

Energy efficiency policy analysis using socio-technical approach and system dynamics. Case study of lighting in Latvia's households



Lelde Timma, Gatis Bazbauers*, Uldis Bariss, Andra Blumberga, Dagnija Blumberga

Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, Riga LV1048, Latvia

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ABSTRACT

Worldwide the lighting sector demands around 1/5 of total electricity used. While the diffusion of new lighting technologies occurs quickly and prices for these technologies drop, at the same time around 1/3 of households in developed European countries continue to choose incandescent light bulbs. This phenomena shows a large potential for saving electricity. Therefore, the aim of our research is to model the diffusion of innovation for energy efficiency solutions in households in Latvia. The methodology combines an empirical study with system dynamics modelling. The model showed that electricity consumption in households decreased by 14% from the year 2015 until the year 2040. The sensitivity analysis shows that changes in the parameters used in this analysis caused expected behaviour, where the uncertainty in electricity consumption in households accounted for $\pm 16\%$ in the year 2040. Although this developed system dynamics model was based on a specific process of diffusion of innovation, its general application to other products and services is possible, since the developed model serves as a white-box. The structure of the model can be used for other studies; the model can be enhanced with the newest results or adapted for other case studies.

1. Introduction

The lighting sector demands up to 19% of total electricity use worldwide, therefore this sector can present high potential for energy savings (Franceschini and Pansera, 2015). Moreover new lighting technologies diffuse quickly and the price for these technologies has dropped by 99.7% in the past two centuries (Nordhaus, 1996). At the same time, there are still around one third of households in Germany in 2012 that choose to replace incandescent light bulbs with the same - incandescent light bulbs (Mills and Schleich, 2014).

We would like to argue that two important aspects for the reduction of electricity consumption should be studied in more detail: (1) the establishment and introduction of technological innovations and (2) change in energy consumption behaviour. The challenge to diffuse novel technologies is given in the review by Karakaya et al. (2014). General models for diffusion of innovation are given by Bass (Bass, 1969) and Rogers (1995), but these models consider coefficients related to the speed of diffusion as external parameters, and therefore the factors affecting diffusion speed are not explored and cannot be triggered purposefully. The influence of personal values on the selection of energy alternatives is given by Perlaviciute and Steg (2015). A study applies discourse analysis to the lighting sector, to show the paths of various future developments, but the work was limited to the

methodological perspective (Franceschini and Pansera, 2015). Agent-based modelling studied various pathways to phase-out incandescent light bulbs (Chappin and Afman, 2013). Some black box modelling has been used to study energy consumption by lighting in households (Reveiu et al., 2015). The factors associated with household decisions to adopt energy efficient bulbs are studied with statistical data analysis methods as well (Mills and Schleich, 2014).

To our knowledge, there have been no studies connecting the aspects of innovation diffusion and personal values in one, comprehensive model for the lighting sector. Also Frederiks et al. (2015) points out that the diffusion of innovations and behavioural aspects has been neglected in the models of energy use in households.

Therefore, the aim of our research is to outline diffusion dynamics, through the application of a model of innovation diffusion for energy efficiency solutions in households. The methodology used is developed by the co-authors and combines an empirical study with system dynamics modelling. The intention of introducing energy efficient lighting solutions in Latvia is used as the case study.

The first part of the work includes the development of a mathematical model based on the results obtained from a questionnaire. The second part deals with the system dynamics model that incorporates the results of the questionnaire to obtain the dynamics of behaviour over time including feedbacks, non-linearities and delays.

* Corresponding author.

E-mail address: gatis.bazbauers@rtu.lv (G. Bazbauers).

