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Assessment of Sustainable Collection and Recycling Policy of Lead-Acid Accumulators from the Perspective of System Dynamics Modelling

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The scope of our research is to outline dynamics of the transition from informal to formal waste collection system, where the influence of social, economic and policy factors are modelled. The case study is based on lead-acid accumulator's collection system in Latvia. The developed model is valid as 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.

1. Introduction

The demand for mobility is growing worldwide, so does the demand for lead resources; where 75.5 % of global lead is used to produce batteries and accumulators (ILZSG, 2009); usage of lead-acid accumulators for starting, lighting and ignition functions in vehicles continues in hybrid electric vehicles sold in 2013 (ALABC, 2014).

Due to the amount of lead in use, closed-loop management is crucial. The BCI (2014) reports on recycling rate of lead-acid accumulators up to 107.4 % in 2011; while Genaidy et al. (2008) shows that the recycling rate depends on method and changes in the range ±10 %.

The recovery rate of lead may be high, but mainly driven by informal sector and takes place in low-income countries (WHO, 2010). The informal private sector is unregistered, unregulated activities preformed to gain revenue; informal workers in waste sector are scavengers (Schubeler et al., 1996).

It is generally believed that in developed countries formal practices dominate, but informal sector still is an integral part in Greece (Papaoikonomou et al., 2009), Romania (Wilson et al., 2009), Austria, Germany, Hungary, Slovakia and Poland (TransWaste project, 2012).

So far Papaoikonomou et al. (2009) and Besiou et al. (2012) analysed effects of informal sector on waste management in Greece and Wilson et al. (2009) in developing countries; these studies found that incorporation of scavengers into formal recycling system is beneficial for communities. Velis et al. (2009) discusses the case study where forced replacement of informal workers dropped waste recycling rate from 100 % to 10 %. These studies suggest that scavengers cannot be neglected and banned from waste management system, but integration and transition should occur. Prior to our knowledge there are no studies on transition dynamics from informal to formal recycling systems.

The novelty of our research lays in outlined dynamics of the transition to formal collection system, where the influence of social, economic and policy factors are modelled. We study the share of scavengers in formal system and translate theses shares into environmental pollution avoided due to the transition. Our model is based on system dynamics methodology, therefore has delays, feedbacks and non-linearities. The case study is based on lead-acid accumulator's collection system in Latvia.

2. Background information

As a study region Latvia was selected due to availability of historical data and information from experts in the field. Latvia lays in Europe near the Baltic Sea; has 2 million inhabitants and real GDP of 6,800 € per

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capita (in EU-28: 23,100 € per capita) in 2012 (Eurostat, 2014). The parliamentary Republic of Latvia is founded in 1918, forcibly incorporated into the Soviet Union after World War II for next 50 y. In 1991 independence was restored and transition from command economy to market economy began.

Extended producer responsibility is conveyed into legislation of Latvia as eco-tax 0.74 €/kg of lead-acid accumulator (from 1st January 2014) unless a collection rate and recycling rate defined by the government in reached: 25 % and 65 % (from 21st November 2009) (Natural Resource Tax, 2014).

In Latvia collection of lead-acid accumulators is carried on under competing organizations model. Also retailers and distributors of accumulators are obliged to take back wasted accumulators free of a charge.

The official statistics on the amount of collected-lead acid accumulators from individual collection points shows the transition from multiple small collectors to couple major players in the market. Moreover, these statistics confirms that various informal collectors have joined in one formal organization or left the market, forced by marginal profits, more attractive job opportunities and/or stricter environmental regulation - say experts in the field; moreover this transition reduced environmental pollution with sulphuric acid and casings from accumulators, which were discharged into environment, since informal recyclers cared only about recovery of metal. There are no official statistics on the collection and recycling rate of wasted lead-acid accumulators in Latvia, but experts in the field claims that collection rate is close to 100 % due to market value for lead and active involvement of informal sector in scavenging near dumpsites.

