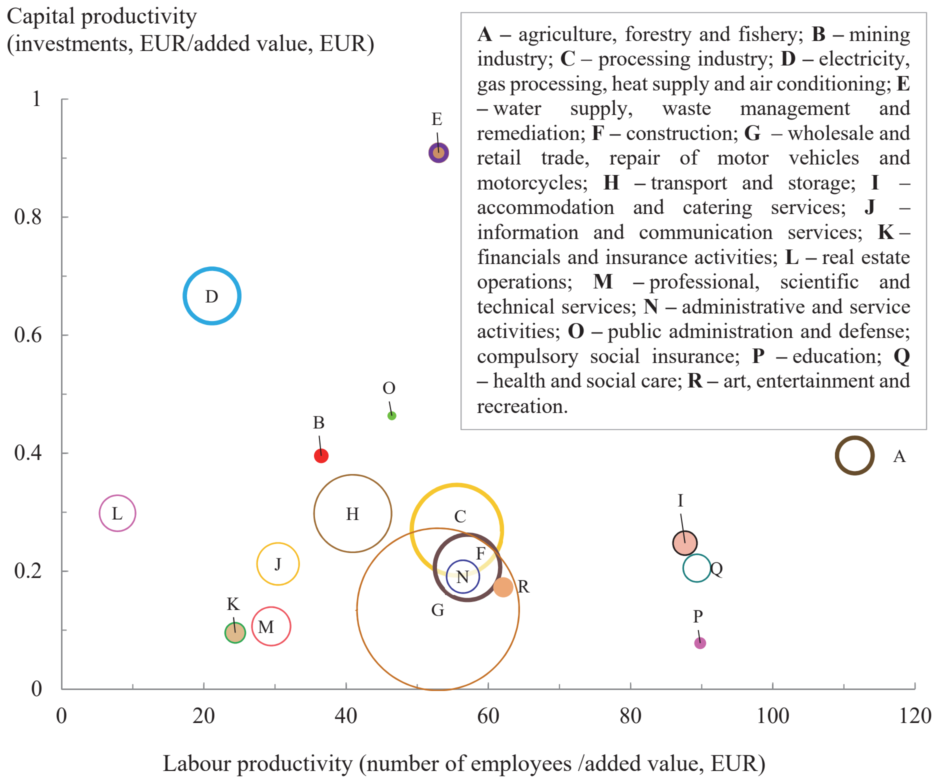

Fig 1.1. Capital and labour productivity in biotechonomy sectors in Latvia during the period from 2008 to 2012, average turnover, million EUR (given as the size of the circle line).

The obtained results (Fig. 1.1.) show that none of the sectors of Latvian economy has significantly higher level of investment and employment intensity at the same time. However, various sectors of the economy have different efficiencies and there is no tendency for any of the industries to be exceptionally capital or labour-intensive. The agriculture, forestry and fishing sector (A), which is most closely related to biotechonomy, has the lowest labour productivity and average capital productivity in comparison with other sectors. This indicates that Latvia still has to overcome numerous challenges to ensure the development of biotechonomy. On the one hand, this is a sector that employs a large number of employees, which is a positive factor and should not be reduced. However, this is not being done efficiently, as the benefits at both the microeconomic and macroeconomic level are too small. In the context of biotechonomy, the agriculture, forestry and fishery sector (A) should be closely linked with the manufacturing industry (C), with the former as a sustainable producer of bioresources, and the latter as a sustainable processor of these resources into the products required by the consumer, including high added value products.

1.2. Biotechonomy and innovation

Biotechonomy combines the use of bioresource extraction technologies and biotechnologies for treatment and processing of bioresources using innovative and advanced technologies to produce new added value products [9]. The innovation is basically what separates products that are produced from biomass through the biotechonomy approach from other biomass products produced within the national economy [11], [12]. According to the innovation concept adopted in Latvia, innovation is a process in which new ideas, developments, and technologies in scientific, technical, social, cultural or other fields are implemented within a market-demanded and competitive product or service [13]. This official definition already implies that innovation generation process is affected by many obstacles. Consequently, they also affect the development of biotechonomy. Within this Doctoral Thesis, barriers to the development of biotechonomy innovations were identified, taking into account the actual situation in Latvia. In order to assess the barriers affecting the development of Latvian biotechonomy innovations, a literature analysis on the barriers identified in various sectors was carried out. The method applied in the Doctoral Thesis was inspired by studies on barriers in energy efficiency [14], [15], [16] and industrial symbiosis [16], [17], [18].

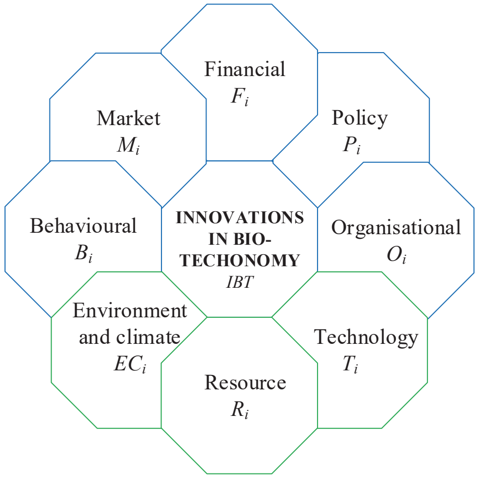

Fig. 1.2. Types of barriers affecting biotechonomy innovation.

Based on the current state of biotechonomy in Latvia, eight main types of barriers affecting biotechonomy innovation were identified: financial, political, market related, behavioural, organizational, technology related, resource related and environment and climate related (Fig. 1.2.). All these types of barriers affect not only biotechonomy, but also each other. Unlike the experience with other concepts, barriers such as resource, technology, environment and climate related barriers, play an important role regarding biotechonomy. The impact of other barriers has also been identified in most of the studies previously performed in other industries. The overall impact of the barriers on the development of biotechonomy innovations can be expressed by a functional relation (1)

$$\sum IBT = \int (F_i; P_i; O_i; M_i; B_i; EC_i; R_i; T_i). \quad (1)$$

When each obstacle is assessed individually, it can be concluded that they are all interconnected, but mainly oriented towards financial and resource barriers. Therefore, it is assumed that by ensuring the availability of funding for the development and commercialization of biotechonomy innovations and by creating innovative, sustainable and economically viable pathways for the use of local bioresources, the innovation in the biotechonomy sectors in Latvia has a future.

One of the preconditions to ensure the development of biotechonomy and sustainable use of bioresources for the creation of high added value products is interdisciplinary cooperation [19]. Latvia requires targeted commercialization of innovations, i.e. innovation transfer from the idea to a product available to the consumer (Fig. 1.3.). The lack of this intermediate step is one of the largest obstacles for the development of biotechonomy. Considering that bioresources are the main resources available in Latvia, start-up measures and policy instruments should be developed to specifically support the development of biotechonomy innovations.

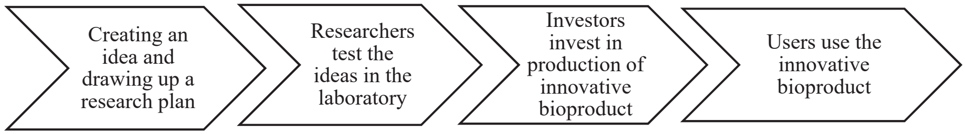

Fig. 1.3. The stages for the development of knowledge-based, innovative bioproducts [9].

The introduction of innovative and scientifically based biotechnologies is linked to the requirement for production of new, knowledge-based, innovative products (and service provision) with higher added value. It is connected to two areas: the efficient extraction and preparation of bioresources and the development and use of bioresource treatment and processing technologies. Knowledge-based use of bioresources is associated with human resources that play a certain role at each stage of the introduction of innovative bioproducts.

2. SECOND LEVEL – SECTORIAL. BIOTECHONOMY IN FORESTRY

Forests are the largest natural resource in Latvia, as more than half of its territory is occupied by forest land [20]. Although forest resources are renewable resources, we must not treat them carelessly, because the rate of forest regeneration is slower than that for agricultural crops, forests are an important ecosystem for biodiversity conservation and they absorb significant amount of CO_2. A tendency to export large part of the round wood is observed in Latvia, while it could be used locally to produce products with high added value and generate greater economic and social benefits [21], [22]. The overall contribution of the forestry sector to value added in Latvia is only 5.9 % despite the fact that its share in GDP (at current prices) is about 62 %. This means that the wood resources in Latvia are not widely used to produce high added value products [23]. Therefore, it is intensely needed to use forest biomass for the production of innovative high added value products in Latvia. Such products would be those that bring higher social and economic benefits at the national level, correspond to Ecodesign principles and are produced in accordance with sustainability principles and the rational use of natural resources. This means that the production of fuels from forest biomass cannot be considered as creation of a high added value product, since wood processing possibilities reach far beyond the classical wood products (e.g. building materials, furniture, household items) and fuels; even extraction of food constituents (e.g. glucose, starch, xylan derivatives), fish and animal feeds, textiles and a wide range of chemical compounds may be produced from wood resources. The development of sustainable and biotechonomy-based use of forest biomass does not mean that the conventional pathways for the use of forest biomass would be disparaged or replaced. Biomass biorefinery is considered as the fundament for bioeconomy, involving the conversion of biomass into marketable bioproducts (food, feed, chemicals, and/or materials) and bioenergy (biofuels, electricity, thermal energy) [24], [25].

