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

Elīna DĀCE
Doctoral Program in Environmental Science

MODEL OF THE INTEGRATED WASTE MANAGEMENT SYSTEM OF PRIMARY PACKAGING

Summary of doctoral thesis

Scientific supervisor
Dr. habil. sc. ing., professor
D.BLUMBERGA

Riga 2013

UDK 628.4.04(043.2)
Dā 050 m

Dāce E. Model of the Integrated Waste Management System of Primary Packaging. Summary of doctoral thesis. - Riga: RTU, 2013. – 36 p.

Published in accordance with the decision of the Institute of Energy Systems and Environment No.35, June 14, 2013.

ISBN 978-9934-507-45-8

DISSERTATION PROPOSED FOR DOCTORAL DEGREE IN ENVIRONMENTAL ENGINEERING AT RIGA TECHNICAL UNIVERSITY

This dissertation is proposed for obtaining the doctoral degree in Environmental Engineering and will be defended on December 12, 2013 at the Faculty of Power and Electrical Engineering of the Riga Technical University, 1 Kronvalda boulevard, room 21.

OFFICIAL OPPONENTS

Academician, Professor, Dr.habil.chem. Māris Kļaviņš
University of Latvia, Latvia

Professor, Dr.sc.ing. Hans Björnsson
Chalmers University of Technology, Sweden

Professor, Dr.sc.ing. Marika Rošā
Riga Technical University, Latvia

CONFIRMATION STATEMENT

I, the undersigning, hereby confirm that I have developed this dissertation submitted for consideration at Riga Technical University for obtaining the doctoral degree in Environmental Engineering. This study has not been submitted to any other university or institution for the purpose of obtaining scientific degree.

Elīna Dāce ....

Date: 12.12.2013.

This dissertation is written in Latvian and contains: introduction, 3 chapters, conclusions, bibliography, 68 figures, 8 tables and 160 pages. The bibliography contains 227 references.

This work has been supported by the European Social Fund within the project «Support for the implementation of doctoral studies at Riga Technical University» and by the European Economic Area and Norwegian Government Financial Instrument within the project «System thinking integration in environmental policy».

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Background and current situation

Packaging creates a barrier to bacterial, chemical, smell transmission and protects a product from mechanical and other damages, as well as informs a consumer about the product packed. Thus, packaging is a very necessary and useful product for human health and safety. However, due to the large amounts of used packaging it also has become a product threatening the surrounding environment and sustainable resource utilization. Therefore, packaging waste reuse and recycling have become one of the European Union's (EU) priorities. The main principles of the EU's waste management policy are developed to minimize the amount of waste generated and to ensure their safe management. The main aims of the EU's waste management policy are towards waste prevention, reuse, recycling and regeneration. Whereas, the long-term objective is to become a recycling and resource effective society, where waste is utilized as a resource and waste generation is prevented.

Some EU countries have developed successful waste management systems by applying specific economic, ecological, administrative and other mechanisms. But there are also countries struggling with meeting the recycling targets caused by an inappropriate choice of policy mechanisms. Latvia, as an EU member state, has to comply with the targets set by the EU Packaging and Packaging Waste Directive 94/62/EC and the Waste Framework Directive 2008/98/EC. Up until now Latvia has managed to reach the targets of the packaging recycling rates set in these directives primarily from the collection and recovery of packaging waste in commercial and industrial sectors. A further increase in recycling rates, though, becomes challenging, since both of the sectors become more and more exhausted as a source of packaging waste to recycle. Therefore, in order to continue compliance of the Directives households have to be involved.

Consumption of primary packaging and its waste management are considered a single complex system. In order to develop a sustainable waste management system of the primary packaging it is necessary to understand the system's dynamic behaviour created by the system's actors and their interaction. One of the aims of system dynamics as a modelling method is expanding the boundaries of mental models. It allows seeing the complex feedback structure within the basis of the system under study. Whereas, a full understanding of overall influence and feedbacks of the decisions made is the basis of development of an effective policy strategy.

Objectives

The aim of this dissertation is to develop a model for analysis of the structure and dynamic behaviour of an integrated waste management system of the primary packaging (WMSPP) and for determining the influence of various policy instruments on the system's efficiency in terms of recycled fraction.

The objectives of the thesis are as follows:

1) To analyse the structure of WMSPP;
2) To analyse factors determining the behaviour and action of the system's actors;
3) To develop a system dynamics model where elements of WMSPP are included and their interactions mathematically characterized;
4) To describe the dynamic behaviour of WMSPP and forecast its development in the future;
5) To select policy instruments with a potential to increase the recycled fraction of the primary packaging waste, and assess their efficiency in complying the recycling targets;
6) To develop potential policy strategies for increase of recycled fraction of the primary packaging waste and assess their influence on the system's sustainability.

Research methodology

Quantitative and qualitative methods have been used in this thesis.

The system dynamics method was used for the development of the WMSPP model. The method is particularly suited for studying the dynamic behaviour of complex systems. The model was constructed in the *Powersim Studio 8* software environment. The modelling was performed in accordance with the stages determined in the system dynamics theory.

The methods of mathematical statistics – correlation and regression analysis – were used to find and describe the relationship between the system's parameters. Descriptive statistics was used to find the average, median and standard error values of datasets.

WAMPS 1.0 software was used to calculate the avoided greenhouse gas emissions. *WAMPS 1.0* is a tool based on life-cycle analysis developed as a decision support instrument for planning waste management systems in the Baltic Sea Region.

The aim of qualitative research methods is to find out how and why a phenomenon is observed in certain conditions. In this thesis, the analysis of the WMSPP operation and its actors' behaviour, as well as content analysis of scientific literature, policy documents, reports and reviews was conducted with the help of quantitative research methods. An electronic questionnaire was used to do a survey in municipalities in Latvia. Local and foreign waste management experts were interviewed in meetings and via electronic and phone communications.

Scientific significance

In this thesis, a system dynamics model is developed for the analysis of the WMSPP structure and behaviour, as well as the efficiency of policy instruments applied to the system. The developed model allows understanding the WMSPP and describing the system's feedbacks. The extended producer responsibility scheme forms the basis of the model. The case of Latvia is modelled. Socioeconomic and environmental factors are integrated in the model. Their interactions are characterized by more than 500 mathematical equations. By changing values of certain parameters the model can be applied to analysis of WMSPP in other countries as well.

The developed model allows performing of an integrated analysis of behaviour of various actors of the WMSPP (consumers, packaging producers, waste management companies). It is also possible to analyse the system of separate collection, deposit-refund system and a combined system of primary packaging waste management. The model allows testing of alternative policy instruments aimed to increase the recycling and reuse rates of packaging waste. Adequacy of the model and the obtained simulation results are tested with several tests, including sensitivity analysis with the method of the Latin hypercube sampling.

A rebound effect caused by an increasing share of cheaper recycled materials and leading to an increase of the total consumption of packaging materials is identified during the modelling and simulation processes. An effect of recycled fraction on changes in material consumption has not been described before. Thus, this is the first case where a rebound effect is described in such a context.

Practical significance

This thesis is of great practical significance. The developed model allows analysing the structure of the WMSPP and the behaviour of system's actors. Therefore, it can serve as a decision support tool for efficiency assessment of various policy instruments and their influence on system's sustainability. In this thesis, several policy instruments are tested and assessed. The results obtained can be used in the development of waste management policy. The model can also be used by waste management companies for business planning purposes and forecasting potential outcomes. Scientists and researchers can develop the model further by expanding the boundaries of the system, adding new elements and/or analysing additional policy instruments. The model developed in this thesis can be used for constructing a model for similar problems. Finally, the results obtained in this thesis give practical benefits to overall society as information about consumers' significant role in WMSPP is provided.

