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

Anna KUBULE
Doctoral student of the study program “Environmental Engineering”

NOVEL METHODS FOR INTEGRATED ASSESSMENT OF INDUSTRIAL SYMBIOSIS AND ENERGY EFFICIENCY

Summary of the Doctoral Thesis

Scientific supervisor
Dr. sc. ing., Professor
M. ROŠĀ

RTU Press
Riga 2016

Kubule A. Novel Methods for Integrated Assessment of Industrial Symbiosis and Energy Efficiency. Summary of the Doctoral Thesis. Riga: RTU Press, 2016. – 46 p.

Published in accordance with the decision of the Institute of Energy Systems and Environment, Minutes No. 64, May 6, 2016.

ISBN 978-9934-10-842-6

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

To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis will be defended on 25 August 2016 at 2 pm at the Faculty of Power and Electrical Engineering, Āzenes Street 12/1, Room 115.

OFFICIAL REVIEWERS

Dr. sc. ing. Ritvars Sudārs
Latvia University of Agriculture

Dr. sc. ing. Elīna Dāce
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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 Engineering Sciences is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to other scientific degree.

Anna Kubule ……………………………. (signature)

Date: ……………

The Doctoral Thesis has been written in English. It contains an introduction, three chapters, conclusions, and a bibliography with 163 reference sources. The Doctoral Thesis has been illustrated by 55 figures and 36 tables. The total volume of the Thesis is 148 pages, including four appendices.

ACKNOWLEDGEMENTS

I must admit that this was the easiest chapter to write during my time as a Doctoral student; however, also one of the most significant as without the inspiration, motivation, criticism, wisdom, and the everyday support from my supervisors, colleagues, and other significant individuals, the work would not result in the research as it is now, and I would not be the person I currently am.

I owe my gratitude to each and every person who has helped me during these four years; especially, I have to thank the scientific supervisor of this Thesis – Professor Marika Rošā whose pragmatism has balanced my impulsiveness in order to find the right pathway from ideas to realization. I would like to express gratitude to the Head of the Institute of Energy Systems and Environment, Professor Dagnija Blumberga for applying corrective actions to my plans exactly when they were required.

Words cannot express my gratitude to Līga Žogla for the encouragement, motivation, and practical collaboration as well as having long discussions and deliberating countless theories while travelling throughout Latvia to visit various industrial companies. On top of all this, she provided an excellent example of PhD writing and defence.

Special thanks to Ilze Laicāne and Jeļena Ziemele for the daily encouragement. Furthermore, Tatjana Kuzņecova must be acknowledged for her bright outlook on life, suggestions, and innumerable proofreadings.

Thanks to my dear laboratory colleagues with whom I started my scientific journey. Special thanks to Jānis Ikaunieks for the daily jokes, and the technical support for the implementation of electricity monitoring. Thank you, Francesco Romagnoli, for the coffee breaks full of ideas and the peaceful Italian view of life, as well as my participation in two international projects that contributed greatly to my personal experience. Thanks to Lelde for the scientific advices. Thanks to Krista for our collaboration, conversations, and technical assistance.

Thanks to my friends, especially, Zane Galindoma for just being there and Ieva Gailīte for the right words at the right time. Thanks to Oskars, my mom Agita and sister Aija, for being there for me and their support. Special gratitude must be shown to my grandmother Inta for her wisdom, and my grandfather Laimonis for all the tricky questions throughout my studies.

This Doctoral Thesis has been developed within the National Research Programme “Energy Efficient and Low-Carbon Solutions for a Secure, Sustainable and Climate Variability Reducing Energy Supply (LATENERGI)”.

CONTENTS

INTRODUCTION

The national economy and prosperity depends on the growth of the tradable sectors: extraction and production industries, services, transport, etc. On the other hand, the growth of the economy relies upon the availability of resources, energy, appropriate technologies, and intellectual capital. An accelerated economic growth significantly increases resource consumption, energy demand, and the amount of generated waste. This, in turn, pressures ecosystems, causes resource depletion, increases areas covered with landfills, increases air, water, and soil pollution, and ultimately compromises sustainability.

The main national targets for the promotion of Latvian economic growth include, among other objectives, an increase in the production industry's share of the total gross domestic product (GDP) by 20 % by 2020 (12.2 % in 2014) [1, 2]. However, achieving this target would also increase the total resource and energy consumption, as well as waste generation. To ensure sustainable development, economic growth and resource consumption patterns must be decoupled, in other words, the growth of the economy must be improved without increasing the consumption of resources and impact on the environment.

Decoupling these two variables is also a substantial challenge at both the international and European Union (EU) level. Particularly, the EU has highlighted the importance of resource efficiency and a circular economy for the promotion of sustainable consumption and production. Although resource efficiency is one of the main EU goals, Rohn et al. [3] note that there are still knowledge gaps regarding the implementation and effectiveness of resource efficiency measures. Concerns about the sustainability of current industrial development are also strengthening the international scientific focus on industrial resource and energy efficiency, resulting in investigation of more efficient pathways for industrial by-product management. However, the implementation of resource efficiency measures strongly depends upon specific local conditions. Therefore, the transition towards a sustainable, decoupled, and resource efficient economy requires both the analysis and evaluation of locally appropriate resource efficiency measures, and the multi-faceted aspects (technical, economical, behavioural, and organisational barriers) of their implementation.

An EU-wide research study [4], which was published in 2015, indicates that only three out of ten types of resource efficiency measures investigated are currently being implemented in Latvia (improving resource efficiency financing, providing resource efficiency information and advice, supporting extended producer responsibility) and this is only being completed to a marginal extent. However, various resource efficiency issues have previously been investigated in Latvia. Dāce [5] evaluated the impact of various policies on the promotion of primary packaging waste recycling in the household sector. Pubule [6] investigated the integration of cleaner production principles in waste management. Ruģele [7] focused on particular options for the reuse of dairy industry by-products. However, the analysis of available scientific research indicates that none of the previous studies includes an investigation of existing industrial by-product exchanges, e.g., industrial symbiosis in Latvian companies. Regarding industrial energy efficiency, Žogla [8] analysed industrial energy efficiency, particularly, the appropriateness of current energy efficiency indicators, and presented a novel benchmarking approach. This approach was approbated for the identification of the theoretical, technical, and economic energy efficiency potential for one industry case study (beer brewing).

To address the identified knowledge gaps, and to add to the existing body of knowledge, this Thesis focuses on the investigation of two resource efficiency issues – industrial energy efficiency and industrial symbiosis.

Objectives

The aim of the Thesis is to improve the existing research framework by the development and approbation of novel methods for the assessment of industrial resource efficiency. Another aim of the Thesis is to gather new empirical data that characterise the real situation regarding the implementation of resource efficiency measures, their impact, and the existence of resource efficiency barriers in Latvian companies so that these data may be further used in resource efficiency policy planning. In order to reach the aims of the Thesis, the following objectives have been set:

- to assess the Latvian and EU level strategies and targets in the areas of resource efficiency, industrial development waste management and to evaluate the current resource efficiency situation in Latvia;
- to identify potential resource efficiency measures, in particular, energy efficiency and industrial symbiosis, and associated savings;
- to identify potential energy efficiency measures at an industrial company by energy consumption analysis at the sub-department level;
- to identify which industrial symbiosis measures have already been implemented in industrial companies in Latvia and to assess the quality of the implemented measures;
- to identify resource efficiency barriers and driving forces in Latvian industrial companies, to analyse the interconnection between barriers, drivers, barrier overcoming mechanisms, and the implementation of resource efficiency measures by the application of statistical analysis and mathematical modelling.

Research Methods

The structure of the applied research methods is presented in Fig. 1. The applied research methods incorporate qualitative and quantitative research techniques: literature analysis, collection and analysis of statistical data, experimental data acquisition, case study analysis, surveying industrial company representatives, statistical data analysis, and mathematical modelling.

Firstly, an analysis of scientific literature, EU and national planning documents, binding directives, and laws has been performed to assess the current situation. To evaluate industrial energy efficiency, data have been collected directly from industrial companies to be able to compare with the available benchmarks. To identify the implemented industrial symbiosis measures and evaluate their quality, the maturity modelling method has been applied. The initial information for the research has been gathered from the pollution permits of 11 companies and supplemented by contacting the companies and performing analyses during site visits. To identify resource efficiency barriers and drivers in Latvian industrial companies, a survey method has been applied. Seventy-three in-depth interviews with owners, managers, and environmental specialists of industrial enterprises have been performed. The data gathered on resource efficiency barriers and drivers have been evaluated not only qualitatively, but for the first time also described quantitatively. The applied statistical analysis and mathematical modelling describes the relationships between various identified variables, and can be further used in similar studies.

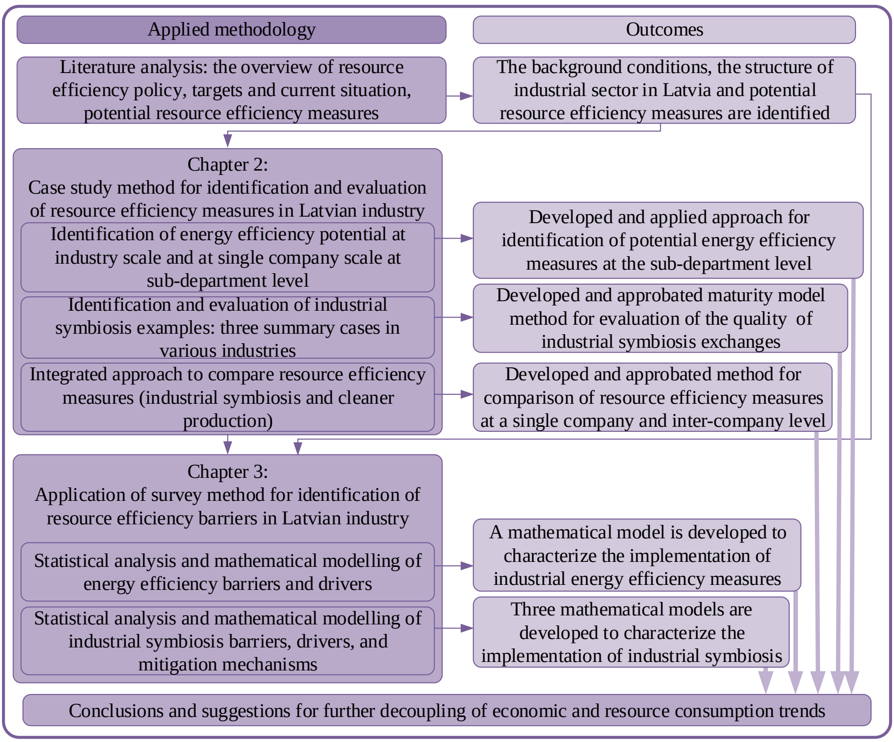

Fig. 1. Generic description of the methodology applied within the research.