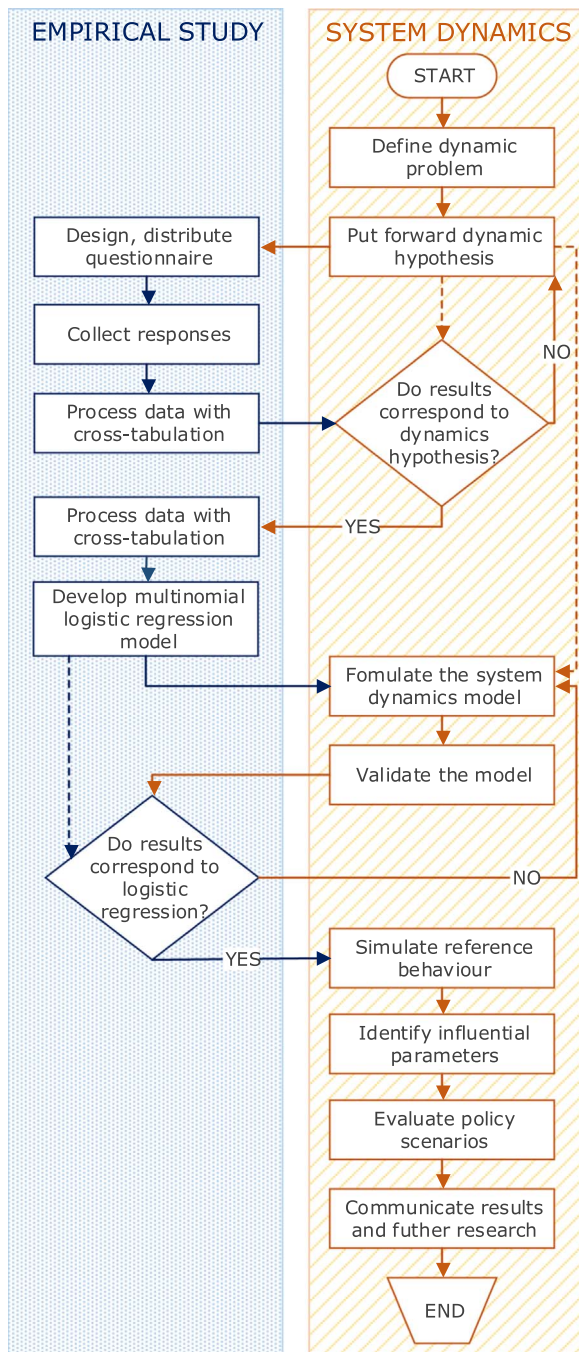


Fig. 1. Algorithm of the used methodology.

Although the system dynamics model was based on the specific innovation diffusion process, its general application to other products and services is possible, since the developed model is a white-box. The structure of the model can be used for other studies; the model can be enhanced with the newest results or adapted for other case studies.

2. Methodology

The methodology used is developed by the co-authors of this paper and the first application of this methodology is presented by Vigants et al. (2015). This work combines an empirical study with system dynamics modelling (see Fig. 1). Initially the dynamic problem and hypothesis are developed. The empirical study starts with the design of a questionnaire and the collection of responses. The responses are processed with cross-tabulation and logistic regression analysis. Later,

the results of the empirical study are used for formulation of the system dynamics model. This model undergoes validation, sensitivity analysis and policy tools are applied for a scenario analysis.

2.1. Empirical study

2.1.1. Questionnaire design and data collection

The questionnaire was computer based. Firstly, respondents were asked to specify the time when they recall last changing a light bulb. The responses with the answer “do not remember”, “did not change a light bulb” or “changed more than two years ago” were not included further in the analysis, since the aim was to study recent light bulb change where respondents specifically remembered the occasion and technologies changed. Therefore, the next question was to specify what type of light bulb was changed. The respondents were also provided photographs of various light bulbs and their name in order to provide a more accurate reply. Those photos included 6 most common types of light bulbs: incandescent lamp (IL), halogen lamp (HL), double ended halogen lamp (DeHL), fluorescent tube lamp (FTL), compact fluorescent lamp (CFL) and light emitting diodes (LEDs). The same photographs are used for the next question, but in this case, the light bulb selected is that which the respondent used to replace the changed bulb.

After the specification of the replacement bulb, the next question is to select the three most important guiding factors used in order to select the replacement light bulb. A list of 10 alphabetically ordered factors were given. The factors were adapted from the study by Mills and Schleich (2014). These factors included: (1) manufacturer or brand of light bulb; (2) service time of the light bulb; (3) rating in the test reports; (4) possibility to change light intensity; (5) electricity consumption of light bulb; (6) price of light bulb; (7) impact to the environment; (8) light intensity of light bulb; (9) shape of light bulb; and (10) quality of light coming from the light bulb.

The questionnaire was carried out in Latvia from May until July 2015. The three distinct study groups were: employees of the largest electricity generation utility company in Latvia, employees of the Riga Technical University and the general public. Links to the on-line questionnaire were distributed via e-mail among the employees of the electricity generation utility company and university, and posted on-line for the general public.

2.1.2. Questionnaire data analysis

2.1.2.1. Cross tabulation. During the cross tabulation, a Chi-square test tabulates a variable into categories and obtains the values for Chi-square statistics. The test allows evaluating the randomness of the various variables fitted into different categories, or in other words, Chi-square evaluates hypothesis on the random distribution of data. In the case when the null hypothesis fails, the observed data is not randomly generated and therefore there is a ground for the evaluation of causal relationships among the observed variables (Greasley, 2008).

The Chi-square test, .. compares $-2 \log$ -likelihood function of current model, $-2l(\tilde{P})$ with the $-2 \log$ -likelihood function of previous model, $-2l(\hat{P})$, see Eq. (1).

$$\begin{aligned} \chi^2 &= -2l(\tilde{P}) - [-2l(\hat{P})] \\ &= -2 \sum_{i=1}^n [w_i y_i \ln(\tilde{P}_i) + w_i (1 - y_i) \ln(1 - \tilde{P}_i)] \\ &\quad - \left\{ -2 \sum_{i=1}^n [w_i y_i \ln(\hat{P}_i) + w_i (1 - y_i) \ln(1 - \hat{P}_i)] \right\} \end{aligned} \quad (1)$$

2.1.2.2. Logistic regression analysis. The multinomial logistic regression analysis was performed to fit a regression model in which the dependent variable characterizes an event with three possible outcomes: substitute incandescent lamp with incandescent lamp

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