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

Jānis VILGERTS
Doctoral Student in the study programme "Environmental Science"

TRIPLE HELIX APPROACH IN HAZARDOUS WASTE MANAGEMENT SYSTEM

Summary of the Doctoral Thesis

Scientific supervisor
Professor *Dr. habil. sc. ing.*
DAGNIJA BLUMBERGA

RTU Press
Riga 2016

Vilgerts J. Triple Helix Approach in Hazardous
Waste Management System. R.: RTU Press, 2016. – 42 p.

Published in accordance with the decision
of the Institute of Energy Systems and Environment,
Minutes No. 62/2016 as of 4 March 2016

ISBN 978-9934-10-850-1

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

To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting on 8 September 2016 – 2 p.m., at the Faculty of Power and Electrical Engineering, 12/1 Azenes Street, Room 607.

OFFICAL REVIEWERS

Dr. sc. ing. Gatis Bažbauers
Riga Technical University

Dr. sc. ing. Oļģerts Nikodemus
University of Latvia

Dr. sc. ing. Sauļius Vasarevičus
Vilnius Gediminas Technical University

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.

Jānis Vilgerts ………………………………….. (signature)

8 September 2016

The present Doctoral Thesis has been written in English. It contains an introduction, 3 chapters, conclusions and bibliography with 150 reference sources. It has been illustrated by 33 figures and 9 tables. The total volume of the Thesis is 110 pages, not including appendices.

TABLE OF CONTENTS

Topicality of the Doctoral Thesis

Sustainable development of society and regions has been an important topic over the past decades. Uncontrolled management of hazardous substances may lead to contamination of ecosystems and damage for human health. Therefore, the author argues that a proper management strategy for hazardous waste is one of the key components for sustainable development.

However, in the practice of hazardous waste management there are various parties involved: enterprises, governmental organizations and research institutions. They are elements of the one system but preforming different functions; nevertheless, they are inevitably linked together.

This means that actions and interplay between these various parties can positively affect the whole system or can create place where the best practices and innovations cannot spread. Interplay between these various parties can create success stories, but the absence of interconnections can create stagnation because innovation does not take place in an institutional vacuum.

The theory on interplay among governmental institutions, research facilities and industry branches is known as a Triple Helix approach. This approach postulates a triadic relationship between university-industry-government in order to move towards knowledge society and innovations.

Aim and Tasks of the Doctoral Thesis

The aim of the present Thesis is to transfer and approbate the Triple Helix approach in the field of hazardous waste management in Latvia.

The following tasks have been set to achieve the aim:

1. to link the university and government by developing a novel forecast and quantification model of hazardous waste streams;
2. to link the university and industry by case studies using the design of experiment methodology;
3. to link the government and industry by the novel methodology based on the IPAT identity;
4. to apply a holistic approach to study an integrated university-industry - government interaction using the system dynamics modelling tool.

Hypothesis of the Doctoral Thesis

The author has formulated the hypothesis that a Triple Helix approach may improve management practices, institutional and research capacity, as well as foster the diffusion of innovations in the sector of hazardous waste management.

Scientific research is dedicated to the common goal of achieving the initiative, which is initiated by different sources of research. The aim is to reduce environmental pollution caused by environmentally harmful emissions from hazardous waste. Initiatives have three sources:

- government, i.e., initiatives are determined by the specific values of environmental pollution component within a specified time period;
- hazardous waste management industry, which is trying to reduce environmental pollution components in a specified period of time;
- scientific institutions that cooperate with hazardous waste management industry to find technological solutions to achieve the objective, as well as with government institutions in order to develop according to the level of development of innovations.

Methodology of Research

In order to test the hypothesis, various types of research methodologies have been used. Two distinct research methodologies can be distinguished: static and dynamic. The distribution of applied methodologies within the triple helix approach is given in Fig. 1.

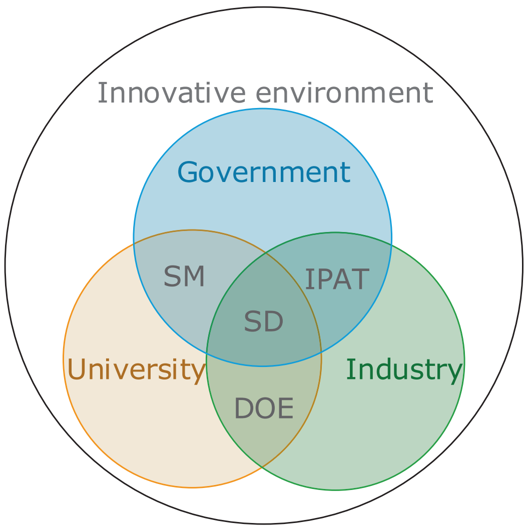

Fig. 1. Applied methodologies for the triple helix approach in the hazardous waste management system.

The following methodologies have been selected for the research: (1) statistical models (SM) to study the relationship between the university and government; (2) design of experiments (DOE) to study the relationship between the university and industry; (3) IPAT identity to study the relationship between the government and industry; (4) system dynamics (SD) to study the relationship of all parties involved. The selection of an appropriate tool is based on the aim of research, complexity of the task, available data and research boundaries, as well as situation-specific limitations.

To accurately illustrate the need for the use of triple helix approach, the research results have been tested at all three levels of institutional interaction.

Table 1

The Expanded Matrix of Research Methodologies

Link	Methodology				
	SM	DOE	DM	IPAT	SD
Government-industry	×		×	×	×
Government-industry-research institution	×		×		
Research institution -industry	×	×	×		
Government-research institution	×				×

The choice of methods is based on the significance assessment, which has been identified with the help of the results obtained.

Scientific Significance of the Doctoral Thesis

A complex study of the possibilities to improve hazardous waste management practices, institutional and research capacity as well as to foster the diffusion of innovations in the sector of hazardous waste management has been performed.

The present research is based on the introduction of the Triple Helix approach for hazardous waste management system in Latvia. The identification of novel methodologies for hazardous waste management practices is given.

These methodologies are tested based on the Triple Helix approach, thus creating 4 distinct research fields: interplay between the university and government is studied by developing novel forecast and quantification models of hazardous waste flows, interplay between the university and industry is studied by developing cases studies using design of experiment methodology, interplay between the government and industry is studied by proposing a novel tool based on IPAT identity and the interplay between all these three parties together is outlined and simulated using the system dynamics methodology. The presented methodologies are validated using various case studies in Latvia and presented in the Doctoral Thesis.

Practical Significance of the Doctoral Thesis

Studies of more effective hazardous waste management practices are a vital step to ensure sustainable development and improved quality of ecosystems and eliminated risks for human health. The application of Triple Helix approach for hazardous waste management sector in Latvia has a practical application at national, regional and local levels. The developed methodologies and obtained results can be transferred to improve performance of hazardous waste management systems.

The interplay between the university and government improves the forecast and quantification models used for hazardous waste flows, thus avoiding installation of oversized capacities of hazardous waste management.

The models given within the interplay between the university and industry improve the transfer of knowledge and increase competiveness of novel products.

The proposed tool for the improved interplay between the government and industry converges towards industrial symbiosis and zero waste practices.

Finally, the system dynamics models given for the interplay between all these three parties involved allow viewing the hazardous waste section in a holistic way, as well as simulating the influence of various internal and external factors, and policy tools. Using these models and Triple Helix concept, a pathway towards sustainable hazardous waste practices is strengthened.

Structure and Description of the Doctoral Thesis

The Doctoral Thesis is based on the thematically unified eight scientific publications. Those publications are published in various scientific periodicals and are accessible in scientific information repositories and cited international databases. The goal of the presented publications is to expand the range of studies on hazardous waste management.

The present Thesis consists of an introduction and three chapters:

1. literature review;
2. research methodologies;
3. results and discussion thereof.

In the introduction, the research aims and tasks are defined, the structure of the thesis is explained, and a short description of the author's studies is given that covers both the main publications and other studies by the author regarding the analysis of hazardous waste management.

Chapter One provides an overview of the literature and focuses on the necessary studies regarding aspects of hazardous waste management system and the improvement thereof as examined in the main publications. Chapter Two examines the methodologies of the issues studied in the main publications. The results obtained in the study are presented in Chapter Three. Conclusions are presented at the end of the Thesis.

An Overview of the Doctoral Thesis on the Triple Helix Approach for Hazardous Waste Management System

Introduction

Hazardous waste management system is an irreplaceable part of environmental protection and economics/society infrastructure, as well as an inevitable part of waste management.

In transition economies, hazardous waste management was, in general, only a governmental problem. It was naturally because hazardous waste, first of all, was an initiative from the society and only the government had all necessary policy instruments to establish a system.

In the system establishment process, the government plays a main role – the government enforces the legal framework of hazardous management and ensures establishment of the main infrastructure. Formally, there was quite wide involvement of the society, particularly – representatives from universities and industry. Mostly all decision-making persons had research background in the past. Interaction between the involved institutions was a static model.

Personal recirculation among institutions is widespread. The entire process should be innovative – creation of legal frame of waste management, i.e., introduction of PPP (Polluter Pays Principle), establishment of PRS (Producer Responsibility System), construction of main HW management infrastructure, creation of socio-economic conditions for establishment of HW industry and derivative organisations as industry associations, research institutions, etc.

Over the past decade the industry has become less dependent of the government, universities become more substantive, and a lot of new non-governmental establishments have started its activities. All those factors have also influenced the institutional interaction, and a static model has become the so-called laissez-faire model.

In Laissez-faire model, each institution (body) is independent and has clearly defined functions – the government should ensure the sustainable development of the society by using policy instruments, research institutions should conduct fundamental research and provide human resources, and the industry should promote the establishment of firms operating in the market to provide economic wealth for their owners and the society in general.

The triple helix is a platform for “institution formation”, creation of new organizational formats to achieve more efficient cooperation among institutions and promote innovation. Figure 2 demonstrates the synthesis of elements of the triple helix.

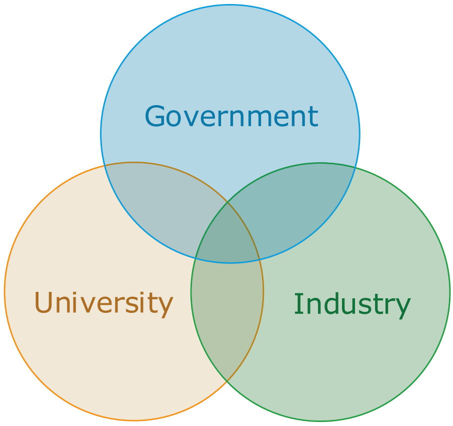

Fig. 2. Interaction between involved institutions in a triple helix model.