Scientific Significance

The Thesis is of high scientific significance in the Latvian and international contexts due to the fact that the investigation and modelling of barrier overcoming mechanisms are currently an extremely topical research area regarding the investigation of energy efficiency and resource efficiency barriers. Three innovative methods for resource efficiency assessment have been developed and approbated within this Thesis. These methods can be adjusted to various research purposes. The first method is intended for the evaluation of industrial symbiosis quality (the maturity model method), while the second method can be applied to the comparison of industrial symbiosis and cleaner production measures (the cumulative intensity evaluation). The Thesis also incorporates the development and application of a novel method for the analysis of energy and resource efficiency barriers. Particularly, the method includes the application of factor analysis for the extraction of the underlying barrier constructs, while mathematical modelling is applied to describe the relationships between the implementation of resource efficiency measures, various situational variables, and company specific barriers. The developed methodology also allows for the modelling of the mechanisms for barrier overcoming and the interrelation between them and to a company's future intention to implement resource efficiency measures.

Practical Significance

The Thesis is of high practical significance in the Latvian and European contexts. The research results provide novel information about actual examples of the implementation of resource efficiency measures in Latvian industrial companies, and refute the previous assumptions [4] that industrial symbiosis is not practised in Latvia. In addition, the analysis of energy efficiency in a small size brewery approbates a profound and internationally significant approach for the identification of potential energy efficiency measures at a sub-department level in small and medium enterprises (SMEs). The results obtained provide both scientific and practical substantiation for the significance of energy consumption monitoring and the necessity for energy management at industrial companies. The Thesis also includes a novel investigation of barriers to energy efficiency and industrial symbiosis measures in Latvian industrial companies based on direct interviews of representatives of 73 manufacturing industry companies. The results of the Thesis may be further disseminated to raise industrial companies' awareness and motivation regarding resource efficiency. The results of the Thesis may be applied for further improvement of the national and international policy, and the selection of appropriate mechanisms for resource efficiency promotion.

Approbation

The research results have been discussed and presented at the following conferences and seminars:

1. Scientific conference "Ģeogrāfija. Ģeoloģija. Vides zinātne: Latvijas Universitātes 74. zinātniskā konference" with the paper "The Climate Adaptation Aspects of Bioresource Technology" – 3 February 2016, Riga, Latvia.
2. International Scientific conference "Global Cleaner Production Conference" with the paper "Barriers and Bridges: Establishing the Pathway to Industrial Energy Efficiency" – 1–4 November 2015, Sitges, Spain.
3. International Scientific conference "CONECT 2015" with the paper "Resource and Energy Efficiency in Small and Medium Breweries" – 14–16 October 2015, Riga, Latvia.
4. International Scientific conference "17th European Roundtable on Sustainable Consumption and Production" with the paper "Efficient Use of Energy in Small Size Brewery" – 14–16 October 2014, Portorož, Slovenia.
5. International Scientific conference "CONECT 2014" with the paper "The Use of Performance Indicators for Analysis of Resource Efficiency Measures" – 14–16 October 2014, Riga, Latvia.
6. International Scientific conference "CONECT 2014" with the paper "Process Benchmark for Evaluation Energy Performance in Breweries" – 14–16 October 2014, Riga, Latvia.
7. International Scientific conference "Science – Future of Lithuania" with the paper "Identification of Industrial Symbiosis Flows in Valmiera Region, Latvia" – 10 April 2014, Vilnius, Lithuania.
8. International Scientific conference "Biosystems Engineering 2013" with the paper "Availability of Herbaceous Resources for Production of Solid Biomass Fuels in Latvia" – 9–10May 2013, Tartu, Estonia.
9. International Scientific conference "17th International Scientific Conference "EcoBalt 2012"" with the paper "Promoting the Development of Industrial Symbiosis in Latvia" – 18–19 October 2012, Riga, Latvia.
10. International Scientific conference "Riga Technical University 53rd International Scientific Conference: Dedicated to the 150th Anniversary and the 1st Congress of World Engineers and Riga Polytechnical Institute" with the paper "The Development of Industrial Symbiosis Networks in Latvia" – 11–12 October 2012, Riga, Latvia.
11. International Scientific conference "9th International Conference of Young Scientists on Energy Issues (CYSENI 2012)" with the paper "Advantages and Obstacles for the Development of Industrial Symbiosis in Latvia" – 24–25 May 2012, Kaunas, Lithuania.
12. International Scientific conference "Science – Future of Lithuania" with the paper "The Modelling of Wood Material Flows in order to Reduce Environmental Impact" – 12 April 2012, Vilnius, Lithuania.

13. Seminar “Bioeconomy. Natural Resources and Their Potential Applications” organised by Riga Technical University, Institute of Energy Systems and Environment with the presentation “Bioresource Wastes. The Ideas for Their Management” – 17 February 2016, Riga, Latvia.
14. Seminar “Environmental Policy Implementation in SME Sector” organised by Ltd. “Demarsch” within the EEA project “Sustainable Environmental Policy Governance in the SME Sector” with the presentation “Cooperation between Industrial Companies in order to Promote Resource Efficiency” – 24 September 2015, Riga, Latvia.
15. Summer School “Ticket to the Future” organised by Riga Technical University, Institute of Energy Systems and Environment with the presentation “How to Consume Less Energy in Industry” – 18 August 2015, Riga, Latvia.

Monographies

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Scientific Publications

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Thesis Outline

The Doctoral Thesis has been written in English. It contains an introduction, three chapters, conclusions, and a bibliography with 163 reference sources. It has been illustrated by 55 figures and 36 tables. The volume of the Thesis is 148 pages, including four appendices. The introduction of the Thesis highlights the topicality of the research, defines the aims of the Thesis and the set tasks, describes the applied research methods, and highlights the scientific and practical significance of the study. In the first chapter, Latvian and EU-level strategies and targets for resource efficiency and other related areas are analysed, and the current state of resource efficiency in Latvia is assessed. The second chapter describes the empirical investigation of various resource efficiency measures, which have been implemented in Latvia. The third section of the Thesis identifies resource efficiency barriers and drivers in Latvian industrial companies, while mathematical modelling is applied to process the gathered data. In the final part of the Thesis, the main conclusions of the research are summarised and the list of references and the appendices are provided. The literature review is not included in the summary of the Doctoral Thesis.

1. RESOURCE EFFICIENCY IN INDUSTRY

At present, resource efficiency is becoming a widespread sustainability strategy in the global, EU and Latvian contexts. Resource efficiency improvement is one of the main development targets of the EU that are included in the “Europe 2020” strategy [9]. Industry is a significant consumer of resources and energy; therefore, it could significantly contribute to reaching the EU targets [10, 11].

Resource efficiency involves numerous technologies, business models, and behavioural change that allow for “producing more or producing better with less” [12]. Resource efficiency enhances the productivity of resource use, increases the cumulative economic value of industrial production, minimises the environmental impact of resource use, reduces the vulnerability to changes in resource availability and prices, provides cost reduction through productivity savings, and contributes to greenhouse gas emission reduction [12].

As an EU Member State, Latvia is required to adopt the common EU requirements and targets in various policy areas. Therefore, the national policy is based on the integration of local and EU level binding targets. The resource efficiency requirements currently adopted refer to energy efficiency, increase of the share of renewable energy in energy production, the requirements for safe waste disposal, etc. [1].

The National Development Plan [1] sets the national medium term development priorities and objectives as well as provides a set of indicators for the evaluation of the progress achieved (see Table 1.1). One of the most significant targets is the increase of the production industry’s share in the total GDP to 20 % by 2020. Although in the years following Latvia’s economic crisis, an increasing trend is evident for this indicator, it has been decreasing since 2013 (13 % in 2012, 12.6 % in 2013, 12.2 % in 2014 [2]).

Table 1.1

Quantitative indicators for the evaluation of the priority area Growth of the National economy [1]

Indicator	Current value in 2014	Target value in 2020**
Output of the processing industry as a percentage of the GDP	12.2 %***	20 %
Export of goods and services as a percentage of the GDP	63 %*	70 %
Productivity in the processing industry (labour productivity), added value EUR/employment	16759*	15794
Investment in research and development as a percentage of the GDP	0.68 %***	1.5 %
Productivity of the use of natural resources	512 EUR/ tonne*	600 EUR/ tonne

* [13]; ** [1]; *** [2]

Assuming that Latvia achieves the planned industrial growth rate, it would be accompanied by an increase of the total resource and energy consumption, as well as industrial waste generation. Without complementary resource efficiency measures and a circular economy approach, the fulfilment of other binding and indicative targets would be jeopardized (e.g. regarding waste management).

To evaluate the current resource efficiency situation in Latvia, resource consumption and productivity, waste generation, and energy efficiency are examined at both the national and industry levels. During the past two decades, Latvia's resource productivity has increased 1.7 times. The highest resource productivity (586 EUR per tonne) was achieved during the economic crisis, indicating that such negative circumstances promoted a more productive use of resources in industry, as well as in private consumption. However, an analysis of the latest data indicates that the system has returned to the previous balance, and resource productivity has decreased. In comparison to the highest resource productivity level in 2009, resource productivity was 12 % lower in 2014, though GDP has been growing consistently since 2010.

In the post-crisis period a significant reduction of generated waste has been evident. The swift recurrence of the increasing trend indicates that waste generation and GDP are still strongly coupled. In order to fulfil the indicative industrial waste target, especially in the case of the envisioned growth of the national economy, the decoupling of the amount of generated waste and GDP growth is required.

Similar to resource productivity, energy productivity in Latvia has been increasing slowly since 1995. With a swift decrease of GDP during the crisis, energy productivity significantly decreased, also showing a coupling trend. Overall, in the post-crisis period, a quite stable national energy consumption can be seen, while GDP is increasing, thus leading to higher national energy productivity. However, industrial energy consumption has increased by 20 % since 2008, while the manufacturing industry production value and added-value have increased by 7 % and 4.5 %, respectively [14]. Consequently, it is evident that industrial energy productivity should be strongly promoted.