Approbation

The results of the research have been discussed and presented in the following conferences:

1. The 53rd RTU International Scientific Conference with a presentation „Evaluation of economic aspects of the deposit-refund system for packaging in Latvia" –October 10-12, 2012, Riga, Latvia.
2. The 6th International Conference „Waste management 2012" with a presentation „Analysis of sustainability aspects of the deposit-refund system in Latvia" – July 4-6, 2012, New Forest, United Kingdom.
3. The 2nd International Conference „Beyond consumption: Pathways to responsible living" with a presentation „Sustainable packaging as part of sustainable consumption: A consumer's perspective" – March 19-20, 2012, Berlin, Germany.
4. The United 3rd World Congress of Latvian Scientists and 4th Letonica Congress, section "Environmental quality in Latvia: Current status, challenges, solutions" with a presentation „No atkritumiem atgūtā kurināmā potenciāla noteikšana Latvijā" – October 24-27, 2011, Riga, Latvia.
5. The 52nd RTU International Scientific Conference with a presentation „Assessment of refuse derived fuel potential in Latvia" – October 12-13, 2011, Riga, Latvia.
6. The 7th International Conference „Natural Sciences and Technologies for Waste and Waste Water Treatment, Remediation, Emissions Related to Climate, Environmental and Economic Effects" with a presentation „Analysis of Waste Sorting Population in Latvia by Using System Dynamics Modeling" – November 22-24, 2010, Kalmar, Sweden.
7. The 51st RTU International Scientific Conference with a presentation „Analysis of ecodesign implementation and solutions for packaging waste system by using system dynamics modeling" – October 14-15, 2010, Riga, Latvia.
8. The 5th International Conference „Waste management 2010" with a presentation „System analysis for integration of landfill energy

production in regional energy supply" – July 12-14, 2010, Tallinn, Estonia.

9. The 7th International Conference „Organic resources in the carbon economy" with a presentation „Optimization model of biogas use in landfills in Latvia" – July 3-7, 2010, Iraklion, Greece.
10. The 50th RTU International Scientific Conference with a presentation „Modeling of installed capacity of landfill power station" – October 14-15, 2009, Riga, Latvia.

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2. Dāce E., Pakere I., Blumberga D. Analysis of sustainability aspects of the deposit-refund system in Latvia// Sustainable Development and Planning VI, WIT Transactions on Ecology and the Environment. – 2013. – pp.729-740.
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Structure of the thesis

This dissertation is written in Latvian and contains: introduction, 3 chapters, conclusions, bibliography, 68 figures, 8 tables and 160 pages. The bibliography contains 227 references. The literature review and bibliography are not included in this summary.

1. METHODOLOGY

In this thesis, a system dynamics model is developed for analysing the dynamic behaviour of the WMSPP and providing the decision makers with the results of the analysis. The aim of the model is to explain the observed phenomena in the WMSPP, to provide an insight into the system's dynamic behaviour and to test various policy instruments with a potential to increase the efficiency of the system in terms of collected and recycled packaging waste from households, prevented waste and reduced deposited waste. The model includes packaging waste sorting, collection, reuse, recycling and disposal stages, as well as packaging design phase depending on the results of the waste management processes. Behaviour of packaging producers, consumers, and waste management companies and their interaction determining the system's dynamic development is simulated in the model.

A separate waste collection system with an extended producer responsibility scheme forms the basis of the model. It corresponds to the case of Latvia. The model is supplemented with a variety of policy instruments that can change the existing system. Management of various packaging materials (paper and cardboard, plastic, metal and glass) is simulated in the model. The following distribution (by weight) of the packaging materials is assumed: (i) paper and cardboard – 39%; (ii) glass – 32%; (iii) plastics – 22%, including PET – 40%; (iv) metals – 7%, including aluminium – 50%.

The model is constructed in system dynamics simulation tool *Powersim Studio 8* environment. The simulation period is 23 years, from 2007 onwards, where in 2007 the time t = 0. The simulation period ends in 2030, which coincides with the implementation deadline of strategy "Latvia 2030". The length of the simulation time step is 1.5 months. The model is based on the analysis of scientific literature and statistical data on packaging waste generation, disposal and recovery, gross domestic product and population, as well as on survey results and discussions with experts.

1.1. Structure of the model

First, the amount of packaging on the market is determined based on changes of exogenous variables – population and gross domestic product. During the next phase, consumer behaviour depending on the availability of sorting facilities, waste management costs, inconvenience costs and other factors is simulated. Then, the recycled, reused and deposited fractions and their changes are determined. Finally, changes in the market demand for materials are analysed. The developed model consists of three main parts or modules: (1) market module, (2) consumer behaviour module, and (3) waste management module (see Fig. 1).

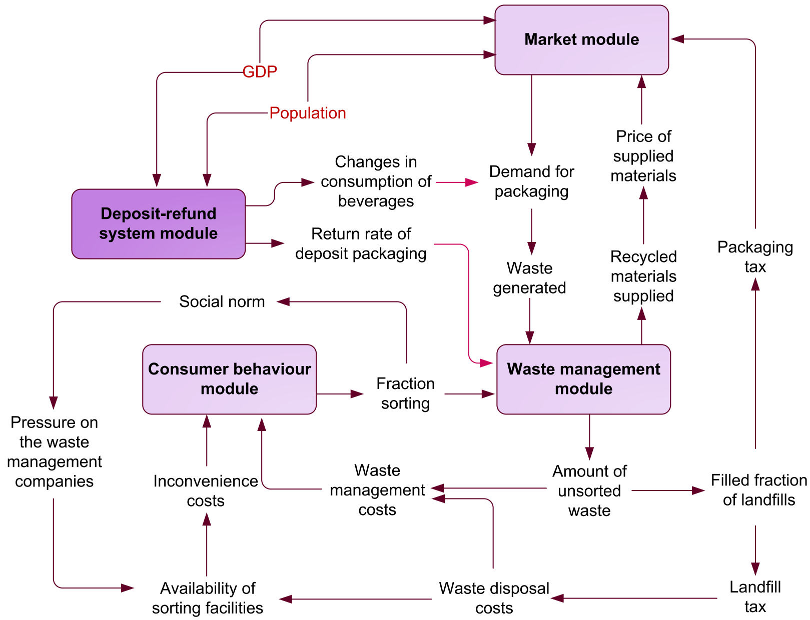

Fig. 1. Diagram of the structure of the developed model

Figure 1 shows that the total demand for packaging materials, consisting of demand for virgin and recycled materials, is defined in the market module. Since packaging has a comparatively short lifetime, it is assumed that all the consumed packaging turns into waste in less than a year. Thereof, as the demand for packaging materials changes, so does the annual amount of packaging waste generated. This amount enters the waste management module where the filled fraction of landfills and the recycled materials supply is determined which in turn affects the results of the market module. The filled fraction of landfills and amount of waste generated affect the availability of sorting facilities and fraction of sorting population, which is used as an input value in the waste management module for determination of the amount of waste sorted.

The structure of the system is altered by applying policy instruments. A deposit-refund system (DRS) implies the creation of a completely different WMSPP. Thus, the structure of the model is significantly extended by constructing an additional – deposit-refund system module (see Fig.1).