The triple helix captures this transformation of roles and relationships as intertwined spirals with different relations to each other. In a laissez-faire triple helix regime, industry is the driving force with the other two spirals as ancillary supporting structures; in a statist regime the government plays the lead role, driving academia and industry. Spirals are rarely equal; one usually serves as a motive force.

At present, the organizations involved in the hazardous waste management system can be included in a triple helix model as given in Fig. 3.

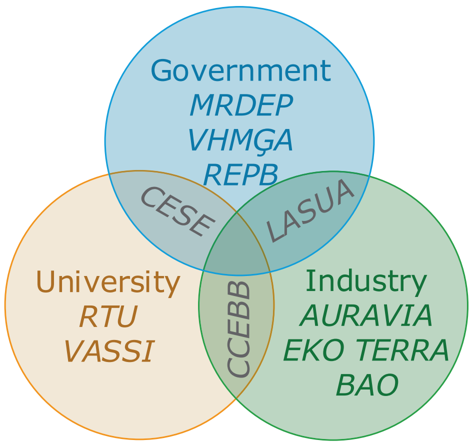

Fig. 3. Triple helix model for bodies involved in the hazardous waste management system in Latvia.

Government: MRDEP – Ministry of Regional Development and Environmental Protection; REPB – Regional Board of Environmental Protection; VHMGA – Latvian Environment, Geology and Meteorology Centre.

University: RTU – Riga Technical University; VASSI – Institute of Energy Systems and Environment.

Industry: Auravia Latvia,SIA;Eko Terra, SIA, JSC BAO

Derivative institutions: CESE – Council of Environmental Science and Education; CCEBB – Competence Centre of Environment, Biotechnology and Bioenergy; LASUA – Latvian Association of Waste Management Enterprises).

In order to reach goals and needs of the society in a sustainable way, these organizations should actively collaborate.

Short Description of the Solutions Used

The solutions for collaboration are presented in the Doctoral Thesis based on 8 scientific publications; the topicality of these publications is schematically given in Fig. 4.

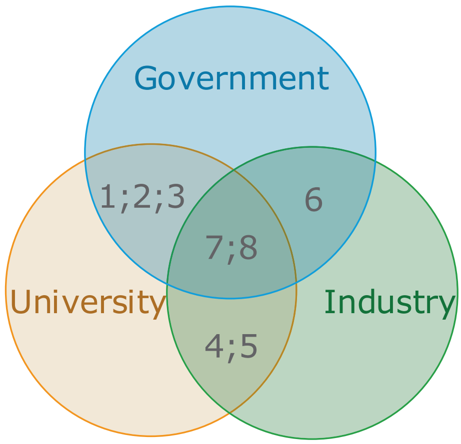

Fig. 4. Triple helix model for scientific publications developed for hazardous waste management in Latvia (number corresponds to the number of scientific publication in Table 2)

Table 2

Scientific Publications Used in the Doctoral Thesis for Hazardous Waste Management in Latvia to Study Triple Helix Approach

Studied interaction	No.	Title of publication
University and government	1	A Methodology for Forecasting Hazardous Waste Flows
	2	Forecast Model for Projecting the Amount of Hazardous Waste

	3	A Methodology for Quantification of Hazardous Waste Flows: Case Study for the Baltic States (Estonia, Latvia, Lithuania)
University and industry	4	Full Factorial Design on Screening Experiments for Biosurfactant Enhanced Remediation of Hydrophobic Substances in Soil
	5	Biosurfactants Enhanced Remediation of Historically Contaminated, Multiple Fraction Soil
Government and industry	6	Decomposition Analysis Based on IPAT and Kaya Identity for Assessment of Hazardous Waste Flow within Enterprise
University and government and industry	7	A System Dynamics Model for the Assessment of Hazardous Waste Management System. Case Study: Waste Batteries and Accumulators
	8	Assessment of Sustainable Collection and Recycling Policy of Lead-Acid Accumulators from the Perspective of System Dynamics Modelling

Further in the Thesis the author refers to these eight major publications as Paper 1, 2, 3, 4, 5, 6, 7 and 8, which correspond to the articles given in Table 2.

Connecting University and Government through Statistical Models

Algorithm of Methodology for Forecasting Hazardous Waste Flows

A new type of the indicator based on the HW intensity within the NACE Rev. 2 sectors and households has been developed (Paper 1). This indicator allows assessing the HW production intensity by taking into account a factor that a rise in the production rate will trigger a higher total amount of HW. The proposed indicator can be applied for the forecasting of future development of the HW intensity within the single sector and in the country. The indicator can be used for the benchmarking analysis of single manufacturers, companies of the same profile and the same sectors in different countries. Moreover, the indicator allows proposing measures for HW management system and monitoring the development of HW production intensity.

The developed methodology for forecasting hazardous waste flows consists of 6 modules: historical data, assumptions, choice of indicators, data processing and data analysis. Data analysis was performed (Paper 2) using STATGRAPHICS tools with input data based on the HW intensity within the Statistical Classification of Economic Activities in the European Community (NACE Rev. 2) sectors and households.

Methodology for Quantification of Hazardous Waste Flows

The dependence of the amount of HW on the GDP values is identified and described by applying the developed forecast model (Paper 3). The results of quantification model show that a multiple linear regression analysis can be used for the analysis of independent variables, which influence the amount of HW. Based on the data analysis and literature review, five independent variables have been chosen for the regression analysis: GDP expressed in millions of Purchasing Power Standard (PPS), primary energy consumption expressed in tons of oil equivalent (TOE), the total population in the country, the expenditure of business enterprise sector for research and development (R&D), and the amount of PPS per capita as the indicator of living standard in the country. The proposed independent variables can be further applied for the analysis and used to develop a forecast on the amounts of HW.

Connecting University and Industry through Design of Experiments

Materials and Methods for Design of Experiments with Artificially Contaminated Soil

The experimental tests given in Paper 4 showed a high reliability for the assessment of degreasing and, therefore, were especially suited for exploration and optimization of different surfactants and their mixes. The screening design was employed for the evaluation of interaction between the response variable and process variables. The results showed that all variables had significant effects on the cleaning efficiency at 95 % confidence level.

Materials and Methods for Design of Experiments with Historical Contamination

Historically polluted soil bioremediation was achieved (Paper 5) by a blend of bio-based anionic glycolipid surfactants for soil samples with light and medium oil contamination. The results of the research showed the potential for applications of "plate" tests for the formulation of new soil washing products and for the selection of proper biosurfactants for the problem under study. The "plate" tests could make engineers' work faster and simpler. Further research could involve another biosurfactant solution for the removal of heavy oil contaminations

Connecting Government and Industry through IPAT Identity

Paper 6 proposed the methodology for the assessment of changes for the aggregate of hazardous waste flow at an enterprise level due to a relative impact of investigated factors; these investigated factors are hazardous waste intensity, material intensity and the amount of raw material consumed by an enterprise. Hazardous waste stream is further decomposed based on the definition of waste hierarchy of reused, recycled, recovered and disposed hazardous waste flows. Based on the proposed methodology, case studies at an enterprise level can be performed in order to explore a cause in the aggregate changes in the past, present the forecast model for future trends, and also identify leverage points for intervention of policy tools with the aim to reduce the amount of hazardous waste.

Connecting the Parties Involved through System Dynamics

The system dynamics model comprising three feedback loops was created for the sector of the interest. To ensure the validity of the model, structural validation tests were carried out. Paper 7 shows that the introduction of innovation diffusion model for the sector of waste batteries and accumulators can decrease environmental pollution. However, based on the developed system dynamics model, scenarios comprising other policies could also be simulated, evaluated and discussed.

The developed model for the management of lead-acid accumulators shows how the transition from informal to formal practices in the collection system occurs, sheds light on the structure, dynamic behaviour, feedbacks, delays and drivers that transform the model. The model is valid as a decision supporting system for policy developers and as a platform for scientists for further research on dynamics of informal waste management practices. The model can be extended for other boundaries and case studies. Future studies could be performed to investigate the cost of the implementation of specific policy measures for the sector.

Approbation of the Research Results

The research results have been approbated in 11 international scientific conferences and published as 10 full length articles and 4 abstracts in international scientific journals and conference proceedings.

Reports at International Scientific Conferences

1. 53rd International Scientific Conference of Riga Technical University dedicated to the 150th Anniversary of Riga Polytechnical Institute and the 1st Congress of World Engineers / RTU Alumni Section “Power and Electrical Engineering”, Subsection “Environmental and Climate Technologies”, 10–11 October 2012, Riga, Latvia.

2. Vilgerts J., Timma L., Blumberga D. A Methodology for Forecasting Hazardous Waste Flows // 7th International Conference on the Impact of Environmental Factors on Health “Environmental Health Risk VII”, 23–25 April 2013, Budapest, Hungary.

3. Vilgerts J., Timma L., Blumberga D. Application of System Dynamic Model for the Composting of Petroleum Contaminated Soil under Various Policies //

4th International Conference "Biosystems Engineering 2013", 9–10 May 2013, Tartu, Estonia.

4. Vilgerts J., Timma L., Blumberga D. A Forecast Model for Projecting the Amount of Hazardous Waste // International Conference on Waste Management (ICWM 2013), 13–14 May 2013, Copenhagen, Denmark.

5. Timma L., Sams K., Valtere S., Vilgerts J., Blumberga D. Full Factorial Design on Screening Experiments for Biosurfactant Enhanced Remediation of Hydrophobic Substances in Soil // 4th International Conference on Environmental Engineering and Applications, 24–25 August 2013, Singapore, Republic of Singapore.

6. Vilgerts J., Timma L., Blumberga D. A Methodology for Quantification of Hazardous Waste Flows: Case Study for the Baltic States (Estonia, Latvia, Lithuania) // 13th International Environmental Conference, 05–07 September 2013, Athens, Greece.

7. Timma L., Sams K., Valtere S., Vilgerts J., Blumberga D. Biosurfactant-enhanced Remediation of Historically Contaminated, Multiple Fraction Soil // 2nd Edition of the International Conference and Exhibition WASTES: Solutions, Treatments and Opportunities, 11–13 September 2013, Braga, Portugal.

8. Vilgerts J., Timma L., Romagnoli F., Blumberga A., Blumberga D. A System Dynamics Model for the Assessment of Hazardous Waste Management System. Case Study: Waste Batteries and Accumulators // 8th Conference on Sustainable Development of Energy, Water and Environment Systems, 22—27 September 2013, Dubrovnik, Croatia.