2. RESOURCE EFFICIENCY MEASURES IN LATVIAN INDUSTRY

Although scarcely described in scientific literature, various efficiency measures and the practice of responsible housekeeping have been implemented by Latvian industrial companies. The evaluation and comparison of the implemented resource efficiency measures can provide support for the decision to further improve the resource efficiency and planning of the national policy. In this section of the Thesis, the case study methodology is applied to gather empirical data and examples of implemented resource efficiency measures in industrial companies. Case study methodology is widely applied in both industrial symbiosis [15, 16] and energy efficiency research . Further on, regression analysis, maturity grid modelling, and value chain approaches are applied for the evaluation and comparison of the identified measures.

To set energy efficiency targets, it is first necessary to analyse a company's energy consumption and determine its improvement potential. A company's production performance can be described by specific energy consumption indicators [19]. The specific consumption of thermal and electrical energy is calculated from monthly consumption data and normalized by the amount of production (see Eq. (2.1)).

$$SEC_{i,t} = \frac{E_{i,y}}{Y_{i,y}} \tag{2.1}$$

where
$SEC_{i,t}$ – specific energy consumption at the company *i* in year *t*;
$E_{i,y}$ – energy consumption at the company *i* in year *t*;
$Y_{i,y}$ – production output at the company *i* in year *t*.

A previous study by Ozoliņa and Rosa [20] as well as an analysis of empirical data from nine industrial companies performed within this Thesis indicate that specific energy consumption of individual industrial companies in Latvia is worse than that reported in international benchmarks on average. To follow up on the reasons for the aforementioned situation, a case study of a small brewery shall be investigated. The aim of this case study is to extend the existing approach to energy efficiency analysis in SMEs by focusing on the evaluation of energy consumption and efficiency in various departments.

2.1. In-depth Case Study of a Small Brewery

An analysis of the brewery's energy consumption was initiated by an evaluation of historical energy consumption patterns. Both the specific electricity and thermal energy consumption decreased between 2011 and 2013. Energy efficiency per produced beer improved due to a change to more efficient equipment (e.g. improved efficiency of chillers) and due to an increased production capacity, leading to the resulting economies of scale. The specific monthly thermal energy and electricity consumption in relation to monthly beer production is plotted in Fig. 2.1. Since the P-value for both models is less than 0.05, there is a statistically significant relationship between energy consumption and beer production amounts at a confidence level of 95.0 %.

The results obtained (Fig. 2.1.) also show the benefits of economies of scale, e.g., due to a larger demand in the summer months, the specific consumption improves. In winter months, due to lower production capacity and the need for heating the facility (which cannot be subtracted from available data due to the existing gas accounting system), specific energy consumption is higher.

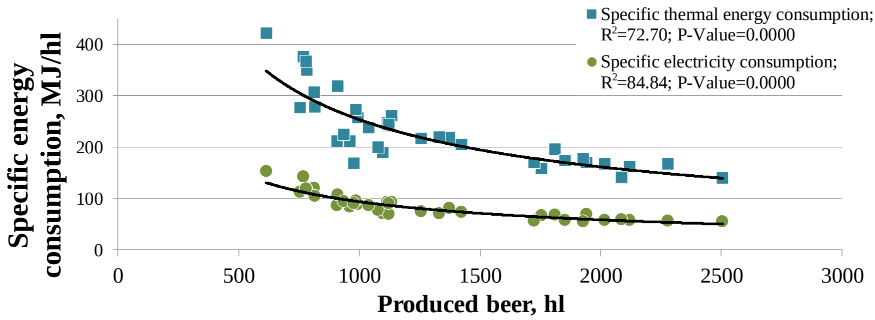

Fig. 2.1. Specific energy consumption according to amount of beer produced.

The specific thermal energy and electricity consumption in the case study exceeds the best practice referred to in the Reference Document on Best Available Technologies and in other more recent studies (see Table 2.1). This could be due to such factors as the availability of better technologies, different capacities of beer production, the continuity of processes, and the production profile. To investigate the cause of higher specific energy consumption, two departments were further analysed: (1) the thermal energy efficiency (through heat loss calculations) of the brew house and (2) the bottling department's electricity efficiency.

Table 2.1

Comparison of specific energy consumption benchmarks reported in the literature

	Specific thermal energy consumption, MJ/hl	Specific electrical energy consumption, MJ/hl
Large size brewery [19]	85–120	37.8–43.2
Medium size brewery [21]	160–180	45–60
Medium size brewery [22]	43.6	-
Small brewery [22]	104.5	-
[23]	110	45.7
[24]	141*	
Case study (small)	219–245	81–92

* data for total energy consumption (thermal and electrical energy)

Brew house energy losses at each process stage were calculated according to the method presented by Sturm et al. [21] – the dimensions of all vessels were measured (vessels were approximated to be cylindrically shaped), fluid filling height was calculated according to the amount of ingredients filled in the tanks, temperature regimes for each process were provided by a brewery representative. The overall brew house heat losses are 22.22MJ/hl, 93 % of the heat losses are due to the evaporation of water during wort boiling. In the referent case study [21], total heat losses are lower by roughly half – 9.68MJ/hl, mostly due to a difference in the evaporation heat losses. Thermal energy loss reduction could be achieved with the installation of an additional heat exchanger to recover energy from steam, and to heat water in the accumulation tank. In this case, both the heat of water vaporization and the additional heat difference between tank water and steam can be recovered – a total of 21.5 MJ/hl of beer produced. This would also allow for the reduction of natural gas consumption by 10 % of the current use, and the same for the total costs of natural gas. Based on the necessary investments versus the fuel cost reduction, the suggested measure has a return-on-investment time of 1.1 years (which is similar to that stated by Sturm et al. [21]).

To analyse the specific electricity consumption of different packaging options, electricity consumption monitoring was conducted in the bottling department. Measuring points were set up at five power inputs. Split core AC current sensors (CTV-A) and four-channel data loggers (U12 U12-006) were installed (see Fig. 2.2). The sample recording time for all loggers was set to 5 minutes. The amount of bottled beer was recorded simultaneously with electricity consumption. Equation (2.2.) was applied to convert the measured data to electricity consumption.

Fig. 2.2. The data logger and its placement on the power input.

$$P = \sqrt{3} \cdot I_{avg} \cdot U_{avg} \cdot \cos\varphi \tag{2.2}$$

where
P – power, [W];
I_{avg} – average-current, [A];
U_{avg} – average voltage at input, [V];
$\cos\varphi$ – power factor.

The obtained results are consistent with those presented in other studies – energy consumption for bottle packaging may be up to three times higher than for filling in kegs [21]. In our case study, an even higher difference is observed, i.e., filling in metal kegs (3.72 kJ/l) has a much lower specific consumption than glass bottling (27 kJ/l) and PET bottling (56.5 kJ/l). However, when assessing specific consumption per litre of beer, all packaging types are more efficient than the benchmarks provided [21].

As energy consumption during production downtime was identified, the consumption during different operation modes (bottling/maintenance/other consumption) was considered at all five power inputs (see Table 2.2). For glass bottling equipment, consumption during production downtime rises when equipment is switched on for maintenance. On the other hand, for glass labelling equipment, 15 % of total electricity is consumed during production downtime, when a daily base consumption of 0.4-0.6kWh is recorded. After consulting with brewery's representatives, it has been identified that there is an additional consumer at this input – an individual lighting fixture. To reduce the excess energy consumption, it is recommended to implement more frequent check-ups as to whether this lighting is necessary. Both PET packaging and bottling equipment show over 10 % electricity consumption share during non-production periods. As PET packaging equipment has the highest overall consumption, a decrease in off-production time consumption can lead to the highest absolute consumption reduction.

Table 2.2

Electricity consumption shares for bottling equipment.

	Consumption for direct purpose, %	Consumption for cleaning or repairs, %	Other consumption, %
KEG filling	86.4	7.8	5.8
Glass bottling	84.8	11.8	3.4
Glass labelling	85.1	-	14.9
PET bottling	64.8	21.5	13.6
PET packaging	42.1	46.2*	11.7

* consumption for packaging of manually bottled beer

Energy consumption in the bottling station can be reduced by reviewing the current energy and production management (at times the equipment is left in stand-by or idle modes during longer breaks in production or during lunch, still requiring important power to keep the necessary temperatures for fast start-up) and by modifying the behaviour of equipment operators (recognising unnecessary energy consumption, the necessity to turn off the non-essential equipment, etc.). On the other hand, the results suggest that the bottling department is not the single culprit for the high energy consumption in the brewery, and further investigation should focus on other electricity consumers, particularly the compressors for the beer conditioning department.

2.2. The Identification and Evaluation of Industrial Synergies

To develop and promote a strategy for the advancement of new and qualitative industrial synergies, it is essential to perform the analysis and evaluation of existing examples of collaboration. To establish a method for the evaluation of the quality of the identified industrial synergies, a literature research on potential methods has been performed. The conclusions of the literature review have indicated that only a few scientific studies account for the geographic proximity of industrial symbioses, and, on the whole, only economic and/or environmental aspects are considered, without looking at the interrelation of these aspects. Therefore, this part of the Thesis aims to complement the existing body of knowledge by proposing a novel method for the evaluation of the quality of industrial synergies.

2.2.1. Development of Industrial Symbiosis Quality Evaluation Method

A significant problem for the comparison of industrial synergies, especially in Latvia, is that companies are reluctant to provide quantitative data about their cooperation, either because they are worried about business competition or because the accounting can be approximate in some cases. Due to the unavailability of quantitative data, the identified exchange flows cannot be evaluated using typical quantitative analysis methods. For this reason, a concept for qualitative evaluation is applied within the current research. The applied maturity model method focuses on categorising the data about industrial cooperation at certain maturity levels so that each higher maturity level characterises a gradual increase of exchange quality. Therefore, each higher maturity level describes the required improvements to reach the maximum maturity level [25]. Within this Thesis, a five-level model has been developed to evaluate three main principles of industrial symbiosis – geographic proximity, environmental performance quality, and economic performance quality (see Table 2.3). The algorithm for the evaluation of the exchange quality is presented in Fig. 2.3.

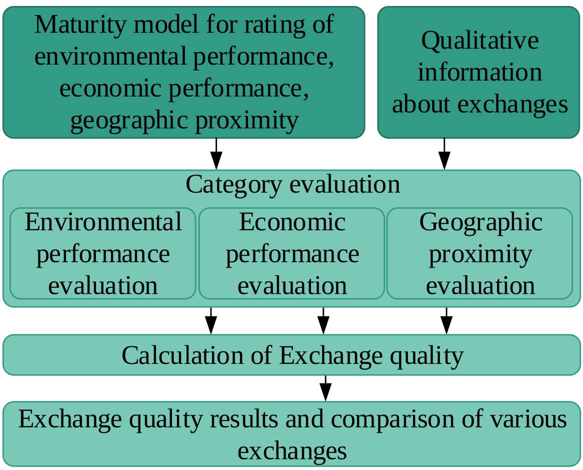

Fig. 2.3. Algorithm for exchange quality determination.

