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System dynamics model for analyzing effects of eco-design policy on packaging waste management system

Elina Dace[a,*], Gatis Bazbauers[a], Alise Berzina[a], Pål I. Davidsen[b]

[a] Institute of Energy Systems and Environment, Riga Technical University, Kronvalda blvd. 1, Riga LV-1010, Latvia
[b] System Dynamics Group, Department of Geography, University of Bergen, Fosswinckelsgt. 6, 5007 Bergen, Norway

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ABSTRACT

EU's long-term objective is to become a recycling and resource effective society, where waste is utilized as a resource and waste generation is prevented. A system dynamics model was developed to analyze the policy mechanisms that promote packaging material efficiency in products through increased recycling rates. The model includes economic incentives such as packaging and landfill taxes combined with market mechanisms, behavioral aspects and ecological considerations in terms of material efficiency (the packaging material per product unit, recycled fraction in products). The paper presents the results of application of various policy instruments for increasing packaging material efficiency and recovery rate and reducing landfilled fraction. The results show that a packaging tax is an effective policy instrument for increasing the material efficiency. It ensures the decrease of the total consumption of materials and subsequent waste generation. The tax helps to counteract a rebound effect, which, as identified by the analysis, can be caused by reduced material costs due to eco-design. The model is applied to the case of Latvia. Yet, the elements and structure of the model developed are similar to waste management systems in many countries. By changing numeric values of certain parameters, the model can be applied to analyze policy mechanisms in other countries.

1. Introduction

Packaging forms an integral part of modern life. Due to the large volumes of packaging materials used and ease of their recovery, packaging waste reuse and recycling have become a priority in the European Union's (EU). The aim of waste recycling is material recovery. Such EU countries as Germany, Denmark and the Netherlands have developed successful waste management systems (WMS) by applying specific economical, ecological, administrative and other mechanisms. But there are also countries struggling with meeting the recycling targets (e.g., Latvia, Poland, and Greece) caused by inappropriate choice of policy mechanisms. As stated by Ulli-Beer et al. (2007) the task of local authorities is "not only to manage the waste, but also to induce behavior change in the overall system". In order to achieve this, it is necessary to understand how the WMS works and its resulting dynamics. Modeling and simulation may help in understanding the influence of policies on the system and its dynamics to create successful solutions.

Many different system's engineering models and system assessment tools have been developed to analyze WMSs, including packaging WMSs, and to handle particular types of the waste management problems. The main aim of the models and tools has been to help the decision makers managing waste in a cost-efficient and environmentally safe way (Eriksson and Bisaillon, 2011). According to Pires et al. (2011), such models and tools are used mostly to find the best management options for different packaging materials, analyze specific parts of the system (collection, treatment and disposal), or analyze different solutions for reaching the recycling targets. Though, as found by Morrissey and Browne (2004) waste management models usually do not consider all three cornerstones of sustainability – economic, environmental and social aspects. They conclude that most of the models are based on cost–benefit analysis, life-cycle analysis or the use of a multi-criteria technique. Finnveden et al. (2007) name several other methods that are used to solve waste management issues, i.e., environmental impact assessment, strategic environmental assessment, cost-effectiveness analysis, life-cycle costing, risk assessment, material flow analysis, substance flow analysis, energy analysis, environmental management system, and environmental auditing. These methods include procedural and analytical methods and may all be referred as system analysis methods. Lately, larger attention is put on waste management systems' thinking, which is confirmed by the Thematic strategy on the prevention and recycling of waste by the European Commission where a large

* Corresponding author. Tel.: +371 67089923; fax: +371 67089908.
E-mail address: elina.dace@rtu.lv (E. Dace).

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Nomenclature

ε	substitution elasticity
FFL	filled fraction of landfills
GDP	gross domestic product
NSort-Env	non-sorting environmentalists
NSort-NEnv	non-sorting non-environmentalists
P_{ave}	average price of materials
P_{rec}	price of recycled materials
PE_{rec}	price elasticity of recycled materials
PE_D	price elasticity of demand for materials
PPU	per product unit
PW	packaging waste
SD	system dynamics
Sort-Env	sorting environmentalists
Sort-NEnv	sorting non-environmentalists
WMC	waste management costs
WMS	waste management system

emphasis is put on the life-cycle assessment and life-cycle thinking (EC, 2005). In modeling WMSs, an assessment of policy instruments is relatively rare. In most cases such methods as strategic environmental assessment and socio-economic assessment are used (Pires et al., 2011). Many of the WMS's models developed have enabled researchers to provide policy-relevant and consistent results. They are all based upon a simplified perception of reality expressed in the form of assumptions and uncertainties (Finnveden et al., 2007). That is a common feature of all system analysis methods and models.