9. Timma L., Blumberga D., Vilgerts J. Index Decomposition Analysis of Energy Sector in Latvia // 6th International Conference on Applied Energy, 30May–2 June 2014, Taipei, Taiwan.

10. Timma L., Vilgerts J., Vanaga R., Kļavenieks K., Blumberga D. Decomposition Analysis Based on IPAT and Kaya Identity for Assessment of Hazardous Waste Flow within Enterprise // 27th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, 15–19 June 2014, Turku, Finland.

11. Blumberga A., Timma L., Vilgerts J., Blumberga D. Assessment of Sustainable Collection and Recycling Policy of Lead-Acid Accumulators from the Perspective of System Dynamics Modelling // 17th Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction PRES 2014, 23–27 August 2014, Prague, Czech Republic.

Publications by the Author of the Doctoral Thesis

1. Vilgerts J., Timma L., Blumberga D. Management Strategy for Hazardous Waste // 53rd International Scientific Conference of Riga Technical University dedicated to the 150th Anniversary of Riga Polytechnical Institute and the 1st Congress of World Engineers / RTU Alumni Section “Power and Electrical Engineering”, Subsection “Environmental and Climate Technologies”. Book of Abstracts (ISBN: 9789934103605). 11–12 October 2012, 179 p.

2. Vilgerts J., Timma L., Blumberga D. A Methodology for Forecasting Hazardous Waste Flows // 7th International Conference on the Impact of Environmental Factors on Health “Environmental Health Risk VII”: WIT transactions (ISSN: 1747-4485). 2013, pp. 227–236. DOI: 10.2495/EHR130191.

3. Vilgerts J., Timma L., Blumberga D. A Forecast Model for Projecting the Amount of Hazardous Waste // World Academy of Science, Engineering and Technology (ISSN: 2010-376X). 2013, pp. 502–505.

4. Vilgerts J., Timma L., Blumberga D. Application of System Dynamic Model for the Composting of Petroleum Contaminated Soil under Various Policies // Agronomy Research (ISSN: 1406-894X). 2013, Vol.11, pp. 391–404.

5. Vilgerts J., Timma L., Blumberga D. A Methodology for Quantification of Hazardous Waste Flows: Case Study for the Baltic States (Estonia, Latvia, Lithuania) // Proceedings of the 13th International Conference on Environmental Science and Technology, 5–7 September 2013, Athens, Greece (ISBN 9789607475510). 2013, 371 p.

6. Vilgerts J., Timma L., Blumberga D. A Methodology for Quantification of Hazardous Waste Flows: Case Study for the Baltic States (Estonia, Latvia, Lithuania) // Proceedings of the International Conference on Environmental Science and Technology (ISSN: 1106-5516), 2013, paper No.0537, 8 p.

7. Vilgerts J., Timma L., Romagnoli F., Blumberga A., Blumberga D. A System Dynamics Model for the Assessment of Hazardous Waste Management System. Case Study: Waste Batteries and Accumulators // Book of Abstracts of 8th Conference on Sustainable Development of Energy, Water and Environment Systems (ISSN: 1847-7178). 2013, Paper ID: SDEWES2013.0467, 1 p.

8. Vilgerts J., Timma L., Romagnoli F., Blumberga A., Blumberga D. A System Dynamics Model for the Assessment of Hazardous Waste Management System. Case Study: Waste Batteries and Accumulators // Digital Proceedings of

8th Conference on Sustainable Development of Energy, Water and Environment Systems (ISSN: 1847-7178). 2013, paper ID: 0508, 12 p.

9. Timma L., Sams K., Valtere S., Vilgerts J., Blumberga D. Biosurfactant-Enhanced Remediation of Historically Contaminated, Multiple Fraction Soil // Book of Abstracts of the International Conference and Exhibition WASTES: Solutions, Treatments and Opportunities (ISBN: 9789899742949). 2013, pp. 403–404.

10. Timma L., Sams K., Valtere S., Vilgerts J., Blumberga D. Biosurfactant-Enhanced Remediation of Historically Contaminated, Multiple Fraction Soil // International Conference and Exhibition WASTES "Solutions, Treatments and Opportunities: Book of Proceedings (ISSN: 2183-0568), 2013, Vol.2, pp. 721–726.

11. Timma L., Sams K., Valtere S., Vilgerts J., Blumberga D. Full Factorial Design on Screening Experiments for Biosurfactant Enhanced Remediation of Hydrophobic Substances in Soil // Journal of Clean Technologies (ISSN: 1793-821X), 2014, pp. 51–56. DOI: 10.7763/JOCET.2014.V2.90.

12. Timma L., Blumberga D., Vilgerts J. Index Decomposition Analysis of Energy Sector in Latvia // Energy Procedia (ISSN: 1876-6102), 2014, Vol. 61, pp. 2180–2183. p.DOI:10.1016/j.egypro.2014.12.104.

13. Blumberga A., Timma L., Vilgerts J., Blumberga D. Assessment of Sustainable Collection and Recycling Policy of Lead-Acid Accumulators from the Perspective of System Dynamics Modelling // Chemical Engineering Transactions (ISBN: 978-88-95608-30-3, ISSN: 2283-9216). 2014, Vol. 39, pp. 649–654. DOI: 10.3303/CET1439109.

14. Timma L., Vilgerts J., Vanaga R., Kļavenieks K., Blumberga D. Decomposition Analysis Based on IPAT and Kaya Identity for Assessment of Hazardous Waste Flow within Enterprise // 27th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy systems, Turku, Finland, 6 p.

1. RESEARCH METHODS

1.1. Connecting University and Government through Statistical Models

This section provides an overview of the methodologies used for forecasting and quantification of hazardous waste flows; this section corresponds to the methodology part in Papers No. 1, 2 and 3.

1.1.1. Algorithm of Methodology for Forecasting Hazardous Waste Flows

The developed methodology for forecasting hazardous waste flows consists of 6 modules: historical data, assumptions, choice of indicators, data processing, and data analysis. Using historical data in the proposed algorithm it is possible to forecast HW flows in various sectors (see Fig. 7).

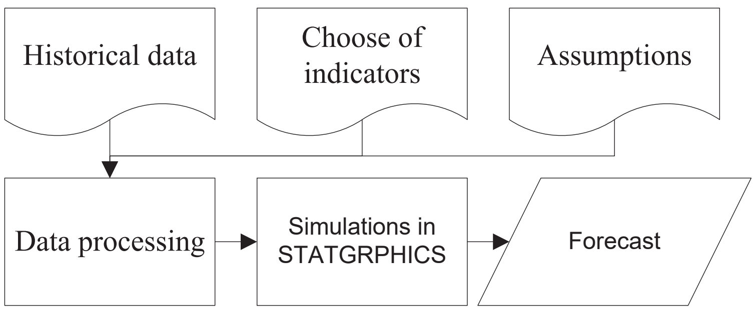

Fig. 7. The algorithm of the methodology.

Data analysis was performed using STATGRAPHICS tools with input data based on the HW intensity within the Statistical Classification of Economic Activities in the European Community (NACE Rev. 2) sectors and households.

1.1.2. Methodology for Quantification of Hazardous Waste Flows

As the dependent variable the amount of HW generated in one year for the time period of 1999–2009 was set. Part I of the report by the European Commission [2] was used as a data source for the amount of generated HW.

Based on the data analysis and literature review, five independent variables were chosen for the regression analysis:

- GDP expressed in millions of Purchasing Power Standard (PPS),
- primary energy consumption expressed in tons of oil equivalent (TOE),
- the total population in the country,
- the expenditure of business enterprise sector for research and development (R&D), and

- the amount of PPS per capita as the indicator of living standard in the country.

In order to obtain empirical model of relationship between the chosen independent and dependent variables, the methodology of regression analysis was applied. The regression analysis is the statistical method for investigation of relationships between one or more response variables (usually called dependent variables) and predictors (also called independent variables). For the given analysis, a multiple linear regression analysis was used because this method allowed incorporating in the model more than one independent variable.

The general form of multiple linear regression is the following:

$$y = \alpha_0 + \alpha_1 x_1 + \ldots + \alpha_n x_n + \varepsilon , \qquad (1)$$

where y is the dependent variable, $x_1, \ldots, x_n$ are independent variables, $\alpha_0, \alpha_1, \ldots, \alpha_n$ are the coefficients of regression equation and ε is the error term, which follows the normal distribution law. The advantages of multiple linear regression analysis include collinearity, inflation of variance, exposure of outliers and influential points as well as the ability to present the diagnosis of regression analysis graphically [36].

1.2. Connecting University and Industry through Design of Experiments

This section provides an overview of the methodologies used for design of experiments using biosurfactant; this section corresponds to the methodology part in Papers No. 4 and 5.

1.2.1. Materials and Methods for Design of Experiments with Artificially Contaminated Soil

Within the research, the interactions between 3 independent variables: temperature of environment (°C), contact time with dilution of biosurfactant (minutes), and concentration of biosurfactant in washing solution (% by weight (wt%)) were analysed. As a response (dependent variable), cleaning efficiency (%) was obtained experimentally by a set of the laboratory tests.

For this research, the factorial design for experimental data was chosen because the design allowed for the determination of factors with the highest impact on the process. Full factorial design of $2^k + k$ runs, where k is the number of variables, was selected for the screening design. The full factorial screening design involves runs at every possible combination at the defined upper and lower limit for each variable (see Table 3). To the matrix of design, additional centrepoints (a set of 3 experiments at the same conditions) were added (see Table 3).

Table 3

Design Matrix of the Experiment

Parameter	Upper limit	Lower limit	Centrepoint
Temperature, ºC	+35	+30	+32
Contact time, min.	15	5	10
Biosurfactant concentration, wt%	0.3	0.1	0.2

The validity of the model is verified by the analysis of values in the ANOVA table. The predication limit is set to 95.0 %. The interactive statistical data analysis tool STATGRAPHICS Centurion 16.1.15 was used to construct the model for factorial screening design.

1.2.2. Materials and Methods for Design of Experiments with Historical Contamination

The main objective of the optimization task was to predict the response value (cleaning efficiency) for all combinations of the process variables within the experimental region, and to define the optimal experimental point.

For the optimization task, the response surface methodology was applied. The defined process variables and experimental region are given in Table 4.