Table 2.3

Evaluation scale for the determination of the quality of industrial synergies

Evaluation score		Level 1 Not recognised	Level 2 Initial efforts	Level 3 Active	Level 4 Proactive	Level 5 Forming the future
		1 point	2 points	3 points	4 points	5 points
Geographic proximity (GP)	Exchange distance	>100 km	30–100 km	3–30 km	1–3 km	<1 km
Environmental performance quality (EnvPQ)	Materials	Waste management (e.g. landfilling)	Energy recovery	Material recovery	Used as raw material (additional pre-treatment needed) or secondary material	Direct use as raw material, no additional pre-treatment needed
	Water	Wastewater treatment; draining in sewage; etc.	Water use for rinsing, washing other than in production	Energy recovery from technical water	Water reuse for secondary purposes in production	Water reuse in production process
	Energy	Dissipating energy into surrounding environment	Use of waste energy, additional upgrading needed	Use of waste energy, avoiding emitting heat into atmosphere	Efficient reuse of waste energy, cascading is maximised, altering production capacity to coordinate by-product utilization capacity	Efficient reuse of waste energy, maximal potential is taken into account, energy cascading is maximised
Economic performance (EnvPQ)	Profit/cost of exchange	Cooperation requires additional expenses	Cooperation poses no direct economic benefits	Negligible economic benefits, cooperation is feasible only if costs are low	Moderate benefits	Significant economic benefits, large gains from cooperation

The scoring range for each evaluation category is within a range of 1 to 5 points (one point being the lowest score, five points – the highest). Decision-makers can apply this method to compare either several existing or potential industrial synergies, by evaluating each synergy according to the maturity model and determining the exchange quality according to (2.3). As the application of the method does not require having any quantitative information about each exchange, the method can also be used at the planning stage of new industrial synergies to determine the potentially most efficient and sustainable by-product reuse pathways.

$$EQ = GP + EnvPQ + EcoPQ \tag{2.3}$$

where
EQ – the overall evaluation score for exchange quality;
GP – the category score for geographic proximity of the exchange;
EnvPQ – the category score for environmental performance quality of the exchange;
EcoPQ – the category score for economic performance quality of the exchange.

To investigate the quality of self-organised by-product synergies in Latvia, three case studies have been analysed (brewery, wood processing and mixed industries – non-metallic mineral processing, fodder and plastic production). The information about the type of exchange, by-product transportation distance, the purpose of reuse, and the costs or incomes from the exchange is used for a qualitative evaluation.

2.2.2. Case Study: Mixed Industries

Based on the information gathered during a survey about existing industrial symbiosis measures in the Latvian industry, this case study evaluates the quality of industrial synergies implemented in various production industries. These exchanges indicate that industrial symbiosis approaches that are common in foreign best practices are also applied in the Latvian industry (see Fig. 2.4). Two generic pathways for synergies have been identified: (1) synergies are promoted by the need to manage specific industrial waste and the existence of contacts with appropriate partners, and (2) the use of production by-products is the core direction of the industry (e.g. wood pellet production, production of fish oil and flour, cement production).

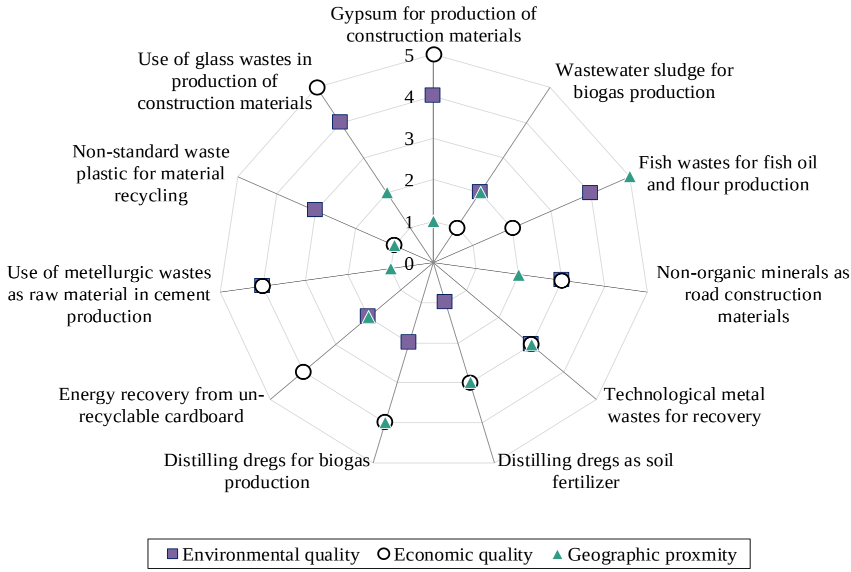

Fig. 2.4. Results of quality evaluation for various industry by-product exchanges

Due to the variability of these exchanges, the evaluation of each exchange differs (see Table 2.4). The highest evaluation is awarded to the reuse of glass for construction materials, and for the reuse of fish by-products for the production of fodder. The lowest evaluation is for the reuse of wastewater sludge in the production of biogas, as this exchange is not located nearby, requires waste treatment expenses, and it is mere energy recovery from an environmental point of view.

Table 2.4

Evaluation scores and results of quality evaluation for various industry by-products

	Gypsum for production of construction materials	Wastewater sludge for biogas production	Use of glass wastes in production of construction materials	Fish wastes for fish oil and flour production	Non-organic minerals as road construction materials	Technological metal wastes for recovery	Distilling dregs as soil fertilizer	Distilling dregs for biogas production
Environmental quality	4	2	4	4	3	3	1	2
Geographic proximity	1	2	2	5	2	3	3	4
Economic quality	5	1	5	2	3	3	3	4
Exchange quality evaluation	10	5	11	11	8	9	7	10

The results of all three case studies indicate that only a few of the assessed self-organised industrial synergies can be beneficial in connection with all three evaluation categories. In cases with higher economic advantages, the environmental quality or geographic proximity of implemented exchanges are lower, and vice versa. This leads to the conclusion that these three categories – environmental quality, economic quality, and geographic proximity – create a triple constraint for the development of qualitative industrial synergies, and the quality of each category should be considered before the planning stage of such collaborations.

2.3. An Integrated Assessment Approach

Although the implementation of cleaner production and industrial symbiosis measures can complement each other, they can also interfere. For example, the profit gained from the by-product exchange decreases the company's willingness to invest in cleaner production measures that improve resource efficiency and reduce by-product generation [26]. Unlike at a single company level, industrial symbiosis or inter-company systems have a crucial limitation because system boundaries are expanding and incorporating many production processes with a multitude of raw materials and products. Therefore, normalization by production amounts (specific consumption indicators) is not applicable, as they cannot be compared at various stages of the industrial symbiosis value chain. Due to these differences, it is challenging to compare the efficacy of various improvement pathways and select an optimised strategy. To develop a method for comparison of intra-firm and inter-firm resource efficiency measures, specific production performance indicators have been derived.

2.3.1. The Value Chain Approach

Hicks et. al. [27] highlight how a series of production processes contribute to the product supply chain by either adding value or generating a loss and waste. This, in turn, influences the total cumulative added value of the product. By analogy to Hicks et. al. [27], industrial symbiosis system can be analysed as a series of single production steps (connected through by-product exchanges) that influence the cumulative added value of the production chain (see Fig. 2.5). Wen and Meng [28] similarly assess resource productivity for three individual stages of the production chain.

Due to the analogy between a single company production process and multi-company industrial symbiosis network, the use of a cumulative intensity indicator has been proposed. The comparison of production systems is based on attributing the impact of various environmental factors to the cumulative added-value over the assessed production stages. Cumulative added-value accounts for the value of all products and by-products of the network at a given stage of the product value chain.

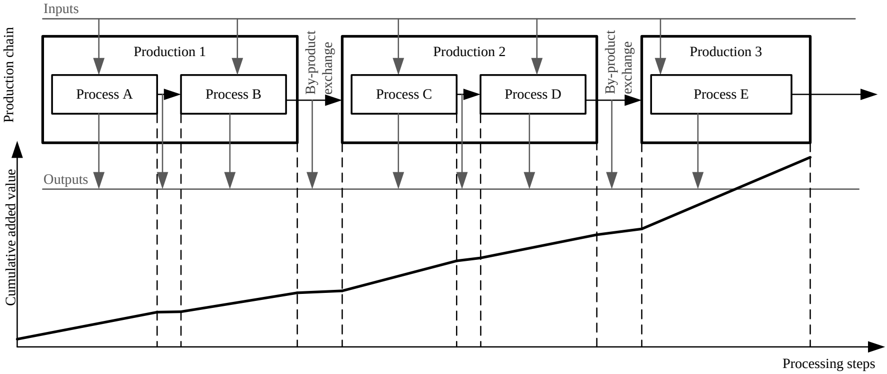

Fig. 2.5. Generic model for the evaluation of industrial symbiosis performance (adapted from Hicks et. al. [27]).

The generic equation for cumulative intensity is presented in (2.4). This equation can be adapted to determine the intensity of various factors, e.g., raw resource consumption, water or energy consumption, generation of waste, wastewater or emissions, amount of exchanged by-products, etc.

$$CI_F = \sum_{i=1}^{n} \frac{F_i}{AV_i}, \tag{2.4}$$

where

CI_F – the cumulative intensity of considered factor F;
F – the value of considered factor F at production stage i;
AV – the added value at production stage i;
i – designation of particular production stage;
n – total number of production stages considered.

If necessary, the sub-processes within the main production can be evaluated separately to compare specific cleaner production measures and other alternatives.

2.3.2. Framework Demonstration: A Case Study

During site visits at five Latvian breweries, plant stakeholders expressed a necessity for an economically and environmentally more effective pathway for the reuse or exchange of the brewer’s spent grain (BSG). To demonstrate an application of the cumulative intensity indicator, two alternative scenarios for BSG reuse have been constructed. Scenario 1 involves an exchange between the brewery and a biogas plant (industrial symbiosis), where BSG is used for the production of biogas. Scenario 2 involves the installation of an onsite dryer at the brewery to increase the quality of BSG so it can be used as a food supplement (cleaner production). Energy consumption aspects are evaluated for the two scenarios, and the cumulative intensity indicators are determined by two factors: energy consumption and CO_2 emission generation. The input data are based on information acquired during site visits to the breweries. However, the dataset used presents a generalised case and considers three-year average values for one of the visited breweries.