1.1.1. The market module

The market model imitates the actions of the market mechanism, in which one material can be substituted by another in response to an increase in its price, and in which changes in price influence supply and demand while the demand-supply ratio in turn determines the price. The market model calculates the total demand for packaging materials and how this demand is split between recycled and virgin materials depending on the price of these materials. Variables describing market elasticity are used. The price elasticity of demand for materials (e_d) characterizes how flexibly the demand will react to changes in the average price of the materials. The price of packaging materials changes with the change in the packaging tax. Elasticity of substitution (ε) is used to describe the willingness and/or ability of packaging producers to replace one material with another. The greater the absolute value of elasticity of substitution, the faster the demand for one material decreases if the price of that material increases in proportion to the average price, and the more the demand for the substitute material increases. A response of the price of recycled materials to changes in the demand-supply ratio is described by the sensitivity of price to demand-supply ratio (σ). The market elasticity variables are considered constant and exogenous in the model. Eq.1 shows how the demand for virgin materials (P_j) is calculated by using ε.

$$\mathrm{P_j} = \mathrm{P_j^{ref}} \cdot \left(\frac{\mathrm{C_j'}}{\mathrm{C_{vid}}}\right)^{-\varepsilon} \tag{1}$$

where P_j^{ref} – reference demand for virgin materials, kg;
C_j' – perceived price of virgin materials, EUR/kg;
C_{vid} – average price of materials, EUR/kg.

Likewise, the demand for recycled materials is determined, though the material substitution ratio (τ) is considered:

$$\mathrm{P_r} = \mathrm{P_r^{ref}} \cdot \frac{1}{\tau} \cdot \left(\frac{\mathrm{C_r'}}{\mathrm{C_{vid}}}\right)^{-\varepsilon} \tag{2}$$

where P_r^{ref} – reference demand for recycled materials, kg;
C_r' – perceived price of recycled materials, EUR/kg.

It is assumed in the model that the packaging producer cannot immediately perceive changes in the price of materials and alter the packaging design to one that uses less expensive materials. The packaging producer needs time to detect changes in the market and process and respond to new information. This creates an information delay. It is expressed by a perceived material price calculated as follows:

$$C_j' = \int_{t=0}^{t=1} \left(\frac{C_j + T_i - C_j'}{t'} \right)(t) \cdot dt + C_j^{init} \tag{3}$$

where C_j – price of virgin materials, EUR/kg;
T_i – packaging tax, EUR/kg;
t' – perception time, years;
C_j^{init} – initial price of virgin materials, EUR/kg.

The initial price of virgin materials is an exogenous variable, because it is not influenced by the action, or behaviour, of the model. Whereas, the perceived price of virgin materials is an endogenous variable, as its value is determined by model variables. As the market model is integrated into the general model, it is anticipated that the packaging tax changes depending on how the impact on the environment changes, which in this model is characterized by the filled fraction of landfills. This rate in turn depends on the amount of demand for packaging and the fraction of sorted waste. The perceived price of virgin materials thereby becomes an endogenous variable determined by adding the exogenous variable C_j to the endogenous variable T_i.

The price of recycled materials (C_r) is an endogenous variable. It is determined by the ratio of demand for recycled materials (P_r) to supply (delivery) (S_r) of recycled materials in the market and the packaging tax:

$$C_r' = \int_{t=0}^{t=1} \left(\frac{C_r \cdot \left(\frac{P_r}{S_r}\right)^{\sigma} + T_i - C_r'}{t'} \right)(t) \cdot dt + C_r^{init} \tag{4}$$

where C_r^{init} – initial price of recycled materials, EUR/kg.

The demand-supply ratio is created by dividing the demand for recycled materials by the potential delivery of recycled materials. The demand for recycled materials depends on C_r'. The potential delivery of recycled materials depends on the amount of sorted and recycled waste (determined by the fraction of the population that sorts its waste) in the waste management module and the time to make the recycled materials available for supply.

Time to perceive the price of materials and coefficient σ characterizes the disequilibrium behaviour of market makers (waste recyclers and packaging producers). σ shows how price of materials reacts to changes in demand-supply ratio. The higher the value of σ the more rapid changes in material prices when the demand-supply ratio changes.

The average price of materials in the market (C_{vid}) is determined by perceived prices of virgin and recycled materials and ε (see Eq. 5). The greater the ε value, the slower the growth in average price as the price of a material increases. This corresponds to a situation in which, as the market demand for a relatively cheaper material grows (which is possible when the ability to replace a more expensive material with a cheaper one grows), the increase in average price is slower than if the ε were small.

$$C_{vid} = \left[\frac{1}{2} \cdot \left(C_j^{'}\right)^{(1\text{-}\varepsilon)} \cdot \left(C_r^{'}\right)^{(1\text{-}\varepsilon)}\right]^{\frac{1}{(1\text{-}\varepsilon)}} \quad (5)$$

The market module imitates a situation on the market where a packaging producer chooses the cheapest of the materials assuming that the quality of the recycled and virgin materials is equivalent. If the $C_j^{'}$ is higher, then the average price increases as well and the demand for virgin materials falls. However, when the $C_r^{'}$ remains lower than the $C_j^{'}$ and the average price increases, then the recycled materials become relatively cheaper and the demand for recycled materials grows increasing the demand-supply ratio. The total demanded amount of packaging materials serves as an input value for determining the amount of packaging waste generated in the waste management module.

1.1.2. The consumer behaviour module

The Consumer behaviour module simulates the dynamics of consumer involvement in waste sorting activities and calculates the fraction of sorting consumers. The consumer's choice to engage in waste sorting is determined by several internal and external factors. It is assumed in the model that consumers can be divided into four groups based on their motives and possibilities: (i) “Consumers-not-sorting” – consumers that do not sort waste and are not yet willing to be involved in sorting; (ii) “Non-sorting environmentalists” – consumers that are concerned for the environment and would like to sort waste, but who have no access to sorting facilities (kerbside containers, drop-off points, etc.) (NSEnv); (iii) “Sorting environmentalists” – consumers sorting because of environmental concerns (SEnv); and (iv) “Sorting economists” – consumers sorting because of economic considerations (SEcon).

It is assumed in the model that involvement into sorting activities is driven mainly by two types of factors – state of the surrounding environment and economic considerations. It is assumed, that the filled fraction of landfills signals about the extent of impact on the environment – the higher it is the more acute is the consumers' reaction. Whereas, waste management costs and inconvenience costs to involve into waste sorting determine the economic benefits of sorting – consumers evaluate their costs and maximize benefits by starting to sort waste or continuing waste disposal in a landfill.

Various rates determine how fast the transition between the groups is. The rates, on their turn, are determined by various factors. The rate at which Consumers-not-sorting decide to sort their waste and move to the NSEnv group ($V_{V \to Z}$) depends on a number of people who are guided by environmental concerns, i.e. the sum of the NSEnv (Z) and SEnv (S) (see Eq.(6)). It is assumed that the maximum (indicative) number of people who are guided by environmental concerns and potentially could become NSEnv and subsequently SEnv (Z_{Ind}) is 70% of society. Thus, 30% of society will sort their waste only if there is sufficient economic incentive.

$$V_{V \to Z} = \frac{(Z_{Ind} - (Z+S))}{a - b \cdot L - c \cdot Z'_d} \qquad (6)$$

The time necessary to move from the NS group to the NSEnv group depends on the extent of environmental pollution expressed by the filled fraction of landfills (L) and the perceived fraction of consumers that are already sorting due to environmental concerns and consumers that have decided to start sorting as soon as they have the access to sorting facilities (Z'_d). Equation (6) shows that the maximum time needed for Consumers-not-sorting to decide to begin sorting their waste is equal to the constant a (assumed to be equal to the length of the simulation period, i.e. 23 years). The maximum time is decreased by the positive example shown by those consumers who already sort their waste or are getting ready to do so in order to protect the environment as soon as they are given the opportunity (fraction of consumers guided by environmental reasons) multiplied by the constant b. The greater the fraction of such consumers the more time is reduced and the rate $V_{V \to Z}$ increased. Thus, Equation (6) shows the influence of a diffusion of the positive example on the increase rate of NSEnv. It is considered that in order to perceive this positive example consumers need time expressed by an information delay.