Table 4

Design Matrix of the Experiment

Parameter	Upper limit	Lower limit	Centerpoint
Temperature, ºC	+25	+15	+20
Hydrophilic-lipophilic balance	16	11	14
Biosurfactant concentration, wt%	0.6	0.1	0.3

The validity of the model is verified by the analysis of values in the ANOVA table. The predication limit is set to 95.0 %. The interactive statistical data analysis tool, STATGRAPHICS Centurion 16.1.15, was used to construct the model for surface response design. The general form of the quadratic model is given in (2).

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^{\ 2} + \beta_{22} x_2^{\ 2} + \beta_{12} x_1 x_2 + \ldots + \varepsilon \quad (2)$$

where y is the predicted response, β_0 is a constant, β_1, β_2 are linear coefficients, β_{11}, β_{22} are second order coefficients, β_{12} is an interaction coefficient, x_1, x_2 are variables, and ε is a constant representing noise [7].

1.3. Connecting Government and Industry through IPAT Identity

This section provides an overview of the methodology used for IPAT identity development to account for resource efficiency; this section corresponds to the methodology part in Paper No. 6.

The IPAT equation proposed identity (3) expresses the relationship between interdependent variables and the pressure on environment, where:

$$\text{Impact} = \text{Population} \cdot \text{Affluence} \cdot \text{Technology} \quad (3)$$

As a result of (3), the pressure on environment *I* or "Impact" can be given by the function of three variables: the level of population *P*, affluence *A*, which is expressed as per capita consumption, wealth or GDP per capita, and technology *T*, which is given by the pressure on environment per amount of consumption or the impact on environment per economic activity.

While the IPAT identity defines pressure on environment generally, a Kaya identity [10] focuses more specifically on environmental impact trough carbon dioxide emissions expressed by:

$$CO_2 = \frac{CO_2}{TEC} \cdot \frac{TEC}{GDP} \cdot \frac{GDP}{P} \cdot P \quad (4)$$

The Kaya identity can be viewed as a derivative of the IPAT identity; hence, (4) contains analogy with (3); in both equations the terms of "Population", "Affluence" and "Technology" are present. The term "Technology" in the Kaya identity is decomposed down to the product of carbon intensity and primary energy intensity.

To present quantitative values of the relative impact of investigated factors on the alternation in the aggregate indicator, the methodology of index decomposition analysis was used [11]. The use of the LMDI method is justified based on the following advantages given by Ang [11]: perfect decomposition (a proof given in the paper by Ang and Liu [12]), the results given in multiplicative and additive decomposition share a simple relationship between them, LMDI is consistent in aggregation.

1.4. Connecting All Involved Parties through System Dynamics

This section provides an overview of the methodology used for the modelling of waste battery and accumulator collection system; this section corresponds to the methodology part in Papers No. 7 and 8.

Forrester (1958) introduced the methodology of system dynamics (SD) and at present SD technique is widely used. The SD allows obtaining the interactions between a cause and effect in complex and dynamic systems that have delays, feedbacks and non-linearities. The methodology of SD applies a computer simulation model, which is developed for the problem under the review. The structure of SD model is built on diagrams of causal loop, which defines the main feedback mechanisms within the system (Forrester, 1961; Sterman, 2000) (see Fig. 8 a).

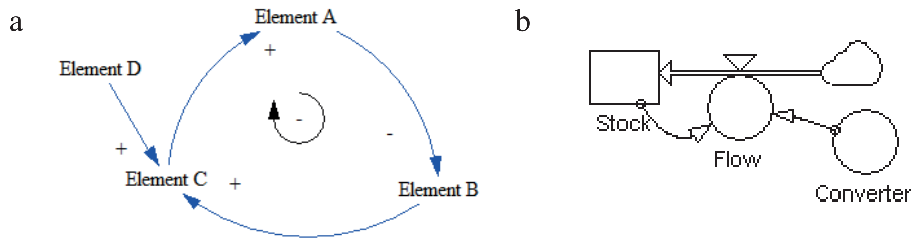

Fig. 8. a) a diagram of causal loop and b) a stock-flow diagram.

The diagram of causal loop consists of elements (Element A, B, C) and causal links (given as the arrows) between the elements. A causal link is ‘+’ in the case if A adds to B or an alteration in A gives an alteration in B in the same direction. A causal link is ‘–’ in the situation when A subtracts from B or an alteration in A produces an alteration in B in the opposite direction. A diagram of causal loop allows exploring the chain effects of a cause.

The diagram of causal loop is converted to a stock–flow diagram in order to obtain a quantitative model. The stock–flow diagram consists of 4 main ‘building blocks’: a stock, flow, converter and connector (see Fig. 8 b).

2. RESULTS AND ANALYSIS OF THE STUDY

2.1. Forecast Model Used between University and Government

This section provides the results and discussion of the models used for forecasting and quantification of hazardous waste flows; this section corresponds to the methodology part in Papers No. 1, 2 and 3.

2.1.1. Results of Forecast Model for Hazardous Waste Flows

Figure 9 gives the summary of the forecast model for all studied NACE sectors and households in Latvia. The upper limits for 95 % confidence level and the both upper and lower limits for 50 % confidence level are given in Fig. 9.

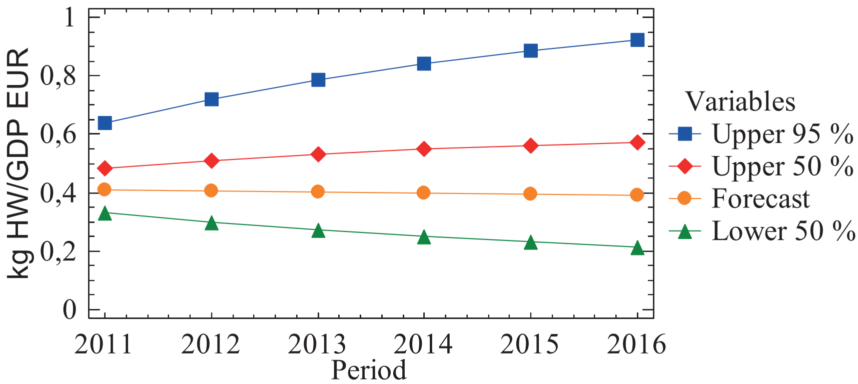

Fig. 9. Summary of the forecast model for all NACE sectors and households.

The results of the study suggest that HW intensity in Latvia is forecasted to slowly decrease by 3.8 % in next six years. The pessimistic prognosis (upper 95 %) gives an increase in HW intensity by 44.5 %, but intermediate (upper and lower 50 %) gives a corridor of +18.4 % to –36.1 %. Within the study a new type of HW intensity indicator has been developed. The proposed indicative value allows forecasting the changes of the HW intensity within the individual sectors. The indicator takes into account the supply and demand tendencies and, therefore, accounts for the fact that an increasing production rate will increase the total amount of HW. The indicative value should stay the same within the sector boundaries or even better if a value declines. The introduced indicator is an applicable tool for the development of waste management strategies and defining the indicative trajectories for the sector. The indicator can also be applied for the benchmarking analysis within the level of sectors or companies.

The summary of the results from the forecast model and historical data on the amount of HW are given in Fig. 10.

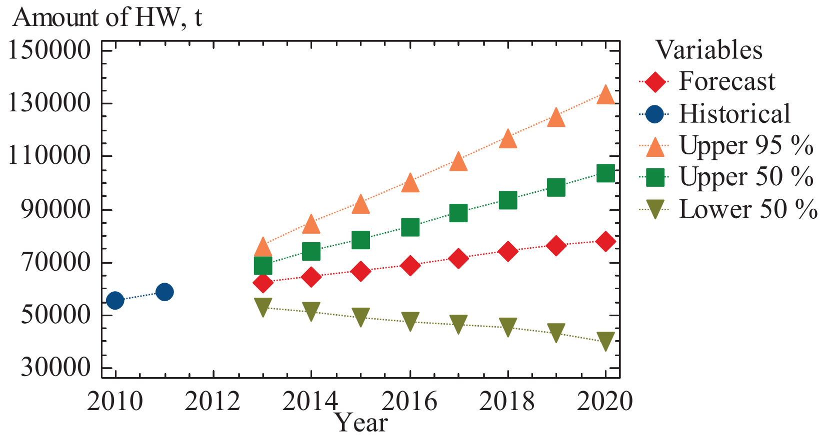

Fig. 10. The results from the forecast model and historical data for the HW amount.

The total amount of the HW is projected to grow by 41.2 % in the period of 2010–2020, which is a higher increase than that projected in the Waste Management Plan for Latvia 2013–2020. For the confidence level of lower 50.0 % (see Fig. 10), which can be referred to as the optimistic scenario, the amount of HW is projected to decrease by 27.7 % from 2010 to 2020. For the confidence level of upper 50.0 % (the pessimistic scenario) the increase of the amount of HW is 87.8 %.

2.1.2. Results from Quantification Model

As a result of the research 3 empirical equations, which describe how five independent variables influence the amount of HW in the Baltic States (Estonia, Latvia and Lithuania), were obtained (see Fig. 11).

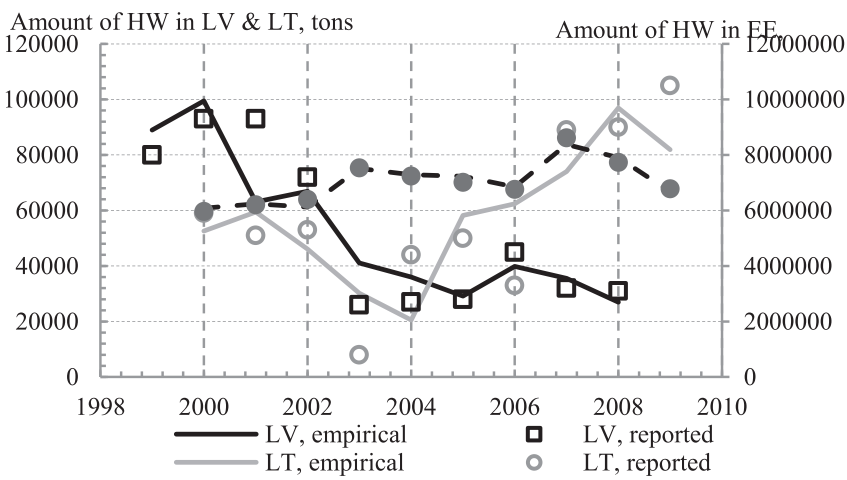

Fig. 11. The amount of HW in the Baltic States from the empirical equations and the reported amounts by the European Commission [2].