Figure 2.6 presents the results for Scenario 1. Resource intensity is the inverse of resource productivity, and according to Kovanda et al. [29] they can be used interchangeably provided that the particular improvement direction is taken into account: resource productivity must be increased and resource intensity decreased.

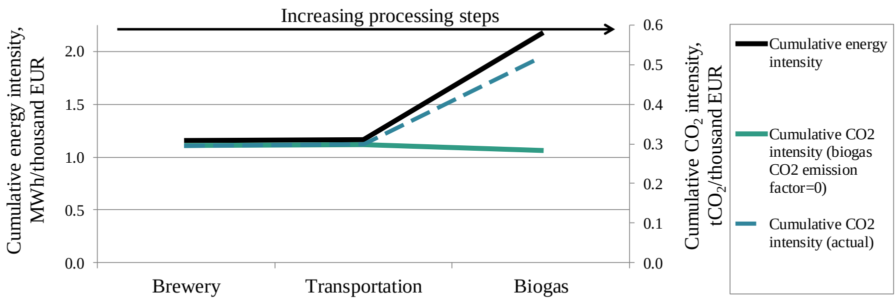

Fig. 2.6. Results of cumulative intensity indicators for Scenario 1.

For Scenario 1, the cumulative energy consumption intensity and cumulative CO_2 emission intensity are increasing further along the production chain. This indicates that the added-value over the latter production stages is not increasing as quickly as the energy consumption and CO_2 emissions. This could be because the reuse of BSG for energy production is not a high added-value commodity. To illustrate how the cumulative CO_2 intensity indicator can represent the advantages of the use of renewable energy resources, the results of the actual and zero CO_2 emissions for biomass are presented.

Figure 2.7 presents results for Scenario 2. Both cumulative intensity indicators follow a similar pathway – the drying process results in an indicator increase; nevertheless, lower energy consumption at baking and higher added-value of cookies produced provide a minimal indicator increase at the third processing step. Considering zero CO_2 emissions for the combustion of renewable biomass, the cumulative CO_2 intensity stays at a constant level at the first two production stages, and decreases minimally at the baking production stage. This is because the drying process does not provide any increase in added-value, and the baking added-value is minimal.

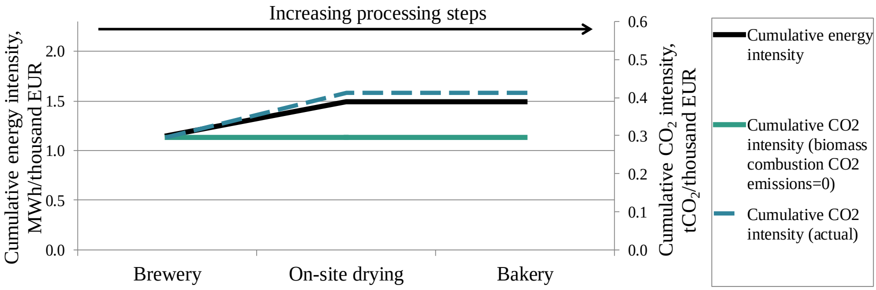

Fig. 2.7. Results of cumulative intensity indicators for Scenario 2: cookie production alternative.

The method presented involves applying production performance indicators (which are typically used for the characterisation of resource consumption at a single company level) for multi-company industrial symbiosis cooperation. The results for both alternatives show a different increase of cumulative intensity in each case. The overall cumulative intensity for both factors is higher in the biogas alternative, meaning that the cookie production alternative ought to be considered more thoroughly in the future.

3. RESOURCE EFFICIENCY BARRIERS IN LATVIAN INDUSTRY

The literature analysis on resource efficiency potential (see Chapter 1) and the empirical research (see Chapter 2) prove that important resource efficiency measures can be implemented in the industrial sector. However, the implementation of even rationally based efficiency measures is hindered by non-technical obstacles or barriers [30]. To overcome these issues, the existing resource efficiency barriers must be identified and analysed, and specific barrier overcoming or mitigation mechanisms must be investigated [31]. To the author's best knowledge, only one scientific study on barriers to the implementation of energy efficiency measures has previously been performed in Latvia. In it, Žogla [8] identified energy efficiency barriers in Latvian breweries. But there is no previous scientific study evaluating barriers in industrial symbiosis in Latvia.

To identify the resource efficiency barriers in the Latvian industry, an integrated methodology has been developed. The algorithm of the applied methodology is presented in Fig. 3.1. The developed methodology has been approbated with two cases – the implementation of energy efficiency measures and the implementation of industrial symbiosis. The data gathering has been carried out through direct interviews of the representatives and key decision-makers in 73 industrial companies. The selection of particular barriers to be identified is based on a comprehensive literature analysis on energy efficiency barriers, industrial symbiosis barriers, their taxonomy, and mechanisms to overcome these barriers.

Each questionnaire included general questions characterising the company's background and specific question regarding energy efficiency barriers and drivers. Even numbered Likert scales (1–6 and 1–4) have been used for the evaluation of specific questions, where the lowest value means "completely disagree" and the highest – "completely agree". The evaluation via Likert scale provides interval data, i.e., arranged qualitative data, for further analysis. The gathered data have been processed by the statistical analysis, factor analysis, and logistic regression analysis. The statistical analysis has been performed using the Statgraphics Centurion XVI software.

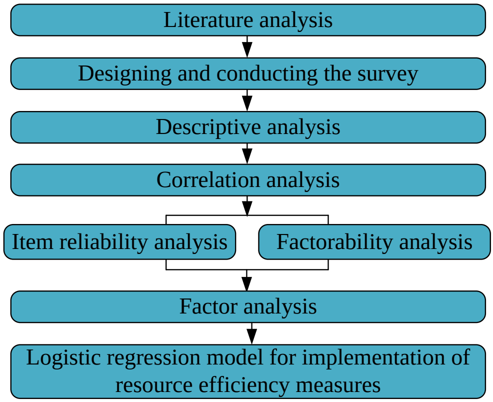

Fig. 3.1. Algorithm of the method for resource efficiency barrier analysis.

The aim of the methodology developed is to transform the qualitative barrier by characterising the data acquired during the surveys into quantitative factors that may further be used for the development of mathematical models. The established mathematical models account for the interrelation between resource efficiency barriers and drivers and facilitate predictions as to which companies are more likely to implement resource efficiency measures. After the identification of the dominant resource efficiency barriers and drivers, potential barrier overcoming mechanisms have been proposed and evaluated.

3.1. Surveys of Industrial Companies

The research results are based on the data gathered in two dedicated surveys. Each of the surveys has multiple purposes – to identify the actual implementation of resource efficiency measures in the Latvian industry, and to identify the presence of resource efficiency barriers and drivers. The target respondents were company owners, managers or environmental managers. As they are the main decision-makers in the companies, they can provide insight concerning the implementation (or non-implementation) of resource efficiency measures. As there is no previous wide-scale research on resource efficiency barriers in the Latvian industry, probability constraints arise because the population is not well defined, and there is limited access to population list. The respondents were selected by the approach purposive non-probability sampling as the respondents had to meet certain criteria (industry representatives). Though non-probability sampling is less desirable than probability sampling, in certain conditions it may be reasonable to apply non-probability sampling [32]. Non-probability sampling was selected to facilitate easier data gathering because probability sampling would lead to considerable costs and time constraints. The non-probability sampling is also advantageous for an exploratory study to determine the approximation of the population so that more appropriate probability sampling may be selected for further research [32].

3.2. Energy Efficiency Survey Results

The energy efficiency survey sample size (n) is 40 respondents. The respondents' contact information was obtained from public databases, through communication with business partners, and from the companies that had already completed the survey. Overall, 25 company owners and 15 executive managers completed the survey. Energy efficiency measures had been previously implemented in 88 % of the analysed companies (see Fig. 3.2), and in most of them the implemented measures were satisfactory. In 25 companies, the implemented measures had led to the planned energy and cost savings. In six companies, the planned energy savings had been reached, but the cost savings were lower than expected. Only in two companies were neither the expected energy, nor cost savings achieved.

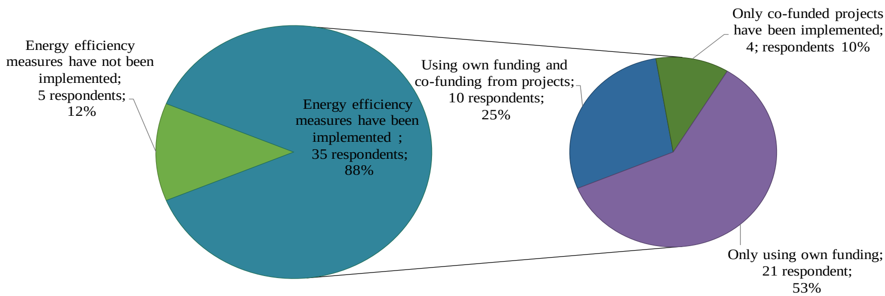

Fig. 3.2. Implementation of energy efficiency measures and the source of funding.

Pertaining to company size, 42.5 % of respondents represented small enterprises, 42.5 % – medium size enterprises, and 15 % – large enterprises. The highest share of respondents (40 %) represented the food production industry, and its diverse subsectors: meat processing, fish processing, dairy, bakery, and sweets production. Other respondents were from the beverage (10 %), textile (5 %), wood processing (2 0%), chemical processing (2.5 %), non-metallic mineral processing (2.5 %) fabricated metal production (17.5 %), and machinery production (2.5 %) industries.

In 29 of the surveyed companies (71 % of respondents), the share of energy costs was more than 5 % of the total costs. Given that a 5 % energy cost share is widely used as the benchmark for energy-intensive and energy non-intensive companies [33], most of the analysed companies are labelled as energy-intensive.

3.2.1. Barrier Ranking

The ranking of the identified barriers and drivers was carried out based on the results of the central tendency measure. The variables were grouped according to the different types of barriers: economic, behavioural or organizational barriers (see Fig. 3.3). In the analysed companies, the most dominant barriers were found to be:

- adverse selection (choice by ease of use rather than energy efficiency),
- investments required for the implementation of energy efficiency measures was considered to be too high,
- lack of internal competence to implement energy efficiency measures (external consultants would be needed),
- stakeholders' perceive the payback time for energy efficiency measures as being too long,
- introduction of energy efficiency measures is hampered by complex decision-making chains in the company.

For the companies with no previous experience with the implementation of energy efficiency measures (the non-implementers), all of the highest ranking barriers were present. Only one of the non-implementers intends to adopt energy efficiency measures in the coming 2–3 years. Therefore, additional mechanisms for the mitigation and overcoming energy efficiency barriers are necessary.