Considering that forest resources are the most abundant type of bioresources in Latvia, within this Doctoral Thesis and in the context of biotechonomy, the focus is put on this type of bioresources and their possibilities to use them. The assessment of Latvian forestry and logging industries is based on the analysis of statistical data and the assessment of strengths, weaknesses, opportunities and threats of the industry (SWOT analysis).

2.1. Possibilities for introduction of biotechonomy in forestry in Latvia

Within this Doctoral Thesis, a combined method (using mapping and indicator analysis method) to evaluate biotechonomy development directions and to identify the most suitable regions for this development is proposed. This method will seek to answer the questions of where and what forest resource-oriented wood processing plant should be best established in Latvia in order to comply with the basic principles of biotechonomy. This methodology combines factor, indicator, correlation and regression analysis methods and mapping (Fig. 2.1.). Thus, obtaining a visually illustrative result for the subject under study – what types of biotechonomy should be established in particular regions and which types of bioresources should be focused on. This biotechonomy indicator mapping method can be adapted and used for any country or region and biotechonomy sectors that use any type of bioresources.

Fig. 2.1. Methodology algorithm.

This methodology was approbated for the evaluation of the most promising place for the establishment of an industrial processing plant focused on Latvian wood resources. For the evaluation of the development prospects of a particular economic sector in the context of biotechonomy, the issue is assessed in a complex manner, accounting for such key biotechonomy influencing factors as economically feasible availability of resources (current and future), the current development of the industry, which simultaneously indicates the competition for resources, and labour availability, which is a particularly topical issue in rural areas. Following the analysis of the factors affecting regional biotechonomy, a list of indicators was developed. A correlation and regression analysis was performed for the indicator list and the statistical data to determine the interactions between various factors. Based on this analysis, five indicators (Table 2.1.) were mapped using the *ArcGIS* program onto the map of Latvia, selecting the county territory as the smallest map unit (a total of 110 counties). To determine the overall impact of all the considered indicators and their relationships for the choice of the most appropriate region for the establishment of a new wood resource processing plant, multi-criteria analysis, i.e. the TOPSIS method was used and weights were attributed to each of the indicators (Table 2.1).

Table 2.1

The Weight and the Required Values for the Indicators Used in Multi-criteria Analysis

No.	Indicator	Weight
1	The wood stock that has reached the cutting age per 1 ha in relation to the total wood stock per 1 ha	0.3
2	Total deciduous wood stock per 1 ha in relation to the total coniferous wood stock per 1 ha	0.1
3	The number of wood processing and wood product manufacturing companies per cutting age wood stock per 1 ha in relation to the total wood stock of the cutting age	0.2
4	Number of the unemployed in relation to the cutting age wood stock per 1 ha	0.2
5	Number of the unemployed to the cutting age wood stock per 1 ha in relation to the number of wood processing and wood product manufacturing companies	0.2

As an example of the applied methodology the analysis of indicator No. 1 will be presented. Figure 2.2. shows a weak correlation between the two indicators – the amount of wood stock that has reached the age of cutting per 1 ha in relation to the existing wood stock per 1 ha ($R^2 = 0.287$).

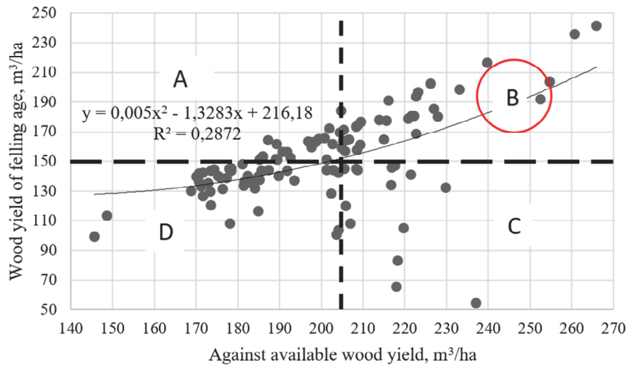

Fig. 2.2. Indicator correlation – regression analysis: wood stock that has reached the cutting age, m^3 per 1 ha, in relation to the total wood stock, m^3 per 1 ha.

By dividing this graph into four quadrants, it is possible to determine in which sections two of the prerequisites are fulfilled simultaneously to identify whether there is sufficient availability of wood resources for the production of innovative products. Those prerequisites are possibly higher existing specific wood stock (m^3 of wood per ha of forest land) and the specific wood stock that has reached the cutting age (m^3 of wood that has reached the cutting age per ha of forest land). Quadrant B includes the counties where the majority of the existing wood stock has reached the age of cutting. This means that these are the regions most properly suited for a worthwhile establishing of new plant for the production of wood based products, since the resources required for the production process will be available.

When the indicator relations at the county level are portrayed onto the map of Latvia (Fig. 2.3.) it can be seen, which regions are best suited from the wood resource availability point of view. The higher the graduation in figure, indicated by the darker colour, the more suitable the region is for the creation of a new processing plant for wood product production. These are Baldone, Ozolnieki, Kekava, Alsunga and Iecava counties. The lowest wood stock that has reached the cutting age has remained in Stopini, Engure, Carnikava, Tervete and Ligatne counties.

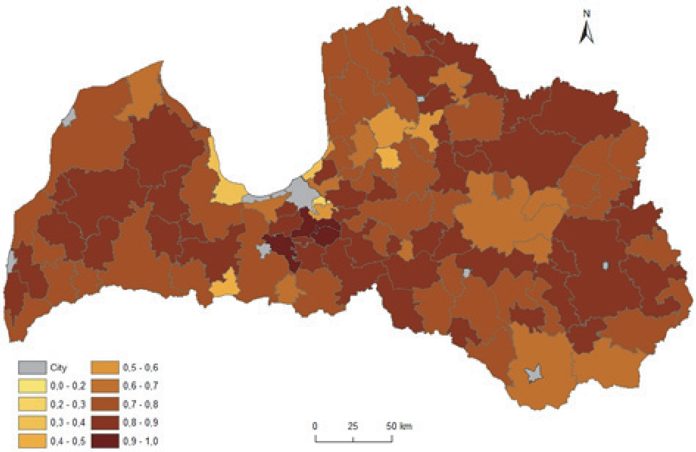

Fig. 2.3. Wood stock that has reached the cutting age per 1ha in relation to total wood stock per 1 ha.

In a similar way, the other four indicators are analysed (Table 2.1.). The resulting numerical values of the indicators are used in multi-criteria analysis. The results of the multi-criteria analysis show that the most suitable location for an industrial production plant that focuses on forest bioresources would be in Rezekne, Madona, Daugavpils, Garkalne, Kuldiga or Talsi counties, while Stopinu county is the most inappropriate. The obtained results are indicative. The developed and applied method is considered as a good approximate for the determination of the potential location for an industrial production plant that focuses on forest bioresources, so that a more detailed analysis may be performed for a particular county.

2.2. Use of logging residues in energy production sector

EU-wide planning documents stipulate that it is necessary to increase the share of renewable energy resource use in the energy sector up to 20 %, to reduce the use of fossil resources [28], [29]. Biomass as an energy source plays an important role in this context [26], [27]. This means that the use of bioresources in energy production will increase [28], [30]. In parallel, the real life implementation of the bioeconomy concept is rapidly developing [2], [31]. On the one hand, it means that bioresources should be used in energy production, but on the other hand, the use of bioresources is limited, as these documents determine that they must be used sustainably. Sustainable use of bioresources includes not only resource efficiency and the necessity to obtain maximum benefits in a sustainable way throughout the whole life cycle [32], but also the fact that agricultural lands are used for the cultivation of food crops rather than energy crops, and that high added value products are produced from bioresources rather than using them as fuel [2]. The pursuit of one of the EU's set objectives may come in conflict with the achievement of other stated goals and concepts. Regarding the sustainable use of bioresources, on the one hand, it is necessary to increase the use of bioresources in the energy sector, on the other hand, bioresources must be used in a sustainable manner, meaning application of the zero waste principle for production of high added value products that do not include the use of bioresources as a classic fuel (e.g. firewood, wood chips, pellets, briquettes). Moreover, one must not forget that the increased use of bioresources should not have a negative impact on the primary use of bioresources (in particular food and feed), degrade biodiversity, degrade or pollute the environment, reduce the diversity of bioresources available in the future or have any negative effects in any other way.

Considering the sustainable exploitation of forest resources in the context of biotechonomy within energy production sector, the main prerequisite set is to use only such wood resources or wood processing by-products for fuel production that may not be utilized for production of other products with higher added value. In parallel, it must be ensured that the use of wood products and processing residues within the energy sector would be higher than the use of fossil resources and that manufactured products are exported instead of the unprocessed wood, so that the biotechonomy principles are followed and foster the development of the economy of Latvia (Fig. 2.4.). In order to respect the principles of sustainable forest management and avoid depletion of the forest soil through intensive use of forest biomass, the biomass ash that remains after incineration of wood fuel should be brought back into the forest. In case all the above mentioned preconditions are meet, it would be possible to create a closed cycle for forest bioresource use to meet the demand for renewable bioenergy resources and products with higher added value, in order to gain greater economic and social benefits without harming the environment and ensuring the availability of resources in the long term.

