RIGA TECHNICAL UNIVERSITY

Maksims Feofilovs

DYNAMICS OF URBAN RESILIENCE TO NATURAL HAZARDS

Doctoral Thesis

RTU Press
Riga 2020

RIGA TECHNICAL UNIVERSITY

Faculty of Power and Electrical Engineering

Institute of Energy Systems and Environment

Maksims Feofilovs

Doctoral Student of the Study Programme “Environmental Science”

DYNAMICS OF URBAN RESILIENCE TO NATURAL HAZARDS

Doctoral Thesis

Scientific supervisor

Professor Dr. sc. ing.

FRANCESCO ROMAGNOLI

RTU Press

Riga 2020

ANNOTATION

The statistics of natural disasters, growing population and increasing urbanization rate is indicate a potential increase of disaster risk in urban areas. Research aiming to provide support to disaster risk reduction policies currently is of high importance.

The question how to measure urban resilience to natural hazard is an actual problem in research and urban policy planning. A consistent support for assessing urban resilience and evaluating alternative policy strategies for strengthening resilience in required. The current methods applied for assessment of urban resilience are failing to capture the set of important aspects in one measurement. Multidimensionality, short-term and long-term perspective and different likelihoods of disaster occurrence are not captured yet in one single tool.

Thus, the Doctoral Thesis aims at creating a novel tool for urban resilience to natural hazard assessment. Three methods – composite indicator, probabilistic simulation, and system dynamics – are applied in a local case study for resilience assessment. Case studies allow understanding the limitations and strengths of the methods. As a result, these methods are integrated into a single tool to overcome limitations of each method.

The Doctoral Thesis has been written in English. It consists of an Introduction; 3 Main Chapters; Discussion, Conclusion and Recommendations; 53 figures; 8 tables and 7 publications in appendices; the total number of pages is 180. The Bibliography contains 160 titles.

The introduction presents the aim of the Doctoral Thesis, the scientific and practical importance of the developed tool together with the scientific articles published on the topic of the Thesis. The approbated results are presented as a list of publications and presentation made at international scientific conferences. In addition, other publications of the author that are not in line with the Thesis are mentioned.

The Doctoral Thesis is based on thematically unified seven scientific articles dedicated to case studies and development of the tool. With help of publications the developed knowledge within this Thesis is transferred to broader scientific community. The publications are published in international scientific journals and are indexed in international scientific databases. The Thesis itself consists of three main chapters.

Chapter 1 of the Doctoral Thesis is a literature review on the current topicality of the research field, the terminological variety and epistemological disjunctions of the studied term "resilience" and methods used to measure resilience. Chapter 2 describes each step of methodology of the Doctoral Thesis, presenting the main steps performed in each of the separate studies made within thematic publications. Chapter 3 presents the achieved result. The focus of the chapter is the construct and application of the developed assessment tool of dynamic urban resilience to natural hazards. Finally, conclusions are given at the end of the Thesis resulting from the development and testing of the tool.

ANOTĀCIJA

Dabas katastrofu statistika un iedzīvotāju skaita pieaugums pasaulē kopā ar urbanizācijas līmeņa pieaugumu liecina par katastrofu riska palielināšanos pilsētās. Turklāt tiek prognozēts, ka klimata pārmaiņu ietekme palielinās dabisko apdraudējumu aktivitātes pieaugumu. Pētījumi, kuru mērķis ir sniegt atbalstu katastrofu riska mazināšanas politikai šobrīd ir ļoti svarīgi.

Jautājumi, kas saistīti ar to, kā izmērīt pilsētu izturētpsēju pret dabisko apdraudējumu, praksē ir aktuāla problēma. Katastrofu riska mazināšanas politikas plānošanai ir nepieciešams konsekvents atbalsts alternatīvu politikas stratēģiju izvērtēšanai, kuru mērķis ir uzlabot izturētspēju. Pašreizējās pilsētas izturētsējas novērtēšanai izmantotās metodes nespēj aptvert svarīgu aspektu kopumu vienā mērījumā. Daudzdimensionalitāte, dinamika, īstermiņa un ilgtermiņa perspektīva un dažādas katastrofu iespējamības vēl nav ietvertas kopā vienā rīkā.

Tādējādi promocijas darba mērķis ir radīt jaunu instrumentu pilsētu izturētspējas pret dabisko apdraudējumu novērtēšanai. Promocijas darbā tiek izmantotas trīs metodes izturētspējas novērtēšanai vietējā gadījumu izpētē: saliktais indikators, varbūtības simulācija un sistēmdinamika. Gadījumu izpēte ļauj izprast katras metodes vājās un stiprās puses. Rezultātā šīs metodes tiek integrētas vienā rīkā, lai pārvarētu katras metodes ierobežojumus.

Promocijas darbs ir izstrādāts angļu valodā, tajā ir ievads, trīs nodaļas, diskusija, secinājumi un recomendācijas, literatūras saraksts, pieliktas 7 publikācijas, 53 attēli, astoņas tabulas, kopā 180 lappuses. Literatūras sarakstā ir 160 nosaukumi.

Ievadā ir izklāstīts promocijas darba mērķis, izstrādātā rīka zinātniskā un praktiskā nozīme kopā ar zinātniskajiem rakstiem, kas publicēti par darba tēmu. Apstiprinātie rezultāti tiek pasniegti kā publikāciju saraksts un prezentācijas, kas veiktas starptautiskās zinātniskās konferencēs. Tiek pieminētas arī citas autora publikācijas.

Promocijas darba pamatā ir tematiski vienotas septiņas zinātniskās publikācijas, kas veltītas gadījumu izpētei un rīka attīstībai. Ar publikāciju palīdzību šajā darbā izstrādātās zināšanas tiek nodotas plašākām zinātnieku aprindām. Publikācijas tiek publicētas starptautiskos zinātniskos žurnālos un citētas starptautiskās zinātniskās datu bāzēs. Tās ir pievienotas Promocijas darba beigās. Promocijas darbs sastāv no trim galvenajām nodaļām, kurās aprakstīta literatūra, metodoloģija un rezultāti no zinātniskajām publikācijām.

Promocijas darba 1. nodaļa ir literatūras apskats par pētījuma jomas pašreizējo aktualitāti, pētāmā termina izturētspēja terminoloģisko dažādību un epistemoloģiskās disjunkcijām un mērīšanas metodēm. 2. nodaļā aprakstīts katrs promocijas darba metodoloģijas posms, iepazīstinot ar galvenajiem soļiem, kas veikti katrā atsevišķā gadījumu pētījumā. 3. nodaļā ir sniegts rezultātu izklāsts. Rezultātu nodaļā tiek prezentēts izstrādātais pilsētu izturētspējas pret dabisko apdraudējumu novērtēšanas rīks. Visbeidzot, darba beigās tiek sniegti secinājumi, kas izriet no rīka izveidošanas un testēšanas.

PATEICĪBAS

Vēlos izteikt pateicību visiem, kas atbalstīja mani šā darba tapšanā. Bez visu jūsu palīdzības un atbalsta šis darbs nebūtu tapis. Milzīgs paldies manam darba vadītājam Francesco Romagnoli, kas mani vadīja cauri visiem šķēršļiem un palīdzēja atrast risinājumus zinātniskām un nezinātniskām problēmām. Es ļoti ceru, ka mūsu sadarbība ar šo darbu nebeidzas un arī turpmāk varēsim iet pretī jauniem izaicinājumiem citos zinātniskos projektos.

Milzīga pateicība Dagnijai Blumbergai, kas motivēja mani, ļāva izpausties un ticēja, ka jaunais pētījumu virziens novedīs pie rezultāta, kas ir svarīgs arī vides zinātņu nozarei. Esmu pateicīgs arī pārējiem kolēģiem, kas man deva padomus saistībā ar sistēmu dinamikas modelēšanas niansēm – Andra, Armands, Aiga. Bez jums es nebūtu attīstījis savas modelēšanas prasmes līdz esošajam līmenim.

Paldies visiem maniem līdzautoriem par pieliktajām pūlēm atsevišķu zinātnisko rakstu izstrādē. Šarlote, ar tavu palīdzību es spēju saskatīt sava darba gala versiju. Mūsu kopējā publikācija bija pagrieziena punkts mana darba izveidē. Armand, Andrea un Marina, novēlu jums arī pievarēt šo lielo pārbaudījumu. Turpiniet neatlaidīgi iet uz mērķi un jūs to sasniegsiet.

Paldies maniem kolēģiem, kas man palīdzēja tikt galā ar dokumentu kārtošanu, darba grafika ievērošanu un citiem administratīvajiem darbiem. Terēza, Antra, Līga, Dace, Alise - jūsu palīdzība atvieglоja manu darbu ar dokumentiem, saziņu ar vadību un iekļaušanos termiņos. Jūs esat lieliskas sava darba lietpratējas.

Paldies Klaudio, Raimondai un Fabianam par pieliktajām pūlēm pie darba noformējuma. Īpašs paldies Jūlijai un Eiropas Sociālā fonda projektam.

Darbs izstrādāts saistībā ar šādiem projektiem:

- Eiropas Sociāla fonda projekta "Rīgas Tehniskās universitātes akadēmiskā personāla stiprināšana stratēģiskās specializācijas jomās" Nr.8.2.2.0/18/A/017

NACIONĀLAIS ATTĪSTĪBAS PLĀNS 2020

EIROPAS SAVIENĪBA
Eiropas Sociālais fonds

IEGULDĪJUMS TAVĀ NĀKOTNĒ

- Eiropas Savienības programma Erasmus + līdzfinansēts projekts "Capacity Building in Asia for Resilience EducaTion (CABARET)" Nr. 573816-EPP-1-2016-1- UK-EPPKA2-CBHE-JP

cabaret

Co-funded by the Erasmus+ Programme of the European Union

CONTENTS

Nomenclature 6
Introduction 7
1. Literature review 15
1.1. Natural disasters: Overview 15
Global Trends 15
Europe and Local Trends 17
Legislative Background 19
1.2. Concept of Resilience 22
1.3. Urban Resilience 24
1.4. Resilience Assessment Methods 25
Indicator Method for Resilience Assessment 28
Computer Simulation Tools for Resilience Assessment 30
System Dynamic Models for Urban Resilience 32
2. Methodology 34
2.1. Composite Indicator Approach in Local Case Study 35
2.2. Probabilistic Simulation Approach in Local Case Study 36
2.3. System Dynamics Approach in Local Case Study 38
2.4. Dynamic Urban Resilience Model 40
Structure of Dynamic Urban Resilience Model 41
Validation of Dynamic Urban Resilience Model 42
Assessment of Urban Resilience in Local Case Study 43
3. Results 45
3.1. Quantitative Resilience Measurement 45
Composite Indicator-based Index in Case Study 45
Probabilistic Simulation in Case Study 45
System Dynamics Approach in Case Studies 46
3.2. Dynamic Urban Resilience Model 47
Selected Definition for Urban Resilience Model 47
Defined Urban Resilience Model Structure 48
Causal Loop Diagrams 49
Definition of Baseline Scenario for Urban Resilience Assessment 51
Urban Resilience Model Validation Results 53
Probabilistic Simulation Integration into Urban Resilience Model 54
Selected Set of Indicators 60
Indicator Normalization 61
URI Definition 64
Integration of URI into Urban Resilience Model 65
Analysis of Selected Urban Resilience Scenarios 66
Monte Carlo Simulations For Urban Resilience Scenarios 71
Summary of the Urban Resilience Scenario Comparison 75
Discussion 77
Conclusions 79
Recommendations 80
References 81
Publications Arising from This Thesis 89

NOMENCLATURE

Greek symbols

ω – weight of indicator, capital, etc.

Latin symbols

CDRI – Community disaster resilience index
CLD – Causal loop diagrams
DH – District heating
DRM – Disaster risk management
DRR – Disaster risk reduction
dt – Time interval used as step of model simulation
E – Maximum permissible error in calculating Z
EEA – European Environmental Agency
EM-DAT – Emergency Events Database
EU – European Union
GDP – Gross domestic product
GIS – Geographical information system
IPCC – Intergovernmental Panel on Climate Change
i – Number of a specific item
M – Matrix
MCA – Multi criteria analysis
N – All possible model output values for the urban resilience index in one scenario
n – Number of items
R^2 – Coefficient of determination
S – Matrix element
SD – System dynamics
SER – Socio-ecological resilience
SWOT – Strengths, Weaknesses, Opportunities, and Threats
t – Time
URI – Urban resilience index
x – Indicator
y – Value of observation
Z – Number of samples

INTRODUCTION

Extreme events like floods, windstorms, tornados, wildfire, and earthquakes are naturally occurring physical phenomenons around the world. These events appear as natural hazards to communities and can turn into a disaster event. Communities experience the impacts of such events in terms of physical damage to material assets, financial loss, and life loss [1]. Over last 60 years the number of natural disasters has increased tremendously and thus have the amount of loss and damage [2]. This has made the disaster risk reduction policies an inalienable part of social welfare, economic growth, and environmental protection.

Disaster risk reduction is achieved through a set of prevention, preparedness, response, and recovery measures and is essential for sustainable development. The set of measures that must be considered with social, economic, and environmental aspects makes disaster risk reduction a complex problem, which requires scientifically sound support. In this direction the term "resilience" has gained an increasing attention in scientific community [3] and is embedded in international policy agreements such as Sendai Framework and Paris Agreement on Climate Change. The term is used to describe the complex behaviour of a system that is able withstand natural disasters.

The hotspots of loss and damage from natural hazards are urban areas because of concentrated exposure of communities and physical assets to natural hazards [4]. This has made the research in field of disaster risk reduction to focus on urban resilience. Studies aiming at measuring urban resilience have emerged over last decades and mostly view urban system functionality level as an indicator for resilience measurement (Fig. 1.).

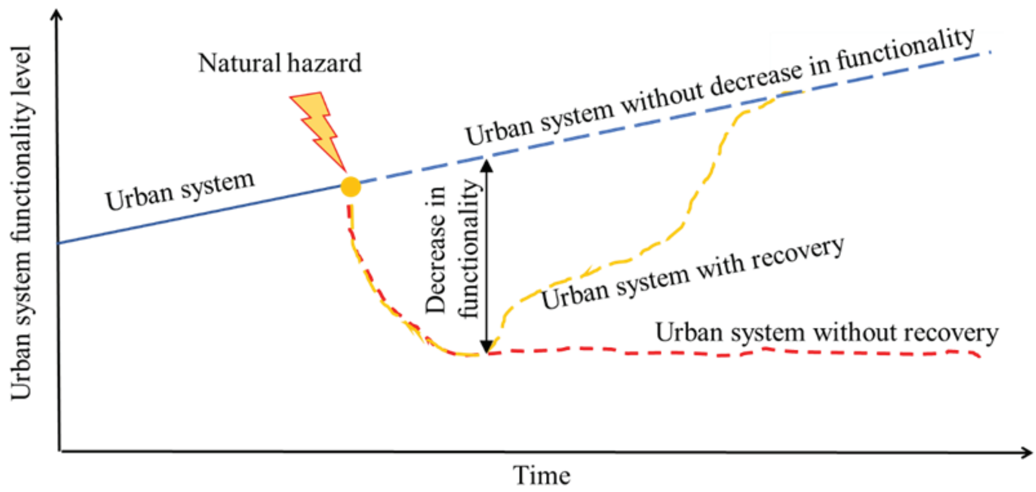


Fig.1. Urban system functionality level as urban resilience measurement indicator.

Measurement of urban resilience in terms of urban system functionality in scientific literature can be found in different forms and has a variety of measurement approaches. Static urban system functionality level is easy to measure, but it does allow capturing the changes in system over time. On the contrary, dynamic change in urban functionality level over time is hard to measure, but it gives a much more detailed information on urban resilience. Because of certain limitations of each approach, urban resilience measurement has been unable to provide a consistent and provident support for disaster risk reduction policy planning in urban areas.

The research within the Thesis is carried out in the direction to provide solutions to the existing resilience measurement problem. The goal is to provide a better approach for measurement of urban resilience and facilitate the pathways for overcoming knowledge gaps reported in literature that could be used in policy planning. For this purpose, several applied studies are made on application of different models for static resilience measurement, discrete event resilience measurement, and continuous event resilience measurement in order to encourage the transition from static to continuous event resilience measurement.

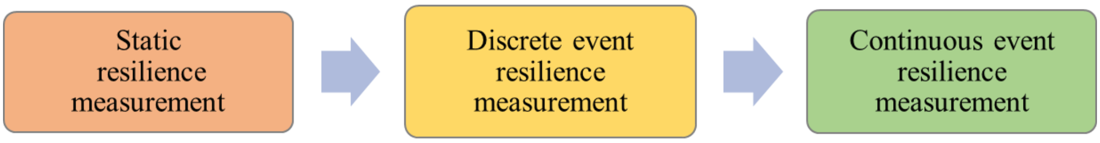


Fig. 2. Transition from static to continuous event resilience measurement.

Within the Thesis static resilience measurement case study on indicator based composite index is made. For discrete event resilience measurement probabilistic sampling method is used. For continuous event resilience measurement system dynamics approach is applied.

Research hypothesis and topicality

The main research hypothesis is based on the need to have a tool that supports a dynamic assessment of urban resilience to natural hazards enabling better decision making for coping with natural hazards. The hypothesis is that integrated approach combining three methods (system dynamics, probabilistic simulation, and composite indicator) based on system dynamic model allows overcoming the limitations of methods when they are used alone for urban resilience measurement.

The topicality of this research is underlined by the current state of climate-change linked disasters threatening sustainable development worldwide. In fact, it is expected that climate change will significantly increase the frequency, intensity, spatial extent, and duration of natural hazards. Moreover, the environmental degradation, population growth and rapid urbanization, poorly planned urban development and insecure livelihoods in combination with the increasing threats of natural hazards pose a high risk for disaster events.

Literature on natural hazards and disaster events shows that the resilience concept represents a guideline toward a valuable hazard risk management and mitigation. Resilience assessment of urban areas is an approach on which scientists and policy makers are strengthening the cooperation. However, the multi-dimensional nature of the problem makes it hard to create a consistent urban resilience assessment methodology and identify best policy strategies for building urban resilience. Despite an increase of studies on the topic of urban resilience the quantitative approach for urban resilience assessment is still an open issue.

Many frameworks and models exist to assess and evaluate the resilience of communities and infrastructural systems; nevertheless, the application is limited to specific case studies, thus showing the lack of a link with the policy planning of urban areas. The reviews of existing urban resilience assessment methods in scientific literature report the following:

- it is very difficult to quantify or measure urban resilience due to multi-dimensionality of urban areas that include social aspects of communities and infrastructure systems;
- dynamics of urban areas are often neglected in existing urban resilience assessment frameworks, limiting the interpretation of the actual status of urban resilience;
- the link between socio-economic and environmental aspects considered in the many definitions of the resilience term is currently lacking the urban resilience assessment;
- indicator-based methods do not provide enough information to create strategies over the long term;
- there are many uncertainties related to complexity of the term "urban resilience" because the terminological variety and different resilience perspectives have made urban policy making difficult because of lack of recognition and reflection of the term.

All of these aspects result in an inability to provide knowledge and support to urban policy planning. Thus, a consistent approach for urban resilience assessment that deals with the existing knowledge gaps in scientific literature is necessary.

Aim and Objectives

The aim the Thesis is to develop a tool for assessment of urban resilience to natural hazards that can support policy planning for building urban resilience at local level. The main objectives for achieving the goal are:

- to examine quantitative methods currently used for measuring resilience of community and infrastructure systems in separate case studies;
- to select urban resilience definition appropriate for developing novel approach for urban resilience assessment;
- to develop a novel approach for urban resilience assessment that deals with the existing shortcomings of methods reported in literature and examined in case studies;
- to verify and test the developed approach in a local case study;
- to compare different urban resilience strategies for a selected case study and present policy planning suggestions for increasing urban resilience based on the results of the performed case study;
- to provide suggestions for further research on the topic of urban resilience and implementations of the developed tool.

Scientific significance

The scientific significance of the work is in the developed tool integrating three quantitative resilience assessment approaches as described in Fig. 3. The developed tool fills the existing knowledge gaps identified in scientific literature on the topic of resilience measurement by providing a novel approach for urban resilience assessment. None of the previous existing tools has captured such scale and scope of urban resilience measurement.

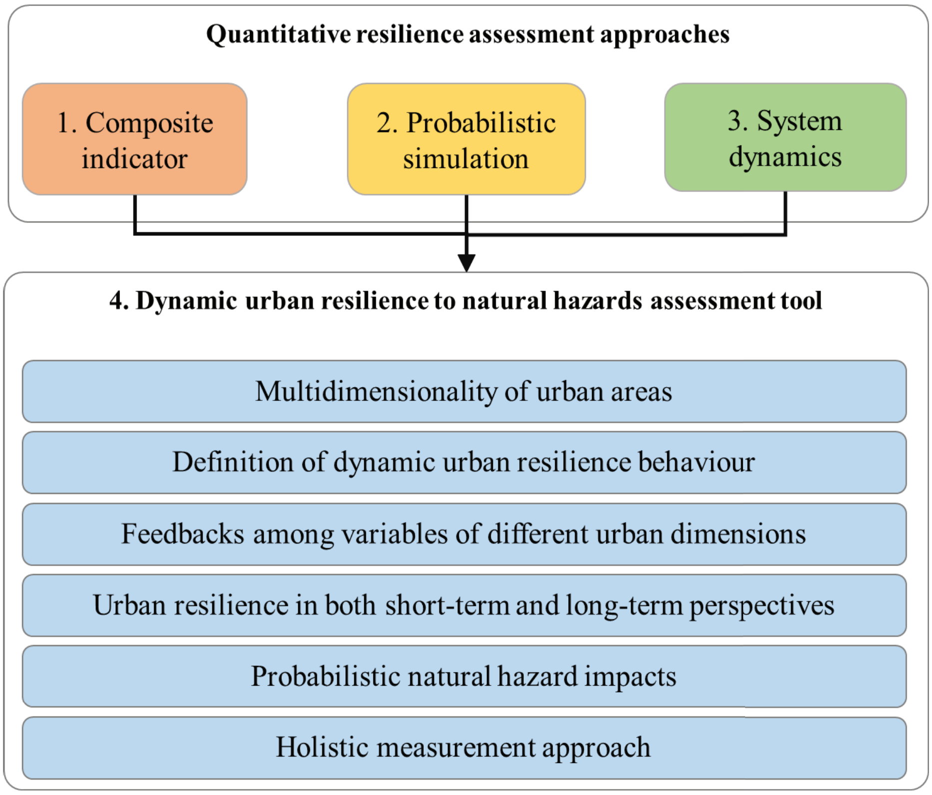


Fig. 3. Steps of methodology and characteristics of the developed tool.