The “empirical” data in Fig. 11 refer to the amount of HW, which is calculated through empirical equations given below, and the “reported” data in Fig. 11 refer to the amount of HW, which is reported by the European Commission [2].

2.2. Response Surface Design Used between University and Industry

This section provides the results and discussion of the models used for design of experiment; this section corresponds to the methodology part in Papers No. 4 and 5.

2.2.1. Results for Design of Experiments with Artificially Contaminated Soil

For the final version of the model, the following empirical equation for cleaning efficiency was obtained:

$$\eta_{cl} = -1013.94 + 57.6467t + 20.3275\tau + 18.487c - \\ -0.74825t^2 - 0.5659t\tau \qquad (5)$$

where η_{cl} is cleaning efficiency, %, t is temperature, °C, τ is contact time, minutes, and c is concentration of the biosurfactant, wt%.

At the upper limit of variables (temperature of 35 ºC, contact time of 15 minutes, and 0.3 wt% concentration of biosurfactant), the cleaning efficiency obtained experimentally was 99.32 %. In Fig.12, the empirical Eq. (5) is shown in 3-dimensional space.

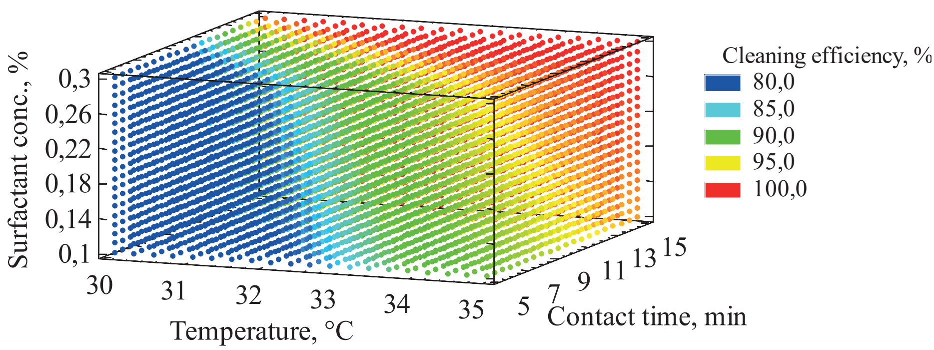

Fig. 12. Response plot for cleaning efficiency in 3-dimensional space.

2.2.2. Results for Design of Experiments with Historically Contaminated Soil

R-squared for the statistical model of sample I was 49.75 % and for sample II – 74.89 %. The plots of the estimated response surface for the model are given in Fig. 13.

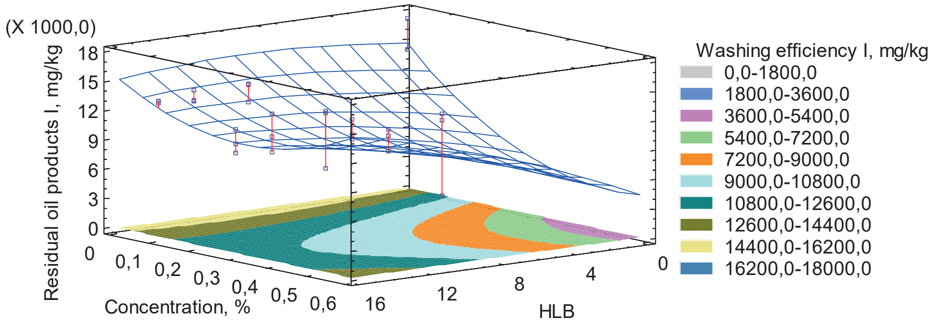

Fig. 13. The plot of the estimated response surface at temperature 20 ºC for soil sample I.

Relatively poor statistics of the statistical model for the coefficient of determination could be explained by the use of samples from historically contaminated soil. The contaminants undergo aging processes, which results in changes of composition of the initial substance.

Also, “possible absorption of molecules into the soil matrix, the formation of non-aqueous phases, interactions with organic matter, and biotransformation” could be present [26]. Therefore, the statistical model has data points with high variance. The research [9] showed that an increased pollution age had a negative effect on hydrocarbon removal from soil. Based on Paria [16] and Mulligan [17], diversity within the results can also be attributed to variable soil composition, which leads to low soil permeability, heterogeneity and insoluble forms of pollution.

During the set of experiments, it was observed that other significant factors influencing washing efficiency were the technological processes applied during washing, which was in agreement with results of the research [9]. Further research needs to account for another process variable: the aspect of the technology applied.

2.3. IPAT Identity Used between Government and Industry

This section provides an overview of the results obtained from the development of IPAT identity; this section corresponds to the result part in Paper No. 6.

The application of combined methodology tools given in the Methodology section is used for decomposition of a hazardous waste flow at an enterprise. The results presented here are of empirical nature.

The amount of hazardous waste from an enterprise can be represented by $I = PAT$ and Kaya type decomposition Eq. (6):

$$HW_i = \frac{HW_i}{CG} \cdot \frac{CG}{M} \cdot \frac{M}{E} \cdot E, \qquad (6)$$

where CG stands for consumer goods or services, M – raw material consumption within an enterprise, E – energy consumption within an enterprise. Thus, HW/CG is hazardous waste intensity of manufacturing consumer goods. It can be said that M represents population within $I = PAT$ equation, HW/CG represents environmental impact, and CG/M represents technology. To reduce the amount of hazardous waste, it is needed to reduce at least one of the factors on the right side.

By transforming (6) into a natural logarithm term and differencing (7), the following expression is obtained:

$$\frac{\mathrm{d}[\ln(HW_i)]}{\mathrm{d}t} = \frac{\mathrm{d}[\ln(HW_i / CG)]}{\mathrm{d}t} + \frac{\mathrm{d}[\ln(CG / M)]}{\mathrm{d}t} + \\ + \frac{\mathrm{d}[\ln(M / E)]}{\mathrm{d}t} + \frac{\mathrm{d}(\ln E)}{\mathrm{d}t} \tag{7}$$

Equation (7) shows that percentage change rate in hazardous waste at a certain time point can be represented by the sum of the change rates in hazardous waste intensity, material intensity and the amount of raw material at an enterprise.

However, it is also important to qualify actions made with hazardous waste within a company. Waste hierarchy defines the following steps: waste prevention, reuse ($HW_{\mathrm{reu.}}$), recycle ($HW_{\mathrm{recy.}}$), recovery ($HW_{\mathrm{recov.}}$) and disposal ($HW_{\mathrm{d.}}$). Further research is needed in order to include this variable in the equation; therefore, four these terms will be accounted as separate terms for HW_i.

$$HW_i = \sum\nolimits_i HW_{\mathrm{reu.},i} + HW_{\mathrm{recy.},i} + HW_{\mathrm{recov.},i} + HW_{\mathrm{d.},i} \tag{8}$$

Moreover, to quantify the relative contribution of each term of (7) and (8) combined on the hazardous waste trend, attention should be paid to the change of variables over a specific time period rather than the instant change rate. The index of hazardous waste between year 0 and year T can be represented by the product of the index of waste intensity, material intensity and amount of raw material at an enterprise. It means that the determinants of changes in hazardous waste from an enterprise between year 0 and year T can be first identified by investigating changes in these compositional factors over the period. For application of multiplicative decomposition:

$$D_{HW}=\frac{HW_i^T}{HW_i^0}=\left[\frac{\left(HW_{\mathrm{reu.},i}/CG\right)^T}{\left(HW_{\mathrm{reu.},i}/CG\right)^0}+\frac{\left(HW_{\mathrm{recy.},i}/CG\right)^T}{\left(HW_{\mathrm{recy.},i}/CG\right)^0}+\right.$$
$$\left.+\frac{\left(HW_{\mathrm{recov.},i}/CG\right)^T}{\left(HW_{\mathrm{recov.},i}/CG\right)^0}+\frac{\left(HW_{\mathrm{d.},i}/CG\right)^T}{\left(HW_{\mathrm{d.},i}/CG\right)^0}\right]\cdot\frac{\left(CG/M\right)^T}{\left(CG/M\right)^0}\frac{\left(M/E\right)^T}{\left(M/E\right)^0}\frac{E^T}{E^0} \tag{9}$$

And for additive decomposition:

$$\begin{aligned}\Delta V_{HW}=HW_i^T-HW_i^0&=(HW_{\mathrm{reu.},i}/CG)^T-\\&-(HW_{\mathrm{reu.},i}/CG)^0+(HW_{\mathrm{recy.},i}/CG)^T-\\&-(HW_{\mathrm{recy.},i}/CG)^0+(HW_{\mathrm{recov.},i}/CG)^T-\\&-(HW_{\mathrm{recov.},i}/CG)^0+(HW_{\mathrm{d.},i}/CG)^T\\&-(HW_{\mathrm{d.},i}/CG)^0+(CG/M)^T-(CG/M)^0\\&+(M/E)^T-(M/E)^0+E^T-E^0\end{aligned} \tag{10}$$

The application of the LMDI decomposition method suggested by Ang and Liu [12] for (10) results in the following identities:

$$\frac{(HW_{\mathrm{reu.},i}/CG)^T}{(HW_{\mathrm{reu.},i}/CG)^0}=\exp\left[\sum_i\frac{(HW_i^T-HW_i^0)/(\ln HW_i^T-\ln HW_i^0)}{(HW^T-HW^0)/(\ln HW^T-\ln HW^0)}\ln\left(\frac{(HW_{\mathrm{reu.},i}/CG)^T}{(HW_{\mathrm{reu.},i}/CG)^0}\right)\right] \tag{11}$$

$$\frac{(HW_{\mathrm{recy.},i}/CG)^T}{(HW_{\mathrm{recy.},i}/CG)^0}=\exp\left[\sum_i\frac{(HW_i^T-HW_i^0)/(\ln HW_i^T-\ln HW_i^0)}{(HW^T-HW^0)/(\ln HW^T-\ln HW^0)}\ln\left(\frac{(HW_{\mathrm{recy.},i}/CG)^T}{(HW_{\mathrm{recy.},i}/CG)^0}\right)\right] \tag{12}$$

$$\frac{(HW_{\mathrm{recov.},i}/CG)^T}{(HW_{\mathrm{recov.},i}/CG)^0}=\exp\left[\sum_i\frac{(HW_i^T-HW_i^0)/(\ln HW_i^T-\ln HW_i^0)}{(HW^T-HW^0)/(\ln HW^T-\ln HW^0)}\ln\left(\frac{(HW_{\mathrm{recov.},i}/CG)^T}{(HW_{\mathrm{recov.},i}/CG)^0}\right)\right] \tag{13}$$