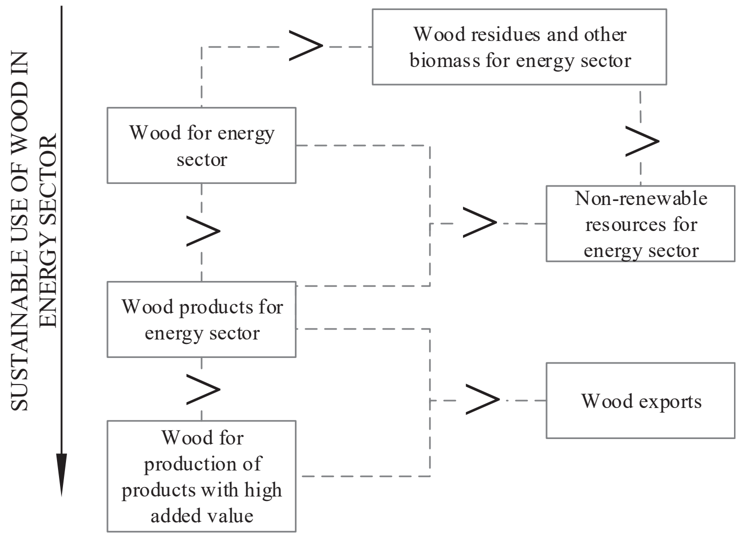

Fig. 2.4. Sustainable use of wood for energy production.

The main benefit of the sustainable use of forest resources in the energy sector is that the maximum amount of forest resources is used for the production of high added value products that partially replace product production from fossil resources, the amount of GHG emissions from forestry are reduced through the accumulation of carbon in wood products, the use of local resources is promoted and the reduction of imported resources and products, as well as increase exports of wood products with higher added value is stimulated, which contributes to the social, economic, environmental and climate benefits gained at the national level.

2.3. Use of low-quality wood and logging residues for the production of high value added products

In order to evaluate the possibilities and potential of using low-quality wood and logging residues for production of high added value products according to the biotechonomy principles, within the Doctoral Thesis a research to identify innovative high added value products from forest biomass and to evaluate the commercialization potential in Latvia for 30 of those products was performed. This part of the Doctoral Thesis is considered as the first step (feasibility study) to identify the most promising innovative products from forest biomass that could be produced in Latvia. It gives an insight into the extent of range of innovation implementation problems and underscores that they are all part of the system of the bioeconomy model. This part of the research was carried out as a contracted research „Forest biomass – new products and technologies" commissioned by JSC „Latvijas valsts meži" (LVM) in 2016.

In order to select innovative products with high added value that correspond to the biotechonomy principles and to selected resources, a methodology and an algorithm consisting of 10 modules were developed (Fig. 2.5.).

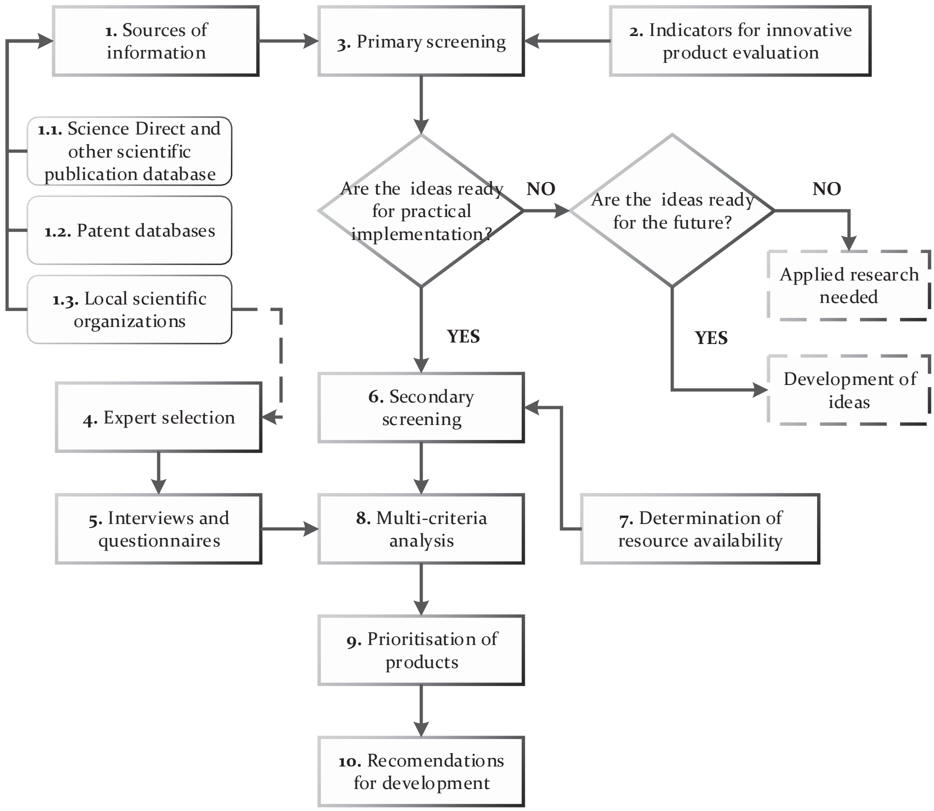

Fig. 2.5. Methodology algorithm.

After questioning 24 experts in the fields of forest industry, innovation and the use of forest biomass for production, the weights of the categories and indicators required for multi-criteria analysis (Fig. 2.6.) were determined. For engineering category the weight was set at 30.8 %, for the environmental and climate category 28.7 %, and for economic indicators 40.5 %.

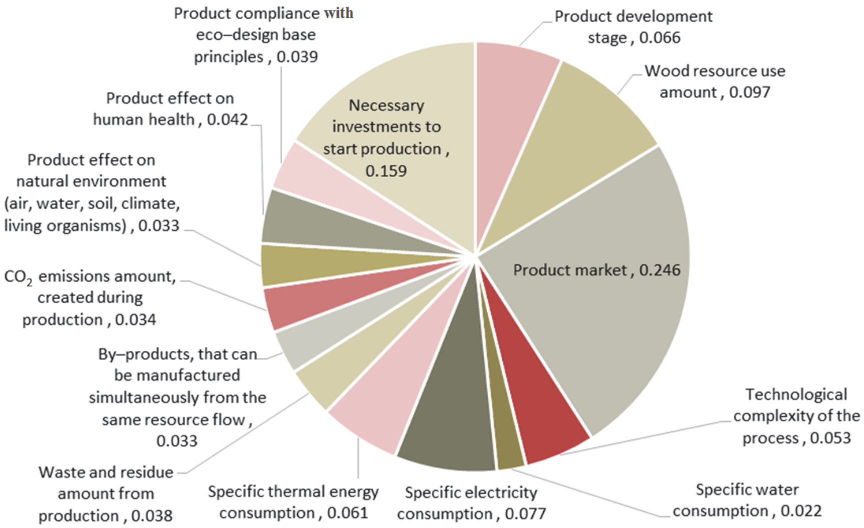

Fig. 2.6. Results for determination of the weights of multi-criteria analysis indicators.

The results of the multi-criteria analysis (Fig. 2.7.) for products in the energy sector show that the greatest potential for commercialization is for biodiesel (0.829) and bio-oil (0.813). A much lower rating is for butanol (0.306), but the lowest potential for commercialization is for bioethanol (0.087). Given that biodiesel can be produced from bio-oil, both of these two products can be produced simultaneously and, depending on demand, bio-oil may be sold as an intermediate product or reprocessed into biodiesel.

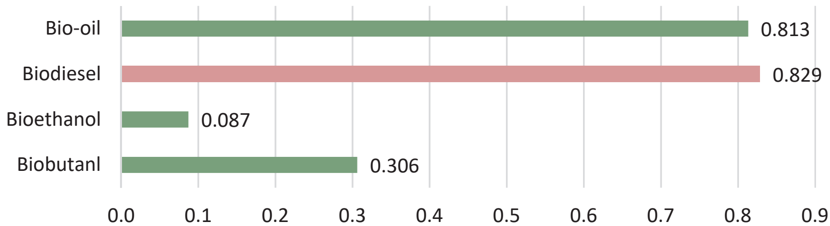

Fig. 2.7. Results of the multi-criteria analysis for identification of the commercialization potential for energy sector products.

Within the textile sector, three types of textile products that can be made from wood fibers – viscose, lyocell and ioncell-F – were compared. According to the results of the multi-criteria analysis, the greatest potential for commercialization is for lyocell (0.767), with lower values for viscose (0.517) and ioncell (0.461) (Fig. 2.8.).

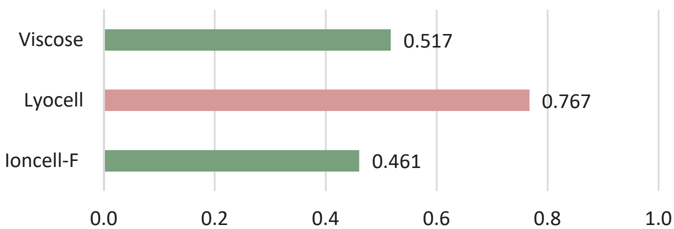

Fig. 2.8. Results of the multi-criteria analysis for identification of the commercialization potential for textile industry products.