It is likewise assumed that as environmental problems grow worse, i.e., as the filled fraction of landfills increases, the time to become NSEnv decreases (multiplied by the constant c). Thus, constants b and c indicate the maximum number of years by which the maximum time needed for Consumers-not-sorting to decide to begin sorting their waste is decreased, when positive example is shown by others or environmental problems increase. Time constants *a*, *b* and *c* are an assumption as no studies could be found indicating their values.

Consumers who have decided to sort waste and are in the NSEnv group can involve into waste sorting only if they have sorting facilities available. The total number of such consumers is equal to indicative number of consumers guided by environmental concerns, Z_{Ind}, multiplied by the parameter indicating the availability of sorting facilities. The rate at which consumers are moving from NSEnv to SEnv depends on the fraction of population that has access to sorting containers and the fraction of population that already belongs to SEnv.

It is assumed in the model that a large part of consumers would not be motivated to sort waste by environmental concerns, but by economic considerations. It means that in the model these consumers never enter the NSEnv group and stay in the Consumers-not-sorting group or join the SEcon group by involving into the waste sorting activities. The rate of such transition ($V_{V\rightarrow A}$) depends on difference between the potential or indicative SEcon (A_{Ind}) and actual SEcon (A), the effect of ratio of waste management costs to inconvenience costs (E_m), and time to become SEcon (see Eq.(7)). Time to become SEcon, in its turn, depends on the availability of sorting facilities (K_p) and the perceived social norm (N_s').

$$V_{V\rightarrow A} = \frac{(A_{Ind} - A)\cdot E_m}{\mathrm{a} - b\cdot K_p - c\cdot \mathrm{N}_s'} \tag{7}$$

The availability of sorting facilities is an important factor in determining waste management costs and consumers' involvement into waste sorting activities. In the model, the availability of sorting facilities is characterized by a dimensionless parameter with values 0 to 1, where 1 means a 100% provision of sorting facilities. When opportunities to sort waste are provided, people begin considering changes in their habits. Thus, the target is to reach the value of availability of sorting facilities equal to 1. The rate at which opportunities to sort increase towards the goal, is calculated by multiplying the difference between the actual availability of sorting facilities (K_p) and the target availability (K_p^*) with effects of various factors on the increase rate of K_p, and dividing by the time to reach the target (t^*):

$$K_p = \int_{t=0}^{t=1} \left[\frac{(K_p^* - K_p) \cdot (E_c + E_s + E_a + E_u)}{t^*} \right] (t) \cdot dt + K_p^{init} \qquad (8)$$

where E_c – effect of price of the collected materials on the availability of sorting facilities;

E_s – effect of collection and pre-treatment costs of sorted waste on the availability of sorting facilities;

E_a – effect of waste disposal costs on the availability of sorting facilities;

E_u – effect of consumer requests on the availability of sorting facilities;

K_p^{init} – initial availability of sorting facilities.

In Equation (8), the effects of various factors on the availability of sorting facilities are nonlinear functions. It is assumed that the time to reach the target is until the end of simulation time, i.e. 23 years.

1.1.3. The waste management module

The waste management module helps to calculate the streams of sorted, recycled, reused and deposited waste and the filled fraction of landfills based on the annual consumption of materials and the fraction of consumers sorting. Since primary packaging is a product with comparatively short lifetime, it is assumed that all the consumed packaging turns into waste in less than a year. As the demand for packaging materials changes, so does the annual amount of packaging waste produced. The waste produced are sorted and recycled (or reused) or deposited. It is assumed that all waste not sorted for recycling is deposited. The exception is the glass packaging part of which is reused.

The amount of sorted waste (W_s) depends on the total fraction of consumers sorting (S_d) and the sorting efficiency (α):

$$W_s = \frac{W_r^{kop} \cdot S_d \cdot \alpha}{t_s} \qquad (9)$$

where W_r^{kop} – total amount of waste generated, t;

t_s – time to sort, years.

Packaging materials sorted at households are mostly contaminated with various impurities that are not recyclable in the specific material flow and are deposited (for example, food remains, stickers, labels, covers etc.).

The sorting efficiency coefficient is used to characterize the quality and purity of materials sorted.

Value of the stock of sorted waste (W_s^{kop}) is equal to the difference of the annual amount of sorted waste (W_s) flowing in and the annual amount of recycled waste flowing out (W_p) of the stock (see Eq.(10)).

$$W_s^{kop} = \int_{t=0}^{t=1} (W_s\text{-}W_p)(t) \cdot dt + W_s^{init} \quad (10)$$

The initial amount of sorted waste (W_s^{init}) is equal to the initial amount of waste generated multiplied by the initial fraction of consumers sorting. The annual amount of recycled waste is calculated by multiplying the total amount of sorted waste with the recycling efficiency coefficient β that characterizes the loss of material's mass and quality (material degradation) as a result of recycling processes. Recycled materials are accumulated and delivered to a packaging producer upon demand.

The annual amount of recycled packaging waste is divided by the annual amount of generated packaging waste resulting in recycled fraction. This is the main result of the model through which the impact of various policy instruments on the packaging waste management systems is assessed and their effectiveness compared in relation to the targets set in the EU directives and national planning documents.

The amount of deposited waste is accumulated in landfills. The available free landfill space is allocated to packaging waste solely and based on that and the deposited amount of primary packaging waste the filled fraction of landfills is calculated. It is assumed in the model that the filled fraction of landfills indicates the extent of the environmental impact that is associated with waste. The model imitates society's reaction to an increase in the filled fraction of landfills by using and increasing the instruments that lead to a decrease in the consumption of materials and divert the waste away from landfills, i.e. the packaging tax and the landfill tax.

1.1.4. The deposit-refund system module

The deposit-refund system module consists of several parts. In the initial stage of simulation the amount of deposit packaging on the market is determined based on beverage consumption. Then, the consumer behaviour under the deposit-refund system (DRS) is simulated depending on the availability of return points, size of the deposit fee and inconvenience costs to return the empty packaging unit into the system. Finally, the fraction of packaging returned for reuse and recycling is determined. The initial calculations are based on the exogenous variables – gross domestic product and population.

The initial structure of the model is modified by supplementing the waste management module so that another flow describing the amount of packaging returned in the DRS exits the stock of the total amount of waste generated (W_r^{kop}). Fraction of returned waste (*AI*) that depends on consumer behaviour is taken into account when the annual amount of sorted waste in the DRS (W_s^{DS}) is calculated (see Eq.(11)).

$$W_s^{DS} = \frac{W_r^{kop} \cdot D_d \cdot AI}{t_s} \tag{11}$$

where D_d – fraction of deposit packaging;
t_s – time to sort, years.

Consumers' habits change as a result of introduction of the DRS. The reason is a price increase of the beverages resulting from the added deposit fee. When the price increases, part of consumers chooses not to purchase the beverage or selects a comparable beverage that is not included in the DRS. These changes of beverage consumption calculated in the DRS module enter the market module determining the reference demand for packaging materials (see Eq.(12)).

$$P^{DS} = P\text{-}P \cdot D_d \cdot \frac{\Delta Q}{Q_0} \tag{12}$$

where P^{DS} – reference demand for packaging after introduction of the DRS, kg;
P – reference demand for packaging (before introduction of the DRS), kg;
ΔQ – changes in demand for packed products, units;
Q_0 – demand for packed products before price changes, units.

When the demand for packaging materials is changed, the amount of packaging waste generated entering the waste management module changes as well. Whereas, the total fraction of recycled waste changes as a result of recycling of the packaging returned in the DRS.

Polyethylene terephthalate and aluminium are the most demanded materials on the recycled materials' market, thus – the most profitable ones. When these profitable materials are diverted from the separate collection (kerbside) system, waste management companies lose their interest in collecting other recyclable materials as well. Therefore, it is assumed in the model that the introduction of the DRS reduces the rate at which sorting facilities of the separate collection system are installed (an effect of introduction of the DRS on the availability of the sorting facilities, the value of which is constant and equal to –1, is added to the sum of the effects in the Equation (8)).