In a number of WMS studies, system dynamics (SD) modeling approach has been applied. The overall WMS (Adamides et al., 2009; Cimren et al., 2010; Inghels and Dullaert, 2011; Oyoo et al., 2011; Sudhir et al., 1997; Sufian and Bala, 2007) or some specific parts of a WMS, e.g., the waste generation stage (Dyson and Chang, 2005; Karavezyris et al., 2002; Kollikkathara et al., 2010) or a specific waste category (Besiou et al., 2012; Chaerul et al., 2008; Ciplak and Barton, 2012; Eleyan et al., 2013; Georgiadis and Besiou, 2008, 2010; Hsiao et al., 2002; Marzouk and Azab, 2014; Ye et al., 2012; Yuan, 2012; Yuan et al., 2011, 2012; Zhao et al., 2011), as well as methane emissions from municipal solid waste disposal (Talyan et al., 2007), waste-to-energy (Sufian and Bala, 2006), waste recycling behavior (Mafakheri and Nasiri, 2013; Ulli-Beer, 2004; Ulli-Beer et al., 2007, 2010) etc., have been analyzed by applying SD. However, there are no studies where SD is applied to modeling packaging WMS and/or eco-design policies. Studies by Wäger and Hilty (2002), and Long et al. (2012) have focused on plastic waste management, part of which is packaging plastics; however they have not analyzed the plastic packaging waste in detail as a short-lived product. Georgiadis and Vlachos (2004) have developed a SD model for a closed-loop supply chain of a general product for evaluating the effect of the green image on demand and on waste management policy for product recovery. Theoretically, the model may be applicable to packaging as a product that is collected and reused or disposed of, but without an option of recycling. Thus, it narrows the applicability of the model to reusable packaging. Later, Georgiadis (2013) has developed a model for planning a recycling capacity in the paper industry that may be just as well applicable to other industries. Decisions of capacity acquisition are investigated with the help of the model to identify the most efficient one in terms of company profit. The model assumes that the recycling capacity is provided by orders to waste collection centers or third-party suppliers. Though, it does not enable a modeler to analyze how the sorting of waste can be enhanced to fill the orders. Conversely, Silvia Ulli-Beer and her colleagues (Ulli-Beer, 2004; Ulli-Beer et al., 2007, 2010) have used the SD method for analyzing the recycling behavior of consumers in response to policy intervention. The model considers human action as "a result of the constant interplay between the internal structure of the actor and the structure of the actor's action context, where processes of perception and action mediate between the two structures" (Ulli-Beer et al., 2007). Furthermore, economic instruments, such as garbage bag charge policy and a prepaid tax for recyclable material in combination with the garbage bag charge, as well as unit prices for both waste qualities are tested to promote recycling behavior while at the same time covering the cost of local solid WMS. These tests show that moderate garbage bag charge and a prepaid tax may satisfy the condition set, and emphasize that the main challenge the decision makers face is to induce the behavior change in the overall system of waste management. The Ulli-Beer-model is not focused solely on the packaging WMS; however it demonstrates the complex structure of the recycling behavior based on interaction of contextual and personal factors, which hold also in the case of the packaging waste. Considering the existing studies, our aim with this study has been to develop a model for packaging WMS in order to analyze how the existing policies and eco-design advancement influence the amount of the materials used for the packaging, and the volume of the waste generated, recycled and landfilled.

The structure of the developed model is based on an extended producer responsibility (EPR) scheme established in most of the European countries and many other countries of the world. In order to eliminate the problem of so-called "free riders" or companies not participating in the scheme, a packaging tax is often applied. The tax rates differentiate between various packaging materials depending on their life cycle impacts, stimulating the producers to choose the more environmentally friendly ones. Since the tax can be several times higher than the EPR scheme's participation fee, a strong incentive exists for companies to get involved in the scheme. Also, a tax for waste depositing in landfills, i.e., a landfill tax, is applied. Certain regeneration targets are set for packaging waste (PW) by Directive 2004/12/EC of the European Parliament and of the Council amending Directive 94/62/EC on packaging and packaging waste. But the trends of waste accumulation clearly show that, in many countries, the existing policies do not cause the reduction in the incremental rate of PW agglomeration in landfill required to leave the rate at least at the existing level. Therefore, other policy instruments have to be used in an attempt at reaching an effective result.

The policy instruments can be economical, administrative and informative (Walls, 2003). In order to raise the efficiency of the packaging WMS, appropriate policy instruments have to be chosen and analyzed. In order to consider rebound effects in the policy design, it is very important to model how certain policy instruments and advances in eco-design will influence the total demand for materials. In this study, we assess the economic and eco-design instruments individually and in interaction with respect to their influence on the efficiency of the packaging WMS in terms of waste generation rate, material recovery rate, and material efficiency (expressed as amount of the packaging materials per product unit).

2. The system dynamics model

System dynamics (SD) is a modeling tool appropriate for WMS policy design (Blumberga, 2010; Hjorth and Bagheri, 2006; Vizayakumar, 1995) since it allows for creating transparent models of complex dynamic systems characterized by accumulations (delays) and non-linear feedback mechanisms that explicitly reflect the relationship between cause and effect. In SD, the structure of the system analyzed is conveniently built into a model using stock-and-flow diagrams. The system analysis is carried out by changing