The main drivers for implementing energy efficiency measures are: increasing company's competitiveness, willingness to share its experience to promote energy efficiency in other companies, and an overall interest in promoting energy efficiency (see Fig. 3.4).

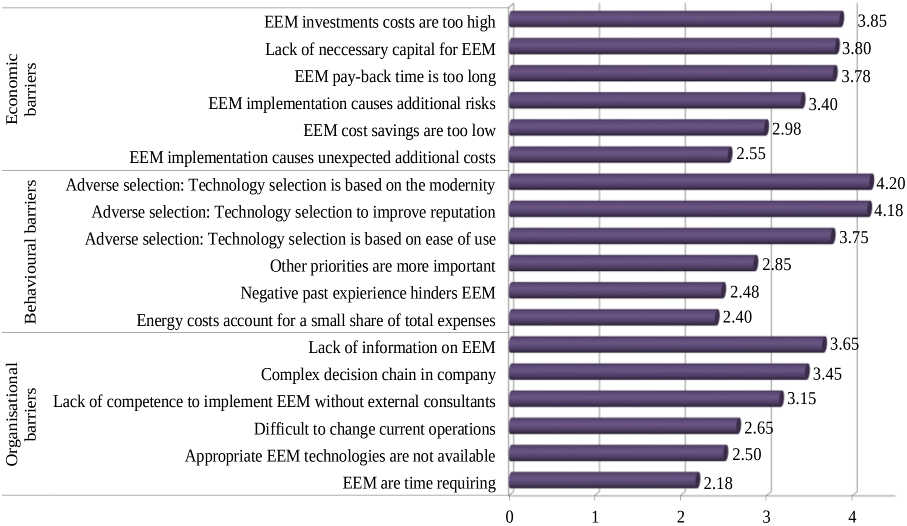

Fig. 3.3. Ranking of energy efficiency barriers.

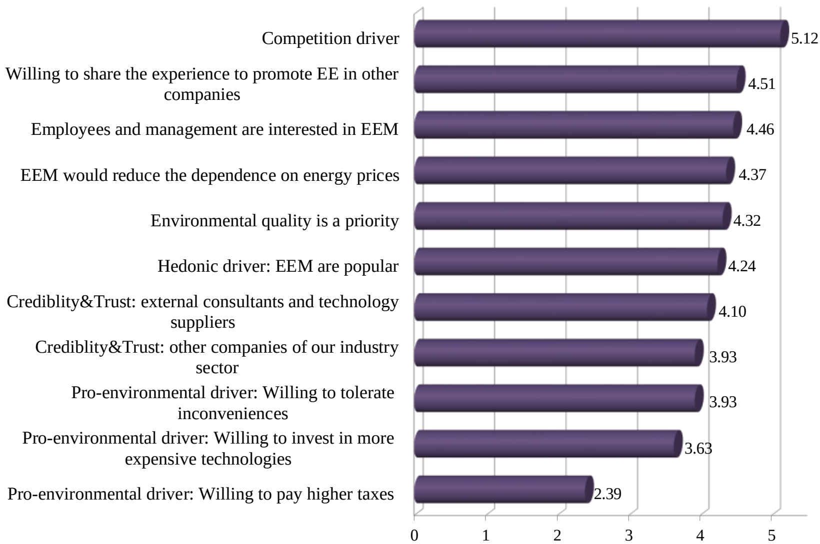

Fig. 3.4. Ranking of energy efficiency drivers.

Similar to the approach of Trianni et al. [34], correlation analysis has been performed to identify the relationships between energy efficiency barriers and drivers. The analysis results indicate 28 mutual correlations with correlation coefficients higher or lower than ±0.4, respectively. These correlations point to potential underlying aspects that could not be identified through direct questions. To gain further insight into these underlying aspects, an exploratory factor analysis with varimax rotation has been performed. The factor analysis has resulted in five constructs with eigenvalues above 1 (see eigenvalues for each of the constructs in Table 3.1) Together these factors account for 73.4 % of the variability in the initial data. According to their context, the variables have been denoted as: habitual behaviour barrier, priority barrier, inertia barrier, organisational barrier, and pro-environmental driver. This empirical data based analysis confirms the interconnection of energy efficiency barriers and drivers, and provides a quantitative derivate that characterises this relationship. All five acquired factors are further employed to develop the mathematical model.

Table 3.1

Results of the exploratory factor analysis for energy efficiency survey data

	Habitual behaviour barrier	Priority barrier	Pro-environmental driver	Organisational barrier	Inertia barrier
Difficult to change current operations	**0.688**	0.340	-0.325	0.205	-0.137
Technology selection is based on ease of use	**0.671**	-0.169	-0.241	0.282	0.219
EEM* implementation causes unexpected additional costs	**0.792**	-0.057	0.208	0.042	0.278
EEM pay-back time is too long	**0.696**	0.258	-0.013	-0.041	0.128
EEM cost savings are too low	0.478	**0.568**	-0.077	0.401	0.088
Energy costs account for only a small share of total expenses	0.089	**0.901**	-0.045	-0.030	0.167
Other priorities are more important	0.038	**0.803**	0.050	0.249	0.056
Willing to pay higher taxes for the environment	0.116	-0.073	**0.782**	-0.082	0.040
Willing to tolerate inconveniences for the environment	-0.051	0.235	**0.772**	0.169	-0.248
Willing to invest in more expensive technologies for the environment	-0.351	-0.160	**0.788**	0.216	0.038
Complex decision-making chain in company	0.049	0.346	0.191	**0.798**	0.037
Negative past experience hinders EEM	0.159	0.019	0.032	**0.835**	0.184
(– 1)* Competition driver	0.244	0.291	-0.169	-0.031	**0.812**
EEM are time consuming	0.142	0.029	0.034	0.290	**0.823**
Eigenvalue	4.11	2.40	1.62	1.17	1.11
KMO for the set of variables			0.61		
Cronbach's α for the set of variables			0.75		
Percentage of deviance explained			74.3 %		

*EEM – energy efficiency measures

3.2.2. The Mathematical Modelling of Survey Results

The company's experience with the implementation (or non-implementation) of energy efficiency measures depends on the specific set of independent variables that may be included, but are not limited to the company's general priorities, background conditions, the decision-maker's personal beliefs, principles, assumptions, as well as availability and quality of information, and other factors that characterise the market. Mathematical modelling is applied to differentiate between the "implementers" and the "non-implementers" of energy efficiency measures. The dependent variable – "Implementation of energy efficiency measures" – is designated with a binary dummy variable (0 for "not implemented" and 1 for "implemented"). The independent variables are the previously extracted factors (interval data) and a company's specific background conditions (categorical data).

The mathematical model is obtained by using the general logistic regression (3.1) and the specific Equation (3.2), which provides an expression for the calculation of the η_i variable. A stepwise backward selection of the variables was applied. The developed model accounts for 65.4% of deviance in the initial data and 38.9% of the adjusted deviance. According to Vīgants et al. [35], the adjusted deviance is similar to that of other studies of this nature. The analysis of deviance identified that a model's P-value is 0.0002, which is less than 0.05; thus, there is a statistically significant relation between the selected variables at a 95 % confidence level.

$$I = \frac{\exp(\eta_i)}{(1+exp(\eta_i))} \tag{3.1}$$

where

I – dependent variable;

η_i– an equation that characterises the independent variables.

$$\eta_i = 21.6 - 1.3\text{*Priority barrier} + \alpha\text{*Energy audit} + \beta\text{*Respondent's role} \tag{3.2}$$

where

Priority barrier – numerical variable;

Energy audit – categorical variable (coefficient values: α=0, if energy audit has been implemented, otherwise α= -19.6);

Respondent's role – categorical variable (coefficient values: β=0, if the respondent was the company's owner, otherwise β=20.5).

The mathematical model developed includes two categorical variables from the general question set. For each of the variable's potential categories, different values for α and β coefficients must be used. The variable Respondent's role is a binary variable, which identifies if the respondent is the owner or a manager of the company. This variable is significant due to a tendency that in those companies that had not implemented energy efficiency measures the respondents were company owners. In all of these cases though, they were also the real onsite managers; thus, they were immersed in the company's daily operations.

Due to the sampling technique applied, the results cannot yet be generalized to the entire Latvian industry. However, the empirical data gathered has allowed for the approbation of the developed methodology, which allows describing the implementation of energy efficiency measures. The interconnectivity of energy efficiency barriers and drivers increases the complexity of these issues and requires a systemic and inventive approach to address them. However, the review of contemporary literature indicates that the effects of various barrier mitigation mechanisms are still insufficiently researched. The approbated methodology provides the necessary insights to further analyse and mathematically describe the effects of various barrier mitigation mechanisms, while considering company specific background conditions and energy efficiency barriers and drivers.

3.3. Industrial Symbiosis Survey Results

The industrial symbiosis survey sample size (n) is 36 respondents. Overall, 45 companies have been approached and offered to respond to the survey, but several companies turned down this proposal. The respondents' contact information has been obtained mainly from public databases (the database on company pollution permits [36], public access of the national statistical report "3-Waste" [37], and an enterprise data base [38]), and from previous contacts with companies.

Most of the survey respondents have been the company's environmental specialists (47 %), company owners or managers (33 %). As many companies do not have a dedicated environmental specialist, other knowledgeable employees have been interviewed (e.g. technical director, production manager, energy manager, technologist, quality manager). The majority of respondents have represented medium-sized enterprises (53 %) and small enterprises (31 %), with large and micro enterprises represented by 8 % of respondents each. The respondents have represented ten different sub-sectors of the manufacturing industry: food production (16.7 %), beverage production (13.9 %), wood processing (11.1 %), printing (8.3 %), chemical processing (8.3 %), rubber and plastic production (8.3 %), non-metallic mineral processing (19.4 %), fabricated metal production (2.8 %), vehicle production (2.8 %), and furniture manufacturing (8.3%). Two types of by-product exchanges have been investigated at each company surveyed:

A. use of other company's by-products in the researched company,
B. transfer of by-products, co-products, or splits generated at the investigated company to other companies to be used for production of other products or energy.

Out of the 36 companies surveyed, Type A exchanges have been identified in 10 companies, and type B exchanges – in 21 companies. Altogether 28 companies have implemented at least one type of exchange, 3 companies have implemented both types of exchanges, while 8 companies have not implemented any by-product exchanges (see Fig. 3.5).