1.2. The causal loop diagram of the system

The causal loop diagram in Figure 2 shows the interacting feedback mechanisms (loops) between the parts of the modelled system.

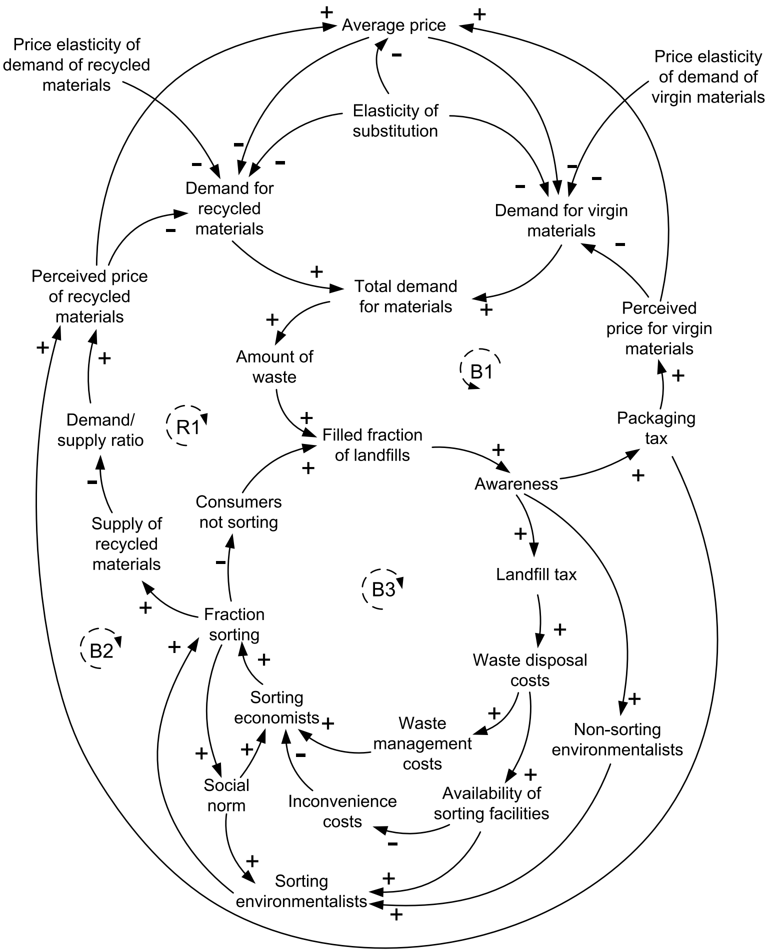

Fig. 2. Causal loop diagram of the modelled system

A packaging producer makes a decision about the type and amount of materials used depending on the prices of virgin and recycled materials and their ratio to the average price of materials. It forms the total demand for materials. The demand for materials increases the amount of waste and therefore also the filled fraction of landfills. The filled fraction of landfills indicates the extent of environmental impact. When the filled fraction increases, the awareness of the society is raised as a result. That increases the number of consumers that are concerned for the environment and would like to sort waste, NSEnv. The society reacts to the environmental impact with raising the packaging tax, which decreases the demand for materials, and the landfill tax, which increases the waste disposal costs (and subsequently waste management costs). The balancing loops (B1 and B2) are thus formed, which slow down the increase in the amount of waste. The increase of waste disposal costs forces waste management companies to install more sorting facilities since waste disposal becomes too costly in comparison to collection and sale of primary packaging waste (recyclables). With greater availability of sorting facilities, the consumers' inconvenience costs to sort waste decrease. When the waste management costs exceed the inconvenience costs, the consumers motivated by economic considerations get interested in decreasing their costs and become involved in waste sorting (subsequently becoming SEcon). The availability of sorting facilities allows NSEnv to become involved in waste sorting, thus becoming SEnv.

Both, SEcon and SEnv increase the fraction of consumers sorting their packaging waste and sorting spreads as a social norm. The social norm, in turn, creates a diffusion of acceptance of the recycling behaviour, increasing the number of SEcon and SEnv even more (a reinforcing loop(s) is formed (not distinguished in the scheme) that drives an increase of the fraction of sorting consumers). As the fraction of consumers sorting increases, the number of Consumers-not-sorting decreases, decreasing the rate at which landfills are filled. The third balancing loop (B3) slows the rate at which waste is disposed of in landfills. However, the supply of recycled materials on the market increases, thereby lowering the demand-supply ratio of the recycled materials and leading to a drop in the price of these materials and the average price. It is assumed that the price of recycled materials is lower than the price of virgin materials. A decrease in the average price of materials, in turn, expands the demand for materials and leads to an increase in the filled fraction of landfills and to a further increase of the fraction of consumers sorting. As a result, a reinforcing loop (R1) is formed that tends to increase the amount of waste.

The causal loop diagram describes the so called "rebound effect" caused by an increasing share of cheaper recycled materials and leading to an increase of the total consumption of the packaging materials. In this thesis, the rebound effect is derived from the policy aimed at increasing the recycled fraction of packaging waste. Most studies in the literature observe the opposite direction, i.e. how the green design, eco-efficiency and consumer behaviour influence the amount of waste generated. Thus, this is the first case where a rebound effect is described in a context of an effect of recycled fraction on changes in material consumption.

1.3. Policy development and scenario generation

The existing WMSPP can be changed by using various strategies based on the development of policies. When a policy design is developed it is tested to see what new decisions, strategies and structures could be implemented in the real system. In order to increase the efficiency of the WMSPP various policy instruments have to be chosen. Economic (fiscal), administrative (regulatory), informative, infrastructure and eco-design instruments were chosen to assess their individual and interactive influence on the efficiency of the system (see Fig. 3).

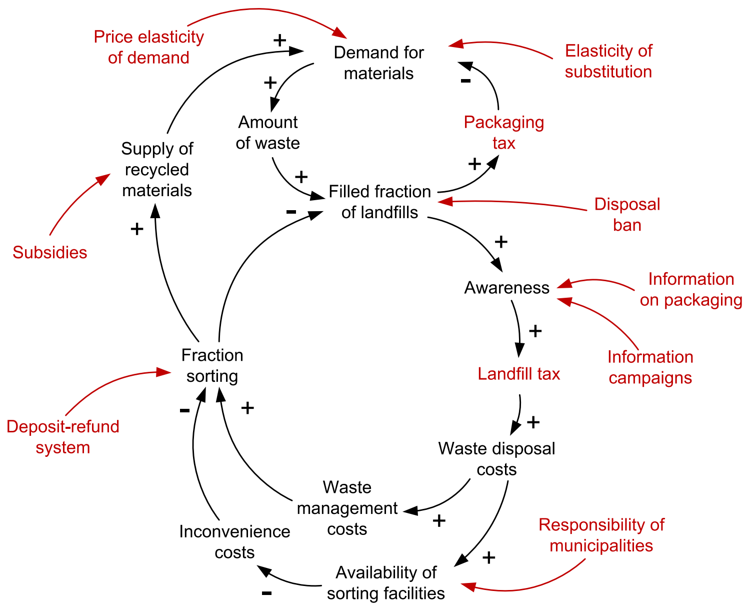

Fig. 3. A simplified causal loop diagram with the policy instruments tested

The instruments were chosen so as to modify the behaviour of specific stages or actors of the waste management system. The influence of the policy instruments on the management of packaging waste was tested by developing several scenarios, where variations and combinations of the instruments applied were tested. The aim of these scenarios was to find out how the packaging WMS can be influenced in order to promote the recycling rate of the primary packaging waste and hinder the accumulation of the waste in landfills.