Comparatively large number of innovative forest biomass products still are promising within such a traditional timber industry as construction, and therefore the section on innovative biocomposites and building materials includes a large range of innovative products. The results of the multi-criteria analysis indicate that all of these products have a moderately high commercialization potential (average of 0.55). The only product with a significantly higher commercialization potential is ICLT – interlocking cross laminated timber (0.701) (Fig. 2.9.).

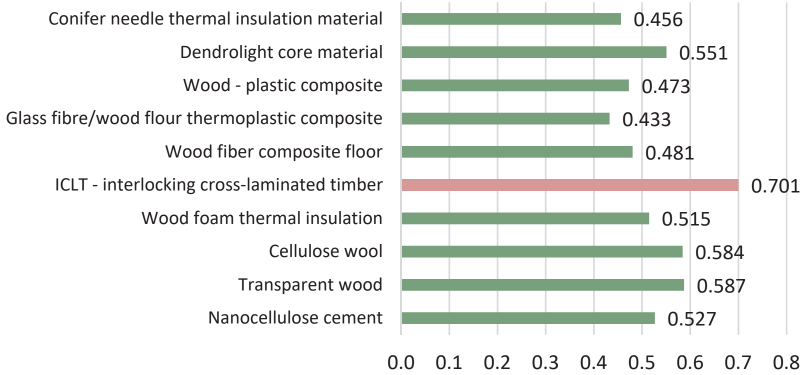

Fig. 2.9. Results of the multi-criteria analysis for identification of the commercialization potential for biocomposite materials and building materials.

The situation within the food industry is similar as the average potential for product commercialization is moderately high (0.57) (Fig. 2.10.). Comparatively best result is identified for fish feed supplement from microorganism proteins (0.65).

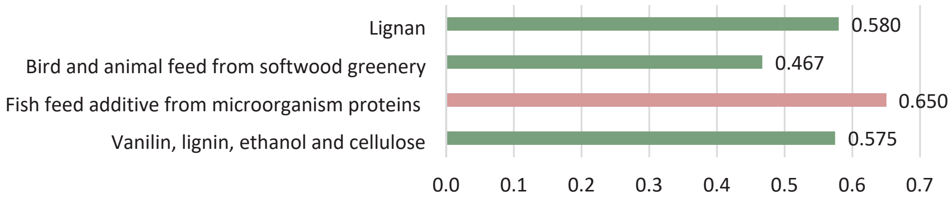

Fig. 2.10. Results of the multi-criteria analysis for identification of the commercialization potential for food industry products.

The section on other innovative products from forest biomass includes products that do not fit into the above mentioned sectors or are widely used in numerous industries. Most of these products are chemicals. By comparing these products with the multi-criteria analysis method, it is evident that the greatest potential for commercialization is for suberin production as a binder (0.71) (Fig. 2.11.). A similar result is for xylan derivatives (0.689).

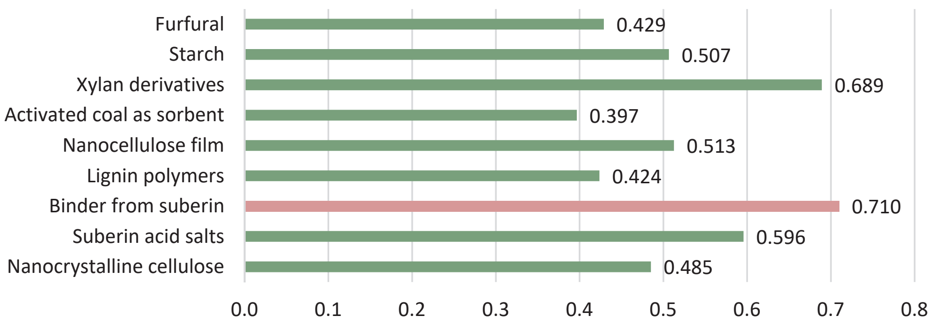

Fig. 2.11. Results of the multi-criteria analysis for identification of the commercialization potential for other innovative products from forest biomass.

The summary of the results of the multi-criteria analysis indicates that the greatest potential for commercialization is for biodiesel, bio-oil, wood textiles (lyocell) and suberin as binder. The commonality of these products is that they do not have specific requirements for the raw material quality (e.g. a specific tree species or only a certain part of the tree, for example, only the bark) or it is possible to combine several products. A comparatively high commercialization potential is assigned to ICLT (interlocking cross laminated timber), xylan derivatives, and fish feed from micro-organism proteins.

Within the future studies for considering the feasibility of producing the most promising products, their economical, technological aspects, environmental and climate impact, it is imperative to account for the possibility to produce these products simultaneously with their by-products. Each of the products included in this analysis has some advantages and disadvantages. This is merely a feasibility study to select the products with the highest commercialization potential within each industry. Therefore, a more detailed analysis (economic analysis, market demand, environmental climate and impact) is required in order to determine the full potential of commercialization of innovative products.

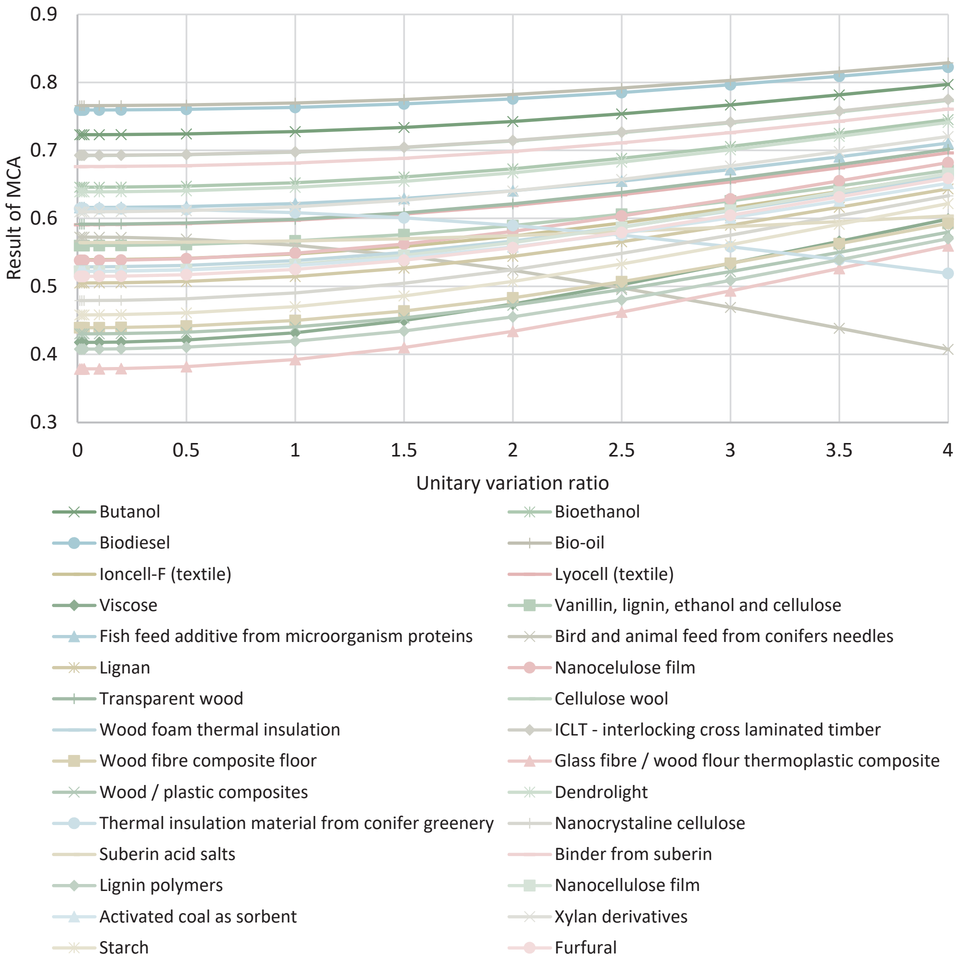

Fig. 2.12. Results of the sensitivity analysis for product market indicator.

The results of the multi-criteria analysis depend on the indicator weights used in the matrix. They incorporate experts' views on the importance of each indicator compared to others. Therefore, it is possible that the results of the study would be different in a similar analysis under other circumstances. Therefore, a sensitivity analysis [33] was performed for the two most relevant indicators according to the experts – the product's market and the necessary investments for initiating the production. The aim of the sensitivity analysis is to determine how changes in the weights of these factors would affect the outcome of the multi-criteria analysis for identification of the commercialization potential. The Thesis summary includes the sensitivity analysis only for most significant indicator – product's market (Fig. 2.12.).

The results of the sensitivity analysis indicate that changes in the weights of the market indicator mainly have a positive impact on the results of the multi-criteria analysis. Only for a few products the result of the multi-criteria analysis may be deteriorating, i.e. bird and animal feed from coniferous greenery and thermal insulation material from coniferous greenery. For these cases, it is due to the fact that the available market for these products was defined only on a small scale – including neighbouring countries: the Baltic and Scandinavian countries.