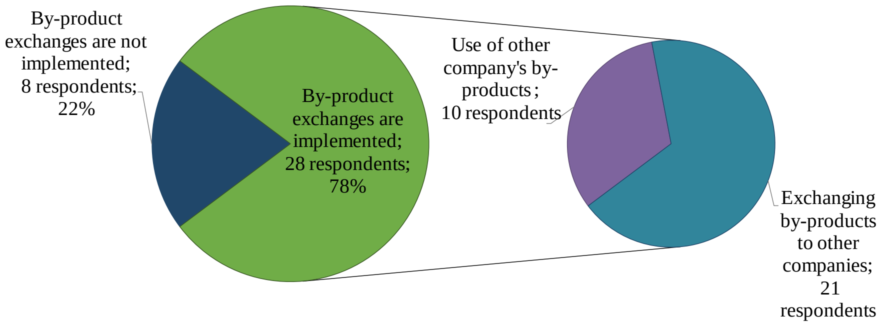

Fig. 3.5. Identified by-product exchanges.

Figure 3.6 depicts the distribution of identified exchanges according to the surveyed industry sectors. The identified types of exchanges are very industry-specific, e.g., all five breweries surveyed haved organised a giveaway of brewer's spent grain to local farms for use as animal feed. Some food producers transfer the organic residues for further processing, or for energy recovery in biogas plants. In the non-metallic mineral processing industry, four Type A exchanges include raw material substitution by other non-organic by-products or recycled materials, but the Type B exchanges include waste-to-energy solutions (energy recovery from non-recyclable cardboard, wastewater sludge for biogas production) and a giveaway of non-organic mineral materials for the road construction industry. The most significant motivation to implement by-product exchanges is to alleviate by-product management, followed by ensuring a more efficient use of natural resources, and to gain profit.

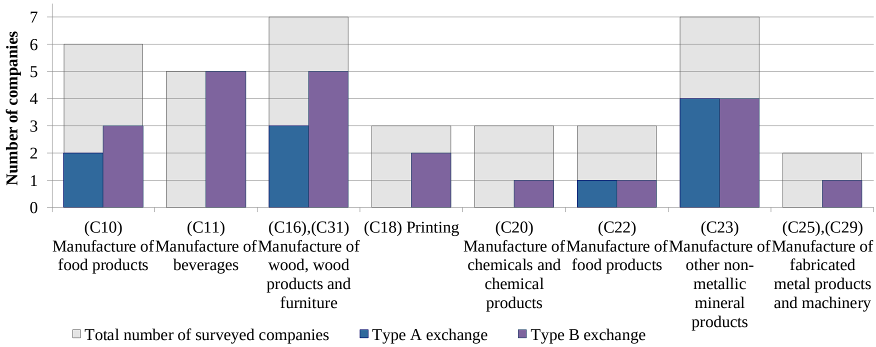

Fig. 3.6. Distribution of the identified by-product exchanges by type of industry.

Within the next 2–3 years, companies will be keener to implement energy efficiency measures (78 % of the respondents) than by-product exchanges (33 % of the respondents), even though most companies have mentioned that resource efficiency issues have a higher priority in their companies. The implementation of these different measures depends on several factors (both technological and behavioural), so it cannot be assumed unequivocally that any of these issues is more important than the other. But to ensure a sustainable, long-term strategy, the integrated implementation of equipment modernisation, energy efficiency, resource efficiency, and industrial symbiosis measures must be pursued.

3.3.1. Barrier Ranking

The most significant barrier for the implementation of industrial symbiosis measures is its low priority in comparison with other priorities, i.e., core business, energy efficiency measures (see Fig. 3.7). Other significant barriers include: lack of time for additional investigation and arrangement of by-product exchanges (organisational barrier), lack of necessary capital, and that the potential profit or savings are too low (economic barriers), as well as technical barriers – the use of by-products is not supported by present technology, or the necessary amount of by-products cannot be ensured. Six out of eight companies that do not implement by-product exchanges indicated that their technological processes do not support any potential use of industrial by-products. However, in cases where the reuse of by-product is possible, barrier mitigating mechanisms ought to be applied to reduce barriers and promote industrial symbiosis and resource efficiency.

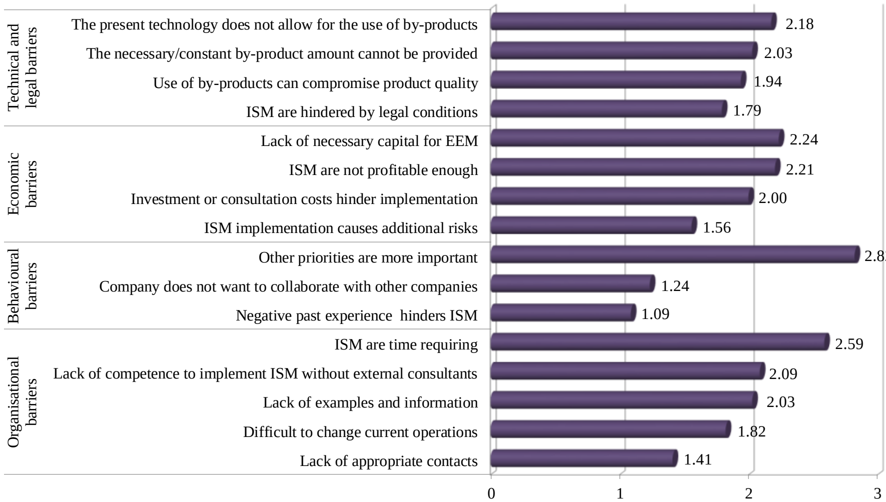

Fig. 3.7. Ranking of industrial symbiosis barriers.

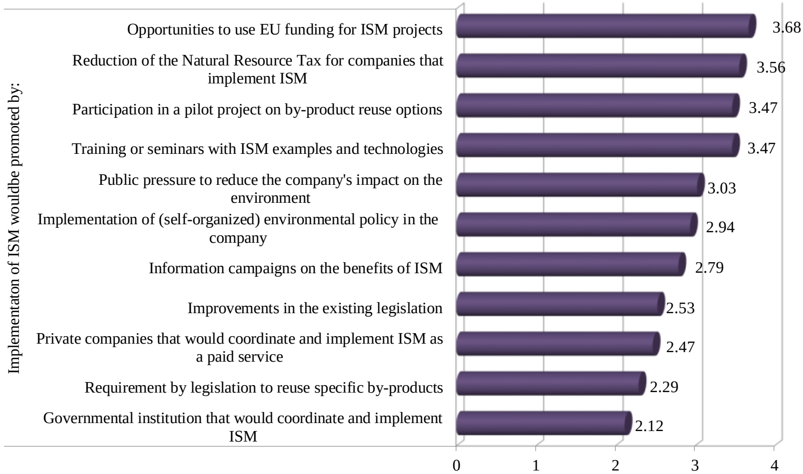

Fig. 3.8 Ranking of mechanisms for overcoming industrial symbiosis barriers.

Regarding barrier mitigation mechanisms (see Fig. 3.8), respondents evaluated most mechanisms rather positively. Economic mechanisms were ranked the highest (subsidies and tax reductions), as well as participation in pilot projects and practical trainings. The lowest evaluation is for top-down mechanisms, e.g., a potential governmental institution for the coordination of by-product exchanges and compulsory legislation requirements.

The respondents (regardless of their position at the company) expressed an unfavourable attitude towards government-related and institutional mechanisms, and a more light-minded attitude towards economic mechanisms, thus characterising the current business environment. However, based on the previous literature review, it should be emphasised that the respondents’ ability to identify barriers is limited by their knowledge and competence. In addition, a respondent may only identify the perceived barriers. For example, it may be more convenient to assume that the costs of resource efficiency measures are too high than to admit that the real barriers are organisational or behavioural. Similarly, company representatives may overrate the effect of their preferred barrier overcoming mechanisms.

Table 3.2

Results of the exploratory factor analysis for the energy efficiency survey data

	Habitual behaviour barrier	Organisa-tional barrier	Economic barrier
Lack of examples and information	**0.606**	0.508	-0.394
ISM are time consuming	**0.746**	0.223	-0.023
Company does not want to collaborate with other companies	**0.681**	0.012	0.175
Other priorities are more important	**0.734**	0.037	0.242
Lack of appropriate contacts	0.080	**0.857**	-0.022
ISM are not profitable enough	0.133	**0.759**	0.386
Investment or consultation costs hinder implementation	0.282	0.288	**0.669**
Lack of necessary capital for EEM	0.047	-0.022	**0.874**
Eigenvalue	2.79	1.46	1.09
KMO for the set of variables		0.6	
Cronbach's α for the set of variables		0.72	
Percentage of deviance explained		66.8 %	

The results of the correlation analysis have identified 37 mutual correlations with correlation coefficients higher or lower than ±0.35, respectively. The results of an exploratory factor analysis with varimax rotation (see Table 3.2) have identified three underlying constructs. Together, these factors account for 66.8 % of the variability in the initial data. Accordingly, the contextual variables are the habitual behaviour barrier, organisational barrier and the economic barrier.

3.3.2. The Mathematical Modelling of Survey Results

By fitting a logistic regression model, the identified variables are related and two mathematical models are developed that predict the implementation of Type A and Type B exchanges. For both models, the dependent variable is designated with a binary dummy variable (0 for "not implemented" and 1 for "implemented").

The mathematical model developed for Type A exchanges is presented by (3.1) and (3.3). The variable "Inappropriate technology" is a categorical variable that describes whether a company's technology would or would not allow for the use of by-products. A stepwise backward variable selection has resulted in a model that accounts for 86.3 % of deviance in the initial data, and 42.6 % of adjusted deviance. The analysis of deviance has identified that the model's P-value is 0.0000 which is less than 0.05; thus, there is a statistically significant relation between the selected variables at a 95 % confidence level.

$$\eta_i = -24.01 - 2.81 * \text{Habitual behaviour barrier} - 3.11 * \text{Organisational barrier} + \alpha * \text{Inappropriate technologies} + \beta * \text{Priority} + \gamma * \text{Waste cost}, \quad (3.3)$$

where

Habitual behaviour barrier, Organisational barrier – numerical variables;

Inappropriate technologies– categorical variable (coefficient values: α=0 for category "Do not agree", α=35.316 for "Rather not agree", α=42.26 for "Rather agree", α=5.85964 for "Agree");

Priority – categorical variable (coefficient values: β=0 for category "Energy efficiency priority", β=- 41.5861 for "Equally important", β=- 0.310106 for "Raw material and by-product priority");

Waste cost – categorical variable (coefficient values: γ=0 for category "Waste costs not too high", γ=- 17.182 for "Waste costs too high").