First, a base scenario was created that shows the potential dynamics of the system provided that no additional instruments are applied and the existing measures remain unchanged, i.e. the development of the existing PC-PW management system was forecasted with the policy instruments in force from 2007 until 2012 (including rates of packaging tax and landfill tax unchanged). Then, by developing 17 scenarios all the policy instruments were tested individually to evaluate the degree of influence each of them creates on the system's dynamic behaviour and effectiveness of the existing system (see Table 1). Finally, six scenarios were developed where the policy instruments were combined creating policy strategies or design and assessing the total effect of application of various policy instruments at a time (see Table 2).

Table 1

Scenarios of the policy instruments tested

The policy instrument applied	Scenario																	
	Base	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17
Deposit-refund system	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Deposit fee	-	1	2	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-
Return points	-	1	1	5	1	-	-	-	-	-	-	-	-	-	-	-	-	-
Information campaigns	-	1	1	1	12	-	-	-	-	-	-	-	-	-	-	-	-	-
Disposal ban	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Landfill tax	0	0	0	0	0	0	1	10	0	0	0	0	0	0	0	0	0	0
Subsidies	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Responsibility of municipalities	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Information campaigns	4	4	4	4	4	4	4	4	4	4	100	4	4	4	4	4	4	4
Information on packaging	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	1	0,1	0,1	0,1	0,1	0,1	0,1
Packaging tax	0	0	0	0	0	0	0	0	0	0	0	0	1	10	0	0	0	0
Exemption from the packaging tax	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Elasticity of substitution	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	2,5	0,5	0,5
e_d for virgin materials	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	2	r.v.
e_d for recycled materials	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	r.v.	2

Table 2

Scenarios of the policy strategies

The policy instrument applied	Scenario						
	Base	S1	S2	S3	S4	S5	S6
Deposit-refund system	0	0	1	0	1	0	1
Deposit fee	-	-	1	-	1	-	1
Return points	-	-	1	-	1	-	1
Information campaigns	-	-	1	-	12	-	1
Disposal ban	0	0	0	0	0	1	1
Landfill tax	0	10	10	0	1	0	1
Subsidies	0,1	1	1	0,1	0,1	0,1	0,1
Responsibility of municipalities	0	1	0	1	0	1	1
Information campaigns	4	100	4	4	100	100	100
Information on packaging	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Packaging tax	0	10	1	10	1	10	1
Exemption from the packaging tax	0	0	0	0	0	0	0
Elasticity of substitution	0,5	0,5	0,5	2,5	0,5	2,5	0,5
e_d for virgin materials	r.v.	r.v.	r.v.	2	r.v.	r.v.	r.v.
e_d for recycled materials	r.v.	r.v.	r.v.	2	r.v.	r.v.	r.v.

In scenario S1, a policy promoting separate waste collection system is analysed. Packaging and landfill tax rates and size of subsidies are significantly increased, societies' awareness is promoted and responsibility of municipalities to reach the recycling rate targets in their territory is established. The aim of scenario S1 is to assess whether an increase in recycled fraction of packaging waste can be achieved without such costly policies as DRS or landfill ban.

An introduction of the DRS is simulated in scenario S2. However, in order to maintain the motivation of consumers to sort waste also in the separate waste collection system, the landfill tax rate is increased significantly. Packaging producers and waste management companies are stimulated by moderately increased packaging tax rate and subsidies.

Scenario 3 helps to understand what would be the effect on the system if recycling of primary packaging waste is promoted through increased demand for recycled materials from the producers' side, but limiting the total amount of packaging materials used by increasing the packaging tax and the price elasticity of demand for materials. To ensure delivery of recycled materials, the responsibility of municipalities is established to foster the installation of sorting facilities in their territory.

In scenario S4, great emphasis is placed on the provision of information to the society to see the system's behaviour in a situation with a relatively low developed sorting infrastructure, but a high level of consumers' awareness. The separate waste collection system is enhanced by moderately increasing the packaging and landfill tax rates. Besides, the DRS is introduced with the minimum increase trend of return points.

The landfill ban on recyclable materials is simulated in scenario S5. Demand for recycled materials is stimulated by the packaging eco-design. Simultaneously the packaging tax rate is increased, and consumers are informed.

Finally, Scenario 6 simulates the dynamics of the system provided that all the policy instruments discussed in the State Waste Management Plan 2013-2020 are implemented in addition to the existing instruments in force.

2. RESULTS

The results obtained with the developed system dynamics model are to be used to observe the causal relationships between the system's elements and to predict the potential development of the system when a new policy is proposed.

Results of the base scenario show that the current policies are not likely to achieve any of the targets set in the EU Directive 2004/12/EC amending Directive 94/62/EC on packaging and packaging waste (EU2015), EU Waste Framework Directive 2008/98/EC (EU2020), Sustainable development strategy of Latvia until 2030 (Latvia2030) and the National development plan of Latvia for 2014-2020 (NDP2020) (see Fig.4). It is therefore necessary to determine by using which of the policy instruments it is possible to achieve a sufficient increase of recycled fraction of the primary packaging waste.

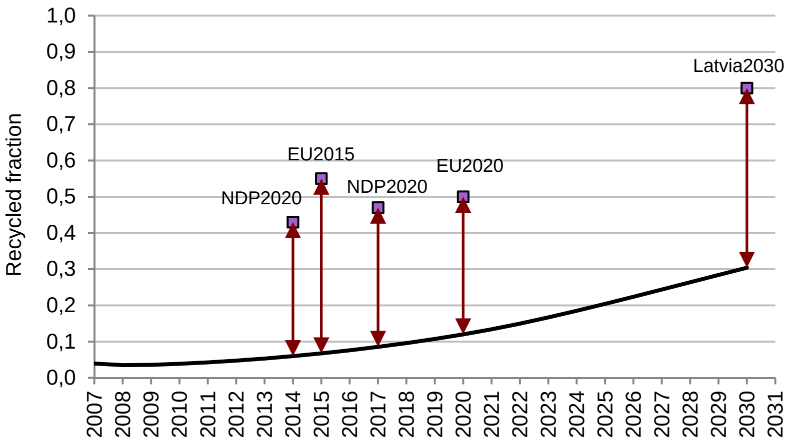

Fig.4. The results of the recycled fraction obtained in the base scenario compared to the targets set in the EU directives and national planning documents

The results of the scenarios P1 – P17 where policy instruments were tested show that the only instrument the implementation of which would theoretically help reaching the target set in the EU2020 is the landfill ban with a timely provided availability of sorting facilities (see Fig.5). The results of this instrument's application are close to the target set in Latvia2030 as well. However, the targets set in NDP2020 and EU2015 cannot be reach in the time left.

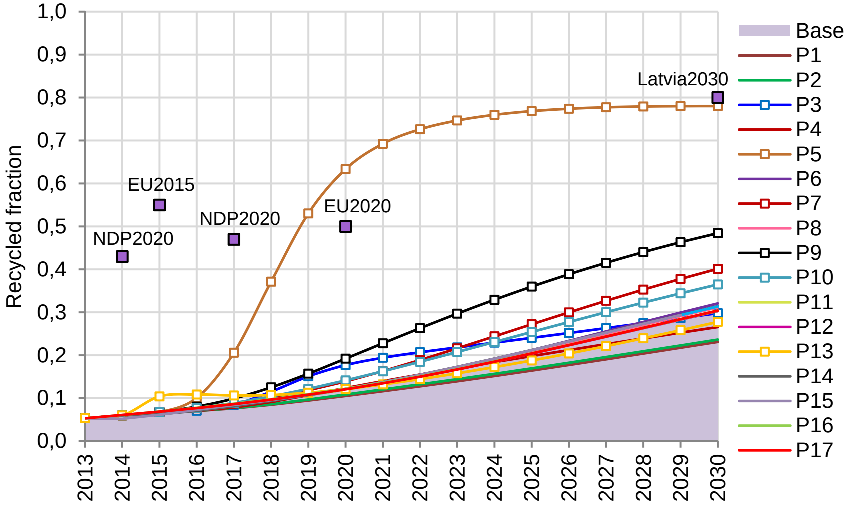

Fig. 5. The results of the recycled fraction in scenarios P1 – P17

Overall, it is necessary to raise the involvement of consumers into waste sorting to enhance recycling of primary packaging. To do this, consumers' inconvenience costs associated with involvement into waste sorting have to be reduced or compensated. They are most effectively minimized by ensuring the availability of sorting facilities. Thus, policy instruments promoting installation of sorting facilities (or return points in case of DRS) have to be applied. Also instruments that raise the level of societies' awareness and environmental consciousness in general promote waste sorting and recycling. Waste is most efficiently prevented by the packaging tax. Whereas, the share of recycled materials in the packaging is increased by eco-design instruments intended to substitute materials and minimize the use of virgin materials.