$$\frac{(HW_{\mathrm{d.},i}/CG)^T}{(HW_{\mathrm{d.},i}/CG)^0}=\exp\left[\sum_i\frac{(HW_i^T-HW_i^0)/(\ln HW_i^T-\ln HW_i^0)}{(HW^T-HW^0)/(\ln HW^T-\ln HW^0)}\ln\left(\frac{(HW_{\mathrm{d.},i}/CG)^T}{(HW_{\mathrm{d.},i}/CG)^0}\right)\right] \tag{14}$$

$$\frac{(CG/M)^T}{(CG/M)^0}=\exp\left[\sum_i\frac{(HW_i^T-HW_i^0)/(\ln HW_i^T-\ln HW_i^0)}{(HW^T-HW^0)/(\ln HW^T-\ln HW^0)}\ln\left(\frac{(CG/M)^T}{(CG/M)^0}\right)\right] \tag{15}$$

$$\frac{(M/E)^T}{(M/E)^0} = \exp\left[\sum_i \frac{(HW_i^T - HW_i^0)/(\ln HW_i^T - \ln HW_i^0)}{(HW^T - HW^0)/(\ln HW^T - \ln HW^0)} \ln\left(\frac{(M/E)^T}{(M/E)^0}\right)\right] \quad (16)$$

$$\frac{E^T}{E^0} = \exp\left[\sum_i \frac{(HW_i^T - HW_i^0)/(\ln HW_i^T - \ln HW_i^0)}{(HW^T - HW^0)/(\ln HW^T - \ln HW^0)} \ln\left(\frac{E^T}{E^0}\right)\right] \quad (17)$$

The application of the LMDI decomposition method for (10) results in the following identities:

$$\left(HW_{\text{reu.},i}/CG\right)^T - \left(HW_{\text{reu.},i}/CG\right)^0 = \sum_i \frac{HW_i^T - HW_i^0}{\ln HW_i^T - \ln HW_i^0} \ln\left[\frac{\left(HW_{\text{reu.},i}/CG\right)^T}{\left(HW_{\text{reu.},i}/CG\right)^0}\right] \quad (18)$$

$$\left(HW_{\text{recy.},i}/CG\right)^T - \left(HW_{\text{recy.},i}/CG\right)^0 = \sum_i \frac{HW_i^T - HW_i^0}{\ln HW_i^T - \ln HW_i^0} \ln\left[\frac{\left(HW_{\text{recy.},i}/CG\right)^T}{\left(HW_{\text{recy.},i}/CG\right)^0}\right] \quad (19)$$

$$\left(HW_{\text{recov.},i}/CG\right)^T - \left(HW_{\text{recov.},i}/CG\right)^0 = \sum_i \frac{HW_i^T - HW_i^0}{\ln HW_i^T - \ln HW_i^0} \ln\left[\frac{\left(HW_{\text{recov.},i}/CG\right)^T}{\left(HW_{\text{recov.},i}/CG\right)^0}\right] \quad (20)$$

$$\left(HW_{\text{d.},i}/CG\right)^T - \left(HW_{\text{d.},i}/CG\right)^0 = \sum_i \frac{HW_i^T - HW_i^0}{\ln HW_i^T - \ln HW_i^0} \ln\left[\frac{\left(HW_{\text{d.},i}/CG\right)^T}{\left(HW_{\text{d.},i}/CG\right)^0}\right] \quad (21)$$

$$(CG/M)^T - (CG/M)^0 = \sum_i \frac{HW_i^T - HW_i^0}{\ln HW_i^T - \ln HW_i^0} \ln\left[\frac{(CG/M)^T}{(CG/M)^0}\right] \quad (22)$$

$$(M/E)^T - (M/E)^0 = \sum_i \frac{HW_i^T - HW_i^0}{\ln HW_i^T - \ln HW_i^0} \ln\left[\frac{(M/E)^T}{(M/E)^0}\right] \quad (23)$$

$$E^T - E^0 = \sum_i \frac{HW_i^T - HW_i^0}{\ln HW_i^T - \ln HW_i^0} \ln\left(\frac{E^T}{E^0}\right) \quad (24)$$

Equations (11)–(24) show that the index of hazardous waste can be represented by the product of index of waste intensity, material intensity and amount of raw material with logarithmic weight function.

2.4. System Dynamics Model Connecting All Involved Parties

This section provides an overview of the results and discussion from system dynamics model for waste battery and accumulator collection system; this section corresponds to Papers No. 7 and 8.

2.4.1. Results for Battery and Accumulator Model

The developed model has 4 feedback loops: 2 negative and 2 positive. The diagrams of causal loop for the model are given in Fig. 14.

In the positive feedback loop R1, an increase in the amount of used B&A will lead to an increase in the amount of B&A imported; thus, the demand triggers supply. In the situation when new products become available on the market (electronic devices, electric vehicles, etc.), the supply will trigger the demand.

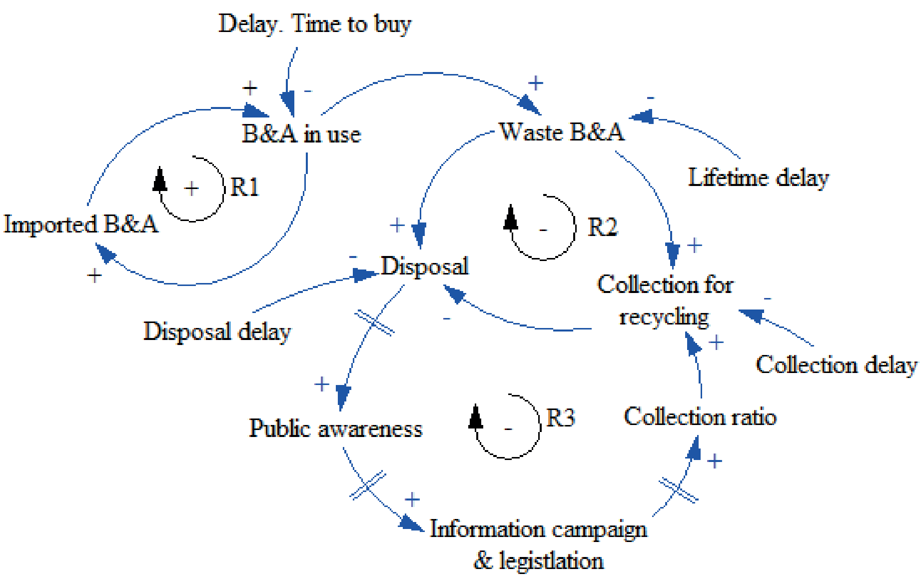

Fig. 14. The diagrams of causal loop (B&A – batteries and accumulators).

An increase in the amount of B&A at the consumers (in use) will inevitably increase the amount of waste B&A. Before B&A become waste, they have predefined lifetime (shown as lifetime delay) and collection delay.

Waste B&A can follow either recycling or disposal stream, where both have delays: recycling delay and disposal delay, respectively. The negative feedback loop R2 illustrates a situation, when the increase in the amount of recycled B&A will lower the amount of B&A going to a disposal site.

The negative feedback loop R3 depicts the innovation diffusion model within the study. The increase in the total amount of landfilled hazardous waste will influence itself in the opposite direction. Disposal of waste will also increase the public awareness regarding the impact of hazardous waste on ecosystems and human health. The public awareness will trigger various mechanics of the information dissemination on the recycling of B&A and also stricter law measures can be adapted. Finally, all the previous activities will increase the collection ratio. The percentage of the collection ratio will follow s-shape curve, which is defined by the innovation diffusion model. The presence of the innovation diffusion mechanisms within the waste recycling sector is described by Chen & Chang (2010).

In the case when the innovation diffusion model in the form of information campaigns and stricter legislation is applied, the total amount of landfilled B&A declines in comparison with the initial model with a constant collection ratio over the years. For the reference scenario, 12.8 % reduction in the total amount of landfilled B&A is achieved in comparison with the initial model within the time period of 15 years. For the stream of SB&A, the reduction is even higher – 30.7 % because in 10 years of simulation time the landfilled amount of SB&A will remain constant, which means that almost 100 % recycling rate will be achieved through the application of the innovation diffusion model.

The results for the introduction of the innovation diffusion model are given in Fig. 15.

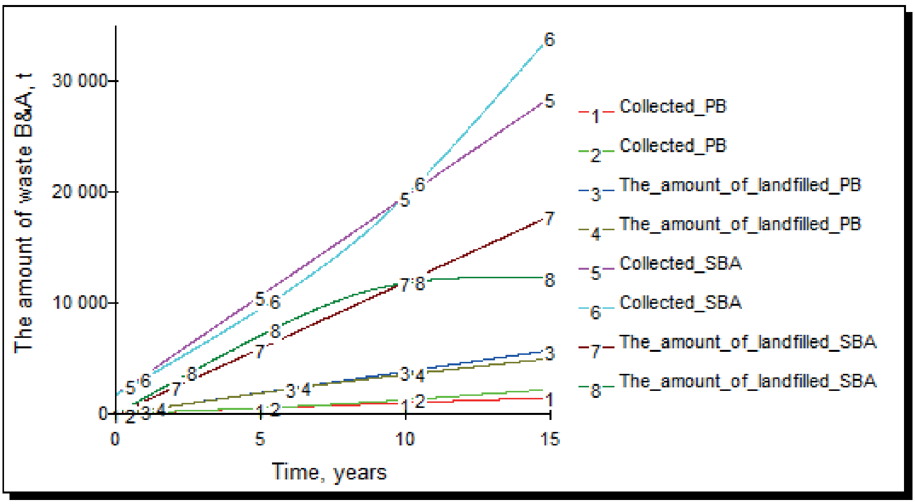

Fig. 15. The results for the introduction of the innovation diffusion model (line 1: collected PB (innovation diffusion model “inactive”), line 2: collected PB (innovation diffusion model “active”), line 3: the amount of landfilled PB (innovation diffusion model “inactive”), line 4: the amount of landfilled PB (innovation diffusion model “active”), line 5: collected SB&A (innovation diffusion model “inactive”), line 6: collected SB&A (innovation diffusion model “active”), line 7: the amount of landfilled SB&A (innovation diffusion model “inactive”), line 8: the amount of landfilled SB&A (innovation diffusion model “active”).