By assessing the commercialization potential in Latvia for 30 innovative products from forest biomass through a multi-criteria analysis method, it was concluded that the key industrial sectors with prospects for forest biomass processing companies include the energy sector, and textile and chemical industries. It was found that the products of these industries (e.g. wood textile fibers (lyocell), bio-oil and biodiesel, and chemical compounds such as xylan and suberin) have the greatest commercialization potential in Latvia. Latvian scientists are advised to focus on unique, efficient and environmentally friendly innovative product development technologies. So that the technologies themselves can become a product, or that they enable initiation of the production of innovative products in Latvia.

3. THIRD LEVEL – RESOURCE. UNDER-UTILIZED FOREST RESOURCES

The existing situation within Latvia forestry sector is that still not all of the forest resources are managed sustainably. In particular, logging residues, which are left in the forest in large quantities. The main application of the woody part of the logging residues is for the production of forestry wood chips, but the needles usually remain in cuttings, creating nutrients. Consequently, the needles from logging of coniferous trees are the under-utilized biomass resources in Latvia. Currently, needles and coniferous greenery as a non-wood resource are regarded as insignificant for the national economy of Latvia [34].

Therefore, in the framework of this Doctoral Thesis, as a case study for the development of biotechonomy in Latvia through manufacturing of products with high added value from forest biomass, it was chosen to evaluate the possibilities to produce innovative products from the coniferous greenery. Within this work, the coniferous greenery is understood as the residues from harvesting of coniferous trees (spruce and pine) – finches (with a diameter not bigger than 5 mm) with needles. Within this Doctoral Thesis, only the potential applications of the greenery from *Pinaceae* family *Picea* genus and *Pinus* genus are considered.

The analysis of literature indicates that there are many possibilities for sustainable use of coniferous logging residues. However, the amount of this resource in Latvia is not known as well as whether this amount would be sufficiently large in order to establish a large scale manufacturing of coniferous greenery derived products. Another issue is whether this resource would be sufficiently available in the future to be used for the manufacturing of products.

Therefore, within this Doctoral Thesis the coniferous greenery extraction potential has been defined dynamically in order to predict the future availability of this resource. A system dynamics (SD) modeling method was used for this purpose. The SD model (Fig. 3.1.) simulates the tendencies for cutting and restoration of conifer trees upon which the availability of the conifer greenery now and in the future depends.

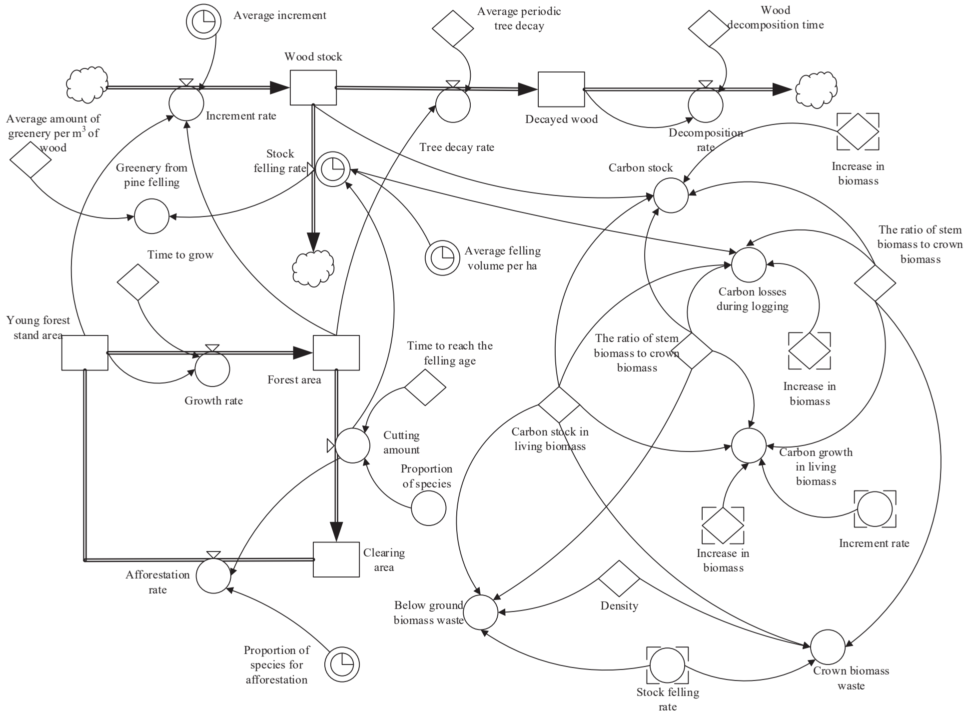

Fig. 3.1. Flow and stock diagram for the coniferous greenery from logging residues.

Based on the historical data, in 2014, about 233 thousand tons of coniferous greenery were technologically available, of which about 112 thousand tons were spruce greenery and 121 thousand tons were pine greenery. From 1 m^3 of spruce stem wood, it is possible to obtain 50 % more mass of greenery than from pine, as a result the available amount of coniferous greenery from the two species is almost the same, despite the fact that spruce trees are cut at least 50 % less than pine trees [35].

The historical data and trend-based scenario is considered as a baseline scenario featuring the technologically available amount of pine and spruce greenery that could be obtained from annual logging residues in the main clearings. The SD model baseline scenario results (Fig. 3.2.) show that based on the current forestry tendencies, the available amount of coniferous greenery from cuttings in state-owned forests tend to decrease.

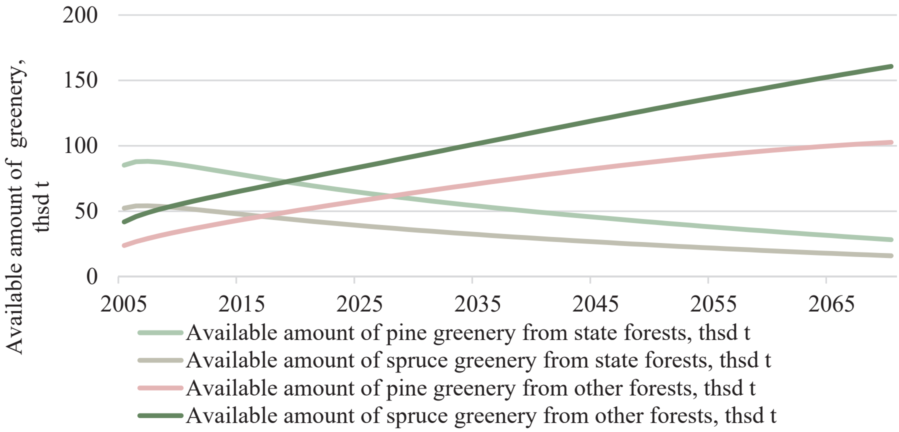

Fig. 3.2. The availability of coniferous greenery in Latvia from logging in state-owned and private forests.

Following the baseline scenario, 5 different scenarios were modeled to determine the dynamics of the potentially available amounts of coniferous greenery for the production of high added value products during the period from 2016 to 2070 (Fig. 3.3.):

- Scenario 1 – only 50 % of the technologically available coniferous greenery is available for industrial production, while the rest remains in the forest;
- Scenario 2 – conifer plantations are increased by 20 %;
- Scenario 3 – logging amounts are increased by 20 %;
- Scenario 4 – Scenarios 2 and 3 are combined to determine what would be the overall tendency of the availability of coniferous greenery if both the logging and plantation of coniferous trees would increase by 20 %;
- Scenario 5 – combination of Scenarios 4 and 1, when increased plantation and logging would provide the possibility to acquire larger amount of coniferous greenery, while simultaneously respecting sustainable forestry principles and leaving at least 50 % of technologically available coniferous greenery at the clearings.

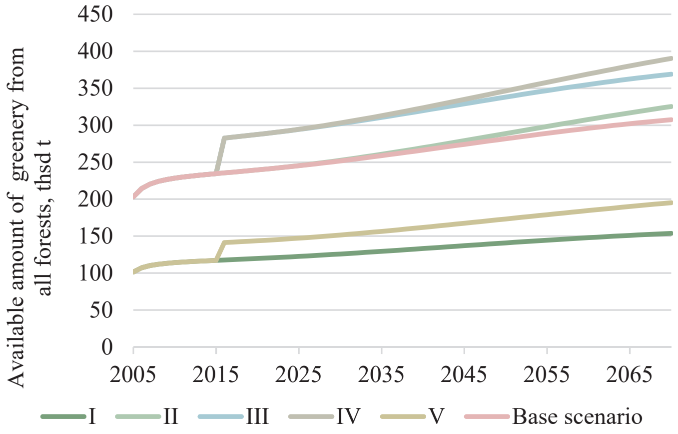

Fig. 3.3. The availability of coniferous greenery in different forestry development scenarios.