The developed mathematical model for Type B exchanges is presented by (3.1) and (3.4). A stepwise backward variable selection has resulted in a model that accounts for 70.6 % of deviance in the initial data and 27.8 % of adjusted deviance. As the model P-value is 0.0001, there is a statistically significant relation between the selected variables at a 95 % confidence level.

$$\eta_i = 3.97 + 5.44 * \text{Behavioural barrier} - 3.14 * \text{Organisational barrier} + \alpha * \text{ISO14001} + \beta * \text{ISO50001} + \gamma * \text{Waste cost} + \delta * \text{Natural resource tax} + \varepsilon * \text{Size}, \quad (3.4)$$

where

Habitual behaviour barrier, Organisational barrier – numerical variables;

ISO14001– categorical variable (coefficient values: α=0 for category "Not implemented", α = –8.57 for "Implemented");

ISO50001– categorical variable (coefficient values: β=0 for category "Not implemented", β = – 8.93for "Implemented");

Waste cost – categorical variable (coefficient values: γ=0 for category "Waste costs not too high", γ=–20.4691 for "Waste costs too high");

Natural resource tax – categorical variable (coefficient values: δ =0 for category "Tax not too high", δ =+ 26.97 for "Tax too high");

Size – categorical variable (coefficient values: ε=0 for category "Micro-enterprise", ε=–17.4961 for "Small enterprise", ε=–10.6185 for "Medium size enterprise", ε= –1.45718 for "Large enterprise").

Though the obtained results apply only to the sample analysed, as the first extended study on the implementation of industrial symbiosis measures in Latvian industry the present research provides invaluable insight on the specific local circumstances that promote or hinder the implementation of resource efficiency measures. The applied methodology allows for a novel analysis of relationships between the predictor variables and a company's perceived barriers and drivers. In the future, these mathematical models may be further validated with data from a broader processing industry-wide study.

3.3.3. The Mathematical Modelling of Barrier Overcoming Mechanisms

To extend the existing approaches, the developed methodology has also been applied to a mathematic model for the future implementation of industrial symbiosis measures depending on the existing industrial symbiosis barriers and potential barrier overcoming mechanisms. Firstly, a factor analysis has been applied to extract the four significant constructs that characterise the underlying aspects of barrier overcoming mechanisms (see Table 3.3). The developed constructs have been further included in the mathematical model (see (3.1) and (3.5)), in which the dependent variable is "Intention to implement industrial symbiosis". The fitted logistic regression model explains 91.8 % of the deviance in the original data, and 60.1 % of the adjusted deviance. The P-value of the model (0.0000) indicates a statistically significant relation between the selected variables at a 95 % confidence level.

$$\eta_i = 142.1 - 43.3 * \text{Habitual behaviour barrier} - 3.6 * \text{Business drivers} + \alpha * \text{Respondent's role} + \beta * \text{ISO14001} + \gamma * \text{Previous experience}, \quad (3.5)$$

where

Habitual behaviour barrier, Business drivers – numerical variables;

Respondent's role – categorical variable (coefficient values: $\alpha=0$ for category "Environmental specialist", $\alpha=-280.5$ for "Owner" or "Manager", $\alpha=-61.6$ for "Other employee");

ISO14001– categorical variable (coefficient values: $\beta=0$for category "Not implemented", $\beta=96.3$ for "Implemented");

Previous experience – categorical variable (coefficient values: $\gamma=-277.9$ for category "No experience", $\gamma=0$ for "Previous experience").

Table 3.3

Results of the exploratory factor analysis for barrier overcoming mechanisms

	Business drivers	Organisational improvements	Legislation improvements	Outside subsidies
Information campaigns on the benefits of ISM	**0.775**	0.250	0.150	-0.169
Public pressure to reduce a company's impact on the environment	**0.701**	0.318	0.233	0.252
Private companies that would coordinate and implement ISM as a paid service	**0.908**	-0.109	0.032	0.063
Training or seminars with ISM examples and technologies	0.368	**0.827**	0.077	-0.090
Implementation of environmental policy in the company	-0.050	**0.617**	0.159	0.295
Reduction of the Natural Resource Tax for companies that implement ISM	0.073	**0.891**	-0.028	-0.044
Legislation requirement to reuse specific by-products	0.242	0.028	**0.751**	0.238
Governmental institution to coordinate and implement ISM	0.176	0.214	**0.803**	-0.118
Improvements in the existing legislation	-0.033	-0.028	**0.774**	0.060
Participation in a pilot project on by-product reuse options	0.013	-0.095	0.052	**0.907**
Opportunities to use EU funding for ISM projects	0.045	0.180	0.068	**0.857**
Eigenvalue	3.34	1.84	1.54	1.31
KMO for the set of variables	0.66			
Cronbach's α for the set of variables	0.75			
Percentage of deviance explained	73.0 %			

The previous implementation of industrial symbiosis has the strongest impact on the future intention to implement these measures followed by the implementation of an Environmental Management Standard (e.g., ISO14001). Company's environmental specialists are more prone to think that industrial symbiosis measures could potentially be implemented in future, than other employees and company's owners. Larger values for the constructs *Business drivers* and *Habitual behaviour barrier* indicate smaller likelihood to implement industrial symbiosis measures in the future.

CONCLUSIONS

1. An analysis of the statistical data indicates that the highest resource productivity in Latvia was achieved during the economic crisis (582 €/tonne in 2009), indicating companies' ability to optimise their production. However, since then, resource productivity has gradually decreased (512 €/tonne in 2014). Though a relative decoupling is seen at the national level, the industry shows a lack of decoupling of the economic growth and the environmental aspects. The current resource efficiency trends indicate the necessity for targeted measures and coordinated policy to achieve the national resource productivity aim, i.e., 600 €/tonne in 2020.
2. The company's decision on the implementation of energy efficiency measures depends on the availability of reliable data. But, in the case of SMEs, the availability of energy consumption data is limited, e.g., energy consumption is rarely accounted for at a sub-department or production line level. This has also been confirmed during the analysis of a small brewery, when the methodology for the assessment of heat losses at the brew house and electricity efficiency at the bottling department has been approbated. For example, it has been calculated that the recovery of the energy from steam emissions during wort boiling can provide a significant reduction (21.5 $MJ/hl_{beer\ produced}$) of thermal energy losses and account for 9.8 % of the total thermal energy consumption per hl of beer produced. The suggested measure has a return on investment time of 1.1 years.
3. The electricity monitoring results in the brewery show that the specific electricity consumption (MJ/hl) can differ by a factor of 14 between the three types of packaging (metal kegs, glass, and plastic bottles) investigated. Furthermore, electricity is consumed inefficiently during off-time (up to 14.9 % of the equipment overall consumption during the monitoring period). On top of this, idling has been recorded. This suggests that a more detailed knowledge on the energy consumption of various equipment and production processes would enable a company's decision-makers to improve energy management and provide an opportunity to select more eco-efficient manufacturing approaches.
4. The analysis of scientific literature indicated a lack of possible approaches for the assessment of the varying quality of common resource reuse pathways. In order to complement the existing international research framework for the evaluation of industrial synergies (and industrial symbiosis networks), a novel industrial symbiosis evaluation method has been developed within this Thesis. This maturity model method allows for the evaluation of three critical aspects of industrial synergy quality: environmental performance, economic performance, and geographic proximity of industrial exchanges. The advantage of the developed method is the ability to compare synergies that involve an exchange of different resources (energy, materials, or water) and that each superior level of the maturity model acts as a guideline for the potential

improvement measures. The developed method has been approbated in 19 cases of industrial synergies.

5. The identified industrial collaborations in Latvia are typically individual cases rather than integrated networks of cooperation as in other countries, e.g., Sweden, Denmark, the United Kingdom, etc. The analysed examples prove that advanced and qualitative resource reuse opportunities are currently being implemented in Latvia – some examples reach the highest ratings in all three assessed sustainability dimensions. However, some types of the identified exchanges are under-performing – by-products are transported over very large distances, they do not provide any economic benefits, or the environmental quality of by-product application is low.
6. Although the implementation of significant energy and resource efficiency measures has been identified and analysed in this Thesis, their widespread adoption is hindered by resource and energy efficiency barriers. Previously in Latvia, these barriers have not been comprehensively identified. Therefore, a novel methodology has been developed for the identification of barriers to the implementation of resource efficiency measures, a statistical analysis, and mathematical modelling of these barriers. The developed method allows for the transformation of the qualitative barrier characterising data, which are acquired during the surveys, into quantitative factors that can be used for the development of further mathematical models. This method is a unique example for describing qualitative assumptions (barriers and drivers) in numerical terms. The developed method has been approbated in two cases: implementation of energy efficiency and industrial symbiosis measures, thus proving its applicability in varying contexts.
7. The modelling of the implementation of energy efficiency measures in Latvian industrial companies has resulted in a mathematical model that accounts for 65.4 % of the deviance in the initial data and 38.9 % of the adjusted deviance. The analysis has also identified high interconnectivity of various industrial energy efficiency barriers and drivers; therefore, factor analysis has been integrated within the developed method. This interconnectivity increases the complexity of the issues analysed and requires a systemic and innovative approach to address them. In the future, the mathematical model may be further validated with data from a broader manufacturing industry-wide study.
8. The modelling of the implementation of industrial symbiosis in Latvian industrial companies has provided two mathematical models that characterise two different types of industrial symbiosis exchanges. Type A exchanges include the use of another company's by-products in the investigated company, and Type B exchanges include a by-product giveaway to be used for reuse at another company. The logistic regression analysis for Type A exchanges has resulted in a model that accounts for 86.3 % of the deviance in the initial data, and 42.6 % of the adjusted deviance, and for Type B exchanges – 70.6 % of the

deviance in the initial data and 27.8 % of the adjusted deviance. The model may be further validated if manufacturing industry-wide data were to become available.

9. The third mathematical model for the implementation of industrial symbiosis characterises and proves the interconnection between a company's future intention to implement industrial symbiosis measures, the existing barriers, and various potential barrier overcoming mechanisms. These results may be applied for the further improvement of the national policy and for the selection of appropriate mechanisms to promote resource efficiency in the industry.
10. The conclusions drawn during the analysis and mathematical modelling of the resource efficiency barriers, drivers, and overcoming mechanisms essentially complement the existing body of knowledge available to decision-makers, policy-makers, and scientists. This knowledge is required for decision-making on the implementation of resource and energy efficiency measures in the industrial sector. The results of mathematical modelling and the provided conclusions may be applied further to improve a company's performance, to perform an in-depth analysis of the industrial sector, and to interpret the significant socio-economic aspects that hinder policy-making and the implementation of resource efficiency measures.

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