3. Methodology

The model was created using system dynamics, which was introduced by Forrester (1958) Methodology reveals the interactions between physical activities, information flows and policy measures, thus exposing dynamical nature of the variables.

The model of lead-acid accumulators' collection system has 3 sectors: "users of lead-acid accumulators", "recyclers of lead-acid accumulators" and "lead-acid market" (see Figure 1).

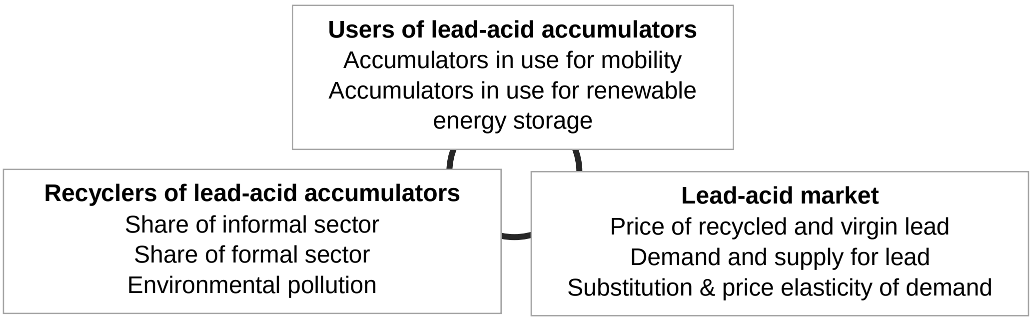

Figure 1. The model's structure for lead-acid accumulators' collection system

Within the sector "users of lead-acid accumulators" we modelled the interaction between GDP and lifetime of accumulators on the stock of lead-acid batteries in use. The sector of "lead-acid market" includes dynamics of price for recycled and virgin lead, demand, supply and substitution elasticity. The sector of "recyclers of lead-acid accumulators" models a transition from informal to formal collection system. A system dynamics model is developed using a program Powersim. As the simulation step 1 year was chosen, since resolution obtained was enough detailed to obtain dynamic in sectors studied.

3.1 Causal loop diagram

The structure of the system dynamics model is described by causal loops (Forrester, 1961); these loops define the feedback mechanisms within the system and show the structure that causes dynamic behaviour of the system under the study (Sterman, 2000); see Figure 2. The diagram of causal loop is converted to a stock–flow diagram in order to obtain a quantitative mathematical model. While the stock and flow model is detailed (contains 75 variables and 55 individual equations – one of these is given in Eq(1)) – the diagram given in Figure 2 illustrates only the main variables interconnected by 4 causal loops.