The evaluation of all the developed SD model scenarios (Fig. 3.1.) indicates that the greatest increase in the available mass of coniferous greenery would be achieved in the case of Scenario 4, when both the logging and planting of coniferous trees would increase by 20 %. From the authors' experience, the best and most probable development tendency of the availability of coniferous greenery would be similar to Scenario 5. Because, when the demand for coniferous greenery increases, the supply also should increase. In order to ensure this, there will certainly be an increase in the amount of conifer cuttings, which are limited by the available amount of cutting age trees and coniferous planting amounts. The 50 % extraction margin from the technologically available coniferous greenery amount are not set as a strict limiting factor for ensuring sustainable forest management, but this is assumed to be real potential that could be recovered from forest owners and logging workers. Therefore, when planning the production of new products from the coniferous greenery and evaluating the availability of raw materials, the maximum amount that should be considered is about 117 thousand tons per year (based on the results of scenario 5 in 2015, calculated from historical data), but in the future (by 2070) about 195 thousand tons. These technologically available amounts of coniferous greenery are, and will be, sufficient to be used as a raw material for the production of high added value products, even while simultaneously ensuring the requirements of sustainable forest management.

4. FOURTH LEVEL – PRODUCT. INNOVATIVE PRODUCT – THERMAL INSULATION MATERIAL

Following the literature analysis on the use of coniferous greenery for product manufacturing, it was found that the largest value of the coniferous greenery lies in the valuable chemical composition of needles. This means that the greatest potential for exploitation of this resource is related to the extraction of various chemical compounds, which would result in the vast majority of this resource remaining as a residue. Therefore, considering sustainable use of bioresources in the context of biotechonomy, it is also necessary to find innovative applications for this flow of resources, in order to obtain even greater economic, social, environmental and climate benefits from one unit of resources.

Within the scope of this Thesis, the possibility to use coniferous greenery that has been harvested from logging residues or coniferous greenery that is available after the extraction of chemical compounds, for the production of an innovative product that corresponds to the principles of biotechonomy is assessed. It was found that, at present, no thermal insulation materials are produced from the coniferous greenery for commercial purposes. At the initial stage of the development of the Doctoral Thesis (2013–2014), no scientific publications or registered patents were available that would prove that the manufacture of this type of product had ever been studied under laboratory conditions. Therefore, in order to case study the use of bioresources in accordance with the principles of biotechonomy, it was decided to study the use of coniferous greenery for the production of thermal insulation material.

Altogether 4 experiments were carried out for the research of thermal insulation material from coniferous greenery, 3 of them were three-factor experiments, and one experiment was a two-factor experiment (Fig. 4.1.). Experiment planning and analysis of the results were performed for all experiments.

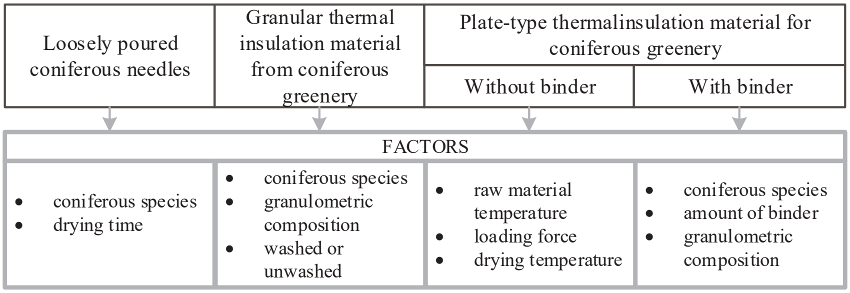

Fig. 4.1. The scheme of the experiments.

During the experiments, it was sought to create thermal insulation material from spruce and pine greenery both in a loose granular form and in a plate type form with and without binder (e.g. see Fig. 4.2.).

Fig. 4.2. Samples of thermal insulating materials – granular (picture on the left) and plate (picture on the right).

For all experiments planning and analysis of results was carried out using *Statgraphic* programme and mathematical modeling methods [36], [37]. The main characteristic for description of the efficiency of thermal insulation material is the thermal conductivity coefficient (λ, W/mK) therefore this indicator was considered as the main parameter in the experiments. The thermal conductivity coefficient was calculated from the heat flux measurements performed on the samples using the *Hukesflux DT01* heat flux meter (according to the requirements of ISO 9869 standard) or with the *Lasercomp* thermal conduction device *FOX600* (according to ISO 8301:2012). For further analysis only those measurements were considered for which the determined measurement error at the 95 % (coefficient τ_{95} = 1.412) confidence level proved the measurement to be reliable. A more detailed description of the performed experiments and the obtained results can be found in the scientific publications prepared by the author of the Thesis and published in the scientific journals indexed in SCOPUS (Publications No. 7, 12, 13, 14).

As an example of the experiments conducted within the Doctoral Thesis, this summary includes one experiment on the development of granular coniferous greenery thermal insulation material.

The performed experiments revealed that the thermal conductivity coefficients for plate type thermal insulation material produced from coniferous greenery (λ = 0.056 W/mK) and for freestanding spruce needles (λ = 0.037 W/mK) are competing with other widely used natural thermal insulation materials. In the experiment described above, it was found that the coefficient of thermal conductivity differs between freestanding spruce and pine needles. The difference was related to the size of the conifers and air gaps. There have been no previous studies on how the thermal conductivity is influenced by the material of the coniferous species used when the coniferous greenery is grounded. Therefore, an experiment was carried out to find out whether the species of the coniferous tree and the proportion of coniferous greenery should be taken into account when producing heat insulation material from the coniferous greenery.

Several problems were identified during the experiment. The most important of these was the poor adhesion performance of the plate type samples when no additional binder was used. This complicates its transportation, use and limits the size. For freestanding conifers, a decomposition tendency was noticed and the formation of fine layer which is denser, and consequently also less able to ensure thermal insulation. As a solution to these problems, a loose granular thermal insulation material from the coniferous greenery was tested. Only three factors related to the production of the material have been selected for the experiment as they can directly or indirectly influence the thermal conductivity of the material: the size of the granules (granulometric composition), used conifer species (spruce or pine), and whether or not the material has been washed and re-dried prior to carrying out the measurements.

During previous attempts, it was discovered that granules made from ground coniferous greenery and potato starch do not break down when soaked for few hours. After repeated drying, their weight decreases (15.5 % on average), but the volume and form does not change. This showed that fine particles are washed out with water, which results in a lighter and more porous material. Porosity is a very important factor affecting the thermal conductivity, because lighter and more porous materials have better heat detention. Therefore, the fact whether the granules were washed or not is taken as the third test factor in this experiment.

The obtained mean values of the thermal conductivity of the granules, the moisture content and density of the samples are summarized in Table 4.1.

Table 4.1

Three–factor Experiment Plan and the Obtained Results

No.	Obtained results			Experiment plan		
	Thermal conductivity coefficient, W/mK	Moisture content, %	Density, kg/m^3	Granulometric composition, mm	Species	Washed or unwashed
1	0.067	5.24	205	<8	pine	unwashed
2	0.077	4.63	175	>16	spruce	washed
3	0.058	7.22	188	<8	pine	washed
4	0.045	3.53	170	<8	spruce	washed
5	0.082	5.89	192	>16	spruce	unwashed
6	0.063	2.92	185	<8	spruce	unwashed
7	0.064	5.27	208	>16	pine	washed
8	0.092	9.68	225	>16	pine	unwashed
9	0.065	6.64	203	8–16	0.5 spruce / 0.5 pine	0.5 washed / 0.5 unwashed
10	0.067	6.64	205			
11	0.069	6.64	205			

It can be seen that the thermal conductivity coefficients of the samples are in the range from 0.0452 W/mK to 0.0916 W/mK. The best thermal conductivity coefficient is for fine (<8 mm), washed and re-dried spruce greenery granules, but the highest thermal conductivity coefficient is for large (>16 mm) unwashed pine greenery granules. The size of the granules significantly affects the thermal conductivity of the bulk material, since the size of the air gap formed between the granules depends on the size of the pellets. The larger the granules, the higher the thermal conductivity of the material. So, small size granules ensure better heat detention.

The performed experiment and the analysis of the obtained data proved that the granular size (granulometric composition) and whether or not the granules have been rinsed priorly is strongly affecting the thermal conductivity of granules made from coniferous greenery for the use as thermal insulation material. The conifer species also has an effect on the thermal conductivity coefficient of the granules. The best thermal conductivity coefficient (λ_4 = 0.045 W / mK) was for a material made of fine (<8 mm), washed spruce greenery granules.

As a result of rinsing, the weight of granules decreases significantly – on average by 15.5 %, which results in a 7.6–8.9 % reduction in density of loosely placed granules (8.2 % on average). The reduction in the thermal conductivity coefficient for each sample is very different and it is not proportional to mass and density reduction. The greatest reduction of the thermal conductivity coefficient is observed for large pine granules, which initially have the highest thermal conductivity coefficient.

The regression analysis of the results showed that the thermal conductivity coefficient is influenced by density (R^2 = 0.603), moisture content (R^2 = 0.63), and granule size (R^2 = 0.737). The species of coniferous trees has no influence on the thermal conductivity coefficient of the material (R^2 = 0.123). The rinsed granules in all cases had a better (lower) thermal conductivity coefficient (R^2 = 0.554), indicating a moderate effect.