When the effect of various policy instruments on the system's behaviour is known, policy strategies can be developed that combine the instruments. The main aim of the strategies developed in scenarios S1 – S6 is to increase the recycled fraction of primary packaging waste. Additional goals are a reduction of the speed of landfills filling up, prevention of waste, increase of the share of recycled materials in packaging etc. indicating the effectiveness of the system.

Figure 6 shows that the highest fraction of recycled waste is obtained in scenarios S5 and S6. In addition, scenarios S5 and S6 are the only ones that reach the target set in EU2020. The key instrument in both scenarios is the landfill ban that provides quick increase of the availability of sorting facilities to consumers.

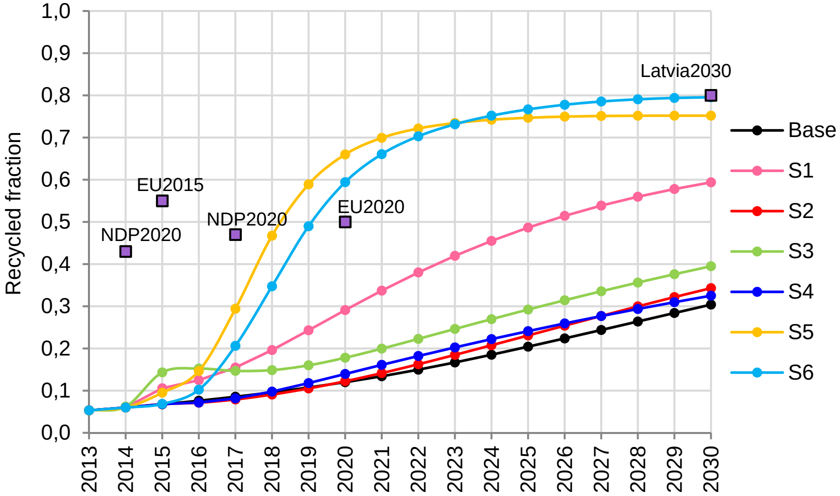

Fig. 6. The results of the recycled fraction in scenarios S1 – S6

A smaller fraction of recycled waste with a significantly slower increase is obtained in scenario S1. Nevertheless, scenario S1 shows that the existing separate waste collection system could be improved without substantial changes to achieve the recycling rate of almost 60% in less than 20 years. In other scenarios, the results of recycled fraction differ relatively little from the results obtained in the base scenario. Therefore, the strategies simulated in scenarios S2, S3 and S4 are considered to be with low efficiency to improve the situation.

It can be seen from Figure 6 that although some of the strategies developed significantly change the existing WMSPP, none of them helps to achieve the recycling targets set in EU2015 and NDP2020. To comply with these documents, the changes in policy should have taken place much earlier than the simulated year 2014/2015.

The results of the total demand for materials show that a significant fall of the demand is obtained in scenarios S1, S3 and S5 (see Fig.7). In these scenarios, the fall in demand equivalent to waste prevention is caused by a rapid increase of the packaging tax rates. The greatest fall is observed in scenario S3, in which also eco-design instruments are used facilitating a reduction of the packaging material capacity.

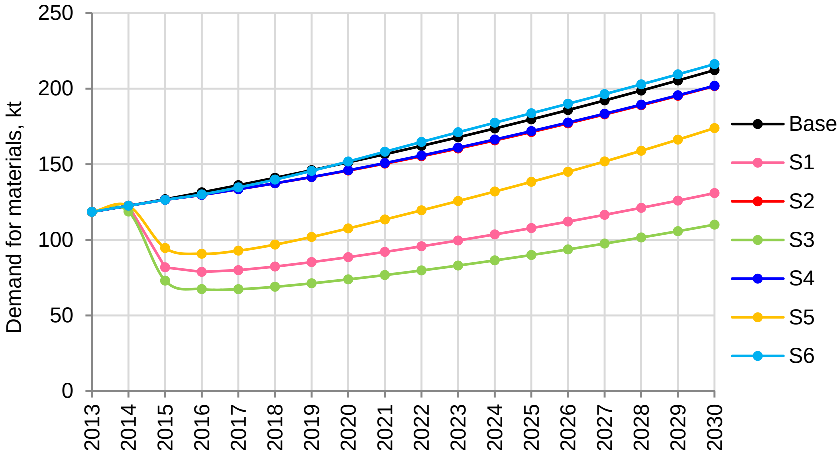

Fig. 7. The results of the demand for packaging materials in scenarios S1 – S6

The results of material consumption and waste recycling explicate the results of filled fraction of landfills. It can be seen from Figure 8 that the fill rate of landfills in scenarios S2 and S4 is close to the one obtained in the base scenario. Whereas, in other scenarios a rapid slowdown of the fill rate (scenarios S1 and S3) or even stop (scenarios S5 and S6) is observed. The slowdown is caused by a fall in demand for materials, and in case of scenario S1 – also due to an increase of the recycled fraction. In turn, a further increase of the filled fraction of landfills stops with the introduction of a landfill ban.

The largest increase in the fraction of recycled materials in packaging is obtained by using the policy strategies simulated in scenarios S3 and S5. Policy instruments that enhance an eco-design of packaging i.e. substitution of materials and increase of the packaging tax rates are in the basis of the strategies simulated (in scenario S3, also raise of the price elasticity of materials is applied). In comparison to the base scenario a higher fraction of recycled materials in packaging is achieved in scenario S1 as well.

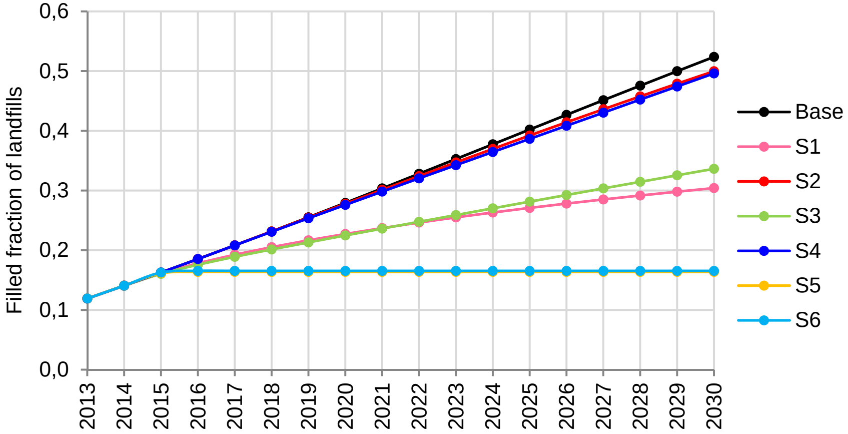

Fig. 8. The results of the filled fraction of landfills in scenarios S1 – S6

The fastest growth of the amount of relative avoided greenhouse gas (GHG) emissions per ton of recycled materials is obtained in scenario S5 (see Fig. 9). It can be seen that similarly to the fraction of recycled waste (see Fig.6) the amount of the relative avoided GHG emissions has practically no further increase after the year 2025. Conversely, in scenario S6, the amount of the relative avoided GHG emissions keeps an increasing tendency through all the simulation period and, from 2025, reaches the largest amount avoided.