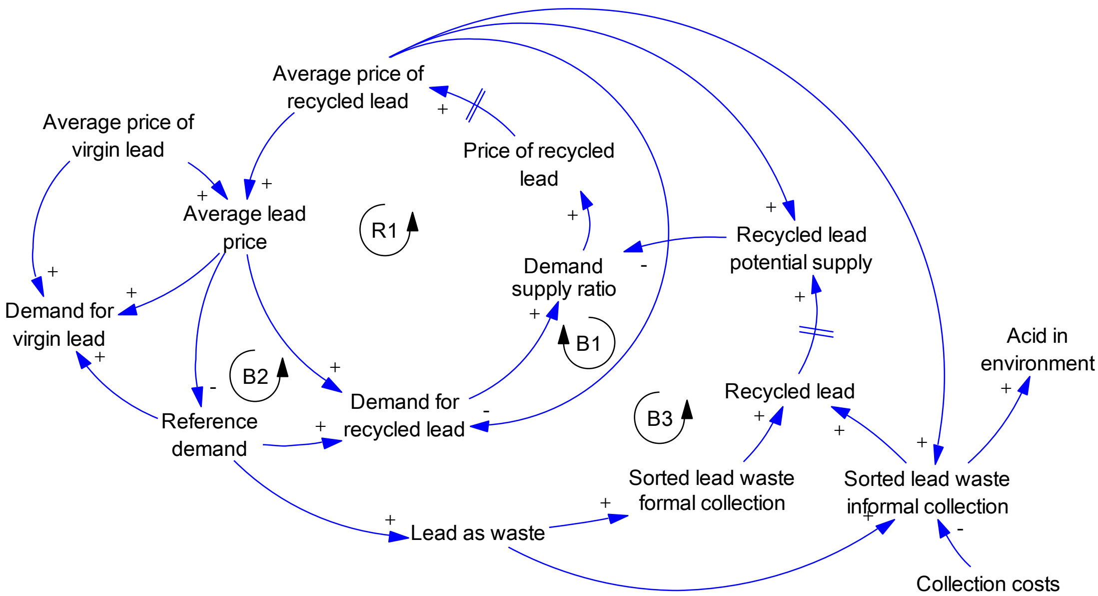

Figure 2. Causal loop diagram for the model of lead-acid accumulators' collection system

The model explains how changes in demand affect the price for lead and how demand is covered by two flows: recycled and virgin lead. When prices are equal for these two flows, a reference demand (see Figure 2) 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 is even. 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 respond to market is incorporated as the lag between the price of recycled lead and average price of recycled lead (in Figure 2 given as the causal link with a delay) because the outcome on the whole market price of recycled materials (average price of recycled lead) due to sudden and/or local changes in price of recycled lead takes time.

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 Eq (1)

$$D_{RL} = RD_L \left(\frac{\overline{P}_{RL}}{\overline{P}_L} \right)^{-\sigma} \tag{1}$$

Where RD_L – reference demand for lead, $\overline{P}_{RL}$ – average price of recycled lead, $\overline{P}_L$ – average price of lead, σ – substitution elasticity.

The increase of average lead price cuts the reference demand therefore reducing the demand for both recycled and virgin materials (the balancing loop B2 counters the positive loop R1). A new equilibrium is achieved at 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 limit 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 rises, the informal sector gains marginal profit and leaves the market – thus convergence to formally dominated collection system is presented. As environmental pressure avoided due to the transition, sulphuric acid pollution is accounted.

3.2 Major assumptions for the model

Although majority of data used in model are available from different sources (Eurostat 2014, LEGMC 2014, World Bank 2014, Sullivan and Gaines 2012, Bio Intelligence 2003, Mao et.al 2008, Rantik 1999, EPA 1994) few assumptions have been made. The main assumptions of the model are:

- An average weight of lead-acid accumulators for passengers cars as assumed 16 kg, for heavy vehicles 24 kg.
- No import and export activities of waste accumulators is assumed within the model.

4. Validation of model

The model undergoes structural and behavioural validation (based on data and observations from the real system) to determine if it is suitable for intended use (Forrester, 1961). Yet the main aim of system dynamics is not to give “point” projections, but to depict the patterns of behaviour (Barlas, 1996). The tests for structural validity judge rationality of individual equations and test the model under extreme conditions. The tests of behavioural validity uses patterns generated for major variables are compare them with historically available data (Barlas, 1996). To determine the robustness of the model, a mean absolute percentage error (MAPE) was used, see Eq (2).

$$MAPE = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{A_i - F_i}{A_i} \right| \tag{2}$$

Where Ai – actual value, Fi – forecasted value and n – number of periods for the forecast generated. Validation was done under the previously defined assumptions for the period from 1996 to 2012.

5. Results and discussion

The main goal of the reference test is to evaluate models’ ability to reproduce the key variable – the amount of collected lead-acid accumulators - see Figure 3. The MAPE - see Eq (2) for the amount of collected lead-acid accumulators was obtained as 26.2 %; these statistics can be explained by presence of informal recycling sectors, which are not accounted in the official waste statistics (given in Figure 3 as historical data) and by financial crisis in Latvia when the real GDP growth rate was negative: −2.5 % in 2008, −17.7 % in 2009 and −1.3 % in 2010 (Eurostat, 2014).