A complete analysis of the experiment plan was carried out in order to express the previously established relations in the form of a single linear regression equation. Not all of the three factors considered in the experiments had quantitative values, therefore, in calculations for the second (species) and third (washed and re-dried or unwashed granules) factor, the maximum value in quantified terms was expressed as 1, but the minimum value was 0 (spruce 1, pine 0, rinsed 1, not rinsed 0). The numerical minimum value for the first factor (the granulometric composition) is 8 and the maximum value is 16. The full regression equation for the thermal conductivity (λ, W/mK), after simplification with natural values, can be expressed in terms of equation 4.1.:

$$\lambda = 0.06844 + 0.00252(g - 12) - 0.01518(sn - 0.5) + 0.00384(g - 12)(ep - 0.5)(sn - 0.5), \quad (4.1.)$$

where *g* granulometric composition – the size of the granules, mm;
sn washed or unwashed material;
ep species (spruce or pine).

In similar way experiment planning, sample preparation and testing, and the analysis of the obtained results were carried out for other experiments.

From the experiments carried out in the framework of the Doctoral Thesis on the development of thermal insulation material for coniferous greenery, it can be concluded that this type of material has the potential for further research as its thermal-physical properties are competitive with other natural thermal insulation materials (Fig. 4.3.) and can even achieve equivalent results as some widely used synthetic materials available on the market.

Up to date, there have been no attempts to commercialize conifer needle based thermal insulation material and its production technology, since further research is required to develop nuanced technology and product. Currently the thermal insulation material is in the TRL2 (TRL – technology readiness level) level, as evidenced by the performed experiments, 4 scientific publications describing the results of those experiments that have been prepared and published and indexed in SCOPUS database, as well as 2 patents registered with the Patent Office of the Republic of Latvia.

This case study on potential applications of a previously under-utilized bioresource for production of high added value products in the context of biotechonomy is only one of many possible options how the national economy may be advanced through the research of innovative products and their commercialization. This proves that the application of the biotechonomy concept in science and research is an effective tool for the development of the local bioresource-based sectors of the economy, by creating and producing products with high added value and using bioresources sustainably.

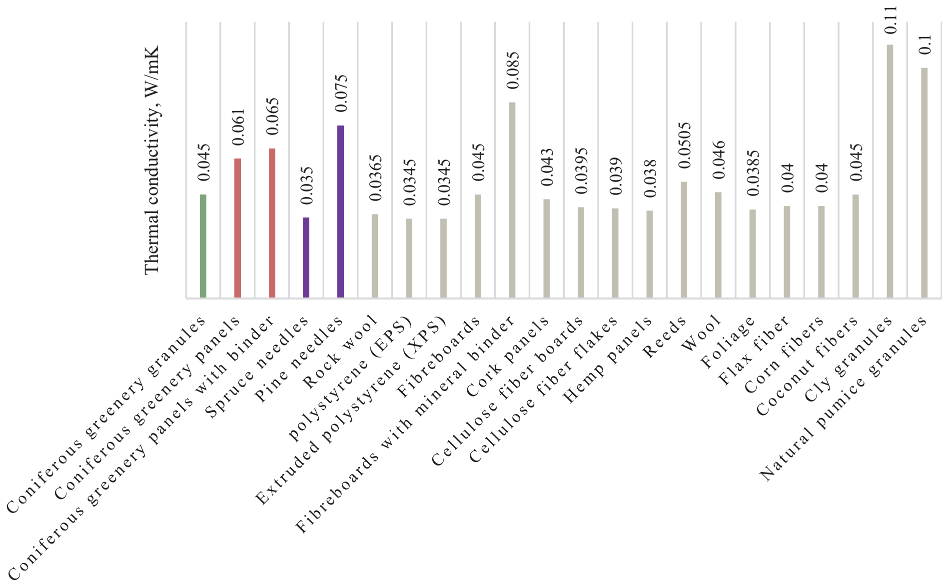

Fig. 4.3. The comparison of experimentally obtained thermal conductivity coefficients for coniferous greenery thermal insulation material with other thermal insulating materials.

5. TOWARDS A TRANSDISCIPLINARY UNDERSTANDING OF BIOTECHONOMY

During the doctoral research on development of a methodology for biotechonomy analysis, it was concluded that there is a lack of research where a systematic approach with a broad view on the interactions between processes that affect bioeconomy or biotechonomy are considered. This point of view is absolutely necessary because biotechonomy is transdisciplinary and linked to the interaction between different sectors and processes in society. Therefore, in the framework of this dissertation, a bioeconomy nexus study, which essentially seeks for interactions between different factors, is proposed as a way of seeking a solution to the transdisciplinarity of biotechonomy.

To the best of our knowledge, so far there are no extensive researches to understand the interactions between the processes in society and nature in the context of biotechonomy. Research of the biotechonomy nexus is most directly related with the resource nexus, but it is just one of the elements of the biotechonomy system. Another element, traditionally considered in the context of bioeconomy, is the resource utilization for the production of higher added value products. But in order to understand how to develop biotechonomy, at first it is necessary to understand what influences it. The answer to this question must be sought in understanding that biotechonomy is transdisciplinary and its development is influenced not only by the availability of resources and resource use efficiency, but also by many other human-controlled processes, which are indirectly linked to the development of biotechonomy. The answer to this question would make it possible to understand how important the processes in the world are for the development of biotechonomy. Therefore, within this Doctoral Thesis, a conceptual idea has been developed for the study of biotechonomy nexus in order to understand what processes, factors and their interactions influence the development of biotechonomy.

Based on the literature analysis, 22 factors, which are influencing the development of biotechonomy, were selected and through logical analysis their mutual interaction links were identified (Fig. 5.1.). It is clear that there are even more significant factors that may be supplemented in the further studies.

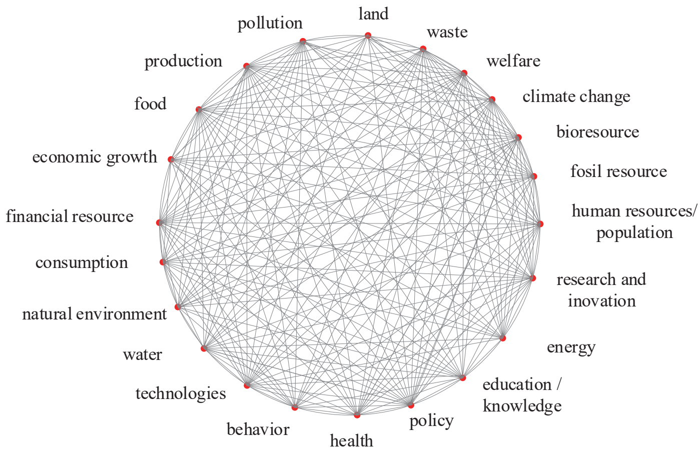

Fig. 5.1. Biotechonomy nexus.

The assessment of the interaction between these factors and whether it could have a direct or indirect impact on the development of biotechonomy, leads to the conclusion that there is a greater or lesser interaction between almost all of these factors. However, it is not yet possible to determine the extent of each interaction on the development of biotechonomy and which of the interactions are more relevant. Therefore, more detailed research is needed in order to implement measures which are oriented towards the most important factors that are influencing future development of biotechonomy. To develop a conceptual biotechonomy nexus research idea, a methodology algorithm was developed consisting of five blocks (Fig. 5.2.). The first step is to define the research question for this study, i.e. what factors and their interactions impact the development of biotechonomy.

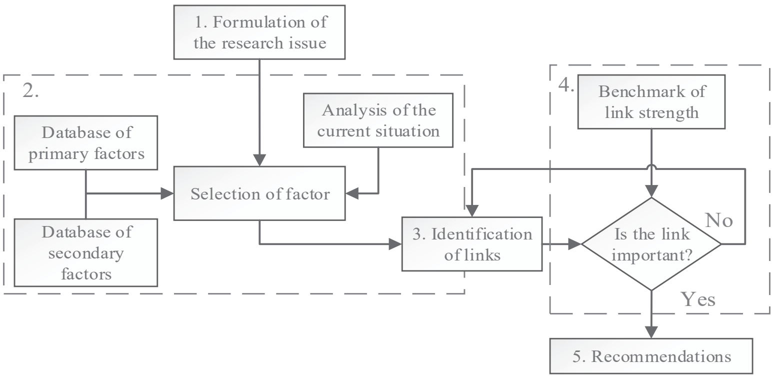

Fig. 5.2. Methodology algorithm for research of the Biotechonomy nexus.

The second step is to select the factors, which influence the research subject. This is done by creating two factor databases – primary and secondary factors. In parallel, within this block an analysis of the current situation is carried out on the level of the issue under study (national, regional, theoretical, etc.), including literature analysis. The literature analysis is necessary to find out what nexus research has been done so far and what factors affect the development of biotechonomy. The selection of secondary factors is carried out in order to understand the transdisciplinarity of biotechonomy and to better understand the causes of impacts. By using the logical analysis and the information available in the scientific literature, in the third step the interconnections between factors that affect the development of biotechonomy are identified. Within this step, factors are not split into primary and secondary. In the fourth step, benchmarks for link strength are determined and a methodology is developed to determine if and how strong the links are. If the link is not strong enough, it does not have a significant impact on the issue under study, the evaluator returns to the third step of the algorithm, identifies the next link and evaluates it following the developed methodology in the fourth step and using benchmarks for link strength. Only the strong links – that have a significant impact on the research subject – are directed to the fifth and final research step that includes the development of recommendations for further, more detailed, biotechonomy nexus research.