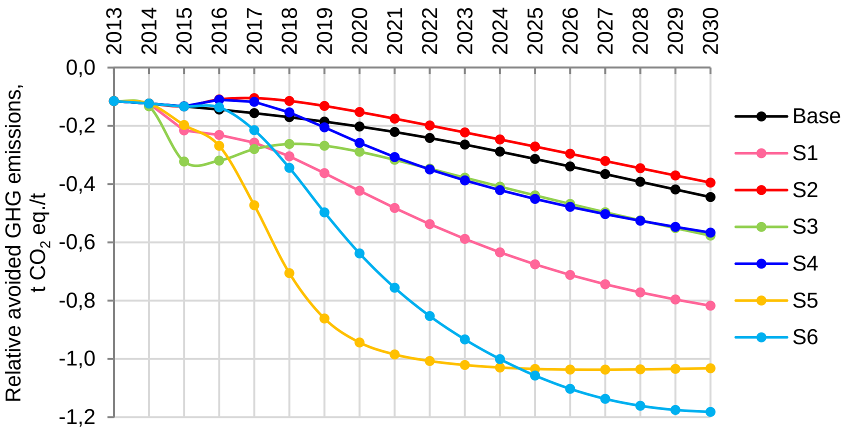

Fig. 9. The results of the relative avoided GHG emissions in scenarios S1 – S6

Overall, the policy strategies giving the greatest positive effect on the changes of system's parameters are simulated in scenarios S1, S3, S5 and S6. Strategy of scenario S3 is relevant if the policy objective is to promote the eco-design of packaging and prevent waste. Whereas, the strategy simulated in scenario S6 is applicable when the objective is waste recycling and minimization of waste disposal. Strategies of scenarios S1 and S5 are adequate if all the objectives are equally important.

The analysis of the policy strategies show that a combination of policy instruments does not provide a summary, but rather a multiplicative and synergetic effect. It is largely determined by the rebound effect or resistance of various policy instruments. It means that the policy instrument or strategy is hindered, poorly implemented or even completely destroyed due to the unforeseen reaction from the side of the system's actors (or elements). The impact of policy instruments or strategies can decrease if public attention becomes more relaxed due to a relative improvement (no further deterioration) of the environmental state. That, in turn, can lead to new environmental pollution problems which would call for a reinforcement of the solution (policy instrument) implemented or finding a new solution.

The results of the sensitivity analysis show that uncertainty of the input parameters does not significantly influence the results of policy strategies obtained with the base values. Thus, it can be considered that the results obtained are reliable and the developed model can be used for testing and analysis of policy instruments and strategies.

CONCLUSIONS

1. In this thesis, a system dynamics model is developed for the analysis of the structure and forecasting of the dynamic development of the integrated waste management system of primary packaging. An analysis of various policy instruments and strategies by assessing their ability to reach specific targets can be performed with the model. The model allows the capture and comparison of such parameters characterizing the WMS-PP as a recycled fraction of waste, amount of waste generated, fraction of consumers sorting their waste, fill rate of landfill etc. Thus, the effect of policy instruments on several system's parameters simultaneously can be obtained and the most appropriate policy instruments for the specific conditions chosen. As a result of testing confidence is gained that the model contains the essential factors determining the real system's dynamic behaviour and that the modelled system's boundaries and level of detail allow reliable characterization of the real system. Therefore the simulation results obtained with the model can be considered reliable and interpretative for the real system. The model is approbated with the case of Latvia.

2. The simulation results show that if the existing packaging waste management policy remains unchanged then the targets set in the EU directives and national planning documents cannot be reached. In the base scenario, the recycling rate of the primary packaging waste reaches only 12% in 2020 instead of 50% set in the EU2020, but in 2030 – only 30% instead of 80% planned in the strategy "Latvia 2030". It shows that it is necessary to propose a policy strategy that would help to reach the targets set.

3. Ten various policy instruments applicable to the WMSPP with different variations of possible implementation are tested in the thesis forming in total 17 scenarios for analysing the efficiency of policy instruments. The results of the analysis show that the most effective instrument for an increase of the recycled fraction and retardation of increase in the filled fraction of landfills is the landfill ban on the condition that all households are provided with a 100% access to sorting facilities, thus diminishing the potential risk of illegal waste disposal. Complying with the condition, the landfill ban is the only instrument which implemented alone can help attaining the target set in EU2020. The result of this instrument is close to the target set in the strategy "Latvia 2030" as well.

4. The DRS is one of the most effective instruments to motivate consumers' involvement into waste sorting. Nevertheless, its contribution to the recycled fraction of packaging waste is too small to be generally regarded as an effective instrument for major improvements of the waste management system. The share of the deposit packaging in the overall mass of the packaging waste composes only 30%. Thus, even if all deposit packaging is returned in the DRS, the total recycling rate would increase only by 26%. The return rate of the DRS is stimulated most effectively by providing convenient access to return points.

5. Six policy strategies for increasing the fraction of recycled waste have been developed based on the results of the analysis of policy instruments. The results of analysis of the policy strategies show that the highest recycled fraction is obtained in scenarios S5 and S6. In addition, both scenarios are the only ones fulfilling the target set in EU2020. The most rapid growth of the recycling rate is obtained in scenario S5 – 66% of packaging waste is recycled in 2020. Whereas, scenario S6 allows to obtain the highest recycling rate in 2030 meeting the target set in the national strategy "Latvia 2030". In addition, the results of scenario S1 show that the existing system of separate waste collection can be improved so as to reach the recycling rate of 60% in less than 20 years.

6. Although some of the strategies developed significantly change the existing WMSPP, none of them helps to achieve the recycling targets set in EU2015 and NDP2020. To comply with these documents, the changes in policy should have taken place much earlier than the simulated year 2014/2015.

7. The policy strategies giving the greatest positive effect on the changes of system's parameters are simulated in scenarios S1, S3, S5 and S6. The strategy of scenario S3 is relevant if the policy objective is to promote the eco-design of packaging and prevent waste. Whereas, the strategy simulated in scenario S6 is applicable when the objective is waste recycling and minimization of waste disposal. Strategies of scenarios S1 and S5 are adequate if all the objectives are equally important. The results obtained allow concluding that an increase of the recycling rate simultaneously with waste prevention is achievable with a policy design where all consumer groups are stimulated to involve into

waste sorting and a decrease of prices of materials and their growth rate is prevented.

8. To achieve an involvement of consumers into waste sorting activities an abatement or compensation of consumers' inconvenience costs is necessary. The most effective way is to provide convenient availability of sorting facilities. Therefore policy instruments enhancing the installation of sorting facilities (or return points in case of DRS) have to be introduced. Also instruments raising public awareness and environmental consciousness in general promote waste sorting and recycling. Waste is most efficiently prevented by the packaging tax. Whereas, the share of recycled materials in packaging is increased by eco-design instruments intended to substitute materials and minimize the use of virgin materials.

9. The analysis of the policy strategies show that a combination of policy instruments does not provide a summary, but rather a multiplicative and synergetic effect. It is largely determined by the rebound effect or resistance of various policy instruments. In the modelled system, the rebound effect is caused by an increased total demand for packaging materials as a result of an increasing share of cheaper recycled materials on the market due to an increase of the recycling rate. Analysis of literature allows concluding that studies previously performed have not described the effect of recycled fraction on changes in material consumption. Thus, this is the first case where a rebound effect is described in such a context.