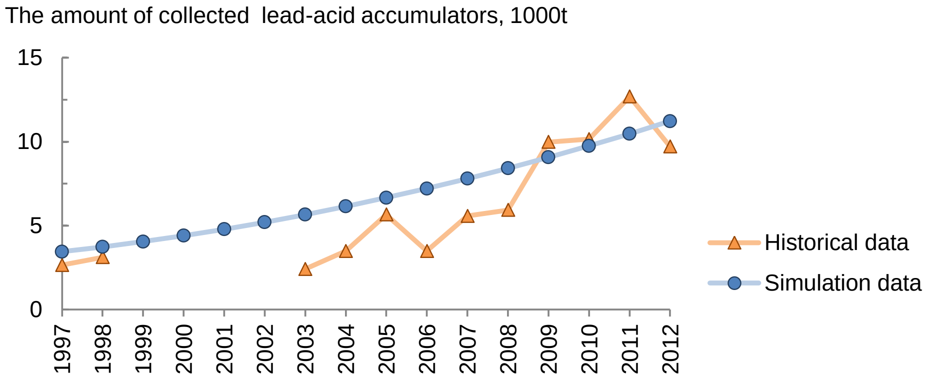

Figure 3. The reference test for the amount of lead-acid accumulators (LEGMC, 2014)

Increasing amounts of lead-acid accumulators could have following reasons: firstly, due to reduction in earning in 2008, more people got involved in waste recycling by selling old accumulators for waste dealers; secondly, stricter environmental regulations and inspections forced informal sector either to leave the market or to consolidate under single formal organization, thirdly, the expansion of economy in the past years (the real GDP growth rate: + 5.3 % in 2011, + 5.2 % in 2012, + 4.1 % in 2013) is increasing the spending rate on mobility and consumed goods (Eurostat, 2014). Moreover, 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 Figure 4).

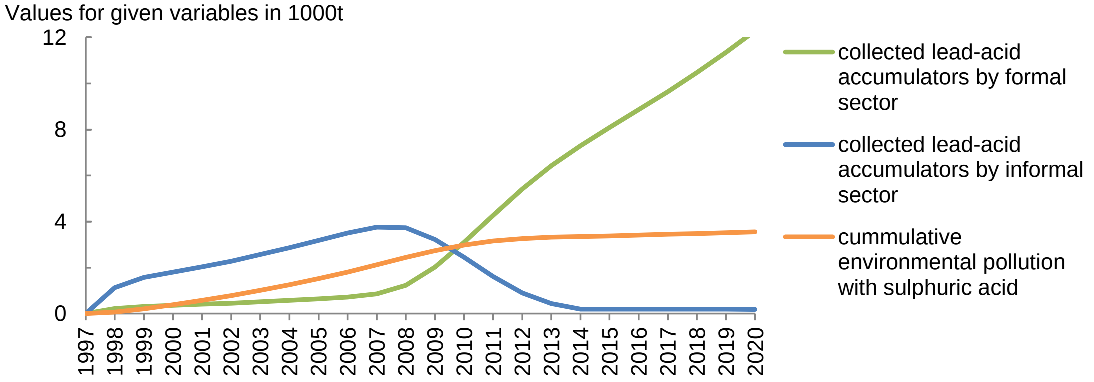

Figure 4. The transition dynamics between informal and formal lead-acid collection schemes and the cumulative environmental pollution with sulphuric acid

The pollution of the environment during the transition to formal practices are expressed as cumulative pollution with sulphuric acid, which has the peak growth in absolute numbers in the period 2007-2008.

6. Conclusions

The developed model shows how the transition from informal to formal practices in the collection system of lead-acid accumulators occurs, sheds light on the structure, dynamic behaviour, feedbacks, delays and drivers that transforms the model. The model is valid as 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.

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