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METHODOLOGY FOR SOCIO-TECHNICAL TRANSITION RESEARCH

Doctoral Thesis

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ANOTĀCIJA

Ekoinovācijas iniciatīva tika izstrādāta kā viens no galvenajiem stūrakmeņiem ilgtspējīgai, viedai un integrētai izaugsmei kā atbildes reakcijas uz finansiālo lejupslīdi un arvien jaunām sociālām problēmām. Tomēr eksperti arvien biežāk norāda, ka viena svarīga saikne joprojām iztrūkst – kamēr, galvenokārt, visa uzmanība tiek koncentrēta uz tehniskajiem jauninājumiem un apkārtējās vides aizsardzību, sociālie aspekti pārsvarā netiek ņemti vērā. Šie sociālie aspekti ietver cilvēkus, ekonomikas, politikas, organizatoriskās un citas mijiedarbības sistēmā. Apvienojot šīs trīs jomas – sociālo, tehnisko un apkārtējās vides – autore pētīja tā saucamās sociotehniskās sistēmas.

Pašlaik izpēte, izmantojot sociālos un tehniskos aspektus, lai studētu pārejas procesus, ir sadrumstalota, gan starp dažādām gadījumu izpētēm, gan dažādām izmantotajām metodēm, gan zinātnes jomām. Jo īpaši enerģētikas izpētes jomā lielākā daļa pētniecības darbu aplūko sistēmu tehnoloģiski ekonomiskos aspektus, līdz šim tikai dažos darbos ir mēģināts iekļaut arī sociotehniskās perspektīvas.

Ir konstatēts, ka trūkst skaidras holistiskas metodoloģijas, tāpēc šī darba galvenais mērķis ir saistīt inženierzinātņu un sociālo zinātņu izpētes jomas, lai radītu šādu holistisku modelēšanas pieeju. Tāpēc promocijas darbs fokusējas uz metodoloģijas veidošanas gaitu. Kā gadījuma izpētes objekts šajā darbā ir izmantots mājsaimniecību sektors. Laika gaitā tika attīstīta izmantoto metodiku sarežģītība, lai atbilstu pieaugošās sarežģītības pētniecības jautājumiem.

Autore šajā darbā apskata sociotehniskos pārejas procesus, raugoties no dažādu nozaru, piemēram, enerģijas izmantošanas, pārveides un pārvaldības, inovāciju difūzijas un citu Pārejas procesi tika aplūkoti arī no dažādu izmantoto metodiku skatupunkta, pētot šo metodiku kombinācijas. Un pēdējais, bet ne mazāk svarīgais – darbā pārejas procesi tiek aplūkoti no dažādu zinātnes nozaru – gan inženierzinātņu, gan sociālo zinātņu – viedokļa.

Promocijas darba pamatā ir sešas tematiski vienotas zinātniskās publikācijas, kas publicētas dažādos zinātniskajos žurnālos, pieejamas zinātniskajās informācijas krātuvēs un ietvertas starptautiskās datubāzēs. Šo publikāciju mērķis ir pārnest un aprobēt sociotehniko pāreju izpētes ietvaru. Šis darbs sastāv no ievada un trīs nodaļām.

Darba ievads definē tā mērķi un uzdevumus, apraksta darba struktūru un sniedz īsu pārskatu par promocijas darba aprobāciju (publikācijas un līdzdalība starptautiskajās zinātniskajās konferencēs).

Pirmā nodaļa izklāsta pētījumos risinātos jautājumus attiecībā uz katru no definētajiem pētījuma segmentiem. Otrā nodaļa apraksta metodiku, kas tiek izmantota sociotehnisko pāreju pētījumos, savukārt izvēlēto metožu izmantošanas rezultāti ir apkopoti darba trešajā nodaļā. Iegūtie secinājumi ir apkopoti darba noslēgumā.

ANNOTATION

As the response to the financial downturn and arising social problems, eco-innovation flagship was elaborated as one of the main building blocks for sustainable, smart and inclusive growth. Nevertheless, the experts are increasingly pointing out that one important link is missing – while focusing mainly on technical innovations and natural environment, social aspect is mostly disregarded. The social aspect includes human, economic, policy, organisational and other interactions in the system. By bringing together these three sectors – social, technical and natural environment –, the author of the present Thesis studied so the called socio-technical system.

Currently, the studies using social and technical aspects for the research on transition processes are fragmented, both in terms of studied sectors, used methods, and scientific fields. Especially, in the field of energy research, the majority of the works study techno-economic aspects of the system, while only few attempts have been made to incorporate socio-technical perspective as well.

Also a clear lack of a holistic methodology has been identified, therefore the ultimate aim of this Thesis is to attempt to link the engineering and social science study field to create such modelling approach. The Thesis work, therefore, guides through the path of the creation of this methodology. As a case study object, the household sector is used in the Thesis. The complexity of the applied methods was developed over time to match the growing complicatedness of studied research questions.

The author of this Thesis views the socio-technical transition processes from the perspective of various sectors, such as energy use, production and management, innovation diffusion, and others. Also, the transitions are looked from the scientific lenses of various possible methods and their combination. And, last but not least, these transition studies are considered from the perspective of various scientific fields, both engineering and social science.

The Doctoral Thesis is based on the thematically unified six scientific publications. Those publications are published in various scientific periodicals, and are accessible in scientific information repositories and cited international databases. The goal of these publications is to transfer and approbate the framework of socio-technical transitions. This thesis consists of an introduction and three chapters.

In the introduction, the goal of the Thesis and the underlying tasks are given, followed by the definition of the Thesis's structure and a short description of the approbation of the results obtained by means of the publications and participation in international scientific conferences.

Chapter 1 provides an overview of the research questions present in the defined study domains. Chapter 2 describes the methodologies used in the socio-technical transition studies. The results obtained from the application of the proposed methodologies are presented in Chapter 3. Finally, conclusions are given at the end of the Thesis.

PATEICĪBAS

„Pasaulē vēl neviens darbs nav pilnībā pabeigts."
Latviešu tautas paruna

Mana skološanās ar šo darbu noteikti nav beigusies, ceru, ka tā nav pat tuvu pusei... Taču šis darbs noslēdz nozīmīgu manas dzīves daļu, un es gribu pateikt paldies tiem cilvēkiem, kas šo posmu gāja man līdzās intensīvā solī.

Cilvēks, kurš mani, ir „ieprogrammējis" atrasties šajā vietā un aizstāvēt darbu ir mans vectēvs Alfrēds. Es uzskatu, ka viņš bija tas, kurš ielika visus vajadzīgos pamatus, lai es izveidotos par inženierzinātņu doktoru! Atskatoties atpakaļ, es labprāt dalītos ar jums šajā receptē.

Pirmkārt, vajadzīga zinātkāre. Kā šodien atceros, ka vienmēr gaidīju tikšanos ar vectēvu, jo viņš parasti bija man sagatavojis kādu „cieto riekstu". Viens no tādiem bija „vai gailis sver mazāk, stāvot uz viena kājas nekā uz divām?" Tajā laikā biju vēl mazs bērns, nepratu ne lasīt, ne rakstīt, bet mani aizrāva šo mīklu risināšana. Tad atceros to burvīgo sajūtu, kad man „pieleca" atrisinājums! Arī tagad, saskaroties ar nu jau mazliet cita līmeņa uzdevumiem, iekšējais dzinulis nav mainījies, gluži kā atkarībniekam gribas to sajūtu gaidīt vēl un vēl „jā, zinu, varu atrisināt, un varu pārējiem to paskaidrot".

Otrkārt, un šis jau paliek grūtāk izpildāms nosacījums, ir nepieciešama rūdīta latgalieša pacietība un neatlaidība. Tās prasmes manī tika ieliktas, kā tagad moderni sacīt, bioloģiskās daudzveidības izmantošanas laikā, lai iegūtu produktu ar augstu pievienoto vērtību jeb bišu saimju apkopšanas laikā. Tā bija sava veida baiļu pārvarēšana – rīkoties gar miljoniem dzeloņiem piepildītu spietu, kad saproti, ka viena neuzmanīga kustība nozīmē pamatīgu (ja paveiksies, tad tikai vienu) dzēlienu. Tāda sava veida mikroķirurģija, tikai pie katras kļūdas ārsts iegriež sev, nevis pacientam.

Un, treškārt, jau specializācija – mīlestība pret dabu, domāšana ilgtermiņā un savstarpējo sakarību izpratne dabā. Pavadot ļoti daudz laika vienā no neskartākajām un skaistākajām Latvijas vietām, kur vietas nosaukums pats par sevi saka visu priekšā – Skaistas pagasts… Šī ir vieta, kur mēs kopā ar brāli uz savas ādas izbaudījām sistēmdinamikas pamatus – cēloņsakarības un akumulācijas spēju. Stāsts par to, ka, pavasarī iesējot burkānus, ne vienmēr visas sēklas ir gadījušās vecas, un pa virsu uzreiz ir jāiesēj vēl viena kārta, jo – kā rāda dzīve – pēc kāda laika izdīgst divreiz vairāk burkānu, nekā bija domāts, un tad tiek pieaicināti divi mazāko pirkstiņu īpašnieki – es un mans brālis – risināt šo problēmu.

Sasaistot visas šīs trīs lietas, pašsaprotama šķiet izvēle stāties RTU vides zinātnes programmā. Mācoties RTU, man nebija nekādas nojautas, ka pēc deviņiem gadiem es pati kļūšu par lektori.

Paldies ir jāsaka profesorei Dagnijai Blumbergai, kura deva man iespēju sevi parādīt un pierādīt. Droši vien reti kurš zina, ka es VASSI sāku strādāt krīzes laikā, es rakstīju Dagnijai jautājumu, vai viņa gadījumā negribētu paņemt mani strādāt par apkopēju. Apkopējas darbu nedabūju. Paldies, ka saskatījāt manī potenciālu un ļāvāt izaugt tik daudz, cik iespējas ļāva.

Paldies profesoram Gatim Bažbaueram par nesavtīgu dalīšanos ar komentāriem, ieteikumiem un pārdomām, lai šo darbu padarītu lasītājiem saprotamu.

Šo gadu laikā daudzi kolēģi ir kļuvuši par vairāk nekā kolēģiem. Katrs no jums ir ienesis manā ikdienā kādu citu dzīves skatupunktu, par to esmu ļoti pateicīga. Īpaši ir jāsaka paldies Andrai, Marikai, Francesco un Claudio, kuri ir bagātinājuši manu redzesloku gan apzināti, gan netieši un viennozīmīgi atstājuši savus nospiedumus manā dzīves skatījumā. Paldies jāsaka arī Ļenai, Annai, Kristai, Dace, Ancei, Indrai, Antrai, Līgai un visiem pārējiem kolēģiem, kas mani atbalstīja un neļāva padoties.

Paldies ceļo arī uz tālām un tuvām zemēm, pa kurām ir izkaisīti mani gara biedri – Inna, Jūlija un Pēteris. Paldies, ka, neskatoties uz attālumu un ikdienas steigu, es vienmēr esmu jutusi jūsu atbalstu.

Noslēgt pateicības vēlos ar to, ar ko sāku – ar ģimeni.

Mamma – ko šeit vispār var aprakstīt vārdots, jo viņa ir tik lieliska tajā, ka viņa vienkārši ir! Manuprāt, viņa ir izdarījusi vissmagāko vecāku uzdevumu – neiejaukties, paļauties un pilnībā uzticēties maniem un brāļa spēkiem. Kā mamma jokojot kolēģiem atbildi: „Es nezinu, kā tā sanāca, viņi paši izauga tik forši!" Tāda nu viņa ir – pieticīga un mīļa kā balta diena.

Paldies tētim par mīlestību, rūpēm un piedalīšanos manā dzīvē tik, cik bija iespējams.

Jančuks – mans lielākais iedvesmas avots! Viņš man katru dienu atgādina par to, ka ir nepieciešams nepārtraukti pilnveidoties un neatlaidīgi iet uz savu mērķi. Iet, neskatoties uz to, ko saka un domā pārējie, neskatoties ne uz ko. Neskatoties atpakaļ, neskatoties uz kritieniem, tikai celties un iet tālāk. Paldies par saliedētību, gādību un stipro muguru blakus!

Paldies sirdsāķītim Aivaram pat to, ka viņš ar sapratni izturējās pret brīvdienām, atvaļinājumiem un naktīm, kas tika pakārtotas darbam. Paldies par to, ka bija mana sirdsapziņa un komandante vienlaikus – atgādinot par to, ka arī doktorantam ir jāēd, jāiet pagulēt, jāatpūšas un jādzīvo ārpus darba. Paldies par nosvērtību, ticību maniem trakajiem projektiem un bezkompromisu mīlestību.

Paldies visiem pārējiem mīļumiem. Babiņai, kura nu jau sargā mani, sēžot uz mākoņa maliņas. Viņa bija Saimniece un Namamāte ar lielo burtu, sabiedrības dvēsele un prasmīga rokdarbniece, vienmēr gribēja, lai es kļūstu par dakterīti. Nu vēlme ir daļēji piepildīta. Krustmātei Ingrīdai un krustēvam Pāvelam mīļš paldies par to, ka iedvesmojat, atbalstāt un lutiniet mani pēc labākajām latgaliešu tradīcijām! ☺ Krustbērniem Emīlam un Madarai daudz, daudz buču, jūs esat mani eņģelīši un prieka avots. Paldies Meļnovas māju saimniecei Irai un saimniekam Andrim par iespēju fiziski un emocionāli restartēties un Ilonai par rūpēm! Visbeidzot – paldies arī jaunākajam ģimenes papildinājumam Hugo par nebeidzamo enerģiju un beznosacījumu mīlestību.

Mīlu jūs visus!