The results given in Fig. 15 show that the main benefit to the environment and public health is given by the introduction of the innovation diffusion model within the SB&A sector. Two factors can be listed, firstly, the total amount of imported SB&A is several times higher than PB. Therefore the potential for the risk reduction is higher. Secondly, in the sector of SB&A the main responsible party for the B&A waste management is private utilities, companies, car repair workshops, etc. that are subject to stricter legislation and control norms when dealing with the hazardous waste.

The cost of the implementation of the innovation diffusion model within the sector has not been assessed within the study, but it can be investigated in the future research.

2.4.2. Results for Lead-Acid Accumulator Model

The model of lead-acid accumulator collection system has 3 sectors: "users of lead-acid accumulators", "recyclers of lead-acid accumulators" and "lead-acid market".

The model explains how changes in demand affect the price for lead and how demand is covered by two flows: recycled and virgin lead.

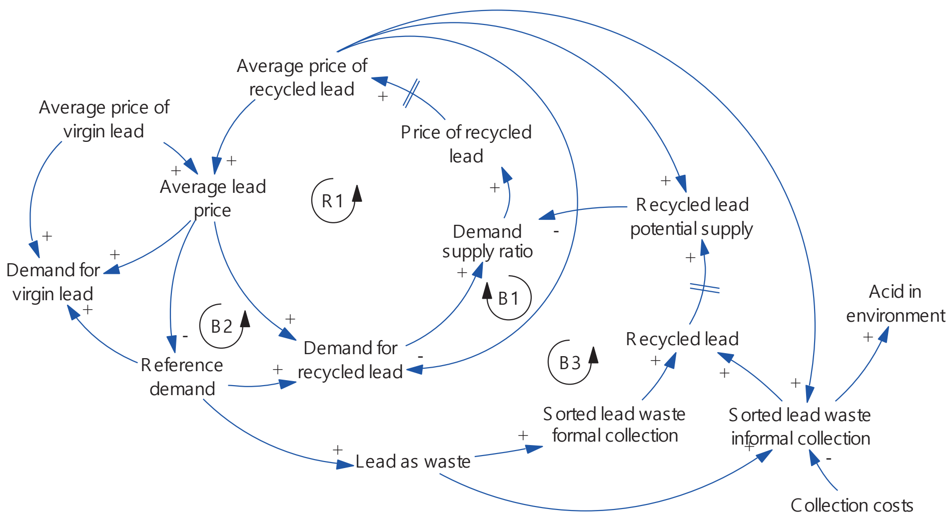

Fig. 16. Causal loop diagram for the model of lead-acid accumulator collection system.

When prices are equal for these two flows, a reference demand (see Fig. 16) divides evenly between the demand for virgin lead and the demand for recycled lead, and the average lead price, average price of virgin lead and average price of recycled lead are uniform. When the average price for virgin lead increases, the average lead price also grows; therefore, the demand for virgin lead shrinks – under conditions that the price of recycled materials is constant or grows slower than the price for virgin resources –, the production from recycled lead becomes relatively cheaper and the demand for recycled lead increases, thereby increasing the demand-supply ratio.

In the model the price of virgin lead is an exogenous variable (not influenced by the action, or behaviour, of the model), but the price of recycled lead is endogenous variable (determined by model variables).

When the amount of recycled lead on the market is unaffected and the reference demand raises, the demand-supply ratio grows, and the market will respond – with delay – by higher price on recycled lead (see positive loop R1). The delay in the response to market is incorporated as the lag between the price of recycled lead and average price of recycled lead (in Fig. 16 given as the causal link with a delay) because the outcome on the whole market price of recycled materials (average price of recycled lead) takes time due to sudden and/or local changes in price of recycled lead.

The demand for recycled lead cannot grow exponentially since the advantage – expressed as the ratio between the price of recycled lead and average lead price – of recycled materials declines as the average price of recycled lead grows up (the balancing loop B1 counters the positive loop R1). At the same time, the rise in the average lead price diminishes the gap between the average lead price and average price of virgin lead, thereby expanding the demand for virgin materials.

In stock and flow model, the demand for recycled lead D_{RL} is expressed as (26).

$$D_{\mathrm{RL}} = RD_{\mathrm{L}} \left(\frac{\bar{P}_{\mathrm{RL}}}{\bar{P}_{\mathrm{L}}} \right)^{-\sigma} \tag{26}$$

where RD_{L} – reference demand for lead, $\bar{P}_{\mathrm{RL}}$ – average price of recycled lead, $\bar{P}_{\mathrm{L}}$ – average price of lead, σ – substitution elasticity.

The increase of average lead price cuts the reference demand, thus, reducing the demand for both recycled and virgin materials (the balancing loop B2 counters the positive loop R1). A new equilibrium is achieved at a higher average lead price and lower reference demand than initially.

As the supply of recycled lead intensifies, the demand-supply ratio drops, which in turn limits the price for recycled lead, – the balancing loop B3 impacts loop R1, thus, adjusting dynamic behaviour of the system.

The flow of lead as waste is collected by two means either as sorted lead waste formal collection or sorted lead waste informal collection. When the collection costs rise, the informal sector gains marginal profit and leaves the market; thus, convergence to formally dominated collection system is presented. As environmental pressure is avoided due to the transition, sulphuric acid pollution is accounted.

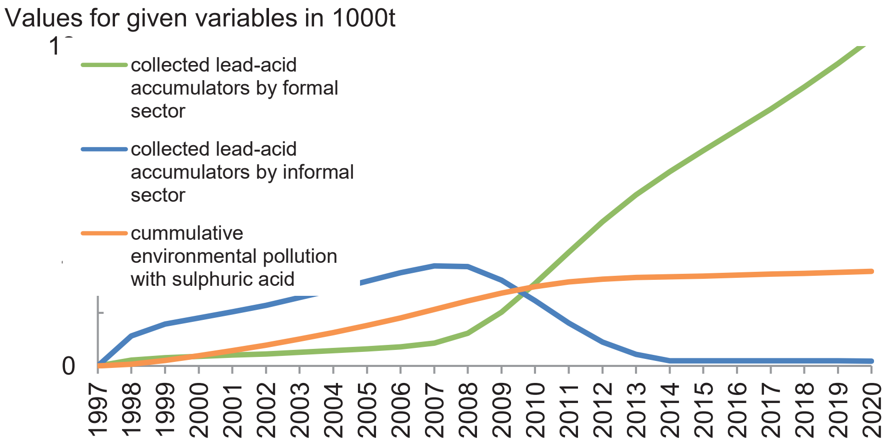

Fig. 17. The transition dynamics between informal and formal lead-acid collection schemes and the cumulative environmental pollution with sulphuric acid.

The amount of collected lead-acid accumulators by informal sector converges to zero since scavengers are driven by more attractive job opportunities and marginal profits arising when the expenses for compliance with environmental standards are included into operational costs. These factors are driving forces for the transition from the informal to formal lead-acid collection schemes (see Fig. 17).

Conclusions

1. Within the present Doctoral Thesis, the Triple Helix approach has been transferred and approbated for the system of hazardous waste management in Latvia. The author of the Doctoral Thesis has studied the interaction of three identified parties within the hazardous waste management: university, government and industry. The case studies performed can be classified under four sections: (1) university and government have been linked by the development of novel forecast and quantification model of hazardous waste streams; (2) university and industry have been linked by case studies using design of experiments methodology; (3) government and industry have been linked by a novel methodology based on IPAT identity; (4) integrated university-industry-government interaction has been studied applying a holistic approach through the system dynamics modelling tool.

2. The formulated hypothesis has been proven, i.e., the Triple Helix approach may improve management practices, institutional, and research capacity as well as foster the diffusion of innovations in the sector of hazardous waste management. The case studies have shown that by cooperation the institutional capacity for the forecasting and quantification of hazardous waste flows is improved (Papers 1, 2 and 3), the competiveness of novel products is increased (Papers 4 and 5), the transition towards industrial symbiosis can be triggered (Paper 6) and, finally, overall performance of the hazardous waste management system can be improved, thus benefiting environment in terms of avoided environmental pollution (Papers 7 and 8).

Further on, the conclusion specific to the studied interactions are given.

Research between University and Government

3. A new type of the indicator has been developed based on the HW intensity within the NACE Rev. 2 sectors and households. This indicator allows assessing the HW production intensity by taking into account a factor that a rise in the production rate will trigger a higher total amount of HW. The proposed indicator can be applied for the forecasting of future development of the HW intensity within a single sector and in the country. The indicator can be used for the benchmarking analysis of single manufacturers, companies of the same profile and the same sectors in different countries. Moreover, the indicator allows proposing measures for HW management system and monitoring the development of HW production intensity.

4. The developed methodology for forecasting of the hazardous waste amounts consists of 6 modules: historical data, assumptions, choice of indicators, data

processing, and data analysis with STATGRAPHICS, and forecast models. The results of the study suggest that HW intensity in Latvia is forecasted to slowly decrease by 3.8 % in next six years. The pessimistic prognosis (upper 95 %) gives an increase in HW intensity by 44.5 %, but intermediate (upper and lower 50 %) gives a corridor of +18.4 % to –36.1 %.

5. Economic development, in this case the growth of GDP, affects the total amount of HW in the country. The dependence of the amount of HW on the GDP values is identified and described by application of the developed forecast model. The total amount of the HW is projected to be within the corridor of –27.7 % in the optimistic scenario up to +87.8 % in the pessimistic scenario with confidence level of 50.0 % for the period of 2010–2020. For the base scenario, the increase in HW amount of 41.2 % in the period of 2010–2020 is calculated with the confidence level of 95.0 %. The obtained projection for the base scenario is higher than the forecast given in the Waste Management Plan for Latvia 2013–2020. The optimistic scenario has shown to be the least flexible to the changes in the GDP growth, since in an optimistic case the HW intensity within a country declines.

6. The results of quantification model show that a multiple linear regression analysis can be used for the analysis of independent variables, which influence the amount of HW. Based on the data analysis and literature review, five independent variables have been chosen for the regression analysis: GDP expressed in millions of Purchasing Power Standard (PPS), primary energy consumption expressed in tons of oil equivalent (TOE), the total population in the country, the expenditure of business enterprise sector for research and development (R&D), and the amount of PPS per capita as the indicator of living standard in country. The statistics on the regression models for the R-squared statistic indicates that the models fitted explain 95.74 % of the variability in the dependent variable HW for the case of Estonia, 80.70 % for the case of Latvia and 61.70 % for the case of Lithuania at the 95 % confidence level. The analysis of the empirically gained equations for the amount of HW also shows the rate at which various factors influence the amount of HW. For instance, the investments in R&D sector decreased the amount of HW more rapidly in Estonia, followed by Latvia and Lithuania. The proposed independent variables can be future applied for the analysis and used to develop a forecast on the amounts of HW.