Using this methodology algorithm it is possible to identify the most important links for future research in order to efficiently use resources and achieve better results. The developed methodology should be used as a feasibility study for conducting further research on the transdisciplinarity of biotechonomy and the identification of development directions.

It is advisable to separately assess the interactions of individual small groups of factors. In this case, the groups are understood as sets of interconnected factors that correspond to commonly accepted (within society, science and management) definitions of processes that are related to the management of resources. In the context of biotechonomy, individual groups of factors, that should be considered separately, include: biorefinery, circular economy, green economy, circular bioeconomy, sustainability, resource efficiency, waste management, biological diversity, biomimicry, industrial symbiosis, resource consumption, ecosystem services, and eco-innovations. It is foreseen, that there are factors that will overlap within these groups. This allows to even more specifically understand that when discussing and implementing different ideas the overall direction is common. It is therefore necessary to understand what the most effective ways are to achieve common goals of different ideas, which are combined under the idea of biotechonomy.

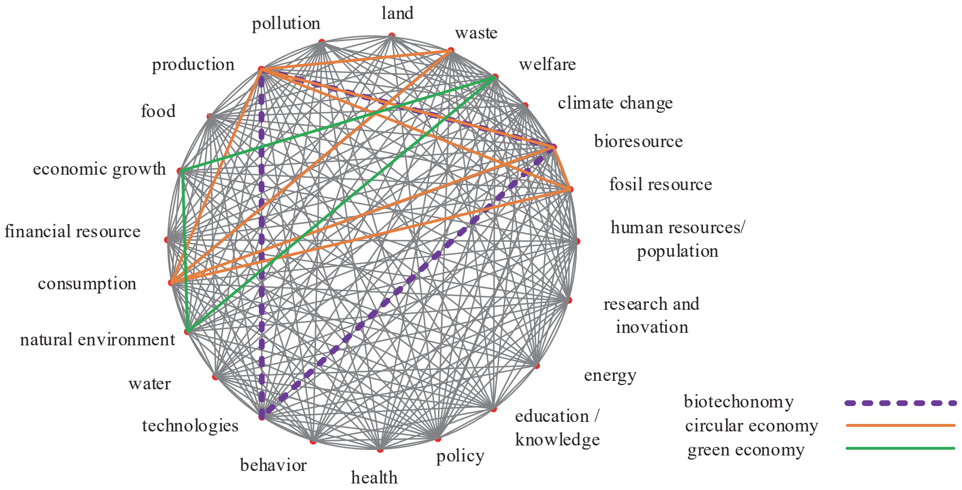

Fig. 5.3. Example. Primary links for biotechonomy, circular economy and green economy.

For example, the main influencing factors of three different concepts – biotechonomy, circular economy and green economy – and their mutual interaction links are presented in Fig. 5.3. It can be seen that the direct coincidence of primary factors is between biotechonomy and circular economy (production and bioresource). It proves that the implementation of one of these concepts will directly or indirectly influence other concepts too. For example, promoting the development of a circular economy through political instruments would also affect the development of biotechonomy. In this case, the ideas of both concepts coincide and the result would be positive, but in other cases it could have a negative effect. This is why a systematic approach to the factors that affect the development is needed and their impact should be evaluated transdisciplinary because human activities and resource use is like an interrelated ecosystem where one activity can have an impact on the entire system.

CONCLUSIONS

1. Within this Doctoral Thesis a novel methodology for biotechonomy analysis, established at four levels of biotechonomy – national, sectorial, resource and product level – has been developed and approbated for the Latvian forestry sector. The approbation of the developed methodology and the obtained results prove its correctness and appropriateness to be adapted and used for sustainability analysis in the context of biotechonomy for various different countries, sectors of the economy, bioresources and bioproducts.
2. Analysis of the sectors of Latvian economy clearly indicated that the agriculture, forestry and fishing sector, which is most closely related to biotechonomy, has the lowest labour employment efficiency and average capital productivity in comparison with other sectors of the economy of Latvia. This indicates that Latvia still has to overcome numerous challenges to ensure the development of biotechonomy. On the one hand, this is a sector that employs a large number of employees, which is a positive factor and should not be reduced. However, this is not being done efficiently, as the benefits at both the microeconomic and macroeconomic level are too small. In the context of biotechonomy, the agriculture, forestry and fishery sector should be closely linked with the manufacturing industry, with the former as a sustainable producer of bioresources, and the latter as a sustainable processor of these resources into the products required by the consumers, including high added value products.
3. Based on the current state of biotechonomy in Latvia, eight main types of barriers affecting biotechonomy innovation were identified: financial, political, market related, behavioural, organizational, technology related, resource related and environment and climate related. All these types of barriers affect not only biotechonomy, but also each other. However mainly they are oriented towards financial and resource barriers. Therefore, it is assumed that by ensuring the availability of funding for the development and commercialization of biotechonomy innovations and by creating innovative, sustainable and economically viable pathways for the use of local bioresources, the innovation in the biotechonomy sectors in Latvia has a future. Latvia requires targeted commercialization of innovations, i.e. innovation transfer from scientific research to a product available to the consumer. The lack of this intermediate step is one of the largest obstacles for the development of biotechonomy.
4. With the application of a complex methodology that includes indicator analysis, mapping and multi-criteria analysis, the most appropriate location in Latvia for forest resource-oriented wood processing plant was determined, taking into account the available wood resources in each county (the amount of wood that has reached the cutting age), labour resources (number of unemployed) and the existing competition (the number of existing wood processing and wood product production companies). The most suitable location would be in Rezekne, Madona, Daugavpils, Garkalne, Kuldiga or Talsi counties. While Stopinu county is the most inappropriate.
5. In the context of bioeconomy, climate change and sustainable use of resources, emphasis is increasingly placed on the use of bioresources to replace fossil resources not only in energy sector but also in industry. Therefore, the topic of the boundaries and preconditions for sustainable use of bioresources should be updated, so that, on the one hand, the climate-related objectives are met, and, on the other hand, to maximize the use of bioresources for the production of high added value products. In Latvia, the discovered problem situation is that forest bioresources are mainly used for fuel production, which can be considered beneficial from the climate point of view, but is not sustainable from the resource use and economic perspectives. Therefore, preconditions for sustainable use of forest resources in energy production have been developed within the Doctoral Thesis, so that efforts to achieve the climate goals would not lead to unsustainable use of bio-resources.
6. Using TOPSIS multi-criteria analysis, the commercialization potential was evaluated for 30 innovative forest biomass products. The main sectors of the economy where forest resource processing companies have promising perspectives to operate are energy, textiles and chemical industry. It was found that products of these industries (e.g. wood textile fibers (lyocell), bio-oil and biodiesel, and chemical compounds such as xylan and suberin) have the greatest commercialization potential in Latvia. Latvian scientists are advised to focus on unique, efficient and environmentally friendly technologies for development of innovative products in these sectors. So that the technologies themselves can become a product, or that they enable initiation of the production of innovative products in Latvia.

7. Currently, the coniferous greenery from the logging residues is an under-utilized biomass resource in Latvia, which can be used to produce various products, including products with high added value, i.e. pharmaceuticals and cosmetics. The system dynamics modeling method determined that the maximum amount of coniferous greenery to be considered is 117 thousand tons per year (based on historical data), but in the future (by 2070) about 195 thousand tons. Despite the different scenarios of forestry development in Latvia, it is expected that the available amount of coniferous greenery will only increase. It is estimated that in the Baltic States, the available amount of coniferous greenery is about 700 thousand m^3 per year. Meaning that this resource is available in sufficient quantities to be used for commercial production.
8. As an innovative solution for the use of coniferous greenery (both raw and pretreated for extraction of chemical compounds) the production of thermal insulation material from coniferous needle is selected, assessed and tested by carrying out laboratory experiments. Experiments were carried out to produce plate type and loose type thermal insulation material with and without binder and determine its thermal conductivity. The obtained thermal conductivity coefficient results are competitive with the thermal insulation materials available in the market (λ = 0.035 – 0.075 W/mK), therefore this idea has a commercialization potential and additional research is required to develop the technology for production of thermal insulation material from coniferous needle that corresponds with the principles of biotechonomy. The production of such coniferous needle thermal insulation material would present a solution for the use of under-utilized forest bioresource, thus gaining larger economic, social, environmental and climate benefits from one unit of forest area managed.
9. The assessment of the concept of biotechonomy and its potential for implementation at the national, sector, resource and product levels leads to a conclusion that biotechonomy has a transdisciplinary nature and its development is influenced by many and varying factors, both directly, indirectly and by mutual interactions. Within the framework of the Doctoral Thesis, the bioeconomy nexus research is proposed as an approach for addressing the issue of transdisciplinarity of biotechonomy. The nexus research aims to identify the mutual interactions between different factors. 22 factors, which are influencing the development of biotechonomy, were selected and through a logical analysis their mutual interaction links were identified. It is currently not possible to determine the extent of each interaction on the development of biotechonomy and which interactions are more relevant. Therefore more detailed research is needed in order to implement the measures aimed at the most important factors influencing biotechonomy development in the future. It is necessary to have a systematic approach to the factors that affect the development and to evaluate their impact in a transdisciplinary way, because human economic activities that use all kinds of resources may be considered as a kind of an ecosystem in which one activity can have an impact on the whole system.

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