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TABLE OF CONTENT

NOMENCLATURE

Greek symbols

α	Cronbach alpha value
β_0	constant of the fitted model
$\beta_1, \beta_2, \ldots \beta_k$	estimates of the fitted model
γ	decay rate
δ	hyper-parameter
η	coefficient for the logistic regression equation
ρ	elements of the correlation matrix
Φ	column eigenvectors
χ	Chi value
Ψ	an orthonormal rotation matrix
ω	network weights

Latin symbols

a	elements of the partial correlation matrix
AA	accumulated avoided
ANN	artificial neural network
AW	households aware of eco-innovation
B	balancing loop
B1, B2, …, Bn	first, second and *n*-th negative or balancing loop
C	consumption
CA	consumption alternative
CF	cofactors of the correlation matrix
CFL	compact fluorescent light
CH	contacts per eco-innovation's users household
CI	confidence interval
CT	cross-tabulation
D	training set
d	number of the time-delays
Df	degrees of freedom
E	network error
EC	European Commission
erf	the asymptotic series of error function
erfc	the complementary error function of asymptotic series

Latin symbols (continue)

EU	European Union
FC	functionality and controllability
fr	fraction
GDP	gross domestic product
GN	green norms
HH	households
i	*i*-th external input or *i*-th row in matrix
IL	incandescent light
j	*j*-th column in matrix
k	identity variables
k	the neuron
KMO	Kaiser-Meyer-Olkin test
LED	light emitting diodes
LRM	logistic regression model
M	architecture of neural network
MAPE	mean average percentage error
MFC	micro-fibre cloth
MLRM	multinomial logistic regression model
MSE	the mean square error
n	number of items
N	sample size
NARX	non-linear autoregressive neural network
OASI	overall attitudes and social influence
p	original variables or p-value
P	probability of the occurrence of the outcome
P. 3	Paper No. 3
P. 4	Paper No. 4
PCA	principal component analysis
r	correlation coefficient
$\bar{r}$	average off all Pearson correlation coefficients
R	reinforcing loop
$\|R\|$	determinant of the correlation matrix
R1, R2, …, Rn	first, second and *n*-th positive or reinforcing loop
R^2	the statistical coefficient of determination
R^2_{adj}	adjusted statistical coefficient of determination
SE	standard error

Latin symbols (continue)

SF	self-efficacy
ST	strength of information campaign
t	discrete time step
T	time delay
u	the output from the summation function
w	weight
WOM	adoption from word-of-mouth
x	input signals
X	variable
y	output signals

Subscripts and superscripts

Latin symbols

A	adopted eco-innovation
AD	adoption
CA	cleaning agent
i	*i*-th input
IC	information campaign
INF	information
init	initial value
j	neural network
k	neuron
NA	not adopted eco-innovation
t	time period, reference time step
VARIMAX	Varimax rotation method
w	weight
week	weekly

INTRODUCTION

"Remember that all models are wrong;
the practical question is how wrong do
they have to be to not be useful"
- Box and Draper (1987)[1]

As the response to the financial downturn and arising social problems, eco-innovation flagship was elaborated as one of the main building blocks for sustainable, smart and inclusive growth. Nevertheless, the experts are increasingly pointing out that one important link is missing – while focusing mainly on technical innovations and natural environment, social aspect is mostly disregarded. The social aspect includes human, economic, policy, organisational and other interactions in the system. By bringing together these three sectors – social, technical and natural environment –, the author of the present Thesis studied so the called socio-technical system.

Currently, the studies using social and technical aspects for the research on transition processes are fragmented, both in terms of studied sectors, used methods, and scientific fields. Especially, in the field of energy research, the majority of the works study techno-economic aspects of the system, while only few attempts have been made to incorporate socio-technical perspective as well.

Also a clear lack of a holistic methodology has been identified, therefore the ultimate aim of this Thesis is to attempt to link the engineering and social science study field to create such modelling approach. The Thesis work, therefore, guides through the path of the creation of this methodology. As a case study object, the household sector is used in the Thesis. The complexity of the applied methods was developed over time to match the growing complicatedness of studied research questions.

The author of this Thesis views the socio-technical transition processes from the perspective of various sectors, such as energy use, production and management, innovation diffusion, and others. Also, the transitions are looked from the scientific lenses of various possible methods and their combination. And, last but not least, these transition studies are considered from the perspective of various scientific fields, both engineering and social science.

[1] Box, G. E. P., and Draper, N. R., (1987), *Empirical Model Building and Response Surfaces*, John Wiley & Sons, New York, NY.

Scientific Significance

In this Thesis, two major points of scientific significance can be viewed. Firstly, the development of socio-technical transition research in the field of energy and environmental protection. Nowadays, experts are increasingly pointing out that one important link is missing; while focusing mainly on technical innovations and natural environment, social aspect is mostly disregarded. This work, therefore, expands the current knowledge in the field of socio-technical transitions by analysing the causes of social and technological changes. This Thesis addresses how these transitions originate, unfold, and finish.

Secondly, the Thesis presents a complex study where novel modelling methodology is developed. The presented methodology combines the aspects of technical and social systems and natural environment, thus providing holistic methodology tools to study socio-technical transitions. The developed methodology contains various levels of complexity, starting with the use of single mixed methodology up to hybrid modelling tools, containing four methods (social psychology, statistical data analysis, system dynamics, and artificial intelligence).

As to the author's knowledge, this is the first time that socio-technical transitions are studied by using the latest knowledge and advanced modelling tools for the engineering and social science field together. Also the development of methodology that uses both white-box models (system dynamics) in combination with black-box models (artificial intelligence) is an important aspect contributing to the development of state-of-the-art modelling tools.

Practical Significance

Currently, the mitigation of climate change does not take the most effective path, since various eco-innovations and energy efficiency solutions have already reached a mature state, but they diffuse slowly into the market. Therefore, in this Thesis, the developed methods for socio-technical transitions are approbated in two study domains: (1) eco-innovations diffusion and (2) energy efficiency and conservation.

As practical applicability for these sectors, policy interventions were offered to move towards greater sustainability. Thus, by using presented frameworks, policy makers can analyse the past trends, for example, in the diffusion of lighting technologies, identify bottlenecks and thus test various policy tools to foster the market up-take of more energy-efficient lighting solutions. Moreover, in the presented framework, also the human behaviour is taken into the account, thus increasing the reliability of obtained simulation results. These outlined methods thus can guide the decision-making process and model the outcomes of various development scenarios. By applying the knowledge obtained, the sectors can be targeted more effectively to reach a sustainable development goal.

The present Doctoral Thesis allows transferring the developed methodology to study other technologies and services at different levels of the economy. The methodology developed can be of practical applicability for academic research, and for policy makers and for entrepreneurs and investors as well.

Approbation of the Study

The research results have been approbated in 12 international scientific conferences and published as 25 full-length articles (19 in *Scopus* database and 15 in *ISI Web of Science* database) and one abstract in international scientific journals and conference proceedings.

Reports at International Scientific Conferences

1. Timma L., Blumberga A., Bazbauers G., Blumberga D. Novel Tools to Study Socio-Technical Transitions in Energy Systems // International Scientific Conference of Environmental and Climate Technologies CONECT 2017, 10–12 May 2017, Riga, Latvia.

2. Timma L., Bariss U., Dandens A., Blumberga A., Blumberga D. Framework for the Assessment of Household Electricity Saving by Integrating Behavioural Aspects // International Scientific Conference of Environmental and Climate Technologies CONECT 2015, 14–16 October 2015, Riga, Latvia.

3. Timma L., Bariss U., Blumberga A., Blumberga D. Outlining Innovation Diffusion Processes in Households using System Dynamics. Case Study: Energy Efficiency Lighting // 7th International Conference on Applied Energy, ICAE 2015; 28–31 March 2015, Abu Dhabi, United Arab Emirates.

4. Timma L., Blumberga A., Blumberga D. Understanding the Technological Substitution by Hybrid Modelling Practice: A Methodological Approach // 18th Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction PRES 2015, 23–27 August 2015, Kuching, Malaysia.

5. Blumberga A., Timma L., Lauka D., Dace E., Barisa A., Blumberga D. Achieving Sustainability in Non-ETS Sectors using System Dynamics Modelling Practice // 18th Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction PRES 2015, 23–27 August 2015, Kuching, Malaysia

6. Timma L., Blumberga A., Blumberga D. Combined and Mixed Methods Research in Environmental Engineering: When Two is Better than One // International Scientific Conference of Environmental and Climate Technologies CONECT 2014, 14–16 October 2014, Riga, Latvia.

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

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

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

10. Bariss U., Timma L., Blumberga D. Smart Metering Pilot Project Results // 6th International Conference on Applied Energy, ICAE 2014, 30 May – 2 June, 2014, Taipei, Taiwan.

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

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

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

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

Publications on the Topic of the Doctoral Thesis

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2. Timma L., Bazbauers G., Bariss U., Blumberga A., Blumberga D. Energy Efficiency Policy Analysis Using Socio-Technical Approach and System Dynamics. Case Study of Energy Efficient Lighting in Households // Accepted for publication in the Journal of Energy Policy http://dx.doi.org/10.1016/j.enpol.2017.07.030 *(Pending in Scopus and ISI Web of Science).*

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Thesis Outline

The Doctoral Thesis is based on the thematically unified six scientific publications. Those publications are published in various scientific periodicals, and are accessible in scientific information repositories and cited international databases. The goal of these publications is to transfer and approbate the framework of socio-technical transitions.

This Thesis consists of an introduction and three chapters:

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

In the introduction, the goal of the Thesis and the underlying tasks are given, followed by the definition of the Thesis's structure and a short description of the approbation of the results obtained by means of the publications and participation in international scientific conferences.

Chapter 1 provides an overview of the research questions present in the defined study domains. Chapter 2 describes the methodologies used in the socio-technical transition studies. The results obtained from the application of the proposed methodologies are presented in Chapter 3. Finally, conclusions are given at the end of the Thesis.

1 LITERATURE REVIEW

As the response to the financial downturn and arising social problems, eco-innovation flagship was elaborated as one of the main building blocks for sustainable, smart and inclusive growth of society[2].

Nevertheless, the experts are increasingly pointing out that one important link is missing – while focusing mainly on technical innovations and natural environment, social aspect is mostly disregarded (Wu et al., 2015). This social aspect includes human, economic, policy, organisational, and other interactions in the system. By bringing together these three sectors – social environment, technical environment, and natural environment –, the author of the present Thesis studied the so called socio-technical system (see Fig. 1).

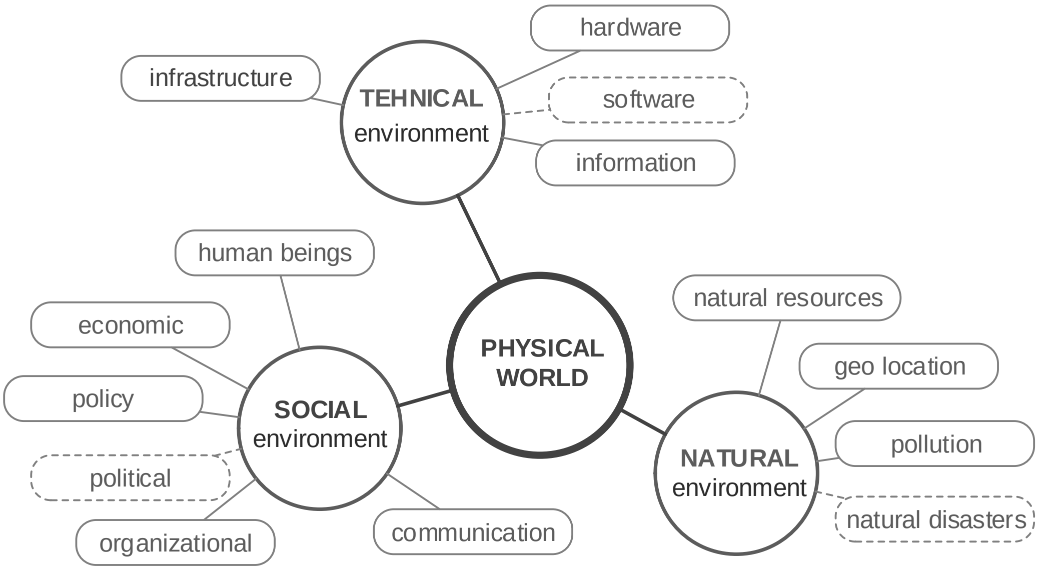


Figure 1.1. Hierarchy of socio-technical systems adopted from Wu et al. (2015).

The research on the socio-technical transitions analyses the causes of social and technological changes, where the main study questions are how these transitions originate, unfold, and finish. The pathways of sociotechnical transition are given by Geels & Schot (2007). Here, the first challenge is to replicate and study historical transitions, and the second challenge is to develop tools for the analysis and finally propose the policy interventions (Papachristos & Adamides, 2016).

In the Thesis, the contribution to socio-technical transitions in the households sector addressed all these challenges. Firstly, by studying the historical transitions in two domains of energy efficiency and eco-innovations (other domains, such as waste management, climate change mitigation, etc., have also been studied, and the references to these studies are given in the publications' list, but the publications are not included

[2] EC, Innovation for a sustainable Future – The Eco-innovation Action Plan (Eco-AP), COM (2011) 899 final, 15.12.2011., Brussels.

as full papers in the Thesis work in order to focus on the most recent scientific work) and by proposing policy interventions for these studied systems. Secondly, by developing and refining the novel tools to study the transition processes.

In the Thesis, the complexity of the applied methods was developed over time to match the growing complicatedness of studied research questions, see Figure 1.2.

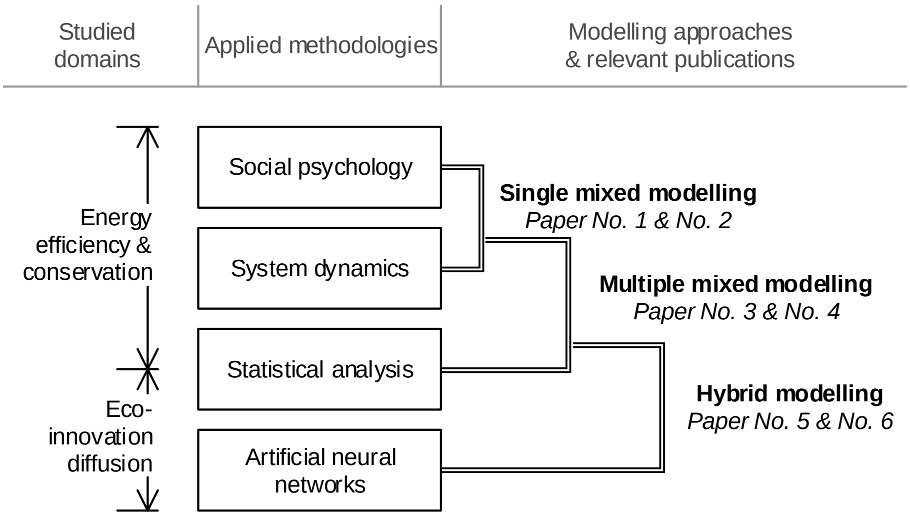


Figure 1.2. The publications used to study socio-economic transitions (the full title of each publication corresponds to the number given in Table 1.1).

The work starts by the use of the social psychology and system dynamics models to study the transition of energy efficiency and conservation solutions in the households. Here, the presence of the aspects from social psychology were identified and implemented in the system dynamics model (see Papers No. 1 and No. 2). Next, the methodology was upgraded with statistical data analysis.

Nevertheless, energy efficiency improvements for a specific technology are always limited; therefore, the socio-technical transitions for fundamentally different products are also under the interest. In this Thesis, the technological substitution of current products with eco-innovation is studied in Paper No. 4 using the methodology developed by the Thesis' author. This presented methodology links statistical data analysis tools with the system dynamics model and uses social psychology to explain the obtained results, thus combining three methods including both social and technical aspects.