Research between University and Industry

7. The experimental tests have shown high reliability and are especially suited for exploration and optimization of different surfactants and their mixes. The experimental test can be adapted to solve the problems encountered by developers of detergent cleaners. These experiments suggest that utilizing

surfactants to increase the solubility of dense organic pollutants can be an effective and relatively inexpensive way of ex situ remediation of contaminated soils and aquifers. The screening design has been employed for the evaluation of interactions between the response variable and process variables. The results have shown that all variables have significant effects on the cleaning efficiency at 95 % confidence level. Antagonistic and synergistic interfaces between the variables have been revealed statistically through a full factorial design and by application of the Pareto plot and half-normal probability plot analysis. The main effect plot shows that gradient for temperature of environment and contact time with dilution of biosurfactant is steeper than for the concentration of biosurfactant in washing solution. The main interaction within the model is observed between temperature of environment and contact time with dilution of biosurfactant. The interference has non-linear nature. Temperature increase has a greater impact on the cleaning efficiency at short contact times. The opposite is also true, at longer contact times the influence of temperature level loses its importance.

8. Historically polluted soil bioremediation has been achieved by a blend of bio-based anionic glycolipid surfactants for soil samples with light and medium oil contamination. The results of the research have shown the potential for applications of “plate” tests for the formulation of new soil washing products and for the selection of proper biosurfactants for the problem under study. The “plate” tests could make engineers’ work faster and simpler. The quadratic interaction model shows that the most influential process parameters for sample I and sample II at 95.0 % confidence level have been observed for the concentration variable of the biosurfactant. Based on the results presented, it can be concluded that an increase in the HLB value and temperature level does not result in a significant improvement in soil washing. Further research could involve another biosurfactant solution for the removal of heavy oil contamination.

Research between Government and Industry

9. The methodology has been proposed for the assessment of changes for the aggregate of hazardous waste flow at the enterprise level due to a relative impact of investigated factors; these investigated factors are hazardous waste intensity, material intensity and the amount of raw material consumed by an enterprise. Hazardous waste stream is further decomposed based on the definition of waste hierarchy of reused, recycled, recovered and disposed hazardous waste flows. Based on the proposed methodology, case studies can be performed at the enterprise level in order to explore a cause in the aggregate changes in the past, to present the forecast model for future trends, and also identify leverage points for intervention of policy tools with the aim to reduce the amount of hazardous waste.

10. The developed methodology takes into account the production scale; the reduction in the total amount of hazardous waste due to the introduction of more effective manufacturing practice can be analysed separately from the increase in the total amount of hazardous waste due to higher production outlet. Moreover, the analysis of overall impact of separate factors can be performed. For example, the question can be answered at what production rate the introduction of more effective manufacturing practices will be offset by the increase from production outlet. The present research is the first attempt to link together government initiatives and hazardous waste flow at the enterprise level based on quantitative indices.

Research Connecting All Involved Parties

11. The application of system dynamics modelling in the waste sector has been studied only in a few particular cases; therefore, this study concentrates on the application of SD modelling for the sector of waste batteries and accumulators. The system dynamics model comprising three feedback loops has been created for the sector of the interest. To ensure the validity of the model, structural validation tests have been carried out. The developed model has passed both the behaviour validity and the tests of behavioural sensitivity. The validation has indicated that the model is capable of generating 'the right behaviour for the right reasons'. The results of sensitivity analysis show that the changes in the collection ratio and import rate have high influence and at the same time in the opposite direction aimed influence on the amount of landfilled B&A. This paper shows that the introduction of innovation diffusion model for the sector of waste batteries and accumulators can decrease environmental pollution by up to 30.7 %. However, based on the developed system dynamics model, scenarios comprising other policies could also be simulated, evaluated and discussed.

12. The developed model for the management of lead-acid accumulators shows how the transition from informal to formal practices in the collection system occurs, sheds light on the structure, dynamic behaviour, feedbacks, delays and drivers that transform the model. The model is valid as a decision supporting system for policy developers and as a platform for scientists for further research on dynamics of informal waste management practices. The model can be extended for other boundaries and case studies. Future studies could be performed to investigate the cost of the implementation of specific policy measures in the sector.

Abstract

Sustainable development of society and regions has been an important topic over the past decades. Uncontrolled management of hazardous substances may lead to contamination of ecosystems and damage for human health. Therefore, the author argues that a proper management strategy for hazardous waste is one of the key components for sustainable development. However, in the practice of hazardous waste management there are various parties involved: enterprises, governmental organizations and research institutions. They are elements of the one system but preforming different functions; nevertheless, they are inevitably linked together. This means that actions and interplay between these various parties can positively affect the whole system or can create place where the best practices and innovations cannot spread.

The theory on interplay among governmental institutions, research facilities and industry branches is known as a Triple Helix approach. This approach postulates a triadic relationship between university-industry-government in order to move towards knowledge society and innovations.

The aim of the present Thesis is to transfer and approbate the Triple Helix approach in the field of hazardous waste management in Latvia. In order to reach the goal the following tasks have been set: to link the university and government by developing a novel forecast and quantification model of hazardous waste streams; to link the university and industry by case studies using the design of experiment methodology; to link the government and industry by the novel methodology based on the IPAT identity; to apply a holistic approach to study an integrated university-industry -government interaction using the system dynamics modelling tool.

The Doctoral Thesis is based on the thematically unified eight scientific publications. Those publications are published in various scientific periodicals and are accessible in scientific information repositories and cited international databases. The goal of the presented publications is to expand the range of studies on hazardous waste management.

In the introduction, the research aims and tasks are defined, the structure of the thesis is explained, and a short description of the author's studies is given that covers both the main publications and other studies by the author regarding the analysis of hazardous waste management. Chapter One provides an overview of the literature and focuses on the necessary studies regarding aspects of hazardous waste management system and the improvement thereof as examined in the main publications. Chapter Two examines the methodologies of the issues studied in the main publications. The results obtained in the study are presented in Chapter Three. Conclusions are presented at the end of the Thesis.

Anotācija

Ilgtspējīga sabiedrības un reģionu attīstība ir pēdējās desmitgadēs aktuāls temats. Pārraudzības trūkums bīstamo vielu apsaimniekošanas nozarē var nodarīt kaitējumu ekosistēmām un neatgriezeniski ietekmēt cilvēku veselību. Tāpēc darba autors uzskata, ka efektīva bīstamo atkritumu apsaimniekošanas stratēģija ir svarīgs priekšnosacījums ilgtspējīgai attīstībai. Tomēr praksē bīstamo atkritumu apsaimniekošanā ir iesaistītas dažādas puses: uzņēmumi, valsts un reģionālā pārvalde un pētniecības iestādes. Tādā veidā sadarbība un mijiedarbība starp šīm dažādajām iesaistītajām pusēm var ietekmēt visu sistēmu gan pozitīvi, gan radīt apstākļus, kur labas prakses piemēri un inovācijas nevar attīstīties.

Teorija par mijiedarbību starp valsts iestādēm, pētniecības iestādēm un uzņēmumiem ir pazīstamas kā trīskāršā spirāle (angliski *Triple Helix*). Šī teorija postulē trīs saišu (starp valsts pārvaldi, augstskolām un uzņēmumiem) pastāvīgu stiprināšanu, lai virzītos uz zināšanām ietilpīgu sabiedrību un inovācijām.

Šī darba mērķis ir aprobēt trīskāršās spirāles pieeju bīstamo atkritumu apsaimniekošanas jomā Latvijā. Lai sasniegtu šo mērķi, tika izvirzīti šādi uzdevumi: saistīt universitāti un valsts pārvaldi, izstrādājot inovatīvu bīstamo atkritumu plūsmas prognozēšanas modeli; saistīt universitāti un uzņēmumus, izmantojot eksperimentu plānošanas metodiku; saistīt valsts pārvaldi un uzņēmumus, izveidojot jaunu metodiku, kuras pamatā IPAT identitāte; visbeidzot, piemērot visaptverošu pieeju pētījumiem par integrētu universitātes, valsts pārvaldes un uzņēmumu mijiedarbību, izmantojot sistēmdinamikas modelēšanas rīku.

Promocijas darbs ir balstīts uz astoņām tematiski vienotām zinātniskajām publikācijām. Šie raksti ir publicēti vairākos zinātniskās periodikas izdevumos, un tie ir pieejami zinātniskās informācijas krātuvēs un starptautiskās datubāzes. Izveidoto publikāciju mērķis ir paplašināt pētījumu loku bīstamo atkritumu apsaimniekošanas nozarē.

Ievadā ir doti pētījuma mērķi un uzdevumi, izskaidrota disertācijas struktūra, īss apraksts par autora veiktajiem pētījumiem, kas aptver galvenās publikācijas un citus pētījumus, ko autors ir veicis bīstamo atkritumu apsaimniekošanas nozares analīzes ietvaros. Pirmā nodaļa sniedz pārskatu par zinātnisko literatūru un koncentrējas uz turpmākās izpētes aspektiem un nepieciešamajiem uzlabojumiem bīstamo atkritumu apsaimniekošanas sistēmā. Otrā nodaļa izklāsta publikācijās izmantoto metodiku. Pētījumā iegūtie rezultāti un to analīze ir dota trešajā nodaļā. Secinājumi ir sniegti disertācijas nobeigumā.

Acknowledgements

I would like to express my greatest respect and gratitude to my scientific supervisor Professor Dr. habil. sc. ing Dagnija Blumberga, without her knowledgeable and safe guidance I would not be able to break through sometimes exuberant and sometimes very modest forest of ideas. Thank you for the valuable advice, exhilarating motivation and patience in this scientific path!

This scientific path would never have been done without support of colleagues and co-authors of publications – first of all, I would like to thank Lelde Timma for her admirable talent in the creation of scientific publications and assistance throughout the Doctoral studies. I cannot help mentioning the colleagues – Prof. A. Blumberga Prof. S. Valtere F. Ramagnoli, K. Sams, J. Vanaga, K. Kļavenieks – whose contribution cannot be overestimated. Thank you!

Thanks to all the friendly colleagues from the Institute of Energy Systems and Environment for their ability to convert sometimes monotonous flow of science to a passionate research process!

I also thank my colleagues – Māris Kalniņš and Guna Bērziņa for taking on additional duties during my studies.

Thanks to my family – Signe and Dāvis – for strength, understanding and support!

Janis Vilgerts