Table 1

Scientific Articles Used in the Doctoral Thesis to Present the Steps of the Developed Methodology

Methodology step	No.	Publication title
1. Composite indicator approach	1	Measuring Community Disaster Resilience in the Latvian Context: an Apply Case using a Composite Indicator Approach.
2. Probabilistic simulation approach	2	Resilience of Critical Infrastructures: Probabilistic Case Study of a District Heating Pipeline Network in Municipality of Latvia.
3. System dynamics approach	3	System Dynamics Model for Natural Gas Infrastructure with Storage Facility in Latvia
	4	Increasing Resilience of the Natural Gas System with Implementation of Renewable Methane in the Context of Latvia: A System Dynamics Model
4. Dynamic urban resilience to natural hazard assessment tool	5	Assessing Resilience Against Floods with a System Dynamics Approach: A Comparative Study of Two Models
	6	Assessment of Urban Resilience to Natural Disasters with a System Dynamics Tool: Case Study of Latvian Municipality
	7	Dynamic assessment of urban resilience to natural hazards

The first step of the methodology is dedicated to research on composite indicator approach, presented in Article 1. The articles present the application of Community Disaster Resilience Index for the case of Latvia.

The second step of methodology is focused on a probabilistic simulation approach, presented in Article 2. The article presents the application results of probabilistic simulation for a district heating pipeline network disruption during extreme cold temperatures period and evaluation of DH network resilience in a Latvian municipality based on the thresholds for recovery time, damage ratio, and damage costs.

The third step of the methodology is dedicated to the implementation of system dynamics approach within the definition of urban resilience, presented in Articles 3 and 4. In Article 3 the development of system dynamics model for natural gas transmission system with storage is reported, while the application of the model for defining dynamic change in resilience of natural gas supplies with application of renewable resource support policy is shown in Article 4.

The knowledge gathered through the separate application of the defined quantitative approaches is used for development of a dynamic urban resilience assessment tool specifically addressed to natural hazards. The hypothesis for such tool together with its causal loop diagram are presented in Article 5. Then the application of the developed tool in a local case study is presented in Article 6 and results of different urban resilience scenario comparison in Article 7.

Integration of different approaches into a single tool allows to include the strong aspects of each approach dealing with weak aspects when used alone.

The system dynamics approach allows to define dynamic urban resilience behaviour in multiple dimensions of urban areas, include the feedbacks among different dimensions, and capture short-term and long-term perspectives of urban resilience.

The probabilistic approach enables the simulation of different natural hazards within the system dynamics model, in this way presenting explicitly the uncertainty of disaster risk management field.

The definition of composite based indicator approach allows capturing the multi-dimensionality and measure it in a holistic way with a single score output, which is used for comparison of different scenarios of strengthening the urban resilience.

Practical significance

The result of this study is a tool for dynamic urban resilience assessment to natural hazards. The tool can be used by local governments for developing their own resilience strategies by assessing future development prospects and help to offset the existing knowledge gaps in urban resilience policy planning.

The structure of the tool includes social, economic, environmental, infrastructural, and environmental aspects of urban areas. Thus, the application of the developed tool also supports the link of disaster risk reduction field with policy planning of other sectors.

Within its multi-dimensional context, the tool allows to compare the effects of different policy strategies for building urban resilience to natural hazards, e.g., strategies for disaster risk reduction, increase of environmental performance or decrease of social vulnerability. Urban resilience assessment tool that will stimulate progress in this field is not created yet in the Baltic regions including Latvia.

Approbation of the results of the research

1. Feofilovs, M., Romagnoli, F. Dynamic Assessment of Urban Resilience to Natural Hazards. (2020) *International Journal Of Disaster Risk Reduction* (In review).

2. Feofilovs, M., Romagnoli, F. Assessment of Urban Resilience to Natural Disasters with a System Dynamics Tool: Case Study of Latvian Municipality. (2020) *Environmental and Climate Technologies*, vol. 24, no. 3, pp 249–264.

3. Feofilovs, M., Romagnoli, F., Gotangco, C. K., Josol J. C., Jardeleza J. M., Campos J., Litam J., Abenojar K. Assessing Resilience Against Floods With A System Dynamics Approach: A Comparative Study Of Two Models. (2020) *International Journal of Disaster Resilience in the Built Environment,* vol. 11, no. 5, pp. 615-629.

4. Feofilovs, M., Gravelsins, A., Pagano, A., Romagnoli, F. Increasing Resilience of the Natural Gas System with Implementation of Renewable Methane in the Context of Latvia: A System Dynamics Model. (2019) *Energy Procedia*, 158, pp. 3944–3950.

5. Feofilovs, M., Romagnoli, F., Gravelsins, A. System Dynamics Model for Natural Gas Infrastructure with Storage Facility in Latvia. (2018) *Energy Procedia*, 147, pp. 549–557.

6. Feofilovs, M., Romagnoli, F. Resilience of Critical Infrastructures: Probabilistic Case Study of a District Heating Pipeline Network in Municipality of Latvia. (2017) *Energy Procedia,* 128, pp. 17–23.

7. Feofilovs, M., Romagnoli, F. Measuring Community Disaster Resilience in the Latvian Context: an Apply Case using a Composite Indicator Approach. (2017) *Energy Procedia*, 113, pp. 12–14.

Other scientific publications

1. Feofilovs, M., Pakere, I., Romagnoli, F. Life Cycle Assessment of Different Low Temperature District Heating Development Scenarios: a Case Study of Municipality in Latvia, (2019) *Environmental and Climate Technologies*, 23 (2), 272–290.

2. Pogano, A. J., Feofilovs, M., Romagnoli, F. The relationship between insurance companies and natural disaster risk reduction: overview of the key characteristics and mechanisms dealing with climate change, (2018) *Energy Procedia*, 147, 566–572.

3. Mola, M., Feofilovs, M., Romagnoli, F. Energy resilience: research trends at urban, municipal and country levels, (2018) *Energy Procedia*, 147, 104–113.

4. Feofilovs, M., Pogano, A. J., Romagnoli, F. Market development and support schemes for biomethane: SWOT analysis in context of Latvia, (2018) *Environmental and Climate Technologies* (accepted for publishing).

Reports at scientific conferences

1. Feofilovs, M., Romagnoli, F. "Assessment of Urban Resilience to Natural Disasters with a System Dynamics Tool: Case Study of Latvian Municipality." *International scientific conference of Environmental and Climate Technologies "CONECT 2020"*, Riga, Latvia, May 13–15, 2020.

2. Feofilovs, M., Romagnoli, F., Gotangco, C. K., Josol, J. C., Jardeleza, J. M., Campos, J., Litam, J., Abenojar, K. "Assessing Resilience Against Floods With A System Dynamics Approach: A Comparative Study Of Two Models." *The 9th International Conference on Building Resilience "09TH ICBR"*, Bali, Indonesia, January 13–15, 2020.

3. Feofilovs, M., Pakere, I., Romagnoli, F. "Life Cycle Assessment of Different Low Temperature District Heating Development Scenarios: a Case Study of Municipality in Latvia". *International scientific conference of Environmental and Climate Technologies "CONECT 2019"*, Riga, Latvia, May 15–17, 2019.

4. Feofilovs, M., Gravelsins, A., Pagano, A., Romagnoli, F. "Increasing Resilience of the Natural Gas System with Implementation of Renewable Methane in the Context of Latvia: A System Dynamics Model". *10th International Conference on Applied Energy "ICAE2018"*, Hong Kong, China, August 22–25, 2018.

5. Feofilovs, M., Romagnoli, F., Gravelsins, A. "System Dynamics Model for Natural Gas Infrastructure with Storage Facility in Latvia". *International scientific conference of Environmental and Climate Technologies "CONECT 2018"*, Riga, Latvia, May 16–18, 2018.

6. Pogano, A. J., Feofilovs, M., Romagnoli, F. "The relationship between insurance companies and natural disaster risk reduction: overview of the key characteristics and mechanisms dealing with climate change", *International scientific conference of Environmental and Climate Technologies "CONECT 2018"*, Riga, Latvia, May 16–18, 2018.

7. Mola, M., Feofilovs, M., Romagnoli, F. "Energy resilience: research trends at urban, municipal and country levels", *International scientific conference of Environmental and Climate Technologies "CONECT 2018"*, Riga, Latvia, May 16–18, 2018.

8. Feofilovs M., Pogano, A. J., Romagnoli, F. “Market development and support schemes for biomethane: SWOT analysis in context of Latvia”, *International scientific conference of Environmental and Climate Technologies “CONECT 2018”*, Riga, Latvia, May 16–18, 2018.

9. Feofilovs, M., Romagnoli, F. “Resilience of Critical Infrastructures: Probabilistic Case Study of a District Heating Pipeline Network in Municipality of Latvia”. *International scientific conference of Environmental and Climate Technologies “CONECT 2017”*, Riga, Latvia, May 10–12, 2017.

10. Feofilovs, M., Romagnoli, F. “Measuring Community Disaster Resilience in the Latvian Context: an Apply Case using a Composite Indicator Approach”. *International scientific conference of Environmental and Climate Technologies “CONECT 2016”*, Riga, Latvia, May 12–14, 2016.

Monograph

Āboltiņš, R., Bariss, U., Blumberga, A., Blumberga, D., Cilinskis, E., Feofilovs, M., Grāvelsiņš, A., Kuzņecova, T., Lupkina, L., Muižniece, I., Rochas, C., Romagnoli, F. Climate engineering and policy. Riga: RTU Press, 2020. 204 p. ISBN 978-9934-22-102-6.

Thesis outline

The Doctoral Thesis is based on 7 thematically unified scientific articles that are presented in international scientific conferences and published in international scientific journals, indexed in Scopus and Web of Science. The articles describe separate case studies on different methodologies that are integrated in a dynamic urban resilience to natural hazards assessment tool.

This Thesis consists of an introduction and three chapters:

- Literature review,
- Research methodology,
- Results and conclusions.

The introduction presents the aim of the Doctoral Thesis, the scientific and practical importance of the developed tool together with the scientific articles published on the topic of the Thesis. In addition, approbated results as the list of publications presented at international scientific conferences and other publications of the author that are not in line with the Thesis are presented.

Chapter 1 is a literature review on the current topicality of the research field, the terminological variety of term “resilience” and epistemological disjunctions. Chapter 2 describes each step of methodology of the Doctoral Thesis. Chapter 3 presents the results of the achieved, mainly focusing on the construct and application of the developed dynamic urban resilience to natural hazards assessment tool. Finally, conclusions are given at the end of the Thesis together with recommendations for application of the tool for policy planning in practice.

1. LITERATURE REVIEW

1.1. Natural disasters: Overview

Global Trends

Natural disasters occur when natural extreme events (natural hazards) like floods, windstorms, tornados, wildfire, and earthquakes hit communities and their physical capital [5]. The available statistics show the impacts of disasters and the amplitude of the problem that communities are facing at the current time. According to the Emergency Events Database (EM-DAT) there is an increase in the reported number of disaster events in the world from 1990 to 2020. Most of the reported disaster events are hydrological and meteorological disasters.

The reported number of disasters started to grow rapidly around the 1960s (Fig. 1.1A). As mentioned in [6], better reporting leads to the accounting of a higher number of events and losses. Growing communication among countries can be the reason for such trend in reported number of disasters.

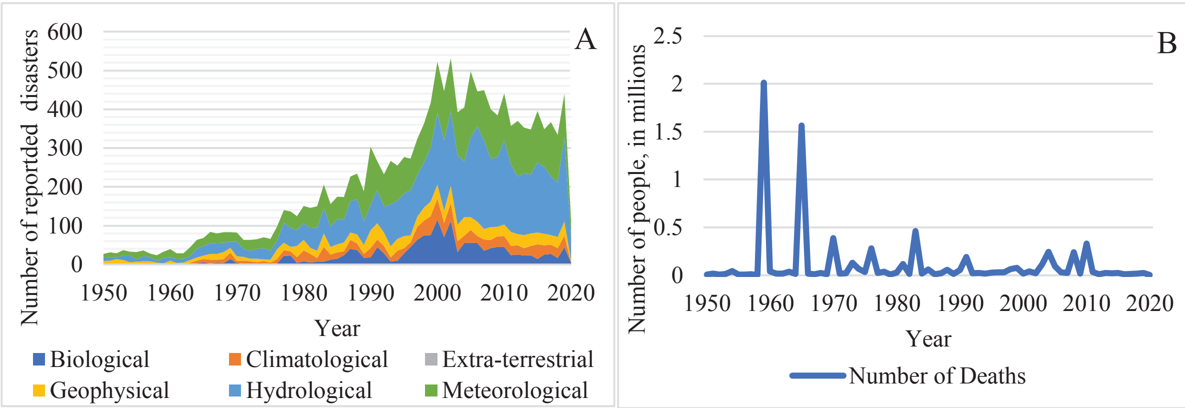


Fig. 1.1. A – number of disaster events by disaster type 1950–2020; B – human life loss in disaster events 1950–2020 [2].

The available data in EM-DAT shows a decrease in the number of deaths in natural disasters from 1950 to 2020 (Fig. 1.1B), which at first seems controversial in relation to the increasing number of disasters. This tendency in human losses decrease can be explained by a learning effect. This means that communities over time have learned from past events to better prepare for disasters also due to the development of infrastructure, for example, more precise weather forecasts and better emergency response to disasters by disseminating information immediately after alarms, on radio and television [7].

Though there is notable decrease in human life loss, still an increasing number of people injured and affected by disaster events is reported (Figs. 1.2A) during the last 60 years. This can be explained by the tendency of both the population growth and the economic and infrastructure development [8], which results as increasing potential loss and disruption associated with the hazard even if the probability and intensity of hazard activity remains constant [9].

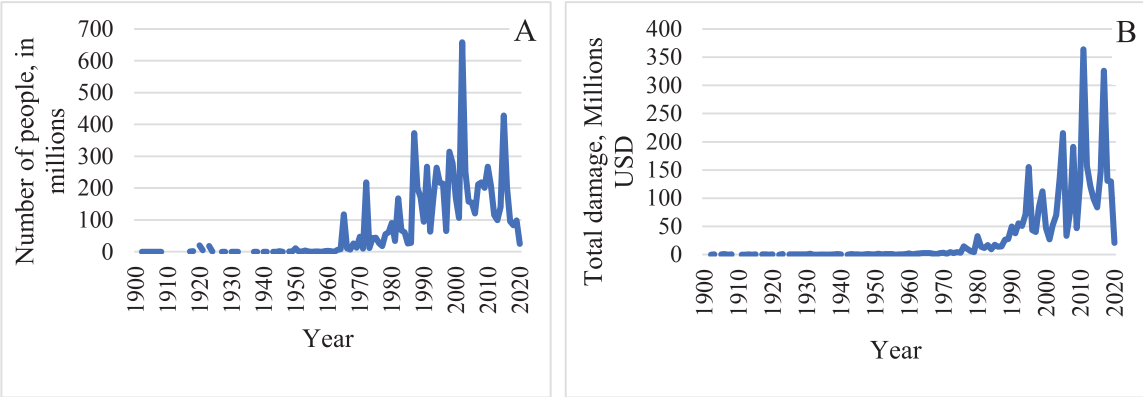


Fig. 1.2. A – number of people affected in disaster events; B – disaster damage costs in millions of USD [2].

Another challenge for disaster response and recovery are cascading effects following natural hazard occurrence. Cascading effects are complex due to factors such as climate change, population migration, economic interconnectivity, and globalization, and can include the spread of food-related and water borne, vector-borne, vaccine-preventable, infectious diseases and zoonosis or even to HIV, STI, and viral hepatitis [10]. For spread of such diseases, the environmental factors in combination with natural disasters are reported to be the main drivers, for example, bad wastewater management in times of floods leading to the contamination of rivers, lakes, springs, and water supplies [11].

Besides the environmental factors, also the financial aspects of losses from disasters are troubling the economics of countries. The reported disaster damage costs have increased tremendously (Fig. 4 B), especially in developed countries [12]. Most of the physical damage occurs mainly to the built infrastructure (e.g., buildings, energy, and water supply structures). EM-DAT database [2] includes a total of 15 thousand natural disasters from 1900 to 2020 with a total reported damage of EUR 3.03 billion. According to Munich Re, one of the world's leading reinsurance companies, 820 natural disaster events in 2019 accounted for EUR 127 billion in losses, and 850 events accounted for EUR 158 billion in losses in 2018 [15].

Disasters are cause for significant damage to economies, to the economic growth in the medium-term, and causes financial losses to the markets within and outside of the affected country and trough repeated natural hazard shocks to physical capital and social cost in terms of food insecurity and having broader effects and consequences in long term [13]. Economic growth at first can seem to be a solution to these challenges, but actually has been reported to pose challenges to provide material resources for disaster response and recovery for many communities around the world [14].

The impacts of disasters measured as GDP ratio are costlier for small and developing countries. For the period of 1950–2014 small countries have experienced disaster damages equivalent up to 30 % of GDP, while in big countries the damage cost is only equivalent to 1 % of GDP on average [16]. This occurs mainly because in developing countries a higher share of the population is located in vulnerable urban zones with weak infrastructure, low provision of services, and incomplete government capacity for disaster risk management, leaving the poor urban areas even more vulnerable after disaster impacts [8].

Europe and Local Trends

Statistics of natural disasters in Europe (Fig. 1.3 A) show that most often disaster events are floods and storms, followed by extreme temperatures. Swiss Re report [17] has reported that return rates of same flood events have increased significantly in the South and Eastern Europe and the following factors are considered to have influenced growing floods risk: change in forestry and agricultural land use, population growth, and urbanization. Moreover, a study of [18] showed that the distance over which multiple rivers flood synchronously has grown by about 50 % over the period 1960–2010 in Europe and is a cause for large scale flood impacts. Similar results about increase in the frequency of extreme events such as floods, heatwaves, droughts, windstorms, and wildfires across Europe are found in the study of [19], which suggests that land-use changes, urbanization, and climate change were reported as contributors to increasing flood risk.

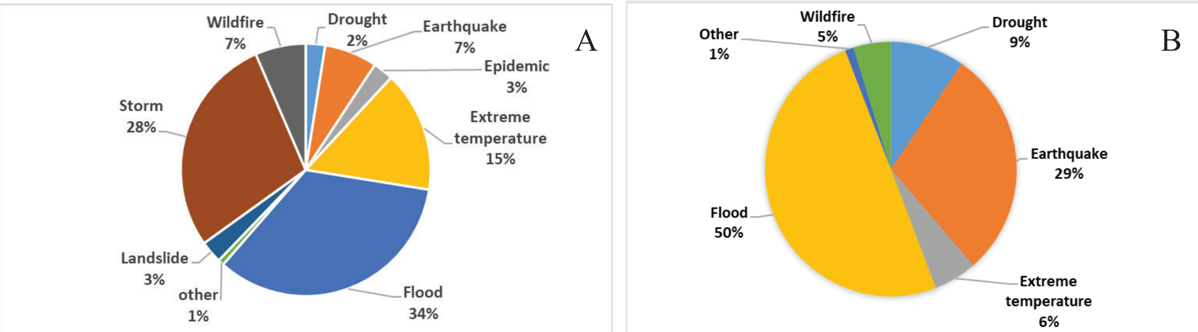


Fig. 1.3. A – disaster events in Europe, 1980–2020; B – disaster damage costs in Europe per type of disaster, 1980–2020 [2].

The shares of disaster damage costs in Europe per type of disaster for the period 1980–2020 are reported in Fig. 1.3 B. Floods are accounted for most of the damages, accordingly, as they are the most often recorded disaster events. Earthquakes were accounted much less than floods, but are responsible for the second-highest share of damage, followed by extreme temperatures and droughts.

According to [20] European cities will face more challenges in the near future due to urban growth and climate change that will influence social and economic aspects. A similar tendency was reported by EEA, which accounted for flooding and storms as the most costly hazards in Europe for the period from 1998 to 2009, with losses recorded up to about EUR 52 billion for floods and EUR 44 billion for storms, followed by earthquakes with losses of about EUR 29 billion [6].

The IPCC report found that economic losses in Europe from disasters have increased in the long term, as exposure of people and economic assets has increased. [12] Compared to other regions of the world, Europe had the highest share of population affected (80 %) by flood risk in 1900–2012 [1].

Munich Re for the year 2018 reported that droughts affected large areas of Europe. The estimated damage of droughts is around EUR 3.3 billion to agriculture and forestry. Two major winter storms in Europe left overall losses of EUR 3.1 billion and tropical storms of EUR 310 million in property damage. Strong gusts of wind in coastal regions account for damage of EUR 3 billion [15].

The large numbers in damage cost are explained by a high population and economic assets in hazard-prone areas [6]. At the same time, concerns of climate change increase in the future and thus frequency and intensity of extreme weather events are projected to grow.

Several studies on future of disaster risk in Europe present disturbing results and underline the need to adapt infrastructure, economy and communities in order to decrease socioeconomic and environmental damage in the future [21]. According to [22], due to climate change sea-level will rise by 0.8 meters in the next century, causing floods to coastal areas and along rivers, leading to chemical and mineralogical changes in coastal soils and threatening human life. Study of [23] applied computer models for climate change and socio-economic development up to the year 2050 referring to floods of 2013, which had a high impact. Study concluded that floods such as in 2013 with a return rate of 16 years may increase to once every 10 years by 2050, with annual average economic losses of EUR 23.5 billion by 2050, while in period 2000 to 2012 losses accounted for EUR 4.6 billion.

The importance of including socio-economic aspects when planning disaster risk reduction (DRR) in long term is underlined by the results of study [24], which suggested that by 2080, floods could have annual losses up to EUR 98 billion.

The study of [25] assessed 186 countries for potential losses to natural hazards and found that developed nations lack the capacity to deal with highly destructive, but less frequent events, while at the same time they are able to cover the costs of relief for less destructive frequent events. Latvia and Lithuania are mentioned in the list of the countries having a resource gap for high-frequency natural hazard events with a period below 25 years, while Estonia showed a resource gap only for events once in 550 years.

The Country Risk Profiles for Floods and Earthquakes of World Bank [26] provides estimates for more intense, but less frequent events such as 100-year floods or 250-year earthquakes. The country risk profiles show that floods pose very high risk for the Baltic States with total annual average affected GDP of EUR 6.44 billion and average affected population of 800 000.

In certain parts of Latvia, riverine floods are occurring every year due to rapid snowmelt in spring that can escalate to disasters. The return rate of such events depending on their severity is estimated to occur from once in 10 to once in 200 years. Altogether, these events lead to loss of land and natural resources, destruction of buildings, disruptions to electricity supply and water management system. This situation is evidence for those communities in Latvia that are not “resilient” enough to natural disasters and therefore studies must be performed to provide a more extensive understanding of the problem related to riverine floods [27].

According to the Latvian Adaptation Plan to Climate Change for Time Period to 2030 [28], in all coastal towns of Latvia the annual increase in damage caused by storm surge to buildings during the period 2040–2070 could be around EUR 1.5 million per year. In the period 2070–2100, damage could reach even EUR 3 million per year. At the same time consequences from increasing rainfall and snowmelt due to climate change could cause annual economic losses of

EUR 40 000–50 000 in the period 2020–2040 and EUR 160 000–210 000 in the period 2070–2100.

The current situation and predicted future impacts indicate that building urban resilience is essential to decrease the impacts of natural hazards in Latvia and must be considered in depth when applied in local policy planning. In this direction, a tool that helps to evaluate effects of different urban resilience strategies and offsets the knowledge gaps on long-term and short-term tradeoff in urban resilience planning can bring great advantage to local governments (i.e. Municipality).

Legislative background

Natural disasters are a global problem faced by communities worldwide. The statistics of disaster events annually show significant numbers of people affected, injured, killed, turned into poverty, and left homeless and are responsible for an enormous amount of damage to physical capital. For this reason, disaster risk management is addressed at all administrative levels, i.e., local, country, regional, and worldwide, by legislative frameworks, action plans, regulations, and other legislative acts.

The summary of legislative acts addressing disaster risk management worldwide, their relationship and link to local context is shown in Fig. 1.4.

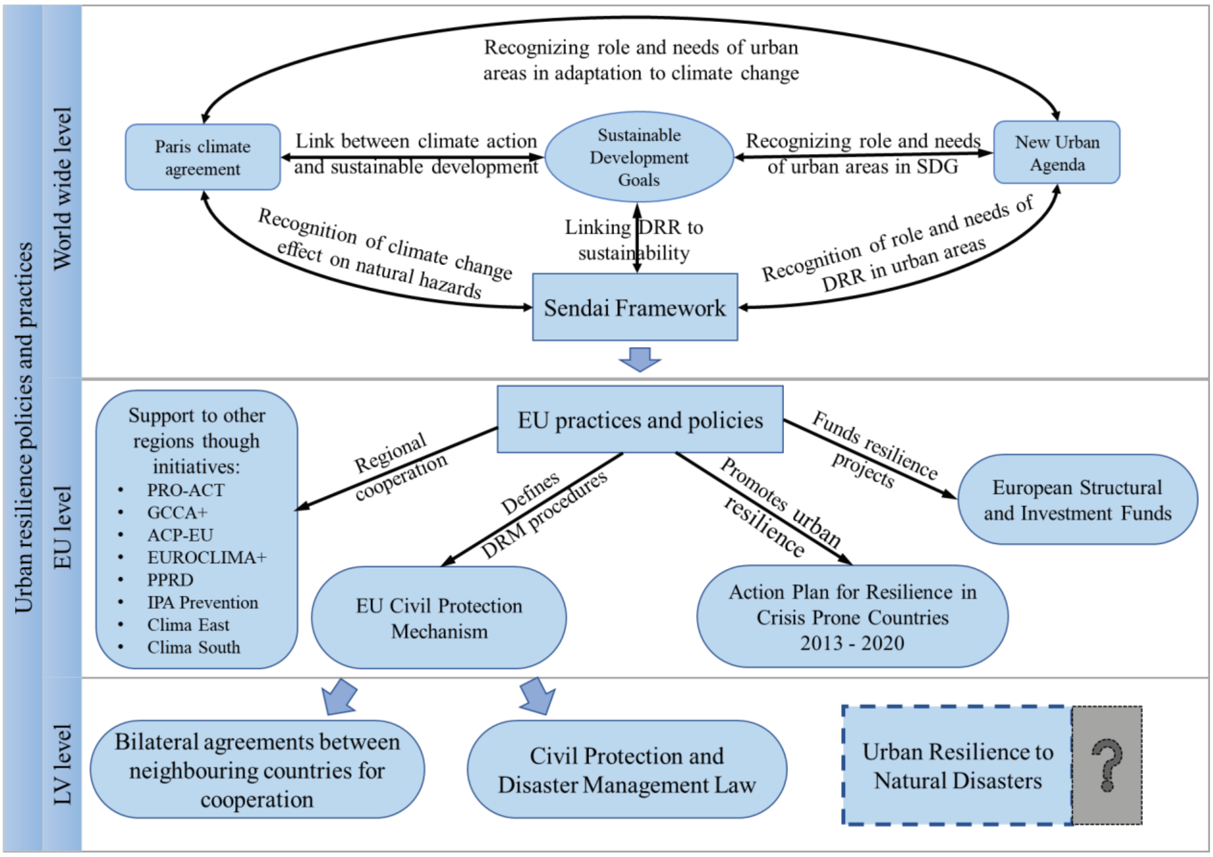


Fig. 1.4. Legislative background for disaster risk reduction from worldwide to local scale.

The most relevant and recognized administrative act is the Sendai Framework for Disaster Risk Reduction 2015–2030 adopted by the United Nations Office for Disaster Risk Reduction. The framework sets seven targets. The aim of these targets is to reduce global disaster mortality, the number of people affected, economic loss, and damage to critical infrastructure and to increase the number of countries with national and local disaster risk reduction strategies, cooperation and support for developing countries, and the availability of multi-hazard early warning systems and disaster risk information and assessments [29].

The Sendai Framework acknowledges that after the adoption of the Hyogo Framework for Action (UN Framework responsible for DRR before Sendai Framework), disasters continue to undermine efforts to achieve sustainable development. Therefore, Sendai interprets that actions made to achieve the set targets considering the adaptation to climate change, critical infrastructure protection, biodiversity protection, research and innovation, health, and food security.

The link between climate change and natural disasters addresses the need for consistency in the implementation of both the Sendai Framework and Paris Climate Agreement [30]. Sendai Framework relates to the aims of the World Humanitarian Summit and the New Urban Agenda, which also serve to plan and contribute to a more sustainable future [31]. The binding of international frameworks enables the synergies for the implementation of sustainable development goals and stimulates the development of a dynamic, local, preventive, and adaptive urban governance system at the global, national, and local levels. The existing synergies are also to be considered when implementing the monitoring of progress connected to the international agreements [32].

According to the information prepared by the UN, approximately 40 percent of countries reporting to Sendai Framework have partly aligned strategies and only six countries have fully aligned strategies to Sendai Framework [33]. The Global Assessment Report on Disaster Risk Reduction shows that only 42 countries reported on local strategies for DRR, and 7 countries reported that they have no local strategies [34].

European Commission supports and monitors the implementation of the Sendai Framework within its member states. In one of the European-level discussions meeting of the Council of European Union [35], the conclusion was made that among key actions for the civil defense the important one is promoting disaster risk assessment and scenario-based analyses and promoting the use of innovative technologies and instruments. Following the discussion, the European Commission published an Action Plan on the Sendai Framework that aims at guiding disaster risk-informed approach for all EU policies [36].

Within European Commission's Action Plan for Resilience in Crisis Prone Countries 2013–2020 [37] the priority number 2 "Innovation, learning, and advocacy" foresees to build evidence on the effectiveness of new resilience approaches that aim at developing urban resilience methodologies. The results of this initiative account for pilot city resilience strategies and operational plans including urban risk assessments, long-term resilience, multi-sector-approaches and enhance resilience knowledge base by conducting research for improved resilience and evaluations of resilience programs and resilience components during the period of 2013–2020. Hence, European urban planning can be understood as a great opportunity for developing quantitative simulations based on urban systems theory for application of ecological, social, and technical resilience in policy planning [38].

Large share of funds from European Structural and Investment Funds for resilience is dedicated to support the Action Plan on the Sendai Framework aiming for support of resilience increase in other regions of the world. This is achieved through such programs as PRO-ACT [39], GCCA+ [40] for least developed countries and small island developing states, ACP-EU in African, Caribbean, and Pacific countries, EUROCLIMA+ in Latin America, PPRD in neighbouring East and South, IPA Prevention in Western Balkans and Turkey, Clima East [41] and Clima South [42] in neighbouring countries.

Plans beyond 2020 have not been published and the main legislative document in the field of disaster risk management for EU member states remains the Civil Protection Mechanism [43], which aims to strengthen the cooperation between EU member states and facilitate the coordination in the field of civil protection. The main tools for DRR within the Civil Protection Mechanism are mentioned to be risk assessment plans.

Civil Protection Mechanism sets a requirement for the member states to develop and refine risk assessments at a national or appropriate subnational level every three years. In addition to risk assessments, EU member states are obliged to perform the tasks according to international guidelines. According to [44], such mechanism is proven to be effective, still for the most part of DRR national legal orders have the main role.

On the national level for Latvia, the main legislative framework is the Civil Protection and Disaster Management Law [45]. The main measures within the legislative framework are focused on the risk assessment specifically addressed to risk identification, risk analysis, and risk evaluation. According to the legislation, the tasks of local governments are mainly related to preparedness, prevention, response, and recovery measures, not having any reference to the implementation of actions towards strengthening of community or urban resilience. Therefore, the policies and practices towards strengthening the resilience on the local level remain a voluntary action, which is still to be acquired by local governments.

The national legislation foresees DRM in terms of Civil Protection and Disaster Management Law and bilateral agreements for cooperation between neighbouring countries, which is constantly updated according to latest requirements and standards. Still, the overall situation in DRR shows that many countries have not aligned with the Sendai Framework.

Civil Protection Mechanism is related to strengthening urban resilience [46] and Action Plan for Resilience in Crisis Prone Countries 2013–2020 foresees creation of knowledge and innovations in terms of tools that can help to strengthen urban resilience in EU. Research projects aiming at strengthening urban resilience are also supported by European Structure and Investment Funds, however, at the moment there is no evidence for already existing national or local scale projects in Latvia that focus on contributing to creation of urban resilience assessment tools.

1.2. Concept of Resilience

The outgrowth of research on resilience in last 20 years shows that resilience has become popular over the past decade, but many definitions seem to make this concept and its quantification hard to apply to practice [47]. Most of the recent studies on resilience are linked to climate change and sustainability [48].

Considering that risk is a static measure that represents the severity of impact on a given system, social or technological [49], resilience is defined as the ability to bounce back from a certain impact after disruptive event to previous functionality level or equilibrium state in which system is stable. In this context natural hazards can be considered as shocks to human-environment systems like urban areas [50], and disaster resilience aims at better preparedness and mitigation measures in the long term and response and recovery in the short term. This makes the resilience a dynamic metric of system performance as functionality level over the disaster management phases including response and recovery, preparedness, and mitigation in one function (see Fig. 1.5).

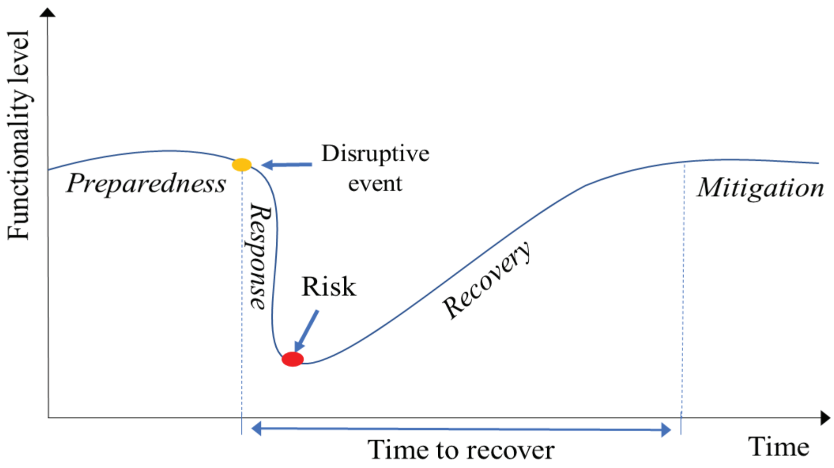


Fig. 1.5. Dynamic metric of resilience [49].

The terms resilience and vulnerability are interrelated, but studies on vulnerability tend to represent the term “vulnerability” as a negative concept [51], and therefore resilience is more preferred when moving from outcome-oriented policies towards process-oriented governance [52].

The “resilience” term has a long-distinguished history according to [53] (see Fig. 1.6). The first use of this term is found in proverbs used even before the creation of the Julian calendar (AD), mostly having a negative meaning of “rebound with an unhappy result”. Much later the term passed to Middle French and came to mean “to retract”, and only after that migrated to the English language in the 16th century, mainly used to describe the “return to a former position”. It was used for the first time in relation to disasters in 1854 to describe the ability to withstand the effects of earthquakes during the recovery of the city of Shimoda, Japan.

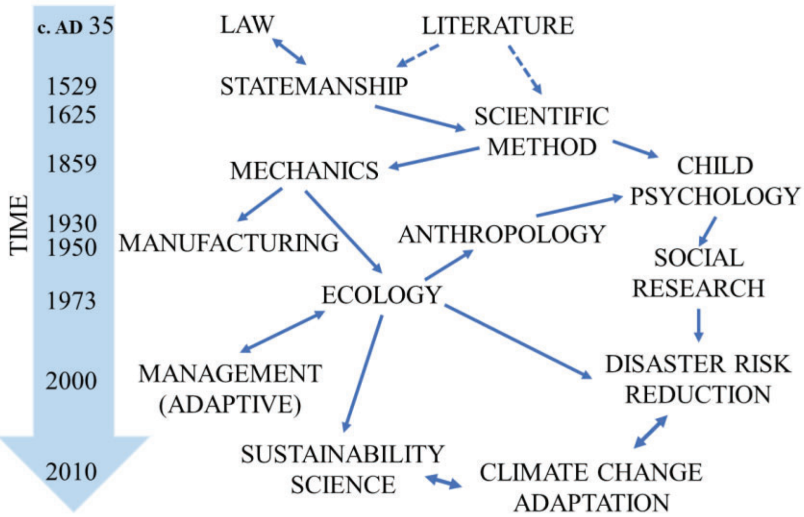


Fig. 1.6. Spread of term "resilience" through history [53].

Holling, C. S. adopted the concept used in civil protection specifically related to a systems theory approach in ecology [54], and at the end of the 1990s, the term made its transition to socio-ecology, where it is recognized as socio-ecological resilience, and later also evolutionary resilience was distinguished.

Ecological resilience is an equilibrium-based approach to defining resilience that focuses on eco-systems [55]. This type of resilience foresees that there can be several equilibrium states. It is defined by the speed of recovery to a state of equilibrium and the intensity of the disturbance that it can absorb while remaining within a "critical threshold" while moving from one equilibrium state to another [56].

Socio-ecological resilience (SER) is a concept also presented by C.S. Hollings to describe ecological system embedded in urban systems, where human-driven processes take place and is the ability to recover from disasters from both social and ecological perspectives [55]. The emerging use of economic resilience for overcoming disaster-related impacts is linked to the classic definitions in socio-ecology for maintaining function and recovering rapidly [47].

From SER also the definition of evolutionary resilience emerged. Evolutionary resilience implies the capability to withstand changes of systems even without any external stressors. The main shortcoming of evolutionary resilience is the lack of the dynamic role of technology, which is engaged by other forms of resilience known as built-in resilience and climate change resilience that also emerged based on SER [57].

Other concepts of term "resilience" include stable and unstable resilience, anticipatory and reactive resilience, or just general resilience, however, all these terms are not well explored [57]. Though the term has become popular, its development is still in early stages, as current methods are yet subjective and have not been tested for their validity, reliability, or their ability to predict future wellbeing [58].

1.3. Urban Resilience

The increasing intensity of hazard activity caused by climate change at the same time with population, urbanization and economy are growing leads higher risk in urban areas [59]. Thus, there is an importance for "resilience" term practical use in the urban context even with such variety of existing perspectives for this term as discussed in literature [60]. Resilience and complex systems thinking can add to policy planning new ways of dealing with poverty, vulnerability, and governance by highlighting the diversity of components influencing these social problems.

The progress towards urban resilience is slow also due to a general lack of consistency in local government DRR strategies despite the aforementioned international initiatives [61]. Urban Resilience has remained mainly a buzzword in international agreements and is not applied fully on the local level in Latvia, nor many other countries. The recent spread of the coronavirus that causes COVID-19 underlined the fragility of urban systems and how important it is to build urban resilience to natural disasters [62]. This indicates that there still exists the need for new consistent methods and tools that can be a support to local policymakers and other stakeholders working on strengthening urban resilience and development of DRR policies.

Currently urban resilience policy is under high uncertainties due to political pressures, emergent nature of threats, speed of change, and the level of complexity of networks that form cities [52]. Regardless of the wide application in policies, the term "urban resilience" still receives a lot of critique due to a lack of clarity on how to apply this concept in practice [63]. Debates for a definition of "urban resilience" are ongoing and there is still no consensus. The terminological varieties and epistemological disjunctions make it difficult to apply the term "urban resilience" in policy planning due to lack of recognition and reflection [64].

The complexity of "urban resilience" definition is also connected to the definition of urban areas. Urban areas are acknowledged as complex socio-ecological-technical systems [65]. The urban areas are developing and change rapidly, are formed by ecological, social, and technical components, which form socio-technical, socio-ecological, and eco-technological networks, and they interact with each other [66]. Thus, also the term "urban resilience" is somehow merged from resilience in engineering, ecology, and social science. The study of [67] concluded that resilience and sustainability are complementary properties necessary to enhance urban development. Both terms are of high complexity with different definitions and areas of applicability [68].

To simplify "urban resilience", [50] grouped various meanings of this term by application as follows: (1) urban ecological resilience; (2) urban hazards and disaster risk reduction; (3) resilience of urban and regional economies; and (4) promotion of resilience through urban governance and institutions. "Urban resilience" term within this Thesis is used within the meaning of urban hazards and disaster risk reduction. The definitions found in literature for term "urban resilience" are presented in Table 1.1.

Table 1.1

Definitions of Urban Resilience

Source, year	Definition
Wamsler et al., 2013 [69]	Disaster resilient city can be understood as a city that has managed to (a) reduce or avoid current and future hazards; (b) reduce current and future susceptibility to hazards; (c) establish functioning mechanisms and structures for disaster response; and (d) establish functioning mechanisms and structures for disaster recovery
Asian Development Bank, 2015 [8]	Urban resilience refers to climate change adaptation, mitigation actions, and disaster risk reduction while recognizing the complexity of rapidly growing urban areas and the uncertainty associated with climate change
Meerow et al., 2016 [70]	Urban resilience refers to the ability of an urban system-and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity

The interpretation of urban resilience concept is linked to concept of panarchy [71] that presents the ways in which complex systems of people and nature are dynamically organized and structured, considering the change of behaviour across scales in space and time.

Urban resilience is in line with the socio-ecological perspective, where urban resilience is addressed as complex social processes that allow local communities to self-organize and ensure positive collective action for community survival and wellbeing, instead of seeing urban resilience just as a set of community capacities, assets, or capitals [72]. This is recognized in the definition of urban resilience provided by [70], which is applied selected as the definition of urban resilience used in this thesis. Other definitions referring to urban resilience found in literature reported in Table 1.1 also recognize the multi dimensionality and complexity of the "urban resilience" term and the aspect of hazardous events and actions aiming on DRR.

1.4. Resilience Assessment Methods

Some existing methods for resilience assessment describe resilience as having such characteristics as redundancy, diversity, efficiency, autonomy, robustness, adaptability, and collaboration, and even sometimes vulnerability is assigned to be related to resilience as an opposite term [47]. However, all the characteristics named here have received critique due to subjectivity and lack of precision in defining the relationship between them.

The long-term planning horizon and holistic context make resilience policies different from traditional hazard mitigation policies [73]. Resilience according to definitions is mostly connected to a system that is subjected to certain stress, shock, or, in the case of this study, disaster. Therefore, disaster risk assessment is also connected to resilience [49], [74]. In relation to resilience, risk is a static metric that does not change over time and represents the severity of impact on a given system, social or technological in a specific reference time.

Resilience assessment is often recognized in the engineering science field and is known as engineering resilience, but also is used in ecosystem resilience measures as a single equilibrium state [75] representing a dynamic metric of system performance over the disaster event [76], [77]. Other science fields have similar approaches to defining the concept but the scope can be completely different, yet most of the disaster resilience models involve engineered systems [78].

Many resilience studies focus on infrastructural system resilience as they provide essential services that support economic prosperity and quality of life [79]. Another type of resilience interpretation is linked to ecosystem resilience, where multiple equilibrium states also known as alternative regimes, exist [80]. This approach underlines the non-linear spatial-temporal interaction of components in a complex adaptive system and is consistent with Holling's definition of thresholds that ecosystem can withstand [81].

The current studies towards applying multiple equilibrium regimes in models with socio-economic aspects are still limited. Based on the review of social resilience studies [82] concluded that different tools of different purposes towards resilience measuring are found in literature, but these tools are not yet capturing the dynamic interactions between social and other dimensions. The concept of resilience depending from its multi- and cross-scale dynamics of system is defined in [78].

The complexity of a given measure is the basis for distinguishing the adaptive resilience and inherent resilience when trying to make a resilience assessment (Fig. 1.7) [83]. Adaptive resilience, or, according to [84], predicted resilience, relates to the post-event processes (response and recovery) and thus can be measured only after a disruptive event, while the inherent resilience is often used as a holistic measure of the community's capacity to deal with a disaster.

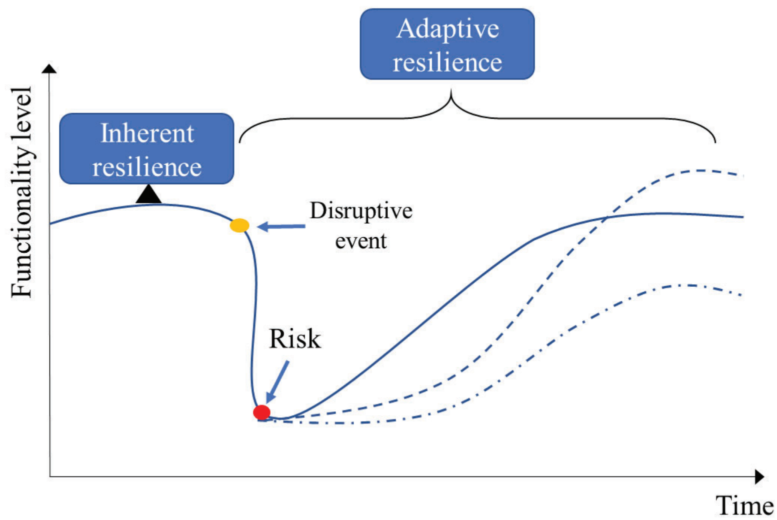


Fig. 1.7. Inherent and adaptive resilience [83].

Measurement of resilience is critical to track progress in resilience at the local level [85], and in this case, inherent resilience can serve as a baseline for improving urban resilience. Information provided by existing tools gives insight into urban resilience, however, they can be biased for comparison of different scenarios [86]. Study of [87] defined the necessary steps in research on resilience measures, which includes the integration of risk assessment procedures in a holistic resilience assessment.

Over the years, studies report that there is a lack of tools for resilience [88], [89] and there is a need for a decision support system that can assist city authorities in planning adaptation measures [69]. The existing tools for resilience assessment are grouped by [82] in two major categories: standard framework, known as generic frameworks on national or other levels, and context-specific resilience frameworks in which hazard-specific, hierarchical level specific, and geographical scope specific frameworks can be distinguished. General frameworks help to uniformly inform the communities, however, can miss important aspects for specific local cases. The context-specific frameworks provide very precise information, but are demanding in terms of resources.

Study [90] suggested a different classification of resilience methodologies, which foresees that there exist three major categories of resilience assessment methodology: qualitative, semi-quantitative, and quantitative. Slightly different classification of methodologies is presented in [86], which distinguishes quantitative, qualitative, and mixed or also called integrated approaches. The classification is presented in Table 1.2 with respective methods and their strengths and limitations.

Table 1.2

Classification of Resilience Methodologies According to [86]

Approach	**Method**	**Strengths**	**Limitations**
Quantitative	Indicator	– Comparable – Easy to use – Multi-dimensional	– Highly generalized – Subjective weighting – Static – Input data dependent
	Computer simulation model	– Time reference – Comparable – Precise in short term – Short-term and long-term analysis – Scenario analysis – No subjective opinion	– Outdated with change of technologies – Mainly applicable to engineering systems – Highly dependent on data availability – Separate model for every system
Qualitative	Survey	– Reflects community's opinion and needs – Detailed	– Time consuming – Hardly comparable – Highly depends on communities' skills and knowledge – Results are meaningful in short term
	Expert opinion	– Highly detailed – Scenario planning – Short-term and long-term analysis	– Time consuming – Hardly comparable – Subjective
Mixed (integrated)	Integration of several methods	– Can include all strengths of methods integrated – Can avoid weakness of one method	– Complicated in development – Can be highly dependent on data

Qualitative methods assessing resilience are based on opinions of experts or local communities and perception of the real situation [91]. Example of studies applying such methods is found in [92]. The focus of the Doctoral Thesis is on quantitative measurement of urban resilience to natural hazards; therefore, the qualitative methods are not discussed further in the work. Different examples of quantitative methods used by policy planners such as reported in [93] and [94] are more discussed further.

Indicator Method for Resilience Assessment

In practice, the social aspects are as important as economic, but are difficult to measure. Sometimes cost-benefit analysis can be used as an indicator. Policy planners have reported that the cost-benefit analysis method misses the critical aspects of resilience multi-dimensional nature [95], which can be captured only by multiple indicators.

To capture the multi-dimensionality, indicators presenting different aspects of urban areas are synthesized into a single number called "index" [96], known as a composite indicator-based method. The composite indicator-based method is known as multi-criteria analysis (MCA) and uses a set of indicators to present different criteria within selected resilience dimensions [49]. Composite indicators methods are often used for assessing the performance of human development, sustainability, corruption, innovation, and competitiveness [97].

According to [98], indicator construction includes developing a theoretical framework to provide a basis for indicator selection, identification of latent dimensions, the weighting and aggregation of indicators, and the visualization and validation. Composite indicators based on MCA can be either quantitative or qualitative.

Qualitative indicator-based methods are found in [99]. However, qualitative indicator makes such approaches resource and time intensive [82].

Quantitative indicators are used more often because they are easy to use and compare with each other. A study of [100] underlined that index approach is comprehensive in comparison when applied within GIS.

One of the early works in this direction [77] suggested four interrelated dimensions of the resilience concept: technical, organizational, social, and economic resilience (TOSE). Dimensions are integrated into the dimensional matrix with respect to resilience performance criteria based on the developed concepts of 4Rs (Robustness, Redundancy, Resourcefulness, and Rapidity). According to 4R's concept [98], robustness means the ability to withstand natural disasters, redundancy means the ability to replace assets with new functioning components in time of disruption, resourcefulness pertains to the capacity to mobilize resources, and rapidity refers to the capability to respond quickly to natural disasters.

The resilience assessment model based on MCA is also known as disaster resilience of place (DROP) and the term was developed by Cutter et al. [78]. The model developed a conceptual framework for the analysis of hazards focusing on the social resilience of places at the community level. It defined six dimensions: ecological, social, economic, institutional, infrastructure, and community competence. The work of [101] presented the baseline resilience indicators for communities (BRIC) with six resilience criteria: social, economic, institutional, infrastructure, community and environmental, to describe community disaster resilience; BRIC was found to be adopted for application in studies of [91] and [102].

Several years after initial work on the DROP model, [101] reported that many conceptual models of disaster resilience for different thematic areas exist in literature, such as climate change, sustainability, urban areas, and rural areas, but indicator-based methods provide only a static snapshot of inherent resilience. This shows that quantitative methods for resilience metrics are in early stage of development and lack the ability to estimate the capacity to increase disaster resilience. This also suggests that earlier work of [77] was already aiming towards such a quantitative assessment of adaptive resilience.

The study of [103] was another attempt to overcome inherent resilience measure towards adaptive resilience measure by linking community capitals (social, economic, physical, human, environmental) with disaster management phases (mitigation, preparedness, response, and recovery) and forming community disaster resilience framework (CDRF). This methodology is also adopted in study [104].

The study of [105] found that the use of many dimensions will make indicators to overlap and therefore narrowed the composite index approach to three dimensions: biophysical, built environment, and socioeconomic dimension, also selecting a different range of variables. Another study [73] found that such methodology based on a set of sub-categories actually does not provide metrics for resilience measure and serves only as a tool to understand the key factors of resilience and the existing tradeoffs between different scenarios by considering the limits of different urban resources.

The involvement of local communities enables the selection of indicators based on community opinion through surveys, while the involvement of experts as assistants that can guide the community trough definitions of relevant indicators increasing the trustworthiness of the selected indicators for policy planning [86]. Study [49] used stakeholders' qualitative statements about the critical functions of infrastructure and climate scenarios and compared them to a baseline scenario and assessed resilience according to four domains: physical, information, cognitive, social.

The studies of [106] and [107] use two dimensional MCA with data based on experts' judgments. Study of [106] quantifies neighbourhood-level urban resilience capacity with the resilience to emergencies and disasters index (REDI) while [107] used a mixed (integrated) method with 5 capitals (human, social, physical, natural, and financial). Study [108] also used a mixed approach in terms of SWOT in the form of a questionnaire the results of which were transformed into MCA through analytical hierarchy process and presented in GIS. Summarizing, the studies indicate that there is no common framework or model to measure and monitor disaster resilience [109]. Moreover, weights of indicators are usually assigned based on subjective opinion.

Despite the suggestions of [105] that the number of sub-categories is too large, the number of sub-categories used in MCA has increased due to the application of two-dimensional matrices and integrating quantitative and qualitative approaches. As a consequence a lack of data for application of such methods has been reported [110].

The study of [83] suggested that it is difficult to apply relevant variables or indicators that are practicable and implementable for every urban system, therefore a way to integrate a systemic approach into urban resilience mapping should be developed. According to [111], one of the most recognized Sendai Framework indicator problems is that they are used to determine global trends in the reduction of risk and losses at the current state of use. They serve for calculating the impact of short-term risks, but do not provide enough information to create a risk reduction and disaster prevention strategies over the long term.

Moreover, indicator-based composite index frameworks are lacking a clear identification of interdependencies between indicators and potential feedbacks making them independent from a time reference [98]. Similar weakness of the existing methods was found earlier in methodologies assessing risks to natural hazards [112].

A review of social resilience frameworks focusing on indicators [82] found that process-oriented indicators based on dynamic properties are not considered in the assessment and the existing social resilience frameworks are limited for interpreting the actual resilience status of a community. Thus, such an approach lacks the definition of a link between socio-economic and environmental aspects in the assessment [113].

Computer Simulation Tools for Resilience Assessment

Computer simulation tools for resilience assessment are based on models created with quantitative methods that describe the interrelationship of system variables. Most common methods for model building are Bayesian networks [114], [115]; input-output economic model [116]; agent based model [117], [118] and system dynamics (SD) [119], [120].

The mentioned methods are mainly applicable to engineering systems. An example using the input-output model reported by [121] quantifies the ability of interdependent infrastructures to move from one equilibrium state to another after a disruption. Another analysis tool is reported in [122] where it was created for assessing the resilience of complex network systems.

The concept of resilience curve of the community is often used in the computer simulation tools and can include different phases of DRR. In computer simulation tools, the idea of a disaster triangle also known as the resilience triangle method is used for resilience assessment (Fig. 1.8).

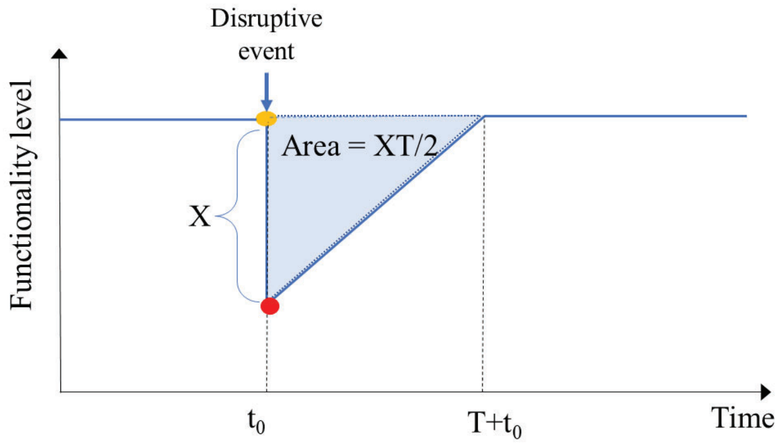


Fig. 1.8. Resilience triangle method [3].

The resilience triangle represents the area under the normal functioning level of the system formed by curve, representing the change in functionality level in time period ($t_0 \ldots T+t_0$), from the disruptive event to full recovery to initial functionality level. A smaller area of the resilience triangle reflects higher resilience of a given system, and bigger area of resilience triangle reflects lower resilience of a given system.

The analysis of different scenarios is an important feature provided by computer simulation tools and can be performed by comparing the total area of disaster triangles. Study of [123] used scenario analysis allows to understand how the studied system reacts to different level of disruption. An example of scenario analysis can be found in [76] that developed a tool with GIS layers of physical networks and socio-economic components of the urban system to support decision-making.

Effective and precise models in short term usually are those that are made for single systems, e.g., for hospitals [124], [125], water supply systems [126], [127], and energy supply [128], [129]. However, these models seem unable to quantify the resilience of the whole urban system, leaving resilience as separate measure for sub-parts of the whole urban system.

More models found in the literature [126], [130]–[132] show that computer simulation tools for resilience assessment are mainly applied to infrastructural systems, leaving socio-economic aspects outside the scope of resilience studies. The social resilience assessments capturing dynamic interactions within and between different social dimensions are not found in literature [82]. For a tool capable of urban resilience assessment including the socio-economical approach is a very important aspect, but linking social and technical resilience faces enormous challenges [133].

Study of [84] applied the disaster triangle method, considering that disaster resilience as a concept receives significant interest not just from the conventional protection and recovery of physical infrastructure, but also protection and recovery in a social and economic context. The study combined different dimensions of resilience in a single graph. The challenge for the application of such methodology is collecting information about changes in indicators at the time of the disaster, and at the same time, such approach is very complex and needs to consider decision maker's perception for correctness [93].

A review of several examples of resilience assessment for urban infrastructure based on the resilience triangle in [134] concluded that existing quantitative approaches are meaningless outside the discipline where they have been developed. Studies [135] and [136] concluded that computer simulation tools are focused on a single disaster and an individual subsystem, neglecting the combined effects of multiple disasters and subsystems. Different scenarios of risks should be considered when assessing urban resilience [137].

Multi-dimensional modeling and a time-dependent resilience metric for planning how different resilience capabilities can be used to engineer interdependencies between subsystems was presented in [138]. Also, agent based models would be a promising tool for resilience assessment in general, however, it requires a large amount of data in the behaviour of actors (agents) in temporal and spatial scale when modeling socio-economic groups [47].

Another example of a computer-based simulation model for urban resilience is found in study [99]. The model considers factors of resilience in terms of adaptability, resistance and recovery, and the effects of a disaster. The model can describe different scenarios of shocks in urban areas and recovery after, and even consider the learning effect.

According to [86], separate approaches towards disaster resilience in the long term and short term are an important issue because solutions for an immediate response can have dramatic effects on long-term recovery. The lack of research addressing long-term effects of natural hazards was also mentioned in study [139].

System Dynamic Models for Urban Resilience

System dynamics (SD) is used to describe the nonlinear behaviour of complex systems that include social and technical aspects. The SD approach is based on linear dynamics and feedback control theory and explains the behaviour of the system through a structure that drives the behaviour of the system itself and therefore the feedback loops are the basis of an explanation of the system behaviour [140]. This allows learning about interactions of system components and their effects on system behaviour and status, understand the reason for specific system behaviour, and to hypothesize, test, and refine resilience strategies [141].

In literature, many studies are found that implement a SD approach to understand and analyze different challenges and problems in urban areas. The scale and scope of these studies differ and cover a wide range of investigated aspects: some are focused on urban areas in general; others are focused on specific aspects of urban areas.

Study of [87] suggested the implementation of SD modeling for complex systems to replace linear models. SD approach offers a useful modeling approach to simulate scenarios in a wide array of disciplines [142]. SD approach has been widely used when modelling complex systems to aid policy planning and decision making. For example, the SD approach is used for creating a model with an integrated economic-social-environmental resource dimension, having single value output in the form of index to evaluate the urban sustainability performance of each dimension [113].

Study [143] presents a conceptual framework for modeling financially self-sustaining water and wastewater networks that involved a system dynamics model and explained it with causal feedback loops. The conclusion suggested that feedback loops might demonstrate a complex dynamic system for which traditional management tools used in the area are deemed inadequate and that system dynamics model can be used for developing both short-term and long-term management plans. Study [144] also applied causal loop diagrams to explain the effect of the selection of a specific set of policy recommendations.

Study [145] showed the SD approach to the topic of water supply under growing population background conditions. The water balance in the model was defined as a stock governed by supply and demand flows that are affected by variables included in the model. Also SD modeling for sustainable water resources planning is reported in study [146].

The study presented in [147] applied an index for measuring the level of discharged pollutants entering the coastal waters as a reference to overall performance, introducing the use of an index for estimation of the condition of the system, to be used for an assessment of specific policy measures.

Similarly, [148] used an index to show how urban electricity demand forecasting can be made based on system dynamics and for economic normal that is composed from energy indicators like GDP, agricultural mechanization level of production, temperature difference, number of residents, awareness of energy conservation, etc. Also, study [149] evaluated sustainable policy in urban transportation by using urban sustainable transportation indicators, with 3 indicators for each key group of environmental, economic, and social sustainability.

SD approach is often found in the literature to be widely used for building energy sector models, which allow studying energy system behaviour at different scales [150], [148]. Other models reported in literature have focused on the quantification of air pollution and CO_2 emissions incorporating sub-models of the economy – building, industrial, commercial, and transportation, as in [151], [152].

A larger model focusing on several aspects of urban areas is presented in work on eco-cities [153] included several sub-models: population, housing, business, energy consumption, environmental pollution (water, emissions, and solid waste).

To assess community resilience in disasters as a dynamic process, a system dynamics model was developed by [154]. The model describes community functioning before, during, and after a disaster for all US counties. The latest work of [155] suggested that while ordinary linear modelling is not able to describe the behaviour of the system through the inner mechanism of the system and thus is not suitable to find efficient solutions to existing problems within the system. The study also presented the urban resilience SD model considering the challenges that are caused to urban areas by internal and external shocks. This includes financial challenges, social quality, floods, disasters, global warming. The model included four subsystems: governance, socio-economics, infrastructure, material, and energy flows. The model also shows that urban resilience cannot grow all the time as it in contradiction with sustainable growth. The study also concluded that the long-term resilience trend is difficult to explain and validate.

Considering that the integration of several methods allows overcoming the weaknesses of a single method [108], it would be preferable to perform a research on mixed assessment methodologies including SD modeling and integrating many aspects of urban areas to define the overall urban resilience.

2. METODOLOGY

The aim of this Thesis is to propose a novel tool for the assessment of urban resilience to natural hazards towards the implementation and improvement of already existing approaches. To reach the aim, the results from different applications of single urban resilience assessment methods are investigated and further reported in author's scientific articles. The final stage is aiming to merge and combine specific characteristics of each urban resilience assessment method taken separated and merge them in a novel approach. The overview of the Thesis is presented in Fig. 2.1 within four steps and corresponding predefined objectives of the Thesis.

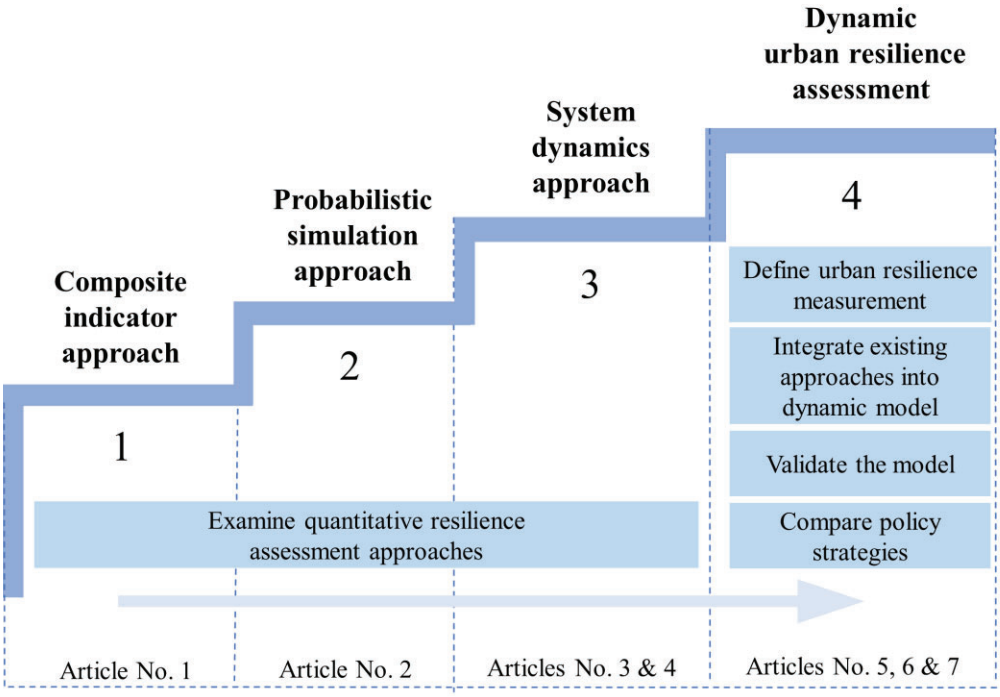


Fig. 2.1. Overview of the Thesis structure.

In Steps 1 to 3 of the proposed methodological research, the approach takes into account separated case studies addressed to examining advantages and limitations of different approaches used for quantification of community and infrastructure resilience. Namely, these quantitative approaches are: composite indicator, probabilistic simulation, and system dynamics. The performed case studies are reported in four scientific articles published in international scientific journals.

The development of a dynamic urban resilience to natural hazards assessment tool is performed in Step 4 after examining each method separately. The tool aims at overcoming the limitations of previously examined stand-alone approaches for urban resilience measurement by combining them into a single system dynamics model. The use of system dynamics allows the transition from a static resilience measurement and single infrastructure resilience measurement towards dynamic resilience measurement within a holistic and complex system-based approach.

Four objectives for the development of such novel dynamic urban resilience assessment are addressed, namely:

- define urban resilience measurement for dynamic assessment;
- integrate existing approaches into a novel urban resilience assessment tool; and
- validate and test the developed model in local case study;
- compare effects of urban resilience strategies to a local case.

A clarification on the definition of urban resilience is necessary for the context of this Thesis to give a precise and focused meaning to what the developed model is aiming to measure. The integration of existing approaches is made to overcome the limitations of application of single approaches and to create an improved resilience assessment tool for the ones that are currently used. The validation of the model is performed to verify the model's consistency and to identify the limitations and assumptions that can have possible impact on the model outputs, mostly when it is supposed to compare different urban resilience strategies.

2.1. Composite Indicator Approach in Local Case Study

The composite indicator approach implements the concept of multi-criteria analysis (MCA) in the form of composite indicator based index, in this study defined as community disaster resilience iIndex (CDRI). With help of CDRI the study aims to provide a holistic measure for community resilience to natural hazards in macro regions of Latvia.

The methodology of CDRI allows to show the link between community capitals (social, economic, physical, human, and environmental) and different phases of disaster risk management that are disaster mitigations, disaster preparedness, response to and recovery from disaster. The link between community capitals and disaster risk management phases is implemented through an indicator's matrix.

Specifically, in Article 1 social capital is used to describe social bonds and aspects within a tailored urban system. Instead, the economic capital describes strength of the market. While physical capital describes the main infrastructural assets of the built environment. Human capital refers to number of people working in different fields and social groups, and finally, environmental capital describes the connection with thresholds from the use of renewable and non-renewable resources. Within the indicators addressed to the definition of the community capitals the link is proposed to four disaster management phases in connection with the disaster cycle phases (i.e. mitigation, preparedness, response recovery).

Indicators of community capitals for resilience evaluation are selected according to their relevance for each disaster risk management (DRM) phase. Indicators are brought to a common scale of measure with the help of z-score method, also known as standard score method. The final CDRI score for selected region is calculated as a sum of the weighted capital scores:

$$CDRI = \frac{\sum_{i=1}^{n}(\omega \cdot capital\ score)_i}{n}, \tag{2.1.1}$$

where

capital score – sum of z-scores for given capital i;

ω – weight;
n – number of capitals.

The validation of the obtained CDRIs is assessed with a correlation and regression analysis in respect to external criteria. For this purpose, social vulnerability index [156], the flood damage costs and risks from natural and man-made disaster (according to the results obtained from evaluations of the Latvian Civil Defense Department) are used.

The proposed CDRI approach is appropriate for any study that is meant to measure disaster resilience at different scales, i.e., urban, country or regional. It allows to compare levels of inherent resilience for different DRM phases among communities. This quantitative approach for resilience assessment is not depending on a specific type of hazards within the investigated area and at the same time captures the complete urban system through the defined dimensions, for this reason it is considered a holistic method.

2.2. Probabilistic Simulation Approach in Local Case Study

The probabilistic simulation is used within this Thesis for the assessment of infrastructural systems resilience to natural hazards. The main results are reported in Article 2. Compared to the holistic method the proposed approach allows to assess the resilience of an infrastructural system with reference to a natural hazard potentially triggering a specific disaster or disrupting events. This quantitative approach is focused on the identification of a specific functionality of the system under investigation characterizing the resilience of a certain system exposed to given hazard and further assessment of the loss of functionality level due to the damage and recovery to a normal functioning state.

The proposed probabilistic simulation tool for generating statistical data of infrastructure network failures is used for resilience assessment and applied in the case study of a district heating (DH) pipeline network of a municipality in Latvia. The tool implies resilience assessment by measuring three infrastructure system resilience aspects: damage ratio, recovery time, and recovery costs.

To accomplish this simulation, a stochastic simulation function is used to generate failures that account as random failure scenarios. The total number of different scenarios is 2^n in a network with n assets. This makes it hard to evaluate real networks with a large number of assets. Still, it is possible to simulate a large number of scenarios for statistical reliability. For this purpose, a matrix is formed to evaluate a number of scenarios with a certain given number of DH network pipelines.

$$M=\begin{pmatrix} S_{11} & S_{12} & S_{1n} \\ S_{21} & S_{22} & S_{2n} \\ S_{k1} & S_{k2} & S_{kn} \end{pmatrix}, \tag{2.2.1}$$

where

M – matrix;
S_k – scenario;
S_n – pipeline.

Random failures for assets (S_n) are generated with a certain failure probability, which is predefined according to failure mode probability distribution function (see Fig. 2.2) for specific disaster.

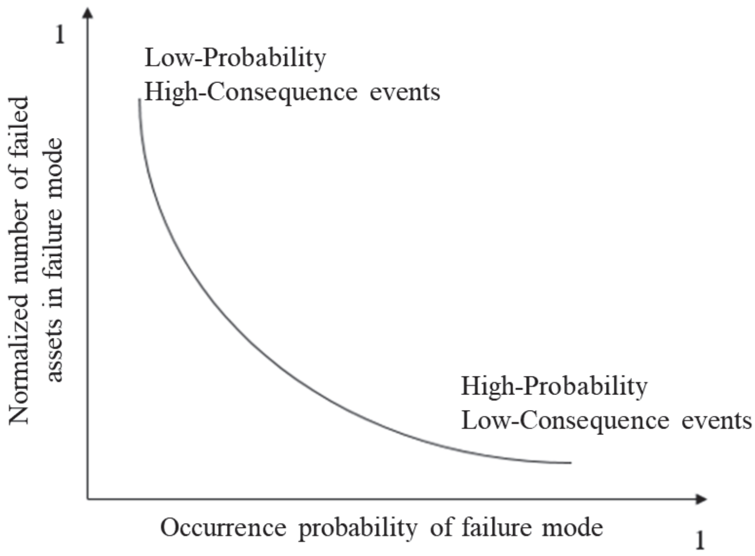


Fig. 2.2. Failure mode distribution.

The asset matrix M assigns failure probability to the system's assets according to a biased sampling method of Wallenius' probability distribution to overcome the univariate problem in a sampling process.

The developed tool can be used with different types of recovery time functions: linear, exponential, and trigonometric. This way, a more straightforward definition of system resilience is proposed and reflected in a more focused calculation for which more precise information is needed about resources and locations.

The proposed method for evaluation of resilience considers the definition of thresholds of available recovery costs, maximum recovery time, and critical damage ratio (see Fig. 2.3)

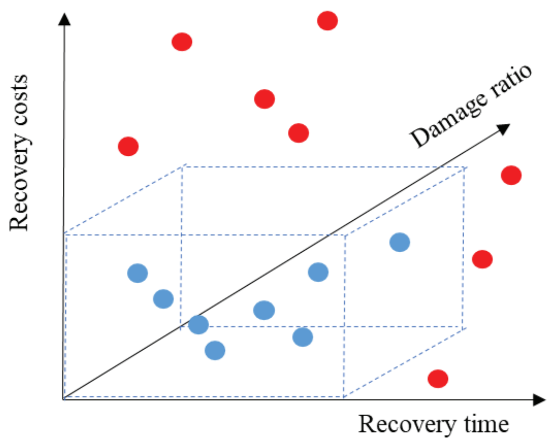


Fig. 2.3. Resilience described by three dimensions.

The simulated scenarios (red dots in Fig. 2.3) that exceed thresholds (dashed blue line in Fig. 2.3) are considered to be outside system resilience limits, therefore the resilience of DH network system is calculated as a ratio of scenarios that are in range of available recovery costs and recovery time (blue dots in Fig. 2.3) to overall number of scenarios simulated.

2.3. System Dynamics Approach in Local Case Study

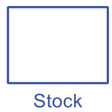
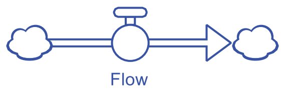
A more advanced approach that can recognize the feedbacks between multiple elements of complex system to show non-linear and dynamic behaviours of the systems known as system dynamics (DS) is proposed within the latest stage of the proposed methodology. SD approach allows to integrate social factor into the simulation model together with technological aspects differently form the other examined probabilistic simulation tools.

More in specific for proposed methodological research approach a SD model is created for natural gas infrastructure with storage facility in order to evaluate and test the application of SD for the evaluation of an infrastructural system resilience, as described in the Articles 5 and 6. SD model is used to analyze infrastructure systems behaviour considering specific endogenous variables that influence the behaviour of the system. The main endogenous components within the model are: imports of gas, exports of gas, domestic supply and flows into and out of storage.

The main types of variables used in SD model can be defined as different components shown in Table 2.1.

Table 2.1

Components of SD Model [157]

Component type	Description of purpose	Visual representation
Stock	Container that accumulates and depletes value over time depending on connected flows	
Flow	Rate of change in stock; arrowhead on the flow pipe indicates the direction of the flow, in or out of stock, in this way increasing or decreasing value of stock	
Converter	Defines external inputs to the model, calculates algebraic relationships and serves as the repository for graphical functions	
Link	Connects model components to each other (stocks with converters, converters with flows, flows with converters)	

SD model has three components used for definition of variables of urban area. These components are known as stocks, flows, and converters. The model is used for simulation of the changes in the components over a simulation period.

Stocks are the components that accumulate and release value over time. This process is driven by inflows and outflows. Flow direction is indicated by arrowhead. Inflow effect is increasing the stock value. The outflow effect is decreasing the stock value. The overall stock value in a given simulation time is the sum of the initial stock value of the given simulation time and all inflows connected to the stock, minus the outflows connected to the stock, as described by Equation (2.3.1), adapted from [141]:

$$Stock\ X_t = Stock\ X_{(t-dt)} + Inflows_{(t-dt)} - Outflows_{(t-dt)}\ , \qquad (2.3.1)$$

where

Stock X_t – the level of Stock X at simulation time t;
Stock $X_{(t-dt)}$ – the level of Stock X at time t – dt;
dt – time interval used as a step of model simulation over which this equation spans;
$Inflows_{(t-dt)}$ – the sum of inflows into Stock X at the simulation time t – dt;
$Outflows_{(t-dt)}$ – the sum of outflows out of Stock X at the simulation time t – dt.

Links can connect stocks to flows and stocks to converters to create the feedback effect. SD models usually have many stocks, flows, and other components, which interact and result in many different complex and dynamic behaviours of stocks.

Converters are used to include in the model such functions as cycle time functions, delay functions, logical functions, mathematical functions, simulation functions, statistical functions, and test input functions. The SD model for natural gas infrastructure with storage facility includes fuzzy-logic based on logical function, which is set to compare different variables in model and switch the regimes of gas flows, in this way imitating the balancing process performed by transmission system operator. The process of regime switch of gas flows in transmission system is representing the feedback loops in SD model and causing the dynamic effect.

Regression analysis equations are used for some converters in order to present the pattern in the set of data, which is not modelled in depth within dynamics structure, or equation explains the process better than if it is modelled with SD components. For example, the thermo-dynamic effects of changes in gas flow directions occurring in the pipelines due to different gas velocity, as physics-based software tools for thermo-dynamics process modelling are more suitable for this purpose than SD modelling.

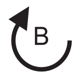
For the purpose of natural gas infrastructure with storage facility the SD model historical data on gas injection is subjected to different regression analysis (linear regression, multi-variable regression, and polynomial regression) in statistics software to determine which type of equation is the best to describe the injection into and withdraw out of the storage facility. Gas injection and withdrawal are selected as dependent variables, and independent variables are supply, imports, and exports.

The dynamic effect in the components of SD model is achieved by feedback loops causing oscillation and non-linear behaviour in changes of component values during the simulation of the model. Feedback loops occur due to several links between the components that create a loop leading back to initial component. A precondition for creating a feedback loop is that at least one stock must be used in the feedback loop [158].

The relationship of different aspects of natural gas transmission system and storage facility in Latvia is shown with casual loop diagrams (CLD). Usually a system has multiple feedback loops that interact with each other and is the main cause for the complex dynamic behaviour, which is commonly presented with CLD that explains this dynamic behaviour through the model structure. The components used in CLD are described in Table 2.2.

Table 2.2

Components of CLD [157]

Component type	Description of purpose	Visual representation
Variables	Indicates variables of the system dynamics model	As text
Link	Indicates the link between variables	
Reinforcing loop	Indicates that the loop has a reinforcing effect on the initial variable value	
Balancing loop	Indicates that the loop has a balancing effect on the initial variable value	

The components of CLD have a specific purpose. The reinforcing loop, denoted as "R" in CLDs is describing the reinforcing and disrupting drivers considered within the system model can be described in the following way: the change in the originating component is the cause for change in other components that after a certain time due to the feedback loop has a strengthening effect also on the output value of initial component. The balancing loop, denoted as "B", is an opposite case, when the response of other components in the loop decreases the original effect of the initial variable, causing counteraction to the change in initial component output value.

The developed SD model is suitable for energy policy planning process with consideration of different renewable energy resource strategies and natural and technological risks of gas supply disruptions.

2.4. Dynamic Urban Resilience Model

The integration of the three previously discussed approaches, i.e., composite indicator, probabilistic simulation and system dynamics (SD), is included into a single model. This stage, implemented in the step 4 of the methodological approach, is finally used to create a tool suitable to describe the dynamics of urban resilience to natural hazards and deal with the existing knowledge gaps in the topic of urban resilience measurement. The process of integrating three of the previously mentioned methods into the proposed tool and performing assessment can be summarized in analytical graph (see Fig. 2.4).

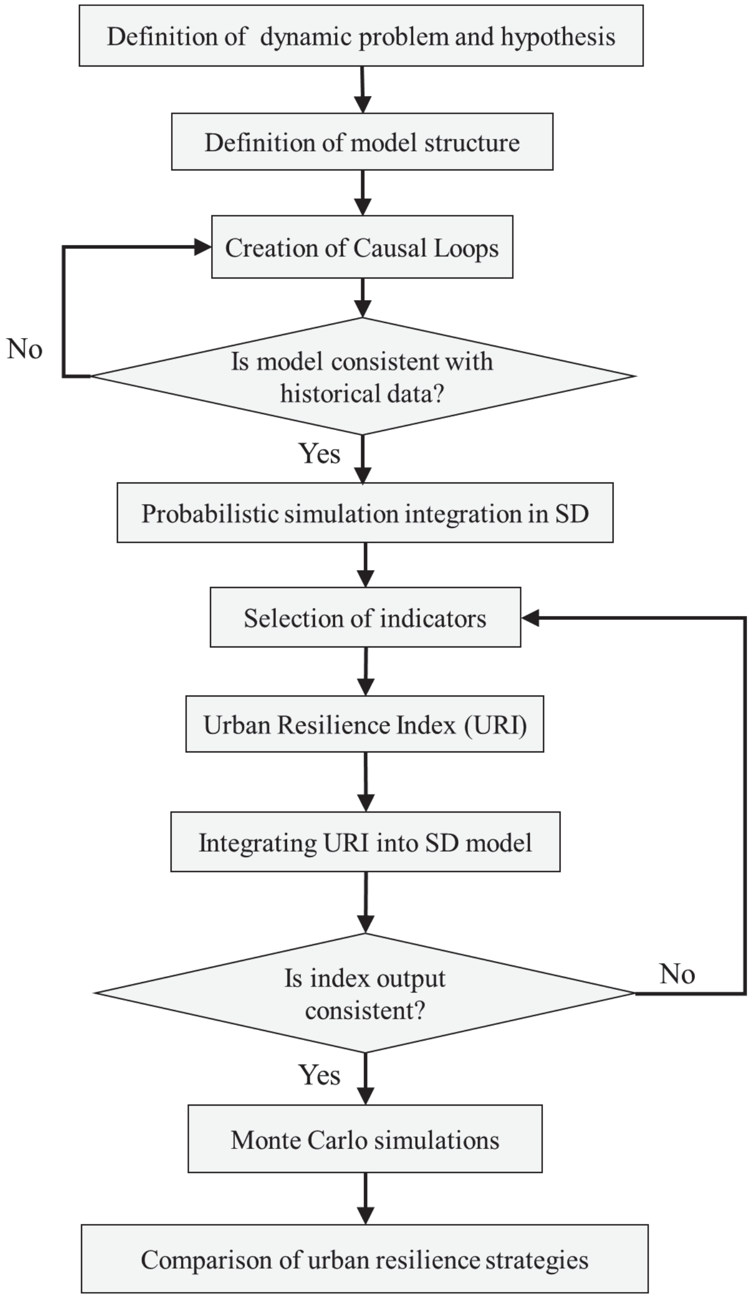


Fig. 2.4. Analytical graph for the development of dynamic urban resilience assessment tool.

The model concept used for the creation of an assessment tool is discussed more in depth in Articles 5 and 6, and results of Monte Carlo simulation for comparison of urban resilience strategies is presented in Article 7.

Structure of Dynamic Urban Resilience Model

Urban systems behaviour is best described by non-linear dynamics, which are the result of many feedbacks between multiple elements of urban systems. Therefore, the developed urban resilience assessment model to natural hazards is made with SD approach, which enables dynamic modelling of urban areas with help of internal feedback loops between different, and well identified, components of urban areas. The study distinguishes different dimensions of urban areas to set the scope at which urban area performances are captured in the model.

The probabilistic simulation is integrated in the developed urban resilience SD model with built-in function in software RANDOM. This function is generating a random impact from a given probability-impact curve and assigns the defined impact to a model variable (i.e., housing, electricity, heating, water services, etc.).

The composite indicator-based index for the urban resilience assessment allows having dynamic output in the form of a single number or score. This enables to catch and represent the dynamic changes within the representative urban dimensions directly selected from the urban resilience SD model. This part is described more in-depth in Article 6.

To make indicator values comparable over the simulation time, a normalization of indicators is made based on reference scale. Thus, indicators are selected from available data sets of statistics to provide definition for reference scale. The selected indicators based on data sets of statistics must also be consistent with the structure of urban resilience SD model.

The available data for reference scale of URI indicators is selected from EUROSTAT. Indicators that did not have data in EUROSTAT for reference scale are excluded from this study because no quantitative reference to low or high value of indicators existed for normalization and URI evaluation. Normalization methods known as z-score, minmax and ranking are tested in order to select the most appropriate method for URI application in urban SD model.

Validation of Dynamic Urban Resilience Model

Validation of the urban resilience SD model and urban resilience index (URI) consistency is performed and presented in Article 7. Model structure is verified for each dimension separately by setting the model to a balanced equilibrium and then testing extreme values as inputs for further simulation. The expected output for balanced equilibrium simulation is a linear behaviour without any changes over time. After finding balanced equilibrium, extreme values are checked that drive the model to critical point in which simulation output does not provide a meaningful result. Such approach allows to verify consistency of the model structure with the defined causal loops and their strengths.

The validation of model content is performed within a local case study by comparing the model output for each dimension with historical trend from statistics. For this purpose, coefficient of determination R^2 is used according to Equation 2.4.1 [159]:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{2.4.1}$$

where

R^2 – coefficient of determination;

n– number of measurements in the selected data set;

y_i – value of the i^{th} observation in the validation dataset;

$\bar{y}$ –the average value of the validation dataset;

$\hat{y}_i$ – predicted value of the i^{th} observation.

In Equation 2.4.1, the fraction is the ratio of the residual sum of squares to the total data sum of squares. Value R^2 allows to understand how close the data is to historical trend. When value R^2 is close to 1, it shows that the model is making a good perdition. A model is considered valid for cases when R^2 value is over 0.9, which is considered a very precise model output. The formal hypothesis F-test is not necessary for the purpose of SD model because the structure of the model is a white box based on deterministic equations and knowledge instead of statistics as in the case of regression models.

The validation of URI output consistency with dynamic change in SD model structure is performed by checking indicator outputs for a baseline simulation in a local case study. The validity of URI is verified when all normalized indicators in the index have the same scale of measure and together are representing the dynamic changes occurring in the short term and long term.

Assessment of Urban Resilience in Local Case Study

In Article 7, urban resilience assessment is performed for a medium-sized city of Jelgava, which is exposed to flood risk related to spring floods due to snow melting and rain, ice congestion, and partly also to wind floods. For natural hazard definition, information on spring floods in Jelgava city prepared by "Latvian Environment, Geology and Meteorology Centre" for preliminary flood risk assessment for 2019–2024 is used in this study. The probability-impact curve is defined according to predefined information based on historical data of hazard events.

The urban resilience SD model input data for hazard event in the case study includes exposed area of 34.02 km^2 and population up to 15600 exposed to spring flood with likelihood of occurrence once in 10 years; exposed area of 64.56 km^2 and population up to 39250 for spring floods with likelihood of occurrence once in 100 years; exposed area of 69.94 km^2 and population up to 42900 for floods with likelihood of occurrence once in 200 years [27].

Dynamic assessment of urban resilience to natural hazard with help of URI is performed for different scenarios developed based on consideration of different possible policy strategies for increasing resilience of selected urban areas. The comparison of scenarios is made by comparing URI score probabilities and their distribution in output of Monte Carlo simulations.

The urban resilience model runs a stochastic simulation with probabilistic input from command RANDOM. This makes the output for every simulation run different, and thus urban resilience SD model simulation is probabilistic instead of deterministic. In such cases, Monte Carlo method is used in the evaluation of complex problems involving random phenomena occurring in probabilistic simulations.

To deal with different URI score in every simulation run and make a consistent assessment of urban resilience, a Monte Carlo method is used to replicate large number of simulation runs. The results of Monte Carlo simulations show likelihood of different outcomes of events, in this case different outcomes in dynamic change of urban area functionality over time under uncertainty of natural hazard event occurrence. This allows having an understanding of statistical nature of the systems performance and making decisions according to the statistical output. The number of trials for Monte Carlo simulation is distinguished by Equation 2.4.2 [160]:

$$Z = \frac{N}{1+N(E)^2}\,, \qquad (2.4.2)$$

where
Z – number of samples;
N – all possible model output values for the urban resilience index in one scenario;
E – maximum permissible error in calculating Z.

The maximum permissible error in this study is considered as ±5 % or 0.05. All possible model output values for the urban resilience index in one scenario depend on the value scale of urban resilience index. The parameters of the urban resilience index are shown in chapter "Integration of urban resilience index in system dynamics model" and are taken into account when determining N and the number of attempts for Monte Carlo simulations.

3. RESULTS

3.1. Quantitative Resilience Measurement

Composite Indicator-based Index in Case Study

Different indicators of community resilience are aggregated into a holistic community resilience measurement with an output presented in the form of a single score. The approach considers different phases of disaster risk management, in this way moving from an inherent resilience measurement towards an adaptive resilience measurement. However, the composite index approach is still a static measure that does not allow considering dynamics behind community resilience.

The created composite indicator-based index, i.e., "Community disaster resilience index", (CDRI) is assessed for macro regions of Latvia. The study showed that according to the definition of the CDRI, urbanized areas can gather higher values for community capitals, and thus can show higher level of disaster resilience. The results show that Riga region has a higher CDRI score than other regions due to its high population, economic activity, and more developed infrastructure. Average CDRI score is depicted for the region around Riga while low CDRI score for other regions.

The results of CDRI correlation with social vulnerability index showed a weak correlation. Also, the multi variable regression analysis with social vulnerability index and CDRI as independent variables and damage costs as a dependent variable showed a P-value greater than 0.05. This underlies the evidence of a non-statistically significant relationship between the CDRI and damage cost.

To deal with the shortcomings of CDRI, various opportunities for further research are identified:

1) many indicators used data that have not been updated, and lack of specific indicators that can be used for describing the inherent resilience is observed, thus a better evaluation of the assumptions and higher quality data should be used;

2) implementation of system dynamics approach would be useful in order to replace linear models with dynamic non-linear model in order to analyze complex systems and take into account resilience variations over time.

The findings and problems in creation of composite indicator-based index are further considered within the development of a dynamic urban resilience assessment model. The results of the study are described in detail in Article 1.

Probabilistic Simulation in Case Study

Probabilistic method is applied for simulation of failures in a DH infrastructure of a Latvian municipality. The study clarifies how district heating system resilience to a specific hazard can be assessed within context of adaptive resilience. For this purpose, the effect of specific investment scenarios aimed to enhance resilience are used to identify the resilience of assets in the DH network system.

Probabilistic simulation is made for 1000 scenarios with possible asset failures according to predefined failure probability. Specifically, such simulation helps to understand the robustness, recovery time, and possible costs of damage for different hazard magnitude.

The output of simulations shows the percentage of assets failed and percentage of assets out of order in all scenarios. In scenarios, the same number of assets failed can have different effect on network performance and a certain pattern can be distinguished: the higher assets out of order percentage, the lower the network performance. Such pattern corresponds to probability-consequence function, where there is high probability for low number of assets to fail with low consequences and low probability for high number of assets to fail and have high consequences.

The adopted probabilistic method provides insight into system abilities to react and cope with certain hazard. It provides a more complete overview than the composite index based method for performance of specific part of infrastructure.

As the result of the study, introduction of multiple effects given by the combination of different types of infrastructure systems and interconnections between systems is suggested. Also, the implementation of system dynamics is more preferable over linear model to analyse multiple effects in a complex system. Full results of probabilistic case study are reported in Article 2.

System Dynamics Approach in Case Studies

The relationship of different aspects of natural gas transmission system and storage facility in Latvia is determined based on the results of correlations and regressions. In specific the definition of a gas injection from transmission system into a gas storage facility and gas injection from storage facility into transmission system are set. For the purpose of evaluation of optimal regression equation P-value and coefficient of determination R^2 is used for different types of linear regression, multi-variable regression, and polynomial regression.

The results of correlation and regression analysis are applied for creating the SD model for natural gas transmission system and storage. The model is able to present the dynamic changes in this system. Causal loops are used to describe the feedbacks included in the model.

The created SD model for natural gas transmission system and storage has casual loop positive reinforcing loops for consumption of gas and balancing loops in order to avoid an infinite growth in the model values.

The model is used to study possible effects of renewable methane implementation in natural gas system in Latvia with the help of support policy for renewable energy sources, which must be implemented to achieve the EU low carbon economy goals. Support policy that increases the subsidies for biomethane, which increases biomethane production and consequently the renewable methane injection into transmission system is considered. The reduction of share of natural gas in transmission system in this way is achieved. Such diversification of gas sources will increase the resilience of natural gas system in Latvia according to the definition of energy resilience.

The studies implementing system dynamics approach show that SD models can be used as a tool to assess quantitative parameters of different policy implementation. Full case studies of system dynamics approach are reported in Articles 3 and 4.

The findings of SD modelling approach case studies combined with findings of probabilistic simulation and composite indicator-based index case studies provide a new perspective for framing a novel type of urban resilience assessment model.

3.2. Dynamic Urban Resilience Model

Selected Definition for Urban Resilience Model

The main output of this study is a model that can provide a measurement for urban resilience to natural disasters considering the dynamic changes in urban areas. Thus, dynamic problem definition addresses the urban resilience measurement is introduced in Article 5. The defined dynamic problem (see Fig. 3.1) is set by assuming a decrease of a certain urban system functionality level over time. Both time frames are considered, long-term and short-term, to describe system functionality under external stress (e.g., natural hazard) and the way in which a system reacts to an external stressor, namely: a) urban system without recovery of the functionality; b) urban system with recovery of the functionality; c) urban system without decrease in functionality.

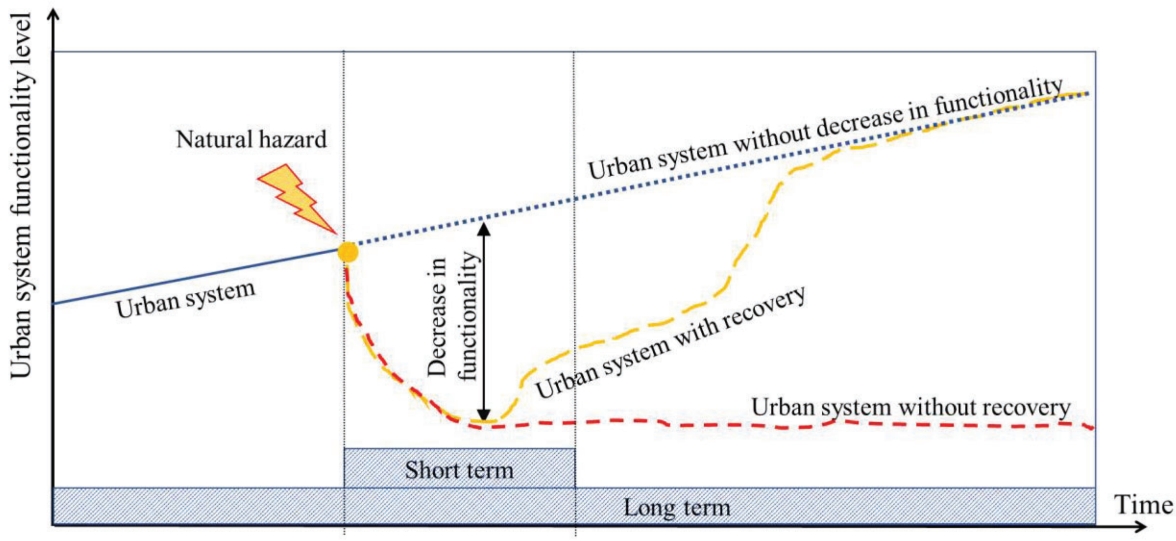


Fig. 3.1. Dynamic problem that study intends to solve.

The problematic behaviour is the decrease of functionality in urban systems after which the system can either get back to the normal functionality level, thus showing a certain resilience (urban system with recovery), or maintain a lower functionality level in fact presenting a lower resilience (urban system without recovery). It is important to note that a system showing resilience (urban system with recovery) can have different decrease in functionality level and recovery trends. Some systems can be resilient and fully recover in short term, others as shown in the example of urban system with recovery in Fig. 1 can fully recover only in long term. The desired state of system is aiming to have the lower decrease in functionality in respect to the initial condition.

The functionality levels of a system after recovery can differ in long term and short term because some effects of recovery measures can occur only with time delays. Both time frames are considered when creating the model. Short-term recovery addresses the system behaviour just after the natural hazard occurrence during time t_1 to t_2, including the response (decrease of functionality level) to natural hazards and recovery phase. Long-term recovery addresses the system functionality level over a period before and after short-term recovery. The long-term recovery as shown by a yellow dotted line in Fig. 3.1 can occur due to delay in indirect effects of natural hazard on socio-economic conditions. The inclusion of both time references allows understanding what are the key feedbacks between dimensions of urban areas and how changes in different variables may affect urban resilience in different time scales.

Thus, the dynamic hypothesis is that preferable state of system is having minimum decrease in system functionality under stress of natural hazard. That can be achieved by increasing or decreasing the strengths of feedback loops between urban dimensions embedded in the urban SD model.

Defined Urban Resilience Model Structure

The structure of dynamic urban resilience model represents urban areas through urban dimensions that are included in SD model as separate sectors. The defined dimensions of urban area for urban SD model are as follows:

- social dimension;
- infrastructure dimension;
- environmental dimension;
- economic dimension.

Urban resilience model considers endogenous structure of urban system, which is created with help of feedbacks between dimensions that represent the dynamic change occurring in urban areas.

The concept of urban resilience SD model structure with integrated probabilistic approach and composite indicator index is presented in Fig. 3.2.

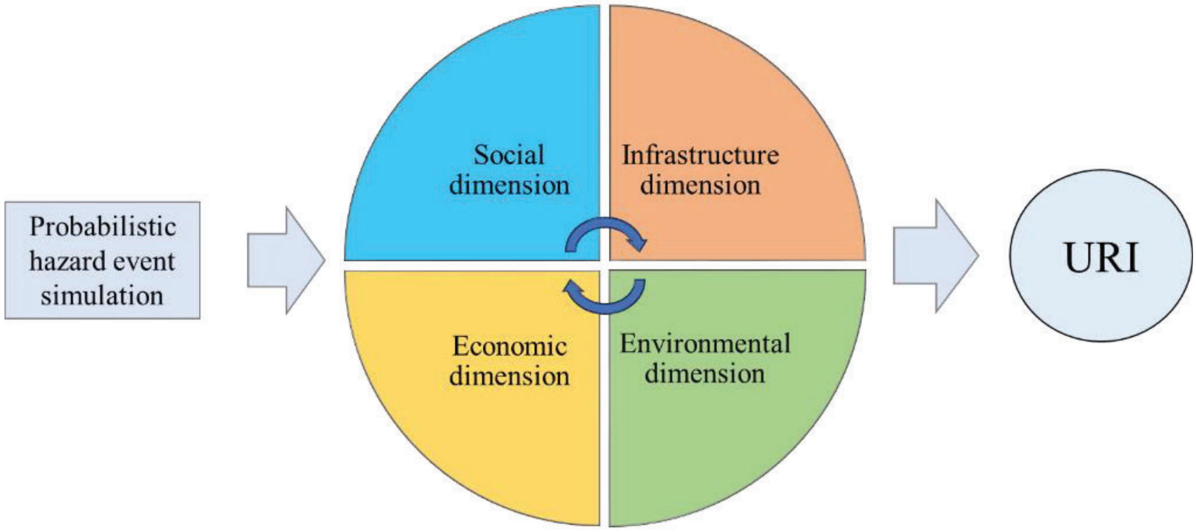


Fig. 3.2. Concept of urban resilience SD model structure.

The model structure includes the natural hazard impact on urban area in the form of stochastic simulation. The natural hazard impact is considered as a shocking event of different scales that occur with a certain predefined probability. The influence of such shocking event is considered in every dimension of the modelled urban system.

The integration of the composite indicator-based index in SD model allows presenting the multi-dimensional and complex dynamic problem measurement of urban resilience to natural hazards as a single value based on the output of SD model simulation. For this purpose, the urban resilience index (URI) is proposed as a proper set of indicators referring to characteristics of urban resilience within the 4 identified urban dimensions.

The indicators composing the value of URI for a specific urban area are normalized to a reference scale in order to make comparable either indicators form different dimensions or URI for different urban systems. In this study the specific distribution from international statistics databases is used for normalization.

Causal Loop Diagrams

Specific causal loops are defined in the model for each dimension. After defining causal loops for each urban dimension, the feedbacks between dimensions are defined. Full set of causal loops considered in creation of the model for each dimension and feedbacks between them with causal loop diagrams (CLD) is introduced in Article 7. Figure 3.3. shows the summary of the main CLD of the urban resilience SD model with four main feedback loops R1, B1, R2, and B2.

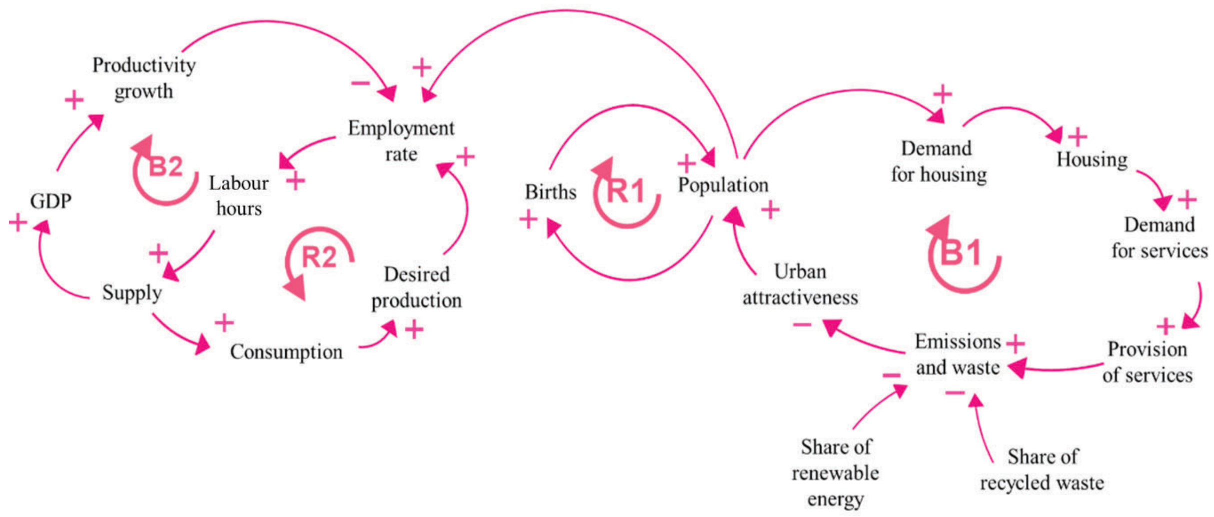


Fig. 3.3. Summary of CLD of urban resilience SD model.

The core loop of the model is births and population reinforcing loop (i.e., R1). These system variables are the main components in the social dimension of the SD model. This loop presents a reinforcing effect of the population growth depending on the number of people living in urban area. The more births, the bigger is the population, and the bigger the population, the more births there are.

Urban attractiveness has effect on urban population, which according to the defined causal feedback depends on the components of environmental dimension, such as emissions and waste. The emissions and waste are considered in the model as the consequence of provision of infrastructure services representing the infrastructure dimension, namely, district heating and electricity supply. The amount of supplied services depends on the occupied dwellings, which depend on population. This feedback between population and urban attractiveness is included in the model as feedback loop B1. This loop is considered as balancing, because bigger population creates a higher demand for services and, consequently, a higher amount of emissions and waste. This is counterbalancing the value of urban attractiveness component having an increased migration from the considered urban area with a consequential decrease of the population.

For the economic dimension, reinforcing loop R2 in economic sector of SD model is included in the feedback on the link between consumption and employment rate. Loop R2 foresees that an increase in the consumption component value will increase the desired production and consequently the employment rate. Employment rate is also dependent on the working age of population in urban area. For this purpose, the model distinguishes different age groups of urban population: young population until age 16, working age population from age 16 to 65 and elderly population over age 65.

The feedback between social dimension and economic dimension is created with the link between population and employment. The increase in population increases the number of working age people that can be employed. This link can increase the production in urban area and thus the value of GDP component.

Balancing feedback loop B2 in economic sector of SD model includes the feedback link between the employment rate and GDP. The balancing effect for loop B2 is created by the productivity growth component. The value of productivity growth component increases with the increase of GDP component value. Consequently, the need for additional employees is decreasing and thus the employment rate is decreasing.

Definition of Baseline Scenario for Urban Resilience Assessment

A case study for testing the urban resilience SD model in terms of application of different urban resilience scenarios is performed. Before implementing a probabilistic hazard event simulation, a baseline scenario without a hazard is defined based on the data gathered from the Central Statistical Bureau for Jelgava city, as decribed in Article 6. The gathered data has granularity of 1 year, and therefore the simulation time step is selected as 1 year. However, the delta time of the simulation (also known as the amount of time between calculations) is defined as 1/12 of 1 year, i.e., 1 month.

The gathered data from the Central Statistical Bureau are used as an initial input for variables of the model at the start of the simulation. During the simulation, the values of model components change due to the endogenous structure of SD model and defined feedback loops. The selected simulation time period is 50 years, which is considered enough to capture different natural hazard probabilities when probabilistic simulation of natural hazard is applied.

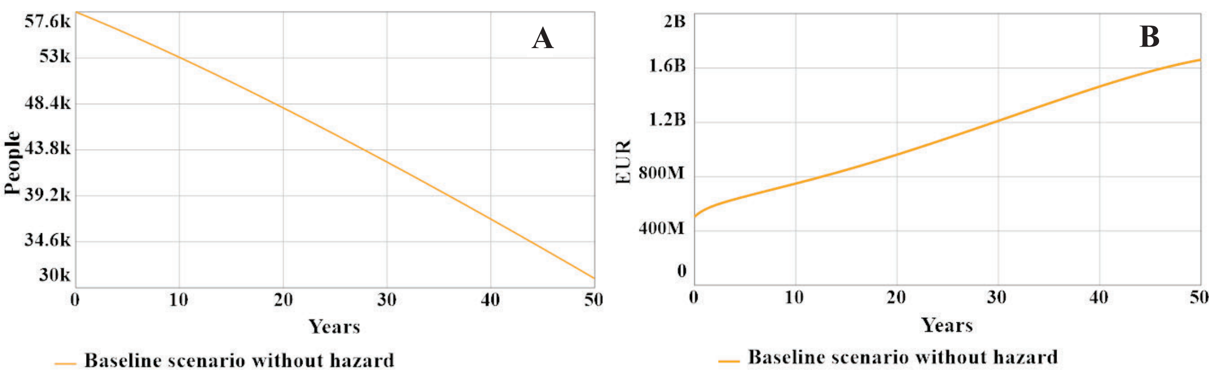


Fig. 3.4. A – simulation output for population; B – GDP in baseline scenario without hazard.

The baseline scenario without hazard simulation output for social dimension and economic dimension components and population and GDP are shown in Fig. 3.4 A, B. The trend of population decrease and GDP increase as already shown in the model validation part is continued in the baseline scenario without hazard.

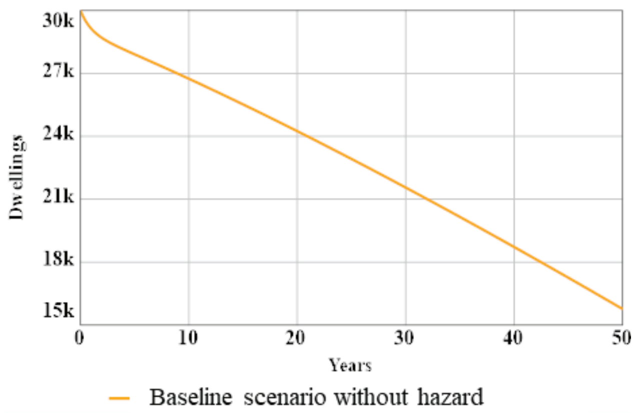


Fig. 3.5. Simulation output for occupied dwellings in baseline scenario without hazard.

Baseline scenario without hazard simulation output for infrastructure dimension component of occupied dwellings in Fig. 3.5 shows how the number of occupied dwellings decreases depending on the total population. Consequently, electricity supply, heating, water supply and wastewater treatment components of infrastructure dimension in Fig. 3.6A, B, C, and D show the decrease of provided services.

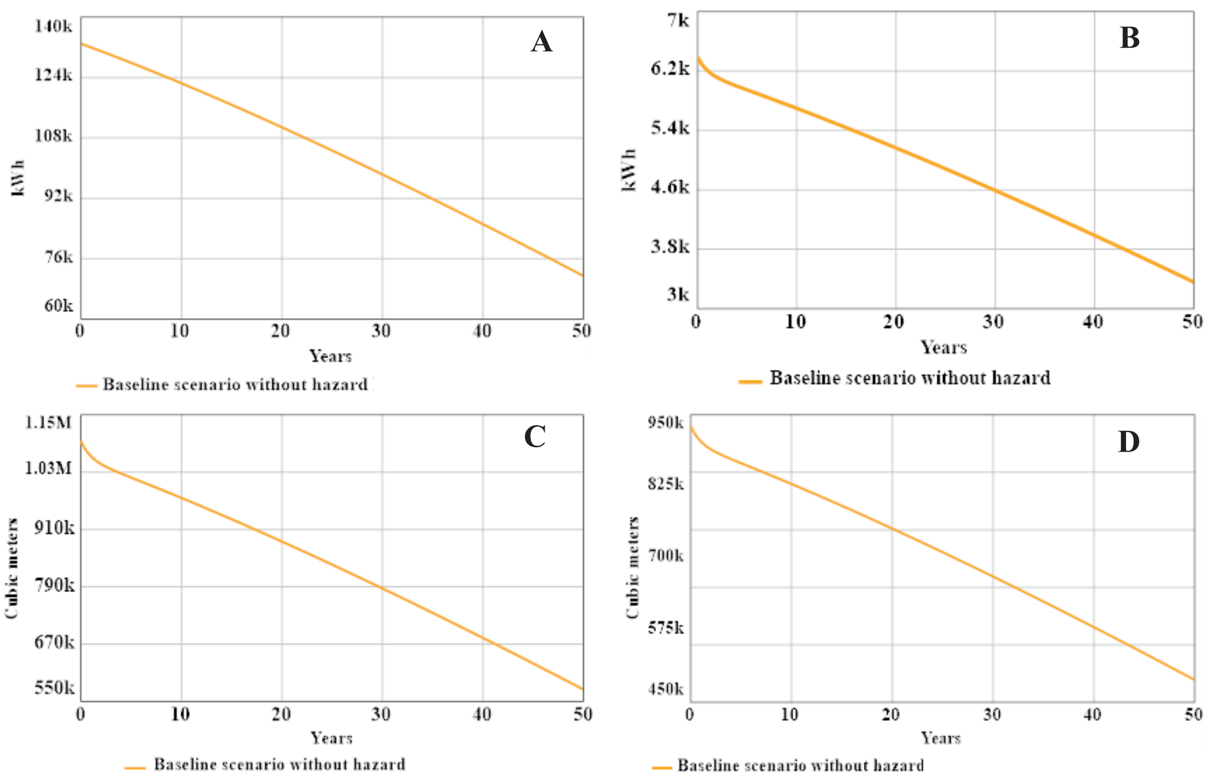


Fig. 3.6. Simulation output in baseline scenario without hazard: A – for electricity supply; B – for heating; C – for water supply; D – for wastewater treatment.

Baseline scenario without hazard simulation output for environmental dimension component CO_2 stock in Fig. 3.7 A. shows how the CO_2 stock decreases because of the decreasing trend in electricity consumption and heating.

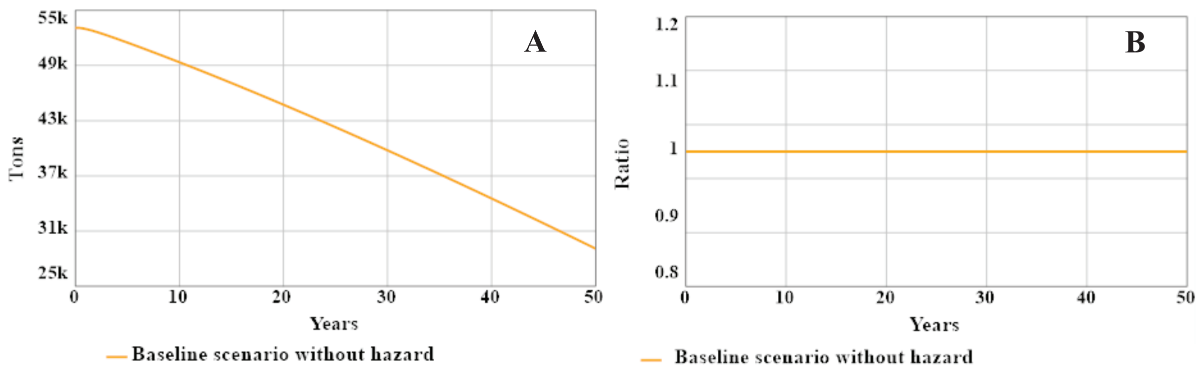


Fig. 3.7. Simulation output in baseline scenario without hazard: A – for CO_2 emissions; B – for waste produced vs waste treated.

The output for environmental dimension component of waste produced vs waste treated in Fig. 3.7 B shows the change in ratio of waste production and waste treatment. Such output of the model is explained by the consideration used in the model that all the waste produced is treated when no natural hazard impact occurs.

Urban Resilience Model Validation Results

The created urban SD model is validated based on historical data for a selected urban area of the case study. The results of validation are presented in Article 7. There is a significant lack of available historical data for urban areas for specific model components and therefore only the components that are most common are validated for data sets in the Central Statistical Bureau. Specifically, these components are population and GDP.

A set of data of the Central Statistical Bureau for Jelgava population is used for the period 2011–2018. The results of validation in Fig. 3.8 show the comparison of the historical data set for the population of Jelgava. The model output for population component fits the historical data of population with coefficient of determination R^2 equal to 0.92669. This is considered as a very high relationship between real data and model data, and the model is valid to provide a consistent output for population component in urban resilience assessment.

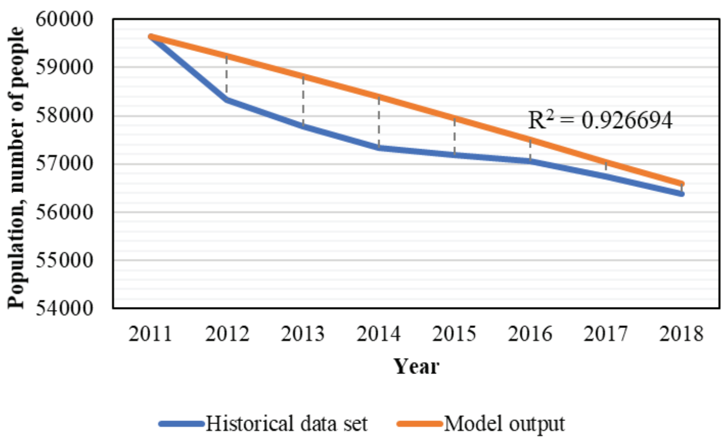


Fig. 3.8. Results of population component validation.

For the purpose of GDP validation, the change in population component is considered for the respective years of historical GDP data set. The validation of model output for GDP of Jelgava is performed for years 2013–2017. No data on GDP for longer period is available for Jelgava city in the Central Statistical Bureau. The results of GDP component validation are presented in Fig. 3.9.

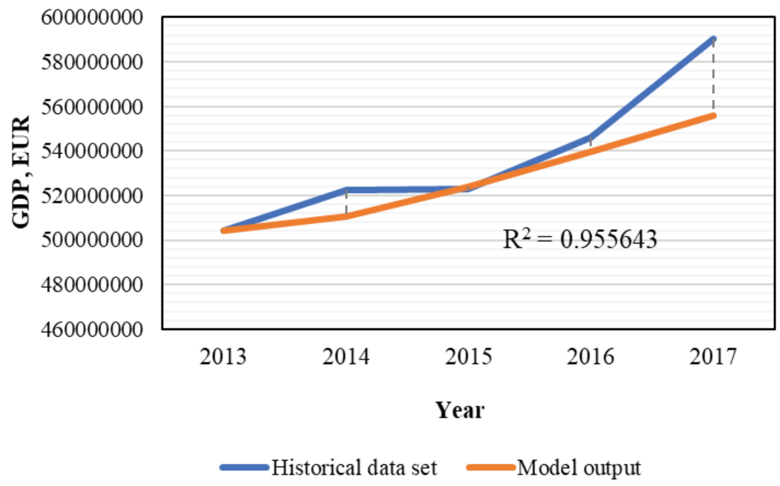


Fig. 3.9. Results of GDP component validation.

The model output for GDP component fits the historical data of GDP with coefficient of determination R^2 equal to 0.95564. This is considered as a very high relationship between real data and model data, and the model is valid to provide a consistent output for GDP component in further urban resilience assessment. The rest of model components do not have a historical data set presenting a trend over several years; however, inputs for the rest of components during the validation in the start of the simulation are used based on average statistics for Latvia or found in literature sources for Jelgava city.

Probabilistic Simulation Integration into Urban Resilience Model

Natural hazard in SD model is defined as an event with certain impact on population and provision of services. The impact for specific component is described by Equation (3.2.1):

$$Hazard\ impact_i = Hazard_j * Exposure_i * Vulnerability_i\ , \tag{3.2.1}$$

where

Hazard $impact_i$ – the effect of hazard on component i of the considered system;

$Hazard_j$ – the hazard magnitude for a hazard of occurrence probability j;

$Exposure_i$ – the exposure of component i to hazard;

$Vulnerability_i$ is the vulnerability of component i.

For natural hazard, the definition for the selected case study is based on information prepared by "Latvian Environment, Geology and Meteorology Centre" for national flood risk assessment is used in this study. The hazard probability and magnitude, in terms of flooded area for spring floods in Jelgava city, in Fig. 3.10 is based on historical data of hazard events occurring once in 200 years (0.5 % probability), once in 100 years (1 % probability), and every 10 years (10 % probability).

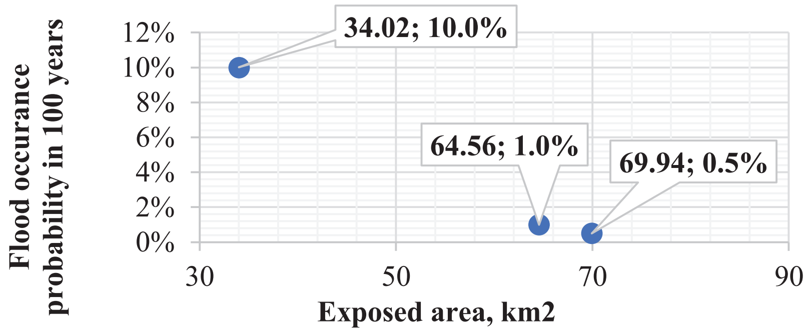


Fig. 3.10. Probability and magnitude of spring floods.

The occurrence probability of hazard event occurring once in 200 years is normalized to 0.5 % occurrence probability in 100 years. The occurrence probability of hazard event occurring once in 100 years is normalized to 1 % occurrence probability in 100 years. The occurrence probability of hazard event occurring once in 10 years is normalized to 10 % occurrence probability in 100 years.

The natural hazard probability in the model is generated by a built-in function. The selected built-in function *RANDOM* allows to generate the number according to uniform distribution in every step of the simulation. This number is used as an entry value for components that incorporate the hazard probability. The hazard intensity is estimated according to logical function in Equation (3.2.2).

$$\begin{gathered} \textit{Hazard intensity} = \textit{If (Random)} \geq 99{,}5 \textit{ Then } (200) \\ \textit{Else (If (Random)} \geq 99 \textit{ Then } (100) \\ \textit{Else (If (Random)} \geq 90 \textit{ Then } (10) \textit{ ELSE } (0))), \end{gathered} \tag{3.2.2}$$

where *Random* is a number from 0 to 100.

The *Random* number is generated by built-in function *RANDOM* and is representing a normalized probability of natural hazard occurrence in 100 years. Values of 200, 100, and 10 are the specific hazard return times according to predefined probability. In this way, *Random* is a generated random number in every step of the simulation.

The logical function defines the hazard intensity according to following steps: if during the simulation step *Random* ≥99.5, then the hazard equivalent to magnitude of once in 200 years is used as a shock. If the generated random number is not ≥99.5 then the logical function will check for random number ≥99, etc. The output Hazard event component is used as an input for $Hazard_j$ component in urban resilience SD model according to the data presented in Fig. 3.10 to determine the hazard event magnitude.

For the assessment of $Exposure_i$ and $Vulnerability_i$ components in connection to a specific Hazard intensity in the proposed SD model, proxy data are used due to lack of historical records.

The exposure is determined as exposed population in Fig. 3.11 according to the flooded area in Jelgava city during the spring floods.

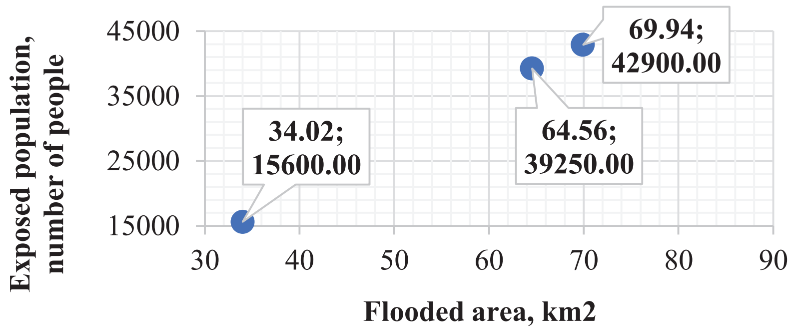


Fig. 3.11. Exposed population to spring floods in Jelgava city

The proxy data for $Exposure_i$ component is based on the exposed population. The $Exposure_i$ of specific components is determined as component's value per capita. The higher the number of exposed population, the higher is the $Exposure_i$.

The $Vulnerability_i$ of component is defined by vulnerability coefficient from 1 to 0, where 1 equals the full amount of impact assigned by $Exposure_i$ per capita and 0 means no assigned impact by $Exposure_i$ per capita. This allows determining the decrease of specific service depending on the magnitude of natural hazard.

The defined specific components *i* of urban resilience SD model for Hazard impact are reported in Table 3.1.

Table 3.1

Defined Components of Urban Resilience SD Model for Hazard Impact

Component	**Hazard impact, units**
Social dimension	
Population	Deaths (number of people)
Economic dimension	
Labour hours	Decrease in labour hours (hours)
Infrastructure dimension	
Dwellings	Damage to dwellings (number of dwellings)
Electricity supply	Decrease in electricity supply (kWh)
Heating	Decrease in heating (kWh)
Water supply	Decrease in water supply (cubic meters)
Environmental dimension	
Wastewater treatment	Decrease in wastewater treatment (cubic meters)
Waste treatment	Decrease in waste treatment (kg)

The urban resilience SD structure allows to incorporate different recovery functions (linear, S-shaped, exponential) for each component after Hazard impact as shown in the example for available number of dwellings in Fig. 3.12. with proxy data. Currently there is no available historical data on the selected case study area that describes the recovery process from the hazard event, thus only the S-shaped recovery function is used for the case study of Jelgava city, as it represents most of possible dynamic changes in the recovery process.

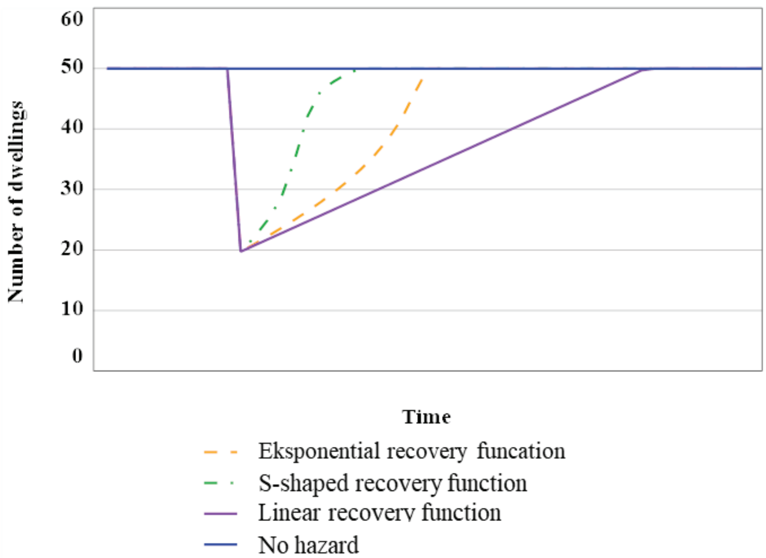


Fig. 3.12. Different recovery functions for available number of dwellings.

The integration of probabilistic simulation within urban resilience SD model for baseline scenario allows generating stochastic hazard events according to Equation 3.2.2. This means that every simulation of baseline scenario with natural hazard will have the number of hazards and their magnitude. The effects of such probabilistic-stochastic simulation is hard to quantify and for this reason Monte Carlo simulation is used, as presented in Thesis section "Monte Carlo simulations for urban resilience scenarios".

An example of model output presented further uses predefined hazard events to show how the model components react to hazard definition. The predefined hazard events are used to show how the baseline scenario with hazard event simulation differs from the baseline scenario without hazard event simulation applied for the case study of Jelgava city. The predefined hazard event simulation in year 10, 20, and 30 with growing magnitude respectively is used for presenting a baseline scenario with hazard.

Figure 3.13 A shows the impact of hazard event on population in the baseline scenario with hazard and Fig. 3.13 B shows the same impact on GDP. There is no recovery for population component, because the hazard impact on population in the model is considered as the number of deaths. For GDP component the model shows recovery due to additional employment after hazard event to satisfy the demand. The model shows lower values for both components in the baseline scenario with hazard compared to the baseline scenario without hazard.

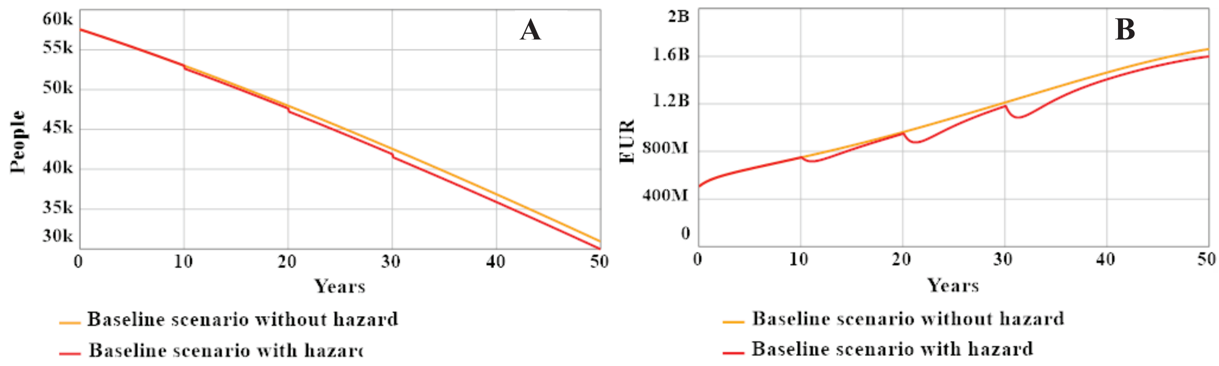


Fig. 3.13. Comparison of impact in baseline scenarios with and without hazard: A – on population; B – on GDP.

In infrastructure dimension for occupied dwellings component, a recovery is considered with the predefined S-type recovery function. In Fig. 3.14 a lower value for occupied dwellings component in baseline scenario with hazard is compared to baseline scenario without hazard because of the feedback from decrease of population after hazard event.

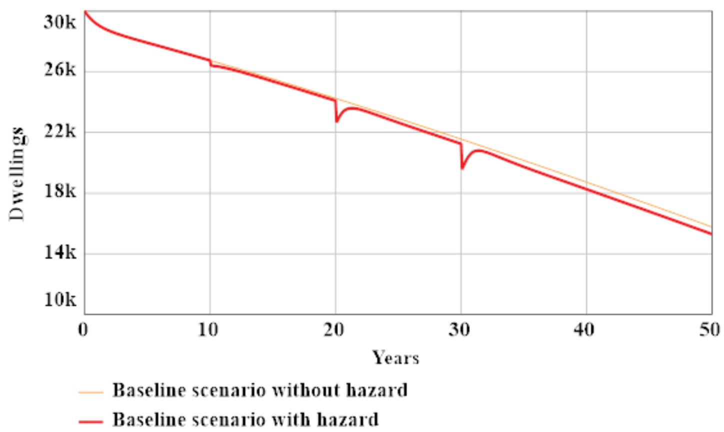


Fig. 3.14. Comparison of baseline scenarios with and without hazard for dwellings

Heating, electricity supply, water supply and sewage water treatment have a similar tendency to occupied dwellings component, because the model considers that the demand for these infrastructural services is dependent on the number of occupied dwellings, shown in Figs. 3.15 A, B, C, and D.

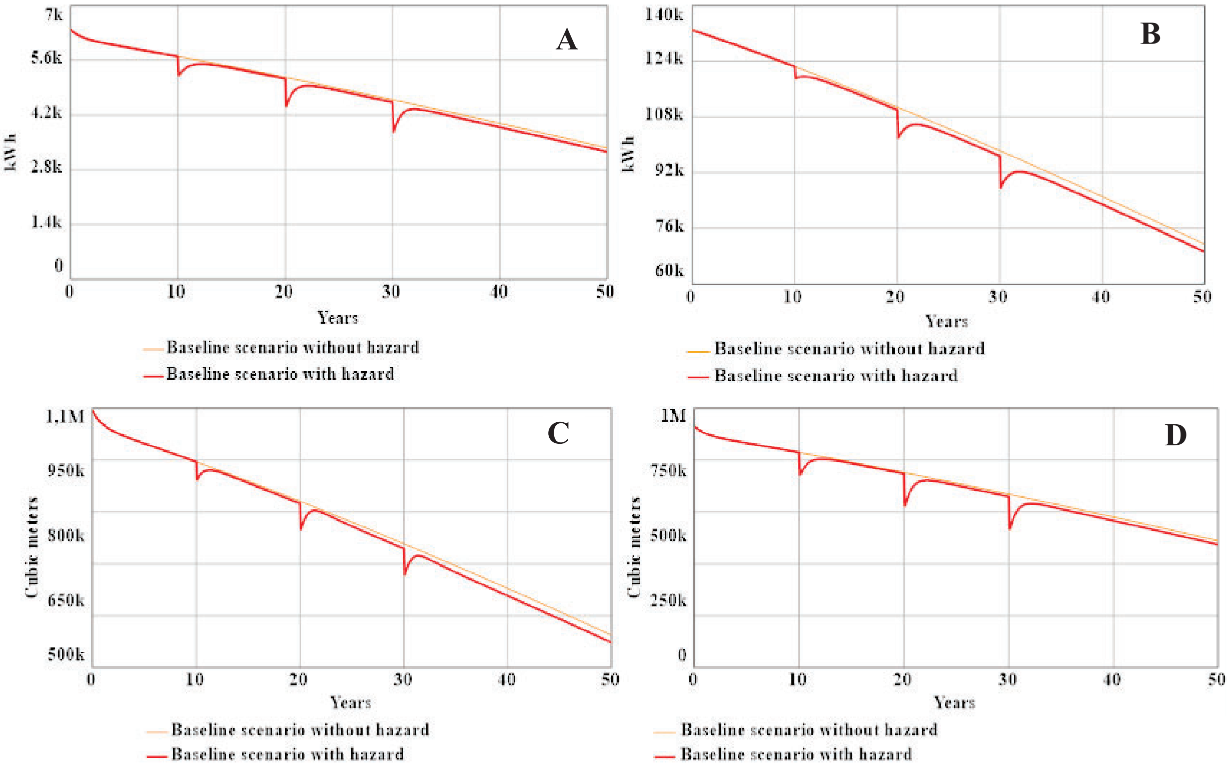


Fig. 3.15. Comparison of baseline scenarios with and without hazard: A – for electricity supply; B –heating; C– water supply; and D – wastewater treatment.

The environmental dimension component for CO_2 stock in the urban resilience SD model is dependent on the heating and electricity supply, thus the reduction of CO_2 emissions is shown by the model when hazard has an impact on heating and electricity supply, shown in Fig. 3.16 A. The decrease in waste treatment is also considered in environmental dimension, shown in Fig. 3.16 B, for the component waste produced vs waste treated.

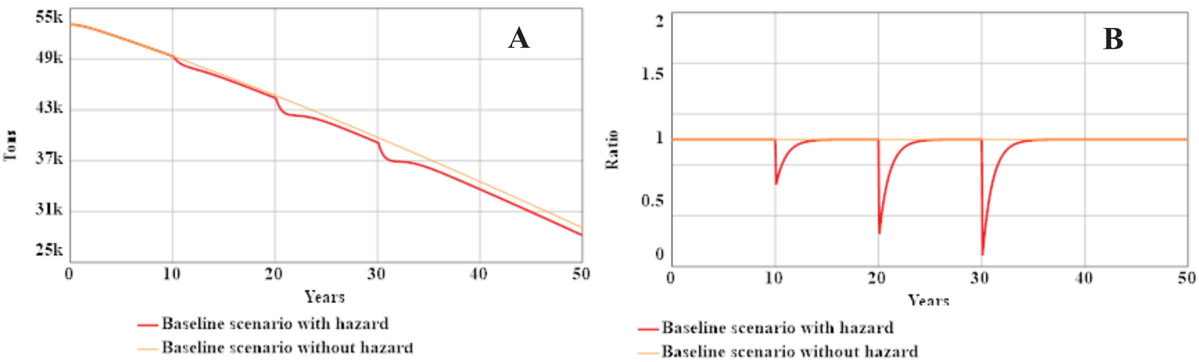


Fig. 3.16. Comparison of impact in baseline scenarios with and without hazard on A – CO_2 emissions component, and B – waste produced vs waste treated component.

To describe the above mentioned complex dynamics of urban resilience SD model and capturing the impact of natural hazard, a set of indicators is selected for creating a composite based indicator index.

Selected Set of Indicators

The selected indicators that fit the model structure and have reference data in EUROSTAT database are reported in Table 3.2. The effect of selected indicators on urban resilience is identified. Positive effect '+' means that increase in indicator value shows increase in urban resilience. Negative effect '–' means that increase in indicator value shows decrease in urban resilience.

Table 3.2

Characteristics of Final Set of Indicators Regarding URI and SD Model.

Selected indicator per urban dimension	**Effect on urban resilience (positive or negative)**
Social dimension	
Unemployed population share	–
Youth dependency	–
Elderly dependency	–
Migrant population share	–
Economic dimension	
GDP per capita	+
Infrastructure dimension	
Share of population experiencing housing deprivation	–
Share of population with electricity supply	+
Share of households with inability to keep house warm	–
Share of population with access to water supply	+
Environmental dimension	
Share of population with wastewater treatment	+
Waste production vs waste treatment	+

For social dimension the indicators are representing the share of different social groups of community. The unemployed population, youth dependency, elderly dependency, and migrant population are social groups considered to be more vulnerable to impacts of natural hazard, and thus increase in social vulnerable group indicator values has a negative effect on urban resilience.

The economic dimension indicators GDP per capita represents the size of economy and growth rate of urban economy. The growth rate of economy is considered to have a positive effect on urban resilience.

Most of the impact from natural hazard in urban area is damage to economic assets. Thus, the infrastructure dimension is represented by a largest number of indicators, that are dependent on the disruption in infrastructural systems in urban area.

The infrastructural dimension indicators used to present the electricity supply, water supply and wastewater treatment are expressed as share of population with access to specific infrastructure service, thus have positive effect on urban resilience. The damage to infrastructure from natural hazard is considered to show decrease in supply of services and the share of population with access to these services will decrease, thus the value of indicator is decreasing.

The infrastructure dimension indicators for housing and heating are expressed as share of population with no access to specific housing and heating, thus have negative effect on urban resilience. The damage to infrastructure from natural hazard is considered to show decrease in these services and the share of population with no access to services will decrease, thus the value of indicator is increasing.

The environmental dimension indicator in the form of ratio of waste production vs waste treatment was found to be the only indicator in EUROSTAT database that fits the construct of the model for environmental dimension. The indicator has a positive influence on urban resilience. In the context of the model the increase in waste treatment increases the environmental performance of the urban area, and thus the value of indicator of waste production vs waste treatment is increasing.

Indicator Normalization

The selected indicators are standardized and normalized. The standardization and normalization of indicators is also described in Article 6. The standardization of indicators was performed in terms of standardizing data per capita or presenting indicator in terms of share of population. This enables the comparison of indicator values with reference data of other European countries gathered from EUROSTAT database.

The different scales of indicators are normalized to a common scale with Min-Max method. This method transforms values of indicators to a normalized scale of 0 to 1. The indicators with positive influence on urban resilience are normalized according to min-max normalization:

$$x^{+}_{i\,norm} = \frac{x_i - Min(x_i)}{Max(x_i) - Min(x_i)}, \tag{3.2.3}$$

where $x^{+}_{i\,norm}$ is the normalized indicator with positive influence on urban resilience value, x_i is the indicator value before normalization, min (x_i) is the minimum value of indicator in EUROSTAT data set, and max (x_i) is the maximum value of indicator in EUROSTAT data set.

The indicators that have a negative influence on urban resilience are normalized according to max-min normalization:

$$x^{-}_{i\,norm} = \frac{Max(x_i) - x_i}{Max(x_i) - Min(x_i)}, \tag{3.2.4}$$

where $x^{-}_{i\,norm}$ is the normalized indicator with negative influence on URI value, x_i is the indicator value before normalization, min (x_i) is the minimum value of indicator in EUROSTAT data set, and max (x_i) is the maximum value of indicator in EUROSTAT data set.

The output for normalized indicators of social dimension from urban resilience SD model simulation of baseline scenario with hazard is shown in Fig. 3.17. According to the negative and positive effects of the indicators on urban resilience considered normalization, indicator value of 0 means high elderly dependency, youth dependency, share of immigrants and unemployment rate. The value of 1 means low elderly dependency, youth dependency, share of immigrants and unemployment rate.

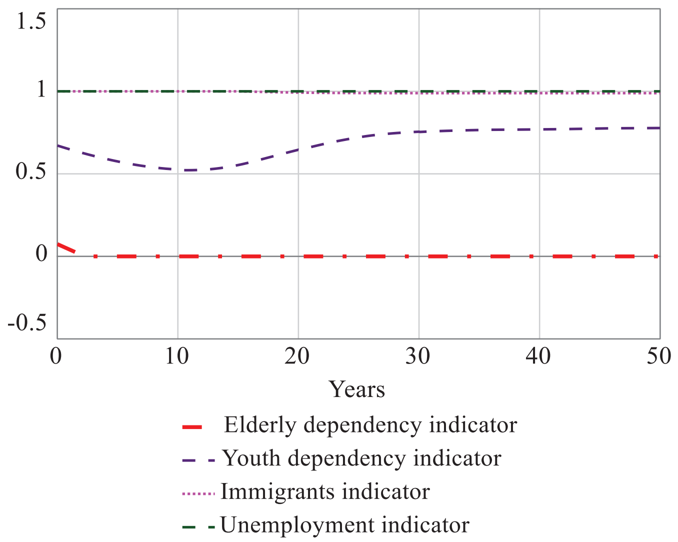


Fig. 3.17. Normalized indicator output of social dimension for baseline scenario with hazard.

The output of simulation shows that the normalized elderly dependency indicator compared to Min and Max values of European countries is low at the start of the simulation and decreases very fast to the Max value of elderly dependency in the reference data set, which after normalization is presented as value of 0. This shows that elderly dependency in Jelgava city is very high.

Normalized youth dependency indicator values are fluctuating over simulation time due to dynamic change in population age groups, at first decreasing and then increasing. The simulation output shows that youth dependency in Jelgava city is going to increase until simulation year 10 and then decrease. During all the simulation youth dependency indicator is closer to Min value of youth dependency in the reference data set, which after normalization is presented by value of 1.

Normalized values for share of immigrants and unemployment indicators are equal to value of 1 during all the simulation. This shows that Jelgava city has a low share of immigrants and unemployment equal to the Min value in the reference data set. None of the indicators show the effect of hazards on the population and therefore refer only to long-term resilience of urban area.

Normalized indicator of economic dimension GDP per capita output for the baseline scenario with hazard is reported in Fig. 3.18. The figure shows an increase in GDP per capita value over simulation time, signifying a growing economy, and also captures the effect of natural hazard in terms of decrease in indicator values in simulation year 10, 20, and 30.

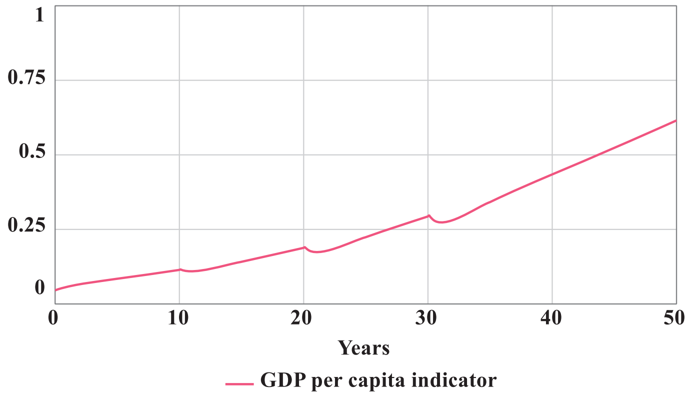


Fig. 3.18. Normalized indicator output of GDP per capita indicator for baseline scenario with hazard.

The output for normalized indicators of infrastructure and environmental dimension is presented in Figs. 3.19 and 3.20. All of the infrastructure and environmental dimension indicators provide an output without long-term trend and capture only the natural hazard impacts on urban area in short term, in this way they are describing the resilience. The normalized values of indicator from infrastructure dimension in long term are equal to 1, signifying the high infrastructure service availability in Jelgava city for all the population.

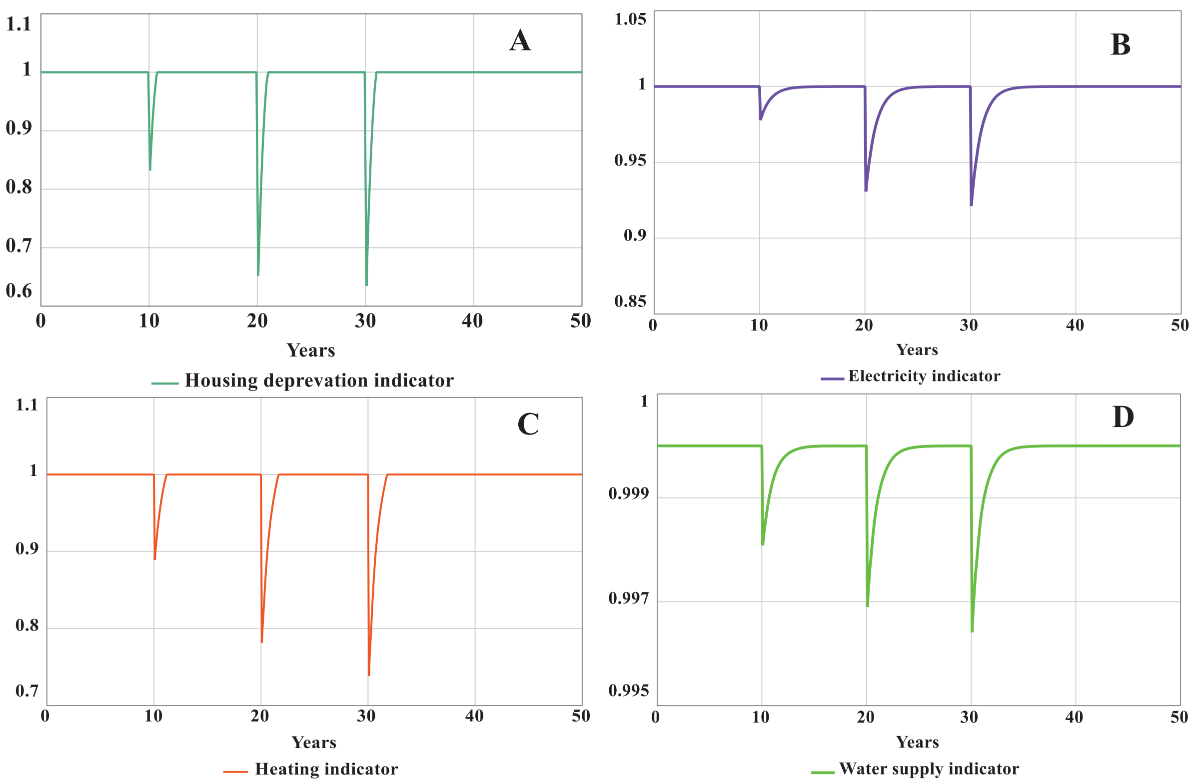


Fig. 3.19. Normalized indicator of infrastructure dimension output for baseline scenario with hazard: A – housing indicator; B – electricity supply indicator; C – heating indicator; D – water supply indicator.

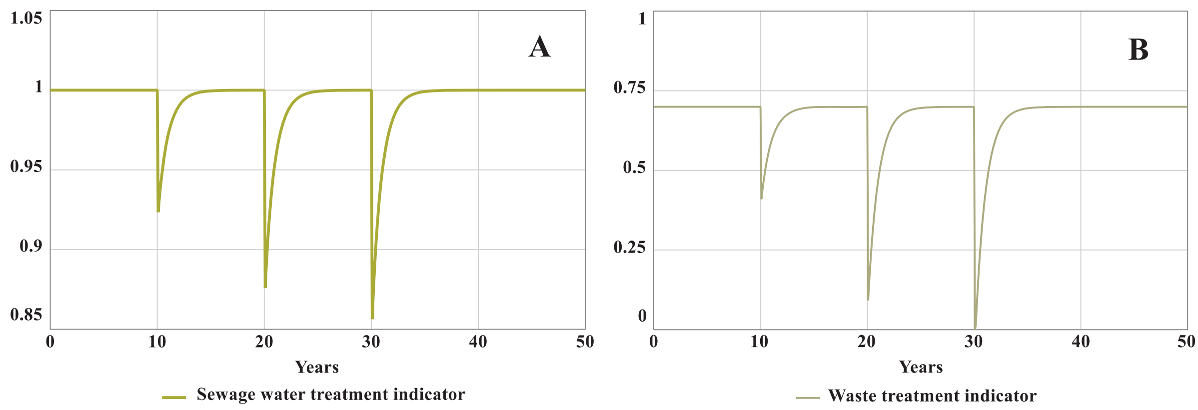


Fig. 3.20. Normalized indicator for environmental dimension output for baseline scenario with hazard: A –sewage treatment indicator; B – waste treatment indicator.

Normalized waste treatment indicator of environmental dimension shows lower value in long term than the indicators for infrastructure dimension. Such indicator value is explained as lower waste treatment service provision in Jelgava city than the Max value for waste treatment provision in reference data set for European countries.

The indicators presented here are used for creation of composite indicator-based index, which is able to present the dynamic change of urban resilience in short term and long term.

URI Definition

From the selected set of indicators, a dimensionless index for urban resilience measurement is defined – urban resilience index (URI). The definition is of URI is presented in Article 6. The index allows capturing the dynamics of urban resilience to natural hazard as estimation based on normalized indicators from different urban dimensions of the created SD model and presenting this dynamic change as a single value measurement.
The definition of URI score used in the model is presented in Equation 3.2.5 and is estimated as mean average of weighted indicators:

$$URI\ score = \frac{\sum_{i=1}^{n}(\omega_i x_{i\,norm})}{n}, \tag{3.2.5}$$

where $x_{i\,norm}$ is normalized indicator, ω_i is weight, i is number of indicator, and n is total number of indicators.

The given URI score allows to set different weights based on the need to underline the significance of the specific indicators or significance of the dimension in a study. There is no uniformly agreed methodology for individual indicator weighting. This study considers requirement for the weighing of indicator that sum of indicator weights must be equal to number of indicators to keep URI score within scale 0 to 1.

Integration of URI into Urban Resilience Model

Equation 3.5 allows to present urban resilience measurement into the proposed SD model with a dynamic metric changing over time due to changes in long-term resilience and short-term resilience.

The long-term change in URI score shown in Fig. 3.21 occurs according to the changes in the value of infrastructure dimension and environmental dimension indicators. The disruptive impact of hazard event on urban area is presented as a short-term decrease in URI values in simulation years 10, 20, and 30. This short- term change in URI values occurs due to change in the value of infrastructure dimension and environmental dimension indicators.

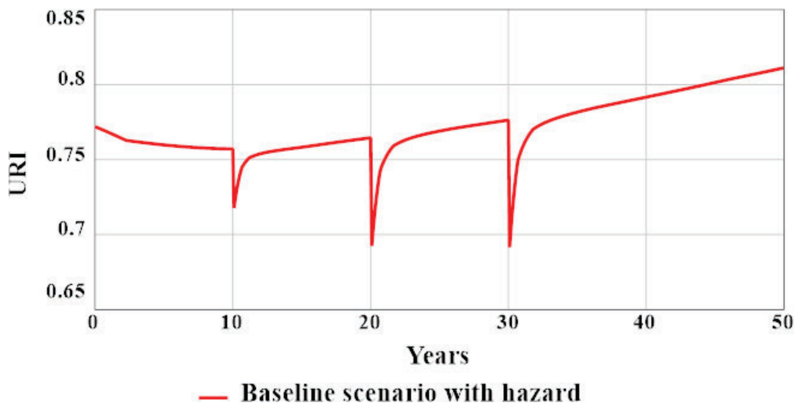


Fig. 3.21. Changes in URI score over simulation period for baseline scenario with hazard.

The long-term change in URI score shown in Fig. 3.21 occurs according to changes in the value of social dimension and economic dimension indicators. The disruptive impact of hazard event on urban area is presented as a short-term decrease in URI values in simulation years 10, 20, and 30. This short- term change in URI values occurs due to the change in the value of infrastructure dimension and environmental dimension indicators.

For the comparison of different urban resilience scenarios URI in the form of converter is not suitable because different URI scores for every time step of the simulation are presented. A more comprehensive way for comparison is to have a URI score for simulation in a single value at the end of simulation. This is achieved by making URI as a stock component in SD model.

URI score during the simulation of urban resilience SD model is used as an inflow into URI score stock. At the end of simulation, the value of stock for URI score is a cumulative value of URI scores over simulation time. This can be presented as an area below URI value over simulation period as shown in Fig. 3.22 with the coloured background.

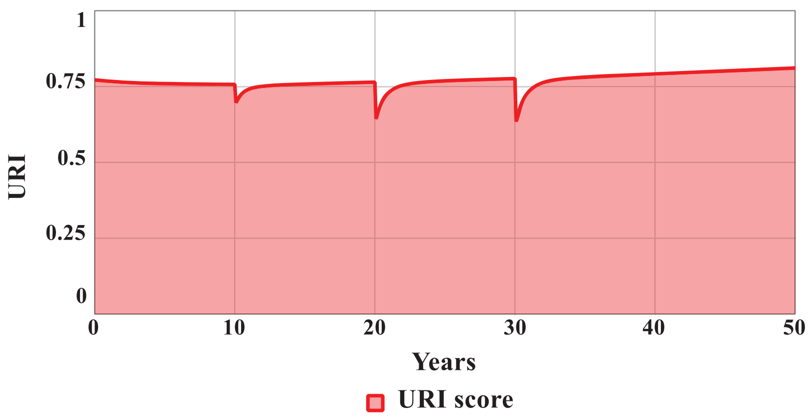


Fig. 3.22. Cumulative value of URI over simulation time presented as area.

The cumulative value of URI over simulation time can be used for comparison of different urban resilience scenarios, however, it is not in line with previously defined URI scale of measure from 0 to 1. For this purpose, the cumulative value of URI is divided by simulation time. This allows keeping the value of cumulative URI score from 0 to 1.

The Stella Architect software used to create the model derives the value of the cumulative urban resilience index from 0 to 1 after Monte Carlo simulations with an accuracy of up to three decimal places. Thus, the maximum number of different values of the city's resilience index is 1000. This number is taken into account when calculating the number of samples in Monte Carlo simulations.

Analysis of Selected Urban resilience Scenarios

Within the case study of Jelgava, two scenarios were selected for comparison with the baseline scenario. The selected scenarios are presented in Article 7. Both comparative scenarios foresee the potential effects of policy strategies aiming at increase of urban resilience by increasing the urban attractiveness and decreasing infrastructure service vulnerability to natural hazards. The changes in input parameters used for urban resilience SD model to present the effects of policy planning strategies are reported in Table 3.3.

Table 3.3

Parameters for Selected Urban Resilience Scenarios

Scenario	**Parameters**		
	CO_2 emissions	Waste recycling	Hazard effect component
Baseline scenario with hazard	18 g CO_2/kWh for heat and 400 g CO_2/kWh for electricity	0 for waste recycling factor	Coefficient 1 for $Vulnerability_i$
Urban resilience scenario 1	S-type function decrease from 18 g/kwh to 9.6 g/kWh for heat and 400 g CO_2/kWh to 215 g/kwh over simulation time 1 to 30 years	S-type function increase from 0 to 1 for waste recycling factor from simulation year 15 to 30 years	Coefficient 1 for $Vulnerability_i$
Urban resilience scenario 2	S-type function decrease from 18 g/kWh to 9.6 g/kWh for heat and 400 g/kWh to 215 g/kWh over simulation time 0 to 30 years	S-type function increase from 0 to 1 for waste recycling factor from simulation year 15 to 30 years	Coefficient of 0.5 for $Vulnerability_i$

The input parameter values for environmental dimension component CO_2 emissions in Urban resilience scenario 1 and Urban resilience scenario 2 are selected based on the estimates of 80 % decrease in of CO_2 emissions by 2050 compared to 1990. The selected S-type function describes a gradual decrease in CO_2 emissions over simulation years 0 to 30, which is equivalent to the time period of 2020 to 2050. The outputs of CO_2 emissions component for simulation of Baseline scenario with hazard and Urban resilience scenarios 1 and 2 are shown in Fig. 3.23 A. The output for Urban resilience scenario 1 and 2 shows how the selected S-type-function changes the CO_2 emissions over simulation time.

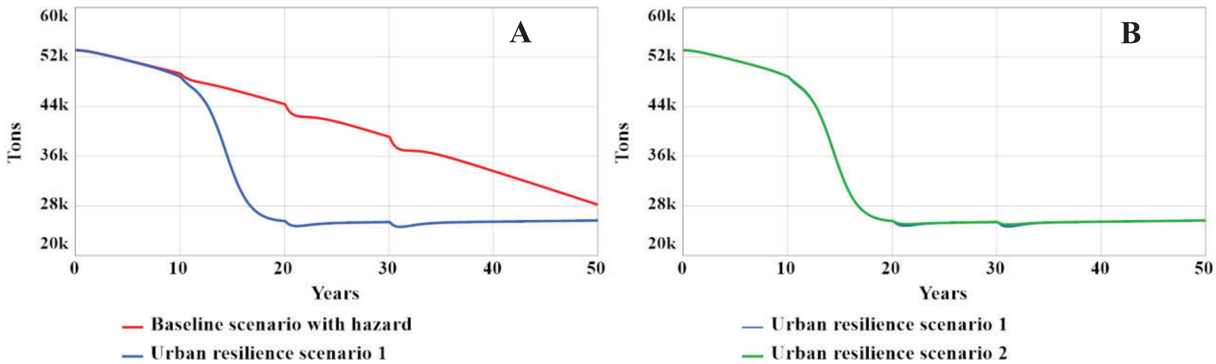


Fig. 3.23 A and B. Simulation outputs from CO_2 emission component for urban resilience scenarios.

The Urban resilience scenario 2 in addition to reduction of CO_2 emissions and increase of recycled waste foresees the reduction of hazard effect. This is considered by changing hazard effect coefficient $Vulnerability_i$ from 1 to 0.5. This results in a decrease in disruption amount in all the infrastructural services in infrastructure dimension and labour hours in economic dimension.

The simulation output from CO_2 emission component for effect of implementing Urban resilience scenario is shown in Fig. 3.23 B. There is a negligible increase in CO_2 emissions for Urban resilience scenario 2 compared to Urban resilience scenario 1 because energy provision services have a smaller disruption amount.

The simulation output for environmental dimension component waste production vs waste treatment is presented in Fig. 3.24 A and B for different urban resilience scenarios input as considered in Table 3.3. The output for waste production vs waste treatment component in Urban resilience scenario 1 and Urban resilience scenario 2 shows how the S-type function increases the ratio of recycled waste amount amount from 0 to 1 meaning that no waste is recycled at value 0 and all the waste produced is being recycled at value 1. In addition, the change of the hazard effect coefficient for $Vulnerability_i$ from 1 to 0.5 is shown in the output for Urban resilience scenario 2.

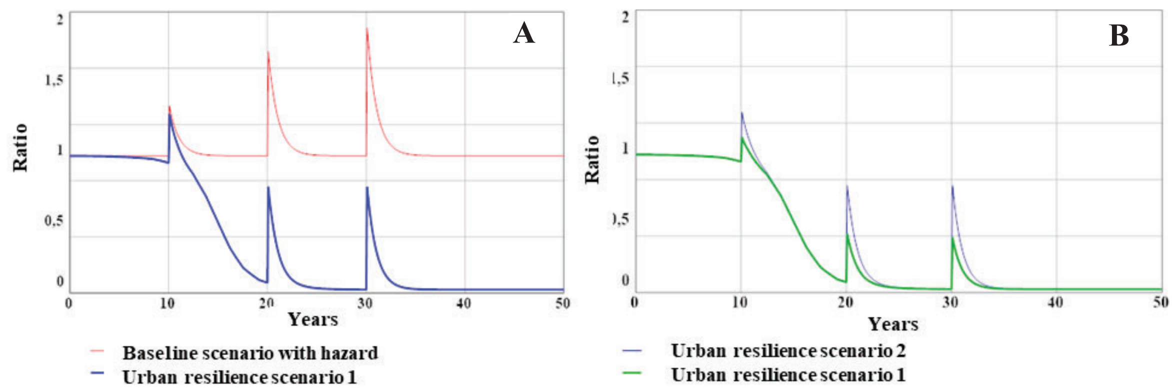


Fig. 3.24 A and B. Simulation outputs from waste production vs waste treatment component for urban resilience scenarios.

According to CLD presented in Fig. 3.3 in section "Causal loop diagrams" there is a feedback on urban attractiveness component from implementing policy strategy aiming at CO_2 emissions reduction and waste recycling increase. Due to the S-shaped function for CO_2 emission decrease and waste recycling increase, the urban attractiveness component also has a S-shaped type increase. For the purpose of this case study this S-shaped type increase is calibrated from a value of –1 to 1. In this sense, value –1 represents the historical record of population migration, which is equal to 400 people leaving the urban area per year. The urban attractiveness component value 1 is calibrated to the opposite tendency in migration, which is equal to the number 400 people arriving to the urban area per year.

The output of model simulation for population component is presented in Fig. 3.25 for urban resilience scenarios 1 compared to baseline scenario with hazard. The model output for population component shows an increase of population due to increase in urban attractiveness component. For urban resilience scenario 2 the output for population component is the same as for urban resilience scenarios 1.

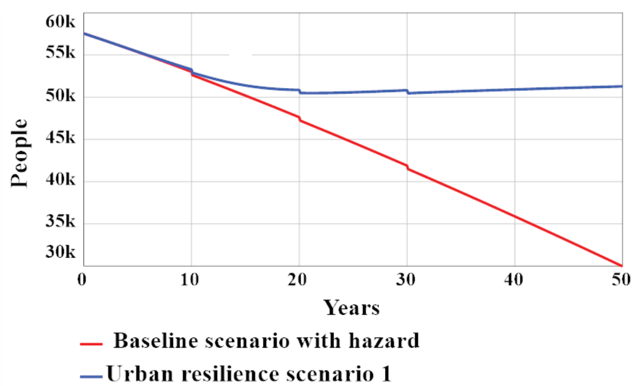


Fig. 3.25. Simulation outputs from the population component for urban resilience scenario 1.

The growth of population allows to increase the employment rate, and thus the production in economic dimension, which increases the GDP of urban area. The increase in GDP component for predefined scenarios is shown in Fig. 3.26 A and B. A notable increase of GDP for urban resilience scenario 1 is observed compared to baseline scenario, and small increase for urban resilience scenario 2 due to decrease of vulnerability in urban resilience scenario 2.

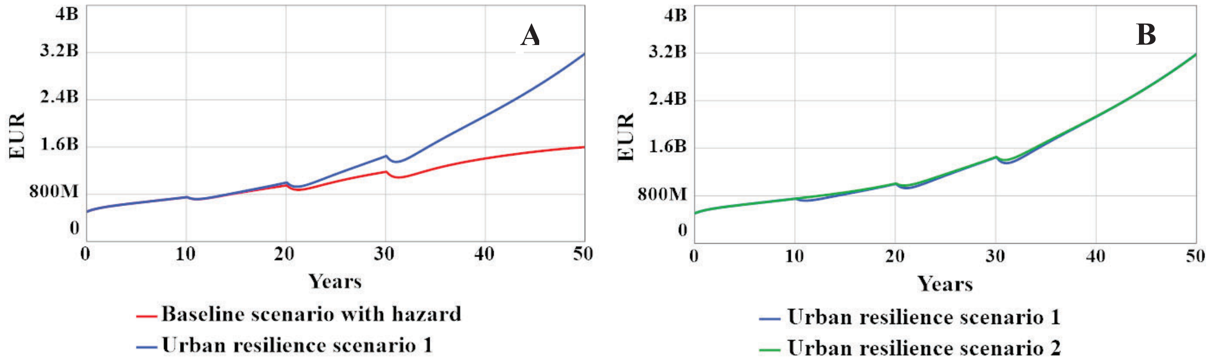


Fig. 3.26 A and B. Simulation outputs from GDP component for urban resilience scenarios.

The growth of population also increases the demand for infrastructural services, considered in infrastructure dimension of urban resilience SD model. Thus, the provision of services in terms of housing and, consequently, in electricity, water and heat supply, wastewater treatment service increases (Fig. 3.27 A and B)–(Fig. 3.31 A and B). All of the figures B mentioned here also show the decrease of hazard effect in Urban resilience scenario 2.