In the Thesis, the author goes even further and adds the fourth method – an artificial intelligence modelling tool – to the previously developed and tested algorithm, thus creating a hybrid or grey modelling tool for eco-innovation diffusion studies (see Paper No. 5). This grey modelling tool is used to describe eco-innovation diffusion with a higher accuracy than that of the models developed so far (see Paper No. 6). In the Thesis, the author refers to the above-mentioned six major publications – Papers Nos 1–6, which correspond to the articles given in Table 1.1.

Table 1.1. The publications used in the Thesis to study the socio-technical transitions.

Field	Studied domain	No.	Title of publication
1	System Dynamics & Social Psychology or **Single mixed modelling approach**	1	*Framework for the assessment of household electricity saving by integrating behavioural aspects*
		2	*Electricity saving in households due to the market liberalization and change in the consumer behaviour*
2	Statistical Analysis & System Dynamics & Social Psychology or **Multiple mixed modelling approach**	3	*Energy efficiency policy analysis using socio-technical approach and system dynamics. case study of energy efficient lighting in households*
		4	*The dynamics of technological substitution: the case of eco-innovation diffusion of surface cleaning products*
3	Statistical Analysis & System Dynamics & Social Psychology & Artificial intelligence or **Hybrid modelling approach**	5	*Combined and mixed methods research in environmental engineering: when two is better than one*
		6	*Understanding the technological substitution by hybrid modelling practice: a methodological approach*

1.1 Energy Efficiency and Conservation

Energy efficiency at the final consumers is one of the priorities for energy sustainability, where households are one of the major energy end-consumers. Therefore, various studies focus on smart metering, for example, Laicane et al. (2015) anticipates electricity savings by 13 % until 2020 in the households with smart meters in Latvia.

Yet the fitting of smart meter alone does not give long term savings. Both Schultz et al. (2015) and Laicane et al. (2015a) showed that feedback itself is not sufficient to reduce energy use in long term and the behaviour of the users should be taken into account. Joachain & Klopfert (2014) came to the same conclusion, suggesting linking feedback with the tools for consumer motivation. To solve this issue various mechanisms linking socio and technical issues are proposed, for example, Anda & Temmen (2014) proposed to use the programs for behaviour change and D'Oca et al. (2014) correctly targeted information.

In the analysed literature, research has been done on policies and programs to target households, but there is lack of studies that model the significance of behavioural aspects. **Therefore, the aim of Paper No. 1 is to search for the major behavioural aspects of electricity savings in households.** This study continues the research by Bariss, Timma & Blumberga (2014)[3] attempting to solve energy reduction causes including the households' behaviour.

[3] On average, 20 % higher electricity savings were observed in households using smart meters compared to the control group (without smart metering); these findings are above the range of previously conducted studies.

In this research the goal frame theory (from field of social psychology) by Lindenberg & Steg (2007) is used to model the behaviour of households. The goal frame theory can be applied to study the general or specific values of consumer in certain situations (Steg, Perlaviciute et al. 2014). The role of goals was studied by Steg et al. (2014) to encourage pro-environmental behaviour and by Steg et al. (2015) to study the sustainable energy use behaviour.

Since the behaviour of single electricity end-consumer agglomerates into the behaviour of the electricity market, **the aim of Paper No. 2 was to study the development scenarios of liberal electricity market under the various technological and behavioural aspects of end consumers.**

The transition to free electricity market includes dynamic changes in average price of electricity (Serrallés 2006), in monopolist withdrawal (Neuhoff & Newberry 2005), in rebound effect (EC 2001), in price elasticity (Krishnamurthy & Kriström 2015), in internal policy (Moreno et al. 2012), in public participation in market and energy efficiency at consumers (ECME 2010) and others. To account for all these factors system dynamics was used. As for now, system dynamics models are used to study the installed capacity in electricity market (Arango et al. 2002), to model free market conditions in Scandinavia (Vogstad 2004), and to analyse British and French interconnection (Ochoa & van Ackere 2015).

Since the lighting sector uses up to 19 % of total electricity worldwide (Franceschini & Pansera 2015) and the price for light bulbs has dropped by 99.7 % in the past two centuries (Nordhaus 1996), this sector has high potential for energy savings. New lighting technologies diffuse quickly, but still around 1/3 of the households in Germany chose to replace incandescent light bulbs with the same incandescent light bulbs in 2012 (Mills & Schleich 2014). These figures shows, that the availability of technological innovations alone cannot provide effective technological transitions. Frederiks et al. (2015) also points out that behavioural aspect has been neglected in the models of energy use in households.

To the Thesis author’s knowledge, there have been no studies connecting the aspects of innovation diffusion and personal values in one, comprehensive socio-technical model. **Therefore, the aim of Paper No. 3 is to develop a model of innovation diffusion for energy efficiency solutions in households.** The methodology used combines an empirical study with system dynamics modelling and statistical data analysis. The intention of introducing energy efficient lighting solutions in Latvia is used as the case study.

Although the developed system dynamics models were based on the case study of Latvia, models’ general application to other countries and electricity markets (Paper No. 2) and other products and services (Paper No. 3) is possible, since the developed model is a white-box. With these models both retrospective situations and the future savings of policy or programs can be studied.

1.2 Eco-Innovation Diffusion

As the founder of system dynamics Forrester (1961) said: *“Growth cannot be limitless in a finite system; when the system reaches its carrying capacity, a collapse occurs”*. Thus, the reductions in production and final consumption are the key challenge for society, here eco-innovations plays a major contribution.

Eco-innovations are increasingly used to substitute the existing products or services (EIO 2011); therefore, Karakaya et al. (2014) states, that understanding the diffusion of eco-innovations is critical as some of them have reached a mature state, but the diffusion rate is slow and the path unclear. Thus, eco-innovations requires a long-time period to be adopted.

Diffusion models are given by Bass (1969) on market players and by Rogers (2003) on market dynamics; they are used to study the diffusion of smart meters by Rixen & Weigand (2014) and electric vehicles by Plötz et al. (2014).

Since consumers are important driver for innovations (Govindan et al. 2015) separate field of science – environmental psychology – proposes multiple approaches to explain pro-environmental behaviour. These include such theories as: norm activation (Schwartz 1977), reasoned action (Ajzen & Fishbein 1980), planned behaviour (Ajzen 1991), value-belief (Stern et al. 1999), attitude-behaviour-context (Stern 2000), goal frame (Lindenberg & Steg 2007) and others.

Behavioural studies are done by Bamberg (2003) on environmental actions, by Abrahamse et al. (2005) on intervention models, Schwarz & Ernst (2009) on the diffusion of technologies, by Zeppini et al.(2014) on technological transitions.

However, holistic theory to explain the diffusion of eco-innovations is not defined yet, and there is little known about the importance of the various factors in the diffusion process. Rennings (2000) states that eco-innovations cannot be treated like other innovations and require a specific theory and policy, also de Medeiros et al. (2014) points out a gap in the research on decision-making processes when consumers are faced with the choice between two products. Moreover, models which are able to forecast the diffusion processes of new products with little or no data available are needed (Meade & Islam 2006).

Therefore, the aim of Paper No. 4 is to propose a conceptual model for eco-innovation diffusion. This can help to study eco-innovation diffusion and pro-environmental behaviour as it results from multiple motivations that change over time. Unlike other theories that concentrate mainly on one set of factors, our study tries to integrate factors, as well as find the interconnectedness of multiple motivational levels. Also, the developed model can forecast the influence of policy measures, that are stated important in the diffusion of eco-innovations by Sushandoyo & Magnusson (2014) and Ghisetti & Rennings (2014).

To achieve this aim, the system dynamics model integrated with the statistical analysis tools and theory from social psychology will be outlined. The case study covers micro-fibre clothes for surface cleaning. Although the model was based on one specific eco-innovation's diffusion process, its general application to other products and services is discussed.

The study on eco-innovation diffusion presented in Paper No. 4 and the study on the intention to recycle by Tonglet et al. (2004) observed a similar diapason of the explained data by the model, with the highest adjusted deviance of 33.5 %. While such accuracy is regarded as a medium and acceptable result for behavioural studies (Cohen 1988), the author of the Thesis aims to improve these model's statistics with use of artificial intelligence.

Thus, the goal of Paper No. 5 is to present a conceptual methodology for a hybrid model of eco-innovation diffusion. This methodology integrated both white-box and black-box research methods to improve the model. Since each method has its strengths and weaknesses the application of this hybrid or grey methods can present comprehensive modelling tools (Foucquier et al. 2013). Next, **the aim of Paper No. 6 is to test the hybrid methodology of eco-innovation diffusion for the specific case study.** As the white-box model, the system dynamics and statistical data analysis tools are used (including social psychology aspects), and as the black-box model – artificial intelligence tool is used. To the Thesis author's knowledge, this is the first attempt to model the eco-innovation diffusion process by hybrid modelling, which includes all four given methods.

Although the hybrid model was based on the one specific case study, its general application to other products and services is possible, since the developed model is outlined and can be used for further research of other processes.

1.3 Summary of the Literature Review

The conducted literature review shows that the studies using social and technical aspects for the research on transition processes are fragmented, both in terms of studied sectors, used methods and scientific fields. As given in the work by Li et al. (2015) in the field of energy research the majority of the works study techno-economic aspects of the systems, while only few attempts have been made to incorporate socio-technical perspective as well.

There are also identified clear lack of a holistic methodology, therefore the ultimate aim of this Thesis is to attempt to link engineering and social science study field to create such modelling approach. The Thesis work therefore guides through the path of the creation of this methodology.

Author of this Thesis views socio-technical transitions processes from the perspective of various sectors, such as waste management, energy use, energy production and management, product marketing and other. Also the transitions are looked from the scientific lenses of various possible methods and combinations of those. And last but not least, theses transitions studies are considered from the perspective of various scientific fields, both engineering and social science.

2 RESEACH METHODOLOGY

2.1 Single Mixed Modelling Approach

In the Doctoral Thesis, the single mixed research methodology is defined as the use of a single qualitative and quantitative research method together. As a qualitative method, the survey (based on the goal-frame theory by Lindenberg & Steg (2007)) of focus groups was used. As a quantitative method, the system dynamics was applied.

2.1.1 Goal Frames

Goal-frame theory explains the motivation behind the households' choice, based on three guiding goal frames: gain, normative, and hedonic. In the case of the gain goal, the households would save the electricity because it saves money. In the case of the normative goal, the savings could be explained by social pressure or environmental awareness. And, finally, the hedonic goal would be activated in the case when saving energy brings joy, for example, the commodities with higher energy efficiency are more user-friendly.

To assess the presence of goal frames, the survey of a study group was conducted. For the design of study group, a quasi-experimental design was used, with 500 households in a target group (with smart meters) and 500 – in a control group (without smart meters). Both groups were equally split based on electricity consumption: below 200, 300, 450, 650, 1000 and above 1000 kWh per month, given in more detail by Bariss, Timma & Blumberga (2014).

Survey data were processed, and guiding goal frames were identified (see Paper No. 1). Further, these goal frames were integrated in the system dynamics model, and this model was developed in Paper No. 2.

2.1.2 System Dynamics

System dynamics was introduced by Forrester (1958). This methodology identifies the interaction between and among physical activities, information flows, and policy measures, thus revealing the dynamical nature of the variables. System dynamics is used to identify the means for a reduction of energy consumption (Blumberga et al. 2014a), cleaner production (Dong et al. 2012), and better allocation of investment funds (O'Regan & Moles 2006).

The main structure of the system dynamics model is described by causal loops (Figure 2.1), where the causal loops define the feedback mechanisms within the system under study (Forrester 1961). Causal links (arrows) connect the variables. When a causal link is positive (+) an increase in the cause will increase the effect above what it would otherwise have been. Similarly, a decrease in the cause will decrease the effect below what it would otherwise have been. When a causal link is negative (−) a change in the cause triggers a change in the effect in the opposite direction. The causal links create causal loops; they can have a positive (reinforcing, R) or negative (balancing, B) effect (Sterman 2000). The diagram of causal loops later is converted to a stock and flow diagram in order to obtain a quantitative mathematical model.

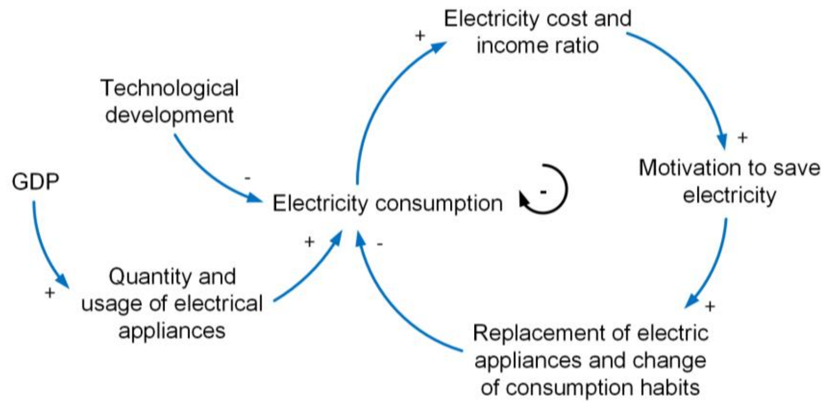


Figure 2.1. The diagram of causal loops for the behaviour aspects of electricity users.

Two major causal loop diagrams were used in the system dynamics model. One of these causal loops are given in Figure 2.1, where an increased welfare (given as Gross Domestic Product GDP) of a household results in the increase in the *quantity and usage of electrical appliances*, thus increasing the *electricity consumption*. On the other hand, the *technological development* of electrical appliances rises the energy efficiency, thus reducing the specific *electricity consumption*.

Electricity cost and income ratio (the share of electricity bill in the total spending budget of the household) influence *motivation to save electricity* and willingness to make the replace, for example, current light bulb with more energy efficient bulb and to reduce time when lighting is used, thus reducing *electricity consumption*.

Electricity consumption in households for the needs of system dynamics model is divided into three major groups: lighting, household electrical appliances, climate control equipment. This dynamic model accounts for the changes in energy efficiency of appliances, the changes in welfare that affect electricity demand, and the influence of electricity price on the electricity consumption patterns. To study the major assumptions used and for more details on the model's structure, see Paper No. 2.

2.2 Multiple Mixed Modelling Approach

In the Thesis, the multiple mixed research methodology is defined as the use of more than one qualitative and/or quantitative research method together. As the qualitative method, the survey (based on the goal-frame theory by Lindenberg & Steg (2007)) of focus groups was used. As quantitative methods, statistical data analysis and system dynamics modelling were applied.

Multiple mixed modelling approaches were used in both Paper No. 3 and Paper No. 4. Both papers differ in the study fields. However, from the methodological perspective, the fundamental difference between both papers lays in the algorithm how inputs from an empirical study are assembled to fit the research question and the system dynamics model. In the case of Paper No. 4, the diffusion dynamics of one particular eco-innovation – microfibre cloth (MFC) for surface cleaning purposes – is studied, whereas Paper No. 3 studied the transition dynamics among various types of light bulbs.

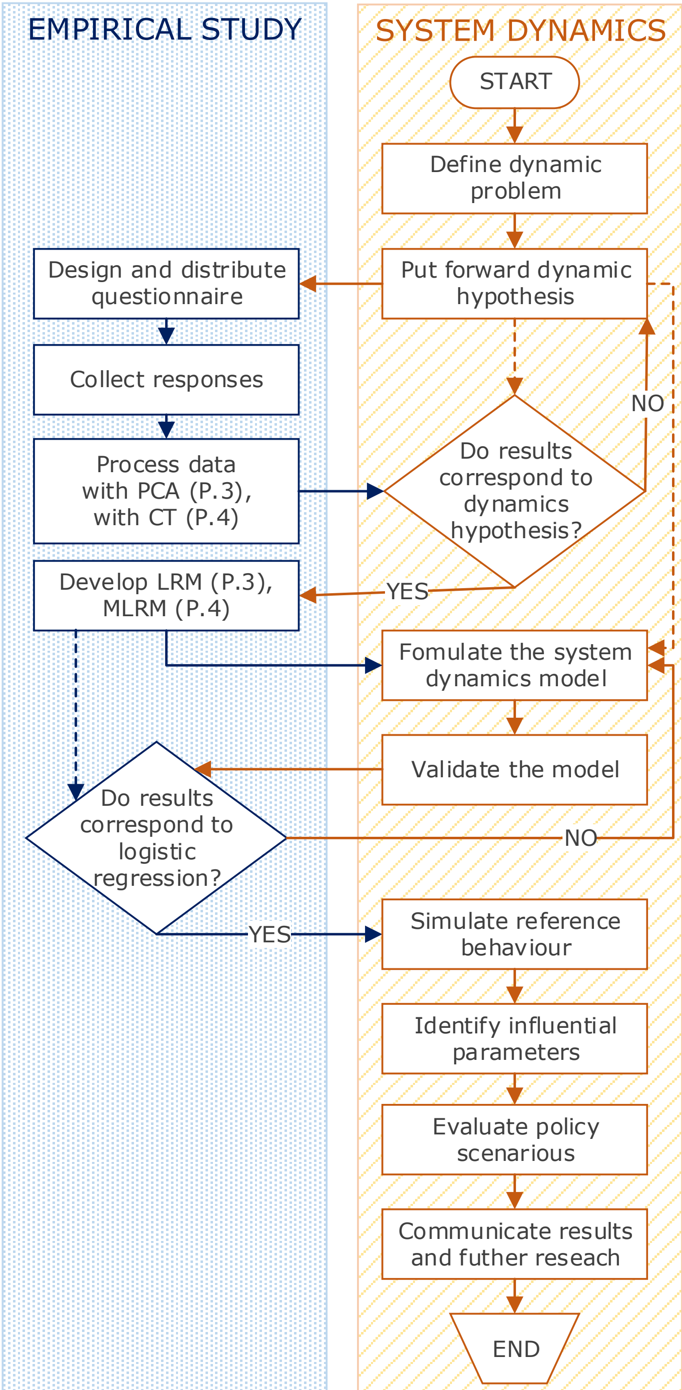


Figure 2.2. Conceptual scheme of methodology used to study the transition dynamics in lighting sector (Paper No. 3) and eco-innovation diffusion dynamics (Paper No. 4) with statistical analysis tools, system dynamics and social psychology framework (PCA – principal component analysis; CT – cross-tabulation; LRM – logistic regression model; MLRM – multinomial logistic regression model; P. 3 – Paper No. 3; P. 4 – Paper No.4).

The transition dynamics among various types of light bulbs is studied in Paper No. 3. In this case a person could have situation when he switched incandescent light bulb to the same incandescent light bulb or to compact fluorescent light bulb or even to light emitting diodes. Therefore in this situation the methodology was upgraded to multinomial regression model that allows to model more than two choice responses. Thus, correspondingly, also data refinement step before multinomial regression analysis differs in the form of statistical data analysis tools that are required to apply in order to obtain valid model; instead of principal component analysis, cross-tabulation where used.

In order not to overcomplicate the perception of this methodology and not to duplicate part of the methodology that are common in both case studies, in this Section 2 only details about the Paper No. 4 will be given, while the full text and details on Paper No. 3 are given in the Annex of Thesis. Nevertheless, in the coming sections on results, discussion and conclusions finding from both of these Papers will be presented.

Initially, the dynamic problem and hypothesis is developed, this is followed by the design of a questionnaire using social psychology. After this, the responses are processed by factor and item reliability analysis and next logistic regression model is developed. The results of the empirical study are used for the formulation of the system dynamics model and presentation of assumptions. Later, the system dynamics model undergoes validation and the validation results are crosschecked with the results from the logistic model. After that, the reference behaviour of the system dynamics model is simulated, a sensitivity analysis is used to state the influential parameters, and information campaigns are applied to perform the scenario analysis.

2.2.1 Empirical Study

In Paper No. 4 Author applies empirical study to explore and model the motivations behind the decision to start using micro-fibre clothes (MFC) using social psychology and statistical data analysis tools that describes the probability and its changes for the event of using or rejecting to use MFC.

2.2.1.1 Questionnaire Design and Screening

Both, those respondents who knew about MFC and used them, and those who were aware of the existence of MFC but did not use where surveyed. This allowed for the establishment of the differences between the motivations of users and non-users, as well as to suggest possible further ways to stimulate the adoption of this type of eco-innovation.

Questions regarding motivations were integrated into the questionnaire design which was adopted and adjusted from a questionnaire about the use of green electricity tariffs by Ozaki (2011); the author based his questionnaire on multiple environmental psychology theories. Furthermore, as Ozaki (2011) suggests, that her research methodology can be used to explore the adoption behaviour of consumers for innovative and tangible consumer goods.

All responses were screened, and partly-completed questionnaires were removed from further analysis. Based on the answer about knowledge and use of MFC, all respondents were divided into three groups: 1) those who knew about MFC and used them in households (hereinafter “Users”), 2) those who knew about MFC, but did not use them in households (“Non-users”) and 3) those who have never heard of MFC before and those who have used MFC before but stopped using them (only one case). The answers of the third group where excluded from the statistical analysis, since the aim was to study the motivation behind the decision to use or not to use MFC.

2.2.1.2 Principal Components Analysis

Factor analysis was performed to reduce the amount of variables used in further data analysis by extracting the optimal number of common factors from the initial variables. The model of orthogonal common factors by Johnson & Wichern (2002) was used. The variables were grouped based on the correlation matrix. Principal components were used as the type of factoring. As rotation method, the varimax, $\Psi_{VARIMAX}$, was applied:

$$\Psi_{VARIMAX} = \arg\max_{R} \left(\sum_{j=1}^{k} \sum_{i=1}^{p} (\Phi\Psi)_{ij}^{4} - \frac{1}{p} \sum_{j=1}^{k} \left(\sum_{i=1}^{p} (\Phi\Psi)_{ij}^{2} \right)^{2} \right), \quad (2.1)$$

where Φ –s a $p \times k$ orthonormal matrix (of column eigenvectors); p – original variables; k identifies the variables; Ψ – an orthonormal rotation matrix; Ψ_{ij} – the scalar element in the i-th row and j-th column in matrix Ψ.

The factors where extracted based on the Eigenvalue, scree plot, estimated communality and specific variance. Two types of principal components analysis can be done: exploratory and confirmatory. Item reliability analysis was done to test the consistency of the variables included in the previously done factor analysis. As the measure of sampling adequacy, Bartlett’s test of sphericity and Kaiser-Meyer-Olkin (KMO) test were done, see Equation 2.2 and 2.3, respectively:

$$\chi^2 = -\left[N - 1 - \left(\frac{2n+5}{6} \right) \right] \log_e |R| , \quad (2.2)$$

$$KMO = \sum_{i=1}^{n} \sum_{j=1, j\neq i}^{n} \rho_{ij}^2 \Bigg/ \left(\sum_{i=1}^{n} \sum_{j=1, j\neq i}^{n} \rho_{ij}^2 + \sum_{i=1}^{n} \sum_{j=1, j\neq i}^{n} a_{ij}^2 \right), \quad (2.3)$$

where N – sample size; n – number of items; $|R|$ – determinant of the correlation matrix; ρ_{ij} – elements of the correlation matrix; a_{ij} – elements of the partial correlation matrix. See Equation 2.4 for partial correlation matrix:

$$a_{ij} = -CF_{ij} \Big/ \sqrt{CF_{ii} CF_{jj}} , \quad (2.4)$$

where CF – cofactors of the correlation matrix. The scale reliability was expressed by Cronbach’s alpha:

$$\alpha = \frac{n\bar{r}}{1+(n-1)\bar{r}} = \frac{2}{(n-1)} \sum_{i=1}^{n} \sum_{j=i+1}^{n} r_{ij} \Bigg/ 1 + \frac{2}{n} \sum_{i=1}^{n} \sum_{j=i+1}^{n} r_{ij} , \quad (2.5)$$

where $\bar{r}$ – an average off all Pearson correlation coefficients between items; $r_{i,j}$ – correlation coefficient between item *i* and item *j*; *n* – number of items.

2.2.1.3 Logistic Regression Analysis

The logistic regression analysis was performed to fit the regression model in which the dependent variable characterizes an event with only two possible outcomes: to use MFC, or not to use MFC. The answers were coded in binary for as 1 for "yes, I do know about MFC and us it" and as 0 for "yes, I do know about MFC and do not us it". The model assumes that users of MFC will continue to use this product further on.

As the independent variables factors obtained from principal components analysis were used. The fitted model relates predictor variables, and assumes the probability of an event through a logistic function:

$$\log[P(X)/(1-P(X))] = \exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k)\,, \qquad (2.6)$$

where P – probability of the occurrence of the outcome *Y* to the predictor variables *X*; β_0 – a constant of the fitted model; $\beta_1, \beta_2, \ldots\beta_k$ – estimates. Stepwise backward selection factor selection was chosen with P-value to enter 0.05.

To estimate the accuracy of the fitted model, the percentage of deviance explained by the model (R^2) was calculated in a similar manner to *R*-squared statistics in a multiple regression; and adjusted deviance (R^2_{adj}) in a similar manner to *R*-squared adjusted.

2.2.2 System Dynamics Model

The system dynamics model in Paper No. 4 converts the results obtained from the statistical data analysis into a mathematical model for the diffusion of eco-innovations to allow for the prediction of a system's behaviour over time.

2.2.2.1 Stock and Flow Diagram

The diagram of the causal loop diagram (given in the full Paper No. 4 in Annex) is converted into a mathematical model given with a stock–flow diagram. General diffusion model (Bass 1969) is used as the basis for MFC diffusion among households where the cumulative number of MFC adopters follows S-shaped growth and reaches market saturation.

Two main stocks in the diffusion model are households that have and have not adopted MFC. This is where the substitution of traditional cleaning agents is modelled. The rate of adoption of the MFC depends on the number of households that have not adopted MFC and on the time needed for them to adopt MFC. Adoption time depends on the intention to use MFC – the lower the intention, the longer the adoption time. The intention to use MFC is calculated using an empirical relationship from statistical analysis.

In the absence of any external diffusion drivers, word-of-mouth is the only variable affecting the adoption rate. It depends on the number of households who have and have not adopted MFC, the rate by which contacts are made between non-adopters and adopters (communicating positive experiences of MFC use), the fraction of those non-adopters that become MFC adopters as a result of that contact, and is calculated as:

$$WOM = fr_{AD} \cdot CH \cdot HH_{NA} \cdot HH_{A} /(HH_{NA} + HH_{A}), \quad (2.7)$$

where WOM – adoption from word-of-mouth, household, year; fr_{AD} – adoption fraction; CH – contacts per MFC users household, household/household per year; HH_{NA} – households who have not adopted MFC, households; HH_{AD} – households who have adopted MFC, households.

The word-of-mouth effect is not sufficient to spread the news of a good product in the short term. By means of information campaigns about MFC, awareness of the product is created in the market:

$$AW = \int_{t=0}^{t=1} [WOM + fr_{INF} \cdot HH_{A} /(ST \cdot T_{IC})] t \cdot dt + AW^{init}, \quad (2.8)$$

where AW – households aware of MFC, households; fr_{INF} – information adoption fraction by those non-adopters that become aware of MFC after receiving information by means of information campaign; ST – strength of information campaign (ON or OFF); T_{IC} –perceived information delay time, years; AW^{init} – initial value of households aware of MFC, households.

Information campaigns are used as the only leverage point in the system, the reasons are explained in detail in the Paper No. 4 Section 6.1.4. Information campaigns target four motivations identified in the logistic regression model. Therefore, the diffusion of MFC is triggered and environmental pollution is avoided due to the use of MCF. The accumulated avoided traditional cleaning agents are calculated as given in Equation 2.9:

$$AA_{CA} = \int_{t=0}^{t=1} (C_{week} \cdot fr_{CA} \cdot HH_{A}) t \cdot dt + AA_{CA}^{init}, \quad (2.9)$$

where AA_{CA} – accumulated avoided traditional cleaning agents, tonnes; C_{week} – weekly consumption of traditional cleaning agents, tonne/household per week; fr_{CA} – fraction of traditional cleaning agents used parallel to MFC; AA_{CA}^{init} – initial value of accumulated avoided traditional cleaning agents, tonnes.

Both structural and behavioural validation tests was done to validate a model. A more detailed picture of the stock and flow diagram and the major assumptions of the model are given in Paper No. 4.

2.2.2.2 Validation of Model

The aim of the validation of a model is to determine whether a model is acceptable for its intended use (Forrester 1961). The validation enables confidence to build in a model based on data and observations from a real system. Hence, the aim of the system dynamics modelling is to depict the patterns of wide dynamic behaviour in the real system, not to give “point” projections (Sterman 2000).

Both structural and behavioural validation tests were performed in order to validate the model. Structural validation tests evaluate the reasonableness of the equations within a model. In behaviour validity tests a model's generated patterns for major variables are compared with historically available data (Barlas 1996) . In order to determine the robustness of the model, a mean absolute percentage error (MAPE) was used. Major assumptions for model are given in Paper No. 4.

2.2.2.3 Sensitivity Analysis and Policy Tools

A sensitivity analysis was carried out to determine if the developed model is sensitive to different variables, and what variables have the highest influence on the model. The Latin Hypercube method was used to model variances within selected variables in the range of ± 25 % of the existing value under truncated normal distribution using a risk assessment tool within the Powersim software.

The effect of information campaigns is modelled according to the asymptotic series of error function *erf(x)* see Equation 2.10 and the complementary error function *erfc(x)* see Equation 2.11:

$$erf(x) = 2\big/\sqrt{\pi}\int_0^x e^{-x^2}\,dx\,, \tag{2.10}$$

$$erfc(x) = 1 - erf(x) = 2\big/\sqrt{\pi}\int_x^\infty e^{-x^2}\,dx\,, \tag{2.11}$$

These information campaigns where used as policy tools in Paper No. 4. Since, the system dynamics model explored how and why problematic behaviour is generated, the policy tools where used to discover leverage points to abate the causes of these problems.

2.3 Hybrid Modelling Approach

In the presented Thesis, the hybrid modelling approach is referred to the use of both combined and mixed research methods. In this approach, the combined research method uses both qualitative and quantitative methods, and the mixed research method uses both white-box (system dynamics) and black-box (artificial neural network – ANN) methods.The layout of proposed methodology is given in Figure 2.3.

Hybrid modelling methodology for the case study of eco-innovation diffusion was developed in Paper No. 5, since previous studies where socio-technical transitions were modelled yielded relativity low explained variance; the study by Bariss, Dandens, Timma, Blumberga & Blumberga (2015) explained 13 % of the motivation for energy efficiency, study given in Thesis as Paper No. 4 explained 34 % of motivation to adapt eco-innovations. Also study found in the literature by Tonglet et al. (2004) explained 33 % for waste recycling motivation.

While in the social studies such explained deviance is seen as valid for the research purposes[4], the Author is this Thesis aim to improve these statistics by integrating black-box model in the developed methodology.

[4] Based on Cohen (1988) the interpretation of *R* for behaviour studies is as follows: ±0.1–0.3 small, : ±0.3–0.5 medium and ±0.5–1.0 large

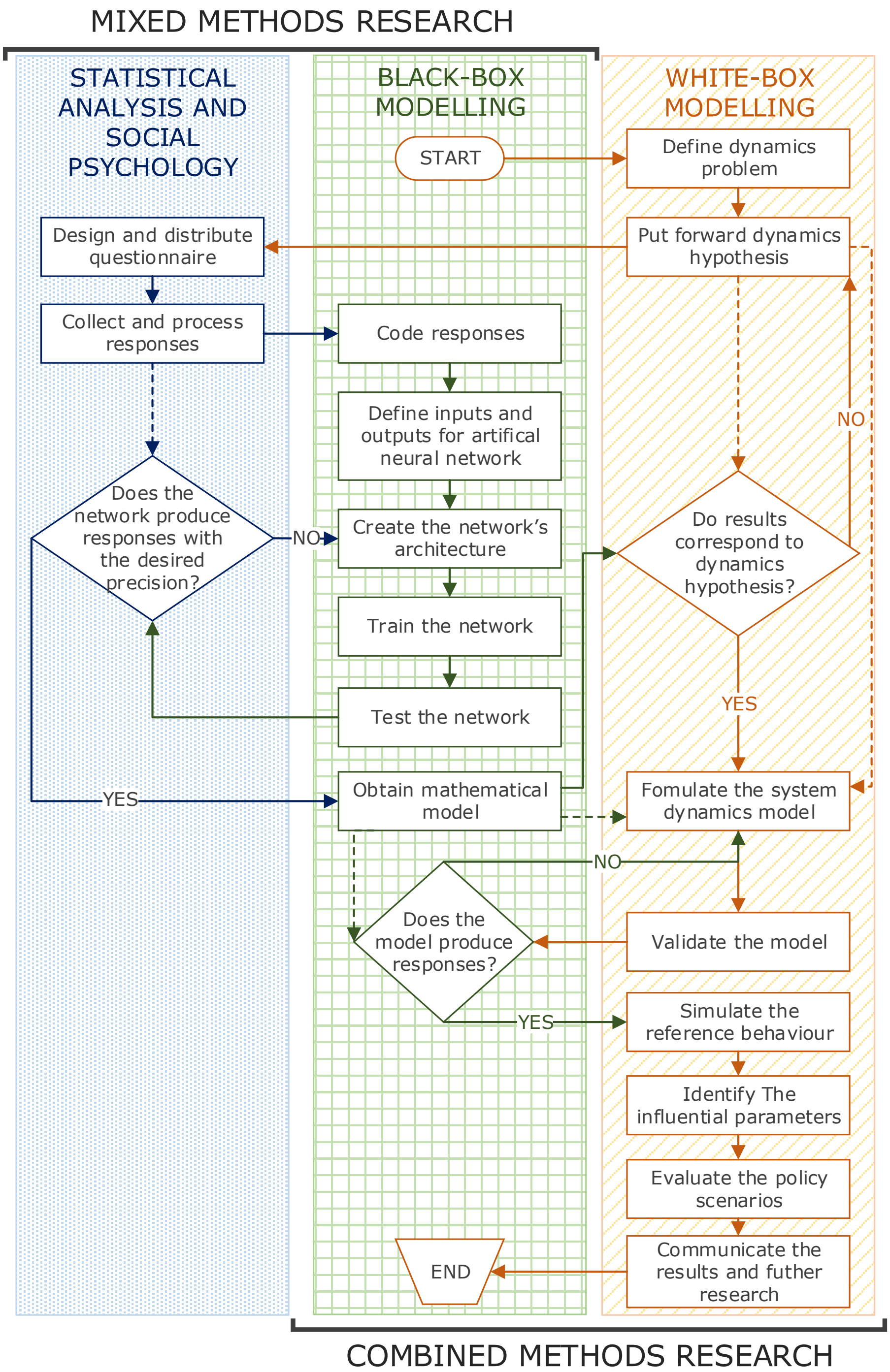


Figure 2.3. The layout of the proposed hybrid methodology for socio-technical transitions.

As black-box modelling, ANN was used, because ANN obtains mathematical relations for relatively small, incomplete and noisy date sets (Dreyfus 2005). Also, ANN better handles the course of dimensionality. In contrast to system dynamics, in ANN for the defined inputs corresponding outputs are obtained, by the user has limited possibility to interfere with the internal structure of the model. On the other side, similarly, to system dynamics all elements in ANN are interconnected and there is possibility to incorporate delays and feedback (Bishop, 2006).

The advantages of artificial intelligence are outlined also in numerous studies, for example on the modelling of biogas production (Kana et al. 2012) and on the degradation of organic pollutants in water (Capocelli et al. 2014). Thus, the main advantages of this proposed modelling tool is improved reliability of the model and requirements for fewer observations.

In order to explore which goal frames might affect the willingness to adopt eco-innovation ANN was developed. The overall attitudes of consumers towards eco-innovation are tested based on the goal framing theory. The inputs to ANN will be fed from statistical analysis and the outputs from ANN will be feed to the system dynamics model. The ANN describes the goal framing theory by mapping the respondents answers from the survey to their behaviour. The system dynamics model is used to outline the broader effects of the consumer's behaviour, such as societal transitions and technological substitution in the society.

2.3.1 Artificial Intelligence

The early aim of the artificial intelligence was to simulate a brain structure and its functions. The main objectives were to store and to represent the acquired knowledge, to give a solution to a problem based on the acquired knowledge and, finally, to obtain new knowledge while a system is running (He & Xu 2009).

Model of artificial intelligence can be created using special units – artificial neural networks. There is clear analogy with the biological systems. The brain is created from the small processing units – neurons. The mathematical model of the basic artificial neural network structure is given in Equation 2.12:

$$u_k = \sum_{i=1}^{n} w_{ki} x_j = w_{k1}x_1 + w_{k2}x_2 + \ldots + w_{kn}x_n \,, \qquad (2.12)$$

where $x_i = (i = 1,2,\ldots,n)$ input signals from n external neurons transmitted to the neuron k; w_{ki} weight between the i-th external input and the neuron k; u_k output from the summation function, see Figure 2.4 for graphical representation.

The relations between independent variables and output are given by Equation 2.13 and Equation 2.14:

$$HiddenLayer\_n_k^{(1)} = \sum_{j=1}^{R} w_{kj}^{(1)} p_j + b_k^{(1)}; a_k^1 = f_{level\_one}\left(n_k^{(1)}\right), \qquad (2.13)$$

$$OutputLayer\_n_k^{(2)} = \sum_{j=1} w_k^{(2,1)} a_k^{\,1} + b_k^{(2)}; \hat{t}_i = a_k^{(2)} = f_{level\_two}\left(n_k^{(2)}\right), (2.14)$$

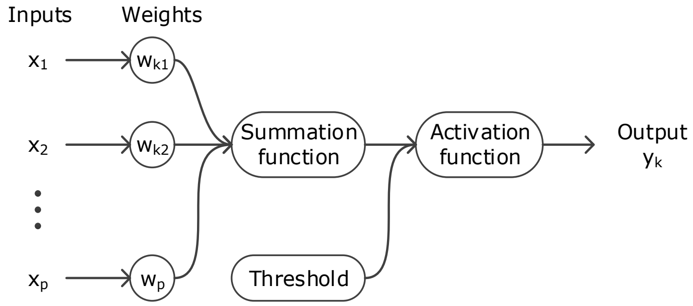


Figure 2.4. Graphical schematic of artificial neural network with main elements.

where inputs are linked with each of N neurons in a hidden layer with weights $w_{kj}, k = (1, 2, \ldots, N)$, these weights are unique for every independent variable j and neuron k connection. When the neuron receives inputs signals, these signals are weighted and transferred. Next, the input signal undergoes an aggregation and non-linear activation. Under conditions when the aggregation signal exceeds a threshold value, the neuron generates an output signal, which is output signal (Yeung et al. 2010).

2.3.2 Construction and Training of Artificial Neural Network

Pre-processing of input data was done by data spitting into three subsets: 70 % of data for the training set, 15 % of data for the validation and 15 % of data for the test set. Data normalization between 0 and + 1 was done with the logistic sigmoid transfer function, and data normalization between − 1 to + 1 was done with the linear or tangent transfer function. A non-linear autoregressive neural network (NARX) with an external input was chosen for training purposes of the ANN (Fischer et al. 2012).

Since there are only empirical equations for the determination of a "proper" number of hidden neurons, in this study an experimentation method was used to determine the number of neurons in a hidden layer.

A training procedure was carried out based on 2 main objectives: to determine best fit for a learning algorithm and to evaluate an optimal number of neurons in a hidden layer (Beale et al. 2010). In this Thesis Levenberg-Marquardt backpropagation, Broyden-Fletcher-Goldfarb-Shanno Quasi-Newton backpropagation, Conjugate gradient back-propagation with Fletcher-Reeves restarts, Conjugate gradient with Beale-Powell restarts, Scaled conjugate gradient, and Resilient Backpropagation algorithms were simulated for the best fit based on the values obtained for a mean square error (MSE) and statistical coefficient of determination (R^2).

When training process of the neural network was finished the feedback loop within the model was closed; the mathematical definition of the closed loop NARX is:

$$y(t) = f(y(t-1), y(t-2), \ldots, y(t-d), x(t-1), x(t-2), \ldots, x(t-d)), \quad (2.13)$$

where $x(t)$ – input for the network; $y(t)$ – output of the network; t – discrete time step; d – number of time-delays. Within the closed loop neural network the output depends on both: on the current input to the ANN and also on the previous input and output of the network.

3 RESULTS AND DICUSSION

3.1 Single Mixed Modelling Approach

This section presents the results of the major behavioural aspects of electricity savings in households. Then these results were integrated into system dynamics model to study the development scenarios of liberal electricity market under various technological and behavioural aspects of end consumers.

3.1.1 Identified Goal Frames

To model the behaviour aspects of the consumption changes, the results from the survey on values for goal frame theory are given in Figure 3.1.

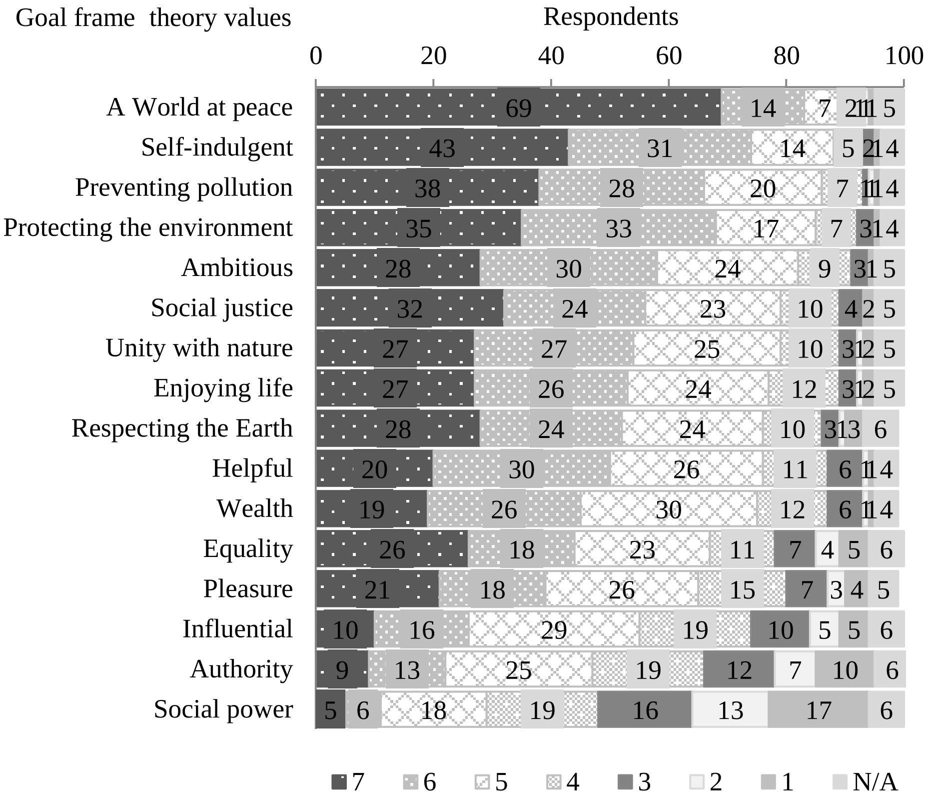


Figure 3.1. Breakdown of values for goal frame theory for the target and control groups combined. Values are given on a scale of 7-1, where 7 – value of supreme importance, 1 – value not at all important, N/A – no answer.

As the most commonly stated value shows to be “a world at peace”, which is an altruistic value, the following are hedonic values “self-indulgent” and two biospherical values describing environmental awareness. These values will be mathematically described for each of the households and coupled with the electricity consumption in the corresponding household. Thus giving inside into what are the statistically significant motivations for the behavioural change in electricity use in households, for more details see Paper No. 1.

3.1.2 System Dynamics Using Behaviour Change Factors

In the system dynamics model, the consumption behaviour was modelled. Here the simulations were carried out to find out how results may differ if households save electricity for the environment reasons or guided by costs (gains). Three theoretical cases were created:

1) base scenario;
2) optimistic scenario, in which half of the households take part in electricity saving due to environmental concerns, and half of the households – due to gains;
3) pessimistic scenario, in which 80 % take action due to gains, but remaining 20 % take action due to environmental concerns.

Such division of households into environmentally motivated and motivated by the economic gains is based on the hypothesis of authors. Nevertheless, this division can be supported by the study of Schwarz & Ernst (2009) on the diffusion of environmental innovations in Germany. The authors use the methodology of aggregated lifestyles, where consumers are divided in various social groups. This study found out that around 20 % of consumers could be regarded as Social Leaders. Based on this study by Schwarz & Ernst (2009), it is assumed that the pessimistic scenario in the Paper No. 2 would correspond to the market situation, where Social Leaders take the role of environmentally motivated households and, therefore, account for about 20 % of the population.

This assumption is also supported by the consumer survey of the largest electricity trader in the Baltic, Latvenergo AS, where 50 % of respondents were motivated to save electricity due to economic reasons, and 13 % due to environmental reasons. It should be noted that sample size was only 375 respondents from Riga city and its neighbouring regions; therefore, these results may be biased.

In case of optimistic scenario, Social Leaders have motivated other groups to start saving due to environmental concerns; thus, the hypothesis of 50 % motivated by environmental concerns is obtained. This scenario is motivated by the models used by Schwarz & Ernst (2009) that capture the roles of consumers for one specific product and specific time and location; nevertheless, their role can change over time. The results for scenario analysis are given in Figure 3.2.

If "environmental" households that act independently of the ratio between electricity price and income are separated from other households, then savings are higher than in the base scenario (in the base scenario, all the households act like economic households). This is only possible if "environmental" households take action faster than economic households. Furthermore, if the proportion of environmentally concerned households increases, the savings become greater.

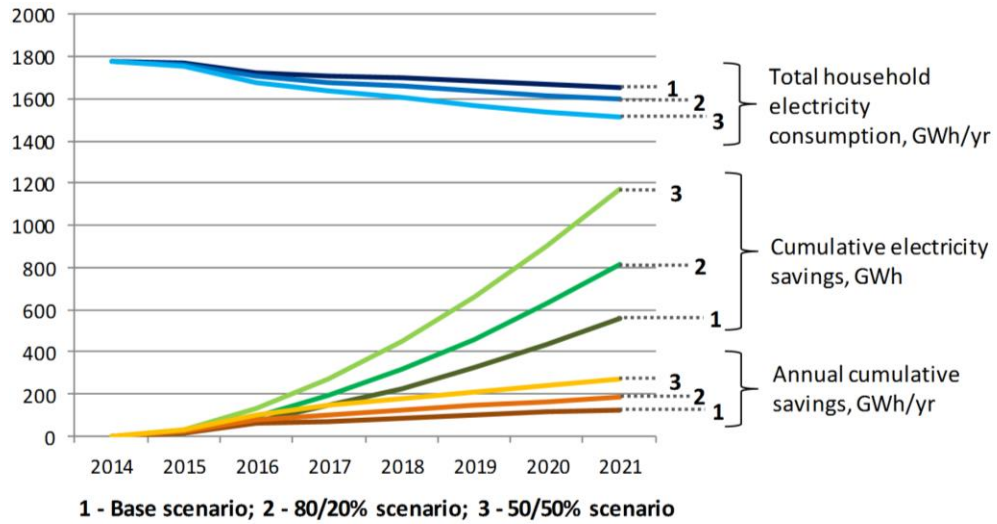


Figure 3.2. Dynamic of household electricity consumption and annual cumulative electricity savings in scenario analysis using change of consumption behaviour.

Bottleneck of the research is that among "economic" households for which survey data from the Marketing and Public Opinion Research Centre are available are also "environmental" households. Households have probably done energy efficiency measures due to several motives, but the only motive observed in this research is the ratio between electricity costs and income. In addition, it is not known how "economic" and "environmental" households would actually act if separate data from each household were obtained; see Paper No. 2 for more details.

3.2 Multiple Mixed Modelling Approach

In this section, the results of two case studies are presented: Paper No. 3 on energy efficiency and conservation, followed by Paper No. 4 on eco-innovation diffusion.

3.2.1 Empirical Study Results on Energy Efficiency and Conservation

3.2.1.1 Cross tabulation

Firstly, the relationship between two purchases of the two types of bulbs – initial and replaced – was tested using the Chi-square test; this test shows whether there are patterns in data or these frequencies happen by chance. The Chi-square test statistics showed a significant pattern among the data: $\chi^2 = 89.560$, $Df = 4$, $p < 0.0001$.

The technological substitution of various light bulbs in Germany in the year 2012 (N = 3028) adapted from Mills & Schleich (2014) and in Latvia in the year 2015 (N = 439) are given in Figure 3.3.

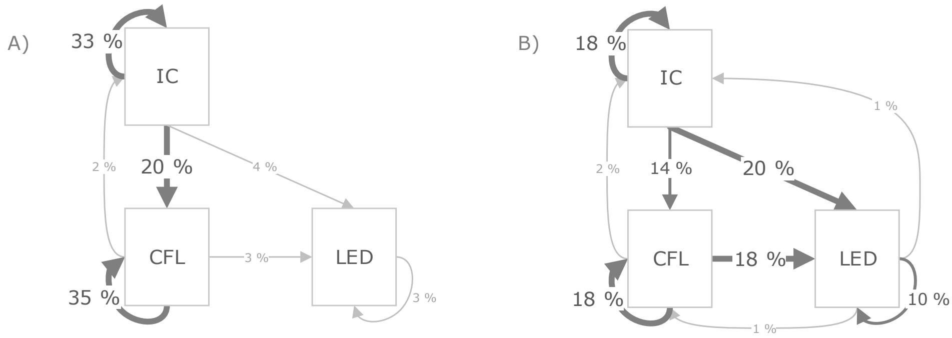


Figure 3.3. The technological substitution of various light bulbs: (A) in Germany in the year 2012 (*N* = 3028), adapted from Mills & Schleich (2014), and (B) in Latvia in the year 2015 (*N* = 439) (IL – incandescent light bulbs; CFL – compact fluorescent light bulbs; LED – light emitting diodes).

Next, the development of the model for the technological substitution was carried out. In this model as the independent variable the important choice factors where identified and as the dependent or response variable the light bulb change. The important choice factors where identified by the survey. In this survey 10 choice factors were given: brightness, electricity use, environment, intensity, light quality, manufacture, price, ratings, service and shape.

From this list the respondent should pick no more than three important factors affecting the choice of light bulb. The choice factors where coded as 0 in the case factor was not selected and 1 in the case factor was selected. These choices made were then linked to the respondent's light bulb change. The lower bond of the statistical significance level was selected as 25 % based on the Hosmer et al. (2013); for the selection of covariates this threshold is defined as acceptable for the initial screening of the variables. Four choice factors showed statistically high chi-square test value: electricity use, price, service life time and shape of light bulb. Also, brightness was found to be statistically significant, and environmental performance and light quality of light bulb was found to be marginally statistically significant.

3.2.1.2 Univariable Analysis

Based on the identified statistically important choice factor, the univariable analysis was performed using multinomial logistic regression. In this case, three possible technological substitutions where analysed as the response variables: IL-IL, IL-CFL, IL-LED. The results obtained by univariable analysis showed similar patterns of a statistically significant variable as in the case of statistically significant variables for cross-tabulation. Moreover the analysis conducted showed coefficients of the multiple logistic regression analysis that can be further used in the system dynamics model.

3.2.1.3 Multivariable Analysis

Next, multivariable analysis was performed using all variables from univariate with at least 25 % statistical significance. The initial model included the following factors: brightness, electricity use, environment, light quality, price, service and shape.

The model with all these variable showed Cox & Snell Pseudo R^2 = 0.536, Chi-square statistics χ^2 = 99.251 under p = 0.071.

The variables with the statistical significance lower than 95 % were excluded from the model using backward selection. The classification table was used to show the results of the final multinomial logistic regression model; see Table 3.1.

Table 3.1: Classification table. Where IL-IL – from incandescent lamp to incandescent lamp, IL-CFL – from incandescent lamp to compact fluorescent lamp, IL-LEDs – from incandescent lamp to light emitting diodes. Sample size, N = 227. The correct predictions given in bold.

Observed	Predicted			
	IL-IL	IL-CFL	IL-LED	Percent correct
IL-IL	**69**	7	4	86.3 %
IL-CFL	12	**27**	22	44.3 %
IL-LED	3	19	**64**	74.4 %
Overall percentage	37.0 %	23.3 %	39.6 %	**70.5 %**

In the classification table for the each case, the observed and predicted response category is shown. The predicted category is calculated by selecting the category with the highest model-predicted probability. The diagonally given cells are ones with the correct predictions (given in bold in Table 3.1).

As given by the classification table the biggest difficulties for the model arises to predict the technological substitution from IL to CFL (44.3 % correct). Nevertheless for the other two categories the predicted percent is high 74.4 % correct prediction for the substitution from IL to LED and 86.3 % correct prediction for the substitution from IL to IL. Where the total percentage of correct prediction based on the classification table reaches 70.5 %, therefore it is safe to claim that the model generated intended behaviour, see Paper No. 3 for more details.

3.2.2 System Dynamics Model's Results for Energy Efficiency and Conservation

Validation of developed system dynamics model was carried out. During the structural validation the reasonability of the equations used in the model was found valid and the model outputs are found valid also under the extreme input values; also the behavioural validation was carried out. Model was found valid for its intended use.

To see which variable has the highest influence in the model, sensitivity analysis was done for 51 variables – describing energy efficiency indicators, the characteristics of living area, households and living conditions accordingly to a statistical distribution. These variables include various technical parameters regarding electricity market, electrical appliances in households and lighting technologies. Also, the values for the previously defined assumptions (given in details in Paper No. 3) are given. 50 simulation sets were done; see Figure 3.4 for the results of the sensitivity analysis for electricity consumption in households.

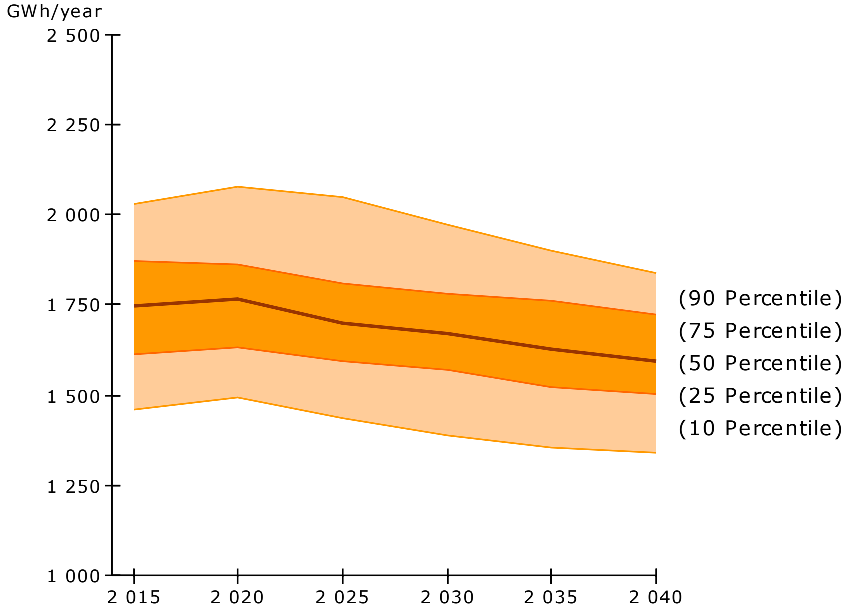


Figure 3.4. Sensitivity analysis for electricity consumption in households.

The sensitivity analysis shows that changes in the parameters used in this analysis caused the expected behaviour, where the uncertainly in electricity consumption in households accounted for ±16 % in the year 2040. In general, the electricity consumption in households decreased by 14 % from the year 2015 till the year 2040.

The model also tested various parameters separately. Average specific electricity consumption of one household appliance, specific electricity consumption for lighting, the coefficient of electricity appliances (amount of the electrical appliances in one household) and lighting technologies usage, total number of appliances, total living area per household and the increase in the income of households were found as the parameters with the highest sensitivity in the model.

The sensitivity analysis for the share of IL, CFL and LED bulbs was done for both the low-income and the high-income households; see Figure 3.5 and Figure 3.6, respectively.

The sensitivity analysis shows the margin of uncertainty for the share of various light bulbs by 2040: for CFL bulbs, this uncertainty is within the margin from −15 % to +6 %; for LED bulbs from −11 % to +16 %, and for IL bulbs ±14 % at the 50 percentile in high-income households. As for the same type of bulbs but in the low-income households: for CFL bulbs from –12 % to +8 %, for LED bulbs ±12 %, and for IL bulbs ±13 %.

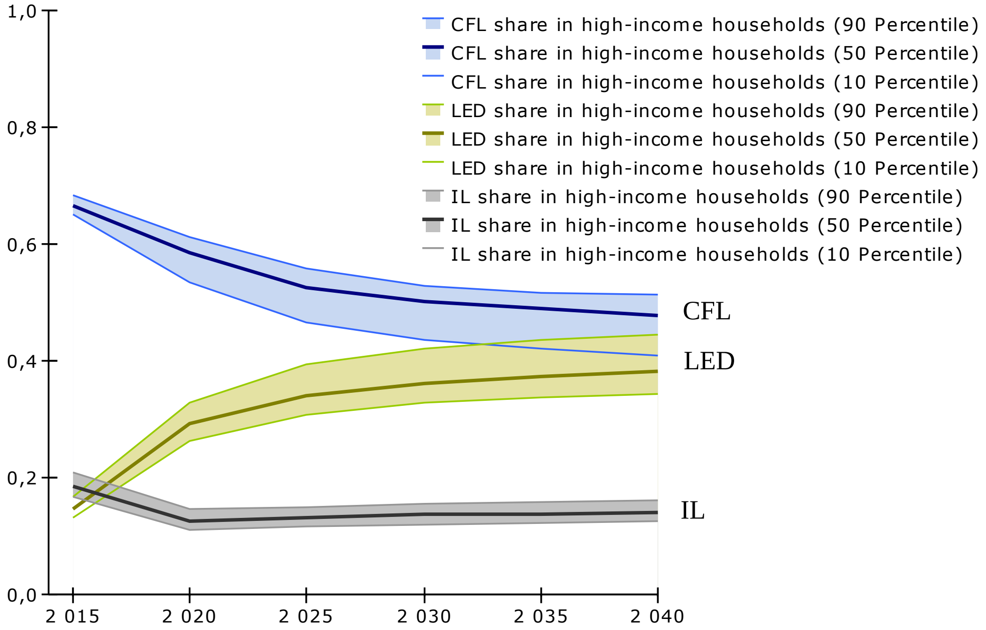


Figure 3.5. Sensitivity analysis of IL, CFL and LED bulbs' share in low-income households.

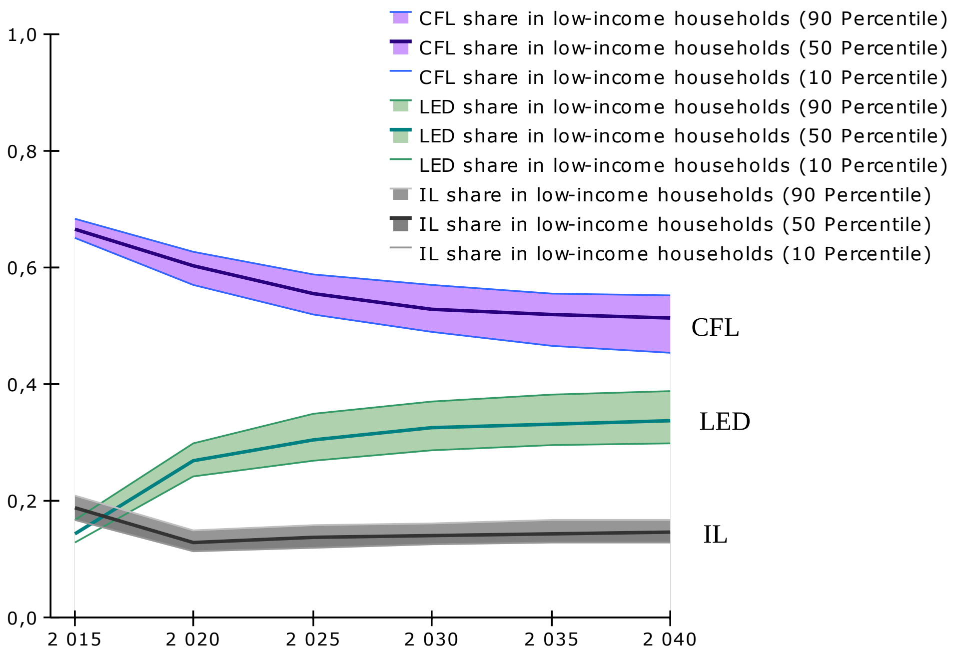


Figure 3.6. Sensitivity analysis for IL, CFL and LED bulbs' share in high-income households.

Two main motivations – financial and environmental – were found for the use of energy-efficient lighting, which is supported by the study of Wall & Crosbie (2009). As given in the high- and low-income households, there are still some proportion of households using the incandescent light bulbs. This phenomenon is found also in the work by Chappin & Afman (2013) where they explain that some individuals look more on the costs of instant purchase but they fail to estimate the longer-term costs expressed as the expenditure for the electricity bills.

The research by Reveiu et al. (2015) even predicts the increase in the consumption of IL bulbs 12 % form 2010 till 2026 in the case no legal restrictions will be placed on this type of bulbs. Also the fact that only two households where found to use only CFL and/or LED light bulb in the work by Wall & Crosbie (2009), leads to the reasoning that for the same lighting purposes there are still widespread use of IL. And last but not least, the aesthetics of IL light bulbs may for some consumers be of greater importance then electricity costs or environmental issues (Wall & Crosbie, 2009).

On the other hand, the adoption of LED lighting technologies can be regarded as not resistant to change, since the change of light bulb from IL or CFL to LED does not require change in habits. The same conclusions are given in the work by Franceschini & Pansera (2015) and Mylan (2015).

It should be taken into consideration that the personal values of consumers affect the choice of bulbs, i.e. some may choose the energy efficient light bulbs for the reason of lower bills for electricity, but some may base their choice on the benefits to the nature as well. Also the work by Perlaviciute & Steg (2015) reveals that disregarding the commonly based assumption that economic gains are the strongest motivator, the biospheric values play an important role in the evaluation of various alternatives in the energy field.

And finally, although the system dynamics model was based on the specific innovation diffusion process, its general application to other products and services is possible. The structure of the model can be used by other researchers and can be enhanced with the newest results or adopted for other case studies.

3.2.3 Empirical Study Results for Eco-Innovation Diffusion

In this section the results of conceptual model for eco-innovation diffusion are given. This study was based on the questioner data. The major part of the respondents did fall into the category “Users” (those who knew about MFC and used them in households), which can be explained by the environmentally inclined persons interests in completing survey related to the environmental issues. Similar issue is described by (Tonglet et al. 2004) in the study on waste recycling behaviour, where majority of study population already did take part in the waste recycling. Tonglet et al. (2004) agrees that results of the study may be biases by pro-environmental respondents, nevertheless the purpose is to evaluate to motivation behind waste recycling, therefore it is reasonable to use obtained data set. We would argue that in our case study, the same motivation behind use of obtained data set is valid.

3.2.3.1 Factor Analysis and Item Reliability

The results of the factor analysis and item reliability tests for motivations are given in Table 3.2.

Table 3.2. Factor analysis and item reliability statistics for the model "Intention to use MFC (mirco-fibre clothes)" where OASI – overall attitudes and social influence, GN – green norms, FC – functionality and controllability and SF – self-efficacy.

Factors	Factors extracted	Cumulative percentage	Minimal Eigenvalue	KMO	Sample size	Cronbach's alpha
OASI	1	73.7	2.2	0.7	137	0.8
GN	2	75.9	1.4	0.8	166	0.8
FC	1	74.7	1.5	0.6	147	0.7
SF	1	72.8	2.2	0.6	142	0.8

The item reliability for all motivations showed Cronbach's alpha of above usually used threshold value of 0.7. These factors explained from 72.8 % to 75.9 % of cumulative percentage in particular studied motivations.

The total amount of motivations where bigger, including access to information, green expectations, green beliefs, green values and consequential beliefs, but these factors are not given here, since they are found to be not statistically significant in following logistic regression model.

3.2.3.2 Logistic Regression Model

The final model "Intention to use MFC" (which combines all motivations given in Table together) explained 34.24 % of deviance and 28.45 % of adjusted deviance. If compared to the study by Tonglet et al. (2004) where intention to recycle was studied, the adjusted deviance in the presented Doctoral Thesis is in the same range (34.38 % vs. 33.3 %) (see Table 3.3).

Table 3.3. Analysis of deviance, residuals and goodness of fit for the model "Intention to use MFC (micro-fibre clothes)" (N = 126).

Model	Deviance explained, %	Adjusted deviance, %	*Df*	MSE	Chi-square at *Df* = 1
Intention to use MFC	41.74****	34.38	4	$1.97 \cdot 10^{-2}$	0.87 (p >0.05)

**** Significant at $p < 0.0001$.

Since the p-value for Chi-square test is greater than 0.05, there is no reason to reject the adequacy of the fitted model and it can be concluded that the logistic function adequately fits the observed data. The statistical model of "Intention to use MFC" (MFC_{USE}) is given as Equation 3.1:

$$MFC_{USE} = \exp(\eta)/(1+\exp(\eta)), \quad (3.1)$$

where η is calculated as given in Equation (3.2), since four motivations were found statistically significant, see Equation 3.2:

$$\eta = 2.33 + 1.26 \cdot OASI - 0.31 \cdot GN - 0.65 \cdot FC - 0.73 \cdot SF \ , \qquad (3.2)$$

where OASI – overall attitudes and social influence; GN – green norms, FC – functionality and controllability; SF – self-efficacy. Detailed results of the statistical tests for these factors are given in Table 3.4.

Table 3.4. Maximum likelihood and likelihood ratio tests for the model "Intention to use MFC (micro-fibre clothes)" (N = 126).

Factors	Estimate (CI)	SE	Estimated odds ratio (CI)	Chi-square	*Df*
Constant	2.33 (1.47; 3.20)	0.44	-	-	-
OASI	1.26 (0.71; 1.81)	0.28	3.53 (2.04; 6.10)	40.89****	1
GN	− 0.31 (− 0.60; − 0.03)	0.14	0.73 (0.55; 0.97)	4.92*	1
FC	− 0.64 (− 1.11; − 0.16)	0.24	0.53 (0.33; 0.85)	8.29**	1
SF	− 0.73 (− 1.18; − 0.28)	0.23	0.48 (0.31; 0.75)	14.92****	1

* Significant at $p < 0.05$; ** at $p < 0.01$; *** at $p < 0.001$; **** at $p < 0.0001$.

The strongest impact on the choice is by the constant term and the social influence of adopting MFC. Where both terms are given with the positive sign, therefore the model's value for the intention to use MFC increases, when this motivation grows. The odds ratio or 3.53 shows increase in the probability of the event to use MFC given expose to this motivation. The interpretation of the constant can be as the inertia of the system, current position of product, or habits.

The remaining motivations show similar statistics, where the estimates are negative and from − 0.31 to – 0.73 and the odds ratio are smaller then 1, therefore exposure to these motivations are associated with lower odds of outcome. Since the confidence level for odds ratio do not includes value 1, these factors are still statistically significant, but plays marginal role in the model (Hair et al. 1998).

3.2.4 System Dynamics Model's Results for Eco-Innovation Diffusion

The model was validated based on structural validation protocol was found valid for its intended use. Behaviour of consumers simulated in the system dynamics model matched with the equations obtained from the questionnaire data analysis.

3.2.4.1 Sensitivity Analysis and Scenario Analysis

A sensitivity analysis (Figure3.7) shows which variables have the highest influence on the model. In total, 9 variables were chosen for examination where variables were set to vary according to a statistical distribution. These variables are: adoption fraction of information from campaigns, the strength of information campaigns, adoption fraction of information received by word-of-mouth, the amount of cleaning agents used in parallel to MFC, the weekly consumption of cleaning agents, contacts per MFC users' household, and the amount of households already using MFC at the beginning of the simulation. These variables account for those that were introduced as the assumptions.

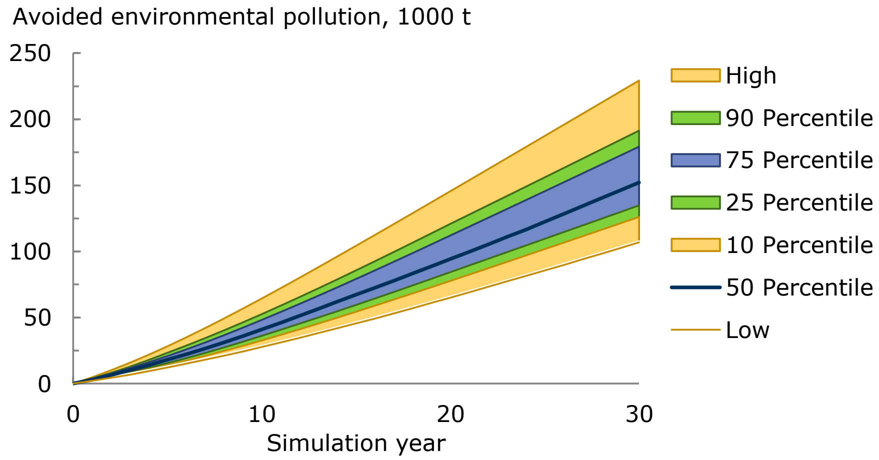


Figure 3.7. The results of the sensitivity analysis for ± 25% changes in the value of parameters the proposed innovation diffusion model.

The sensitivity analysis for the selected parameters changed the total cumulative amount of avoided environmental pollution to the environment by – 29.88 % at the lowest estimate and by + 50.59 % at the highest estimate in the 30th simulation year. The models showed expected behaviour with increasing uncertainty in the future. The adoption faction of information received by word-of-mouth, households adopted MFC at the beginning of the simulation and the contacts per household were found to be the most sensitive parameters in the short term, with decreasing importance in the long term, since the effect of word-of-mouth is the main driver for the diffusion of MFC.

3.2.4.2 Scenario Analysis

Only information campaigns were analysed under the scenario analysis, since Steg et al. (2014) state that the activities targeted to reduce the costs of some particular pro-environmental activities (for example, giving out MFC for free or subsidizing their introduction into households) or to increase the costs of environmentally harmful behaviour (increasing the tax on cleaning agents) have only a short-term effect – in the long term, households will return to their previous cleaning practices. Therefore, the effects of information campaigns targeted to the specific motivations were studied; see Figure 3.8.

In case study, the overall attitudes and social influence is found to have the most influence on the diffusion rate of MFC, given by the combination of the functionality and controllability and self-efficacy.

The most prominent is overall attitudes and social influence, which also includes social acceptance. This finding is directly supported by the research of Ozaki (2011), where signing for “green” electricity is also strongly dictated by social pressure. These results demonstrate that social acceptance is an important source of motivation for consumer choice in Latvia. These data correspond with our findings that social influence, play a significant role in the use of MFC.

All motivations alone are found not effective, and the same conclusions have been found by Abrahamse (2005) – the rewards have encouraged a change in the behaviour but only in the short term.

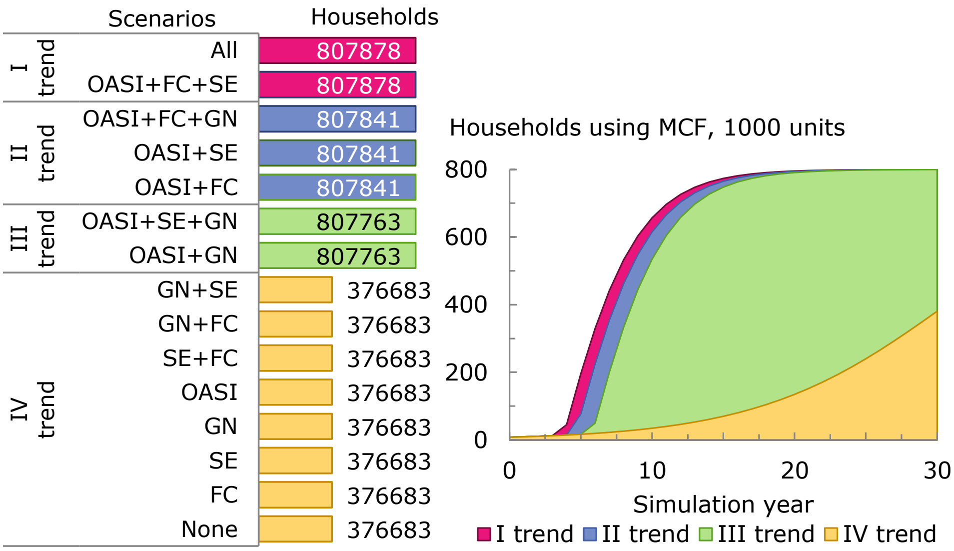


Figure 3.8. The results of the scenario analysis under various information campaigns the proposed innovation diffusion model. Overall attitudes and social influence (OASI), functionality and controllability (FC), self-efficacy (SE) and green norms (GN).

Regarding the strategy aimed to increase the level of knowledge alone, it should be mentioned that information alone is not an effective strategy to promote changes of behaviour; since information leads to higher knowledge levels, but not necessarily to changes in behaviour Abrahamse (2005). The effect of information campaigns on the diffusion speed has also been found in a study by Schwarz & Ernst (2009), but only as the third most effective measure, preceded by regulations and subsidies. There is also evidence that environmental concerns do not directly lead to pro-environmental actions (Bamberg 2003).

The main value of the proposed modelling framework is a conceptual model for the studies on eco-innovation diffusion and, consequently, the reduction of environmental pollution based on consumer choice. The proposed approach can also be used as the basis for other studies of other diffusion processes, since system dynamics modelling is a white-box modelling approach.

The current work has a set of limitations: firstly, the behavioural validation with historical data was not possible as no data was found in the literature or at the resellers of MFC; secondly, the effect of information campaigns on motivations was expressed mathematically with an error function, since specific mathematical expressions from previous studies were unavailable'; finally, in the literature a link between social pressure and diffusion speed is discussed, but to our knowledge no mathematical model of this phenomena have been developed.

To sum up, our model is able to shed light on the questions – how eco-innovation diffusion happens and what impacts the speed of diffusion, but further research is needed to address stated limitations, for more details see Paper No. 4.

3.3 Hybrid Modelling Approach

In this section the results of the upgrading previously developed model (given in the Paper No. 4) with artificial intelligence took part. A non-linear autoregressive neural network (NARX) with external input has been chosen for training of ANN, because structure of the NARX can be used for non-linear fitting and the network is commonly used for time-series modelling and modelling of non-linear dynamic systems (Fischer et al. 2012), see Figure 3.9.

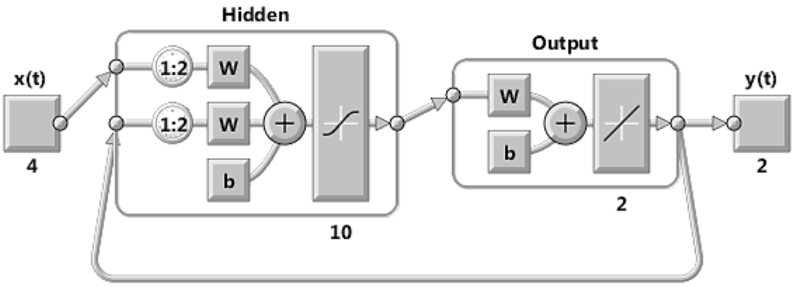


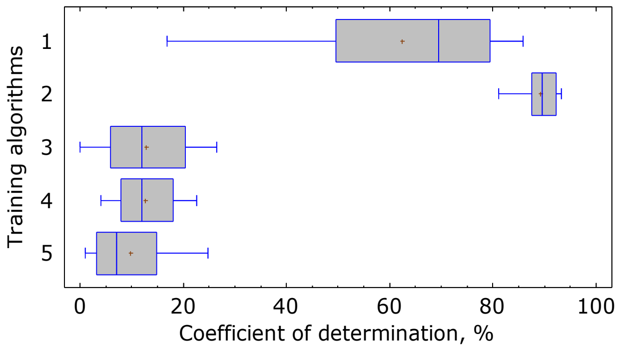
Figure 3.9. Structure of closed loop non-linear autoregressive neural network (NARX) from the MatLab neural network simulation module environment.

Where $x(t) = (x_1, x_2, x_3, x_4)$ are the input and $y(t) = (y_1, y_2)$ output of the network at time discrete time step t. The structure of the NARX network contains input layer, hidden layer and output layer. An input layer has the input 4 cell.

Before inputs are feed to the neural network they are undergoing to the pre-processing, where the function 'mapminmax' maps minimum and maximum values of the matrices to [-1; 1] and the function 'removeconstantrows' removes rows with constant values.

The input weight matrix for the hidden layer of the neural network has 10 neurons, where gradient descent with momentum is used as weight and bias learning function. The weight function receives the input data with time delays. Bias and the recurrent outputs from the output layer of size are added to the summation function. The values from the summation function within the hidden layer are feed to the hyperbolic tangent sigmoid transfer function. The output layer has weight matrix size [2×10] and bias [2×1]. For output layer linear transfer function is applied.

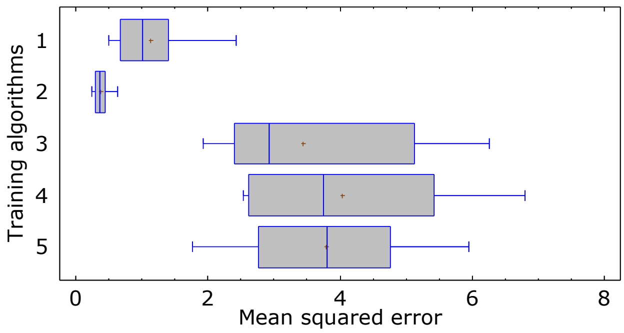
The structure of ANN (given in Figure 3.9) is defined experimentally by testing five different training algorithms. The fit of the ANN is expressed by the coefficient of determination; see Figure 3.10.



1: Levenberg-Marquardt backpropagation,
2: Bayesian Regulation backpropagation,
3: Broyden-Fletcher-Goldfarb-Shanno Quasi-Newton backpropagation,
4: Conjugate gradient with Beale-Powell restarts,
5: Scaled conjugate gradient learning algorithms

Figure 3.10. Testing of best-fit for the learning algorithms with the value of the coefficient of determination.

As given by the Figure 3.10 the training algorithms of Bayesian Regulation backprogagation shows the best fit and more stable learning properties of the ANN. The second measure of fit the mean square error was used, see Figure 3.11Figure .



1: Levenberg-Marquardt backpropagation,
2: Bayesian Regulation backpropagation,
3: Broyden-Fletcher-Goldfarb-Shanno Quasi-Newton backpropagation,
4: Conjugate gradient with Beale-Powell restarts,
5: Scaled conjugate gradient learning algorithms

Figure 3.11. Testing of best-fit for the learning algorithms with the value of mean square error (MSE).

For the MSE the similar trends are observed as for the coefficient of determination: the Bayesian Regulation backpropagation learning algorithm shows the best statistics and more stable performance of the ANN. Therefore the Bayesian Regulation backpropagation algorithm was chosen, see Equation 3.3, where the values of maximum number of epoch to train is set to 1000, maximum validation failures to 6 and minimum performance gradient to 10^{-6}:

$$F = \delta E_D(D|w,M) + \gamma E_W(w|M), \qquad (3.3)$$

where δ and γ – hyper-parameters; E_D – mean sum of squares of the network error; D – training set with input-target pairs; M – architecture of neural network; $E_W(w|M)$ – sum of square of network weights also called weight decay; γ – decay rate, For weight decay see Equation 3.4:

$$E_W = \frac{1}{n}\sum_{i-1}^{n} \omega_j^2 , \qquad (3.4)$$

where ω_j – network weights of *j* independent variables.

As for system dynamics part, the model developed in the Paper No. 4 will be modified by the integration of developed ANN network. The behaviour explained by developed ANN and behaviour explained in other works is summarized in Table 3.5 using adjusted R^2. Nevertheless, these figures given are not reliable for the comparison of the model's quality, they only present the range of the behaviour explained in the models used so far.

Table 3.5. Behaviour explained by the various studies using different method.

Study on	Adjusted R^2	Method use	Reference
Energy efficiency motivation	13 %	Statistical analysis	Bariss, Timma & Blumberga (2014)
Waste recycling motivation	33 %	Statistical analysis	Tonglet et al. (2004)
Innovation diffusion model	34 %	Statistical analysis & system dynamics, & social psychology	Paper No. 4
Upgraded innovation diffusion model	89 %	Hybrid modelling approach	Paper No. 6

As given in Table , 89 % of the behaviour is explained in the case when ANN is used together with the white-box modelling methods and social psychology. While the ANN describes the goal framing theory by mapping the respondents' answers, the system dynamics model is used to outline the broader effects of the consumer's behaviour, such as societal transitions and technological substitution in the society.

CONCLUSIONS

In this Thesis work, a novel modelling methodology is developed. The presented methodology combines the aspects of technical and social systems and natural environment, thus providing holistic methodology tools to study socio-technical transitions. Socio-technical transition processes are studied from the perspective of various sectors, such as energy use, production and management, innovation diffusion, and others. The transitions are studied from the lenses of various possible methods and their combinations.

As to the Thesis author's knowledge, this is the first time that socio-technical transitions have been studied by using the latest knowledge and advanced modelling tools for the engineering and social science field together. Also the methodology that uses both white-box models (system dynamics) in combination with black-box models (artificial intelligence) has been developed and validated in the Thesis.

The presented methods allowed guiding the decision making process and modelling the outcomes of various development scenarios. By applying obtained knowledge, the sectors were targeted to reach a sustainable development goal more effectively. The presented Doctoral Thesis allows transferring the developed methodology to study other technologies and services at different levels of the economy.

Single Mixed Modelling Approach on Energy Efficiency and Conservation

The framework is presented to model household's behaviour and electricity savings in a holistic and dynamic way. The social aspects of the consumer behaviour for higher energy savings are integrated. With the help of this model, not only the retrospective situations could be analysed but also the future savings of policy could be assessed.

For the simulation of electricity market liberalization, system dynamics has been chosen. This method can determine electricity savings, since system dynamics allows conducting the simulation of complex systems and analysing the obtained data to forecast the probability of the development of several scenarios. The obtained results show that cumulative electricity savings in households could reach 560 GWh by the end of 2020 because of the opening of electricity market. In the case of scenario analysis using the change of consumption behaviour, it was obtained that the cumulative electricity saving could be almost twice as big if the majority of households would be guided by the environmental concerns.

Multiple Mixed Modelling Approach

a) On Energy Efficiency and Conservation

The methodology was developed and validated using an empirical study (social psychology with statistical data analysis) together with system dynamics modelling. The adoption intention of energy-efficient lighting solutions in Latvia is used as the case study.

Two main motivations – financial and environmental – were found for the use of energy-efficient lighting. Therefore, policy makers should consider that both in high and low income households, incandescent light bulbs are still in use, since some individuals look more on the costs of an instant purchase but they fail to estimate the longer-term costs expressed as the expenditure for the electricity bills.

Long-term policy should not only take into account the economic side of the bulb purchase but start on putting more and more emphasis on the personal values of consumers. The results reveal that disregarding the common assumption, economic gains are not the strongest motivator, but biospheric values play an important role in the evaluation of alternatives in the energy field.

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 model.

b) On Eco-Innovation Diffusion

The goal of this research was to develop a conceptual model for eco-innovation diffusion based on consumer choice. This study sheds light on the explanation of pro-environmental behaviour. The diffusion of microfibre clothes (MFC) in Latvia for cleaning purposes in households was selected as a case study.

The proposed conceptual model studies the influence of information campaigns to reinforce the adoption of the studied eco-innovation products. Novel methodology has been developed under the system dynamics framework and was coupled with the logistic regression model. The model allows for the outlining of the dynamics under technological substitution within the context of the eco-innovations' diffusion. Structural validation tests were done for the proposed model.

The proposed methodology and developed conceptual system dynamics model can also be used as the basis for other studies of various diffusion processes, since system dynamics modelling is a white-box modelling approach, and the structure of the model can be enhanced with the latest results from other studies.

Hybrid modelling approach on Eco-Innovation Diffusion

The hybrid modelling approach for eco-innovation diffusion is presented. This methodology combines both mixed and combined research methods to improve the validity and reliability of study results. As a quantitative method, the survey of focus groups is used; as qualitative methods, the artificial neural networks, statistical data analysis and system dynamics are applied. All these four methods (quantitative and qualitative) together present the hybrid modelling approach.

With this work, the contribution to the applications of hybrid research methods in the field of eco-innovation diffusion and environmental studies is done. The obtained results show that the model can explain 89 % of the systems behaviour. The application of the presented methodology can be extended for various socio-technical problems. Although the model was based on one specific technological substitution process, its general application to other products and services is possible since the developed model is fully outlined and can be used for further research of other processes.

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PUBLICATIONS ARISING FROM THESIS

Paper 1: Timma L., Bariss U., Dandens A., Blumberga A., Blumberga D. Framework for the Assessment of Household Electricity Saving by Integrating Behavioural Aspects // Energy Procedia on International Scientific Conference Environmental and Climate Technologies, CONECT 2015 *(In Scopus and pending ISI Web of Science).*

Paper 2: Bazbauers G., Bariss U., Timma L., Lauka D., Blumberga A., Blumberga D. Electricity Saving in Households due to the Market Liberalization and Change in the Consumer Behaviour // Energetika *(In Scopus).* Contribution of Thesis author: writing literature review, case study description, defining scenarios for to incorporation of social psychology in system dynamics model, writing the discussion of the practical and policy implication of the obtained results, comparing obtained results with other studies, acting as corresponding author.

Paper 3: Timma L., Bazbauers G., Bariss U., Blumberga A., Blumberga D. Energy Efficiency Policy Analysis Using Socio-Technical Approach and System Dynamics. Case Study of Lighting in Latvia's Households // Accepted with changes in the Journal of Energy Policy *(Will be included in Scopus and ISI Web of Science).*

Paper 4: Vīgants E., Blumberga A., Timma L., Ījabs I., Blumberga D. The Dynamics of Technological Substitution: The Case of Eco-Innovation Diffusion of Surface Cleaning Products // Journal of Cleaner Production *(In Scopus and ISI Web of Science).* Contribution of Thesis author: writing literature review, case study description, developing survey, carrying out data analysis, formulating logistic regression model and integrating this model in system dynamics, writing part on empirical analysis, carrying out sensitivity analysis of system dynamics model, writing the discussion of the practical and policy implication of the obtained results, comparing obtained results with other studies, acting as corresponding author.

Paper 5: Timma L., Blumberga A., Blumberga D. Combined and Mixed Methods Research in Environmental Engineering: When Two is Better Than One // Energy Procedia on International Scientific Conference Environmental and Climate Technologies, CONECT 2014 *(In Scopus and ISI Web of Science).*

Paper 6: Timma L., Blumberga A., Blumberga D. Understanding the Technological Substitution by Hybrid Modelling Practice: A Methodological Approach // Chemical Engineering Transactions on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction *(In Scopus and ISI Web of Science).*

PAPER 1: FRAMEWORK FOR THE ASSESSMENT OF HOUSEHOLD ELECTRICITY SAVING BY INTEGRATING BEHAVIOURAL ASPECTS

PAPER 2: ELECTRICITY SAVING IN HOUSEHOLDS DUE TO THE MARKET LIBERALIZATION AND CHANGE IN THE CONSUMER BEHAVIOUR

PAPER 3: ENERGY EFFICIENCY POLICY ANALYSIS USING SOCIO-TECHNICAL APPROACH AND SYSTEM DYNAMICS. CASE STUDY OF ENERGY EFFICIENT LIGHTING IN HOUSEHOLDS

PAPER 4: THE DYNAMICS OF TECHNOLOGICAL SUBSTITUTION: THE CASE OF ECO-INNOVATION DIFFUSION OF SURFACE CLEANING PRODUCTS

PAPER 5: COMBINED AND MIXED METHODS RESEARCH IN ENVIRONMENTAL ENGINEERING: WHEN TWO IS BETTER THAN ONE

PAPER 6: UNDERSTANDING THE TECHNOLOGICAL SUBSTITUTION BY HYBRID MODELLING PRACTICE: A METHODOLOGICAL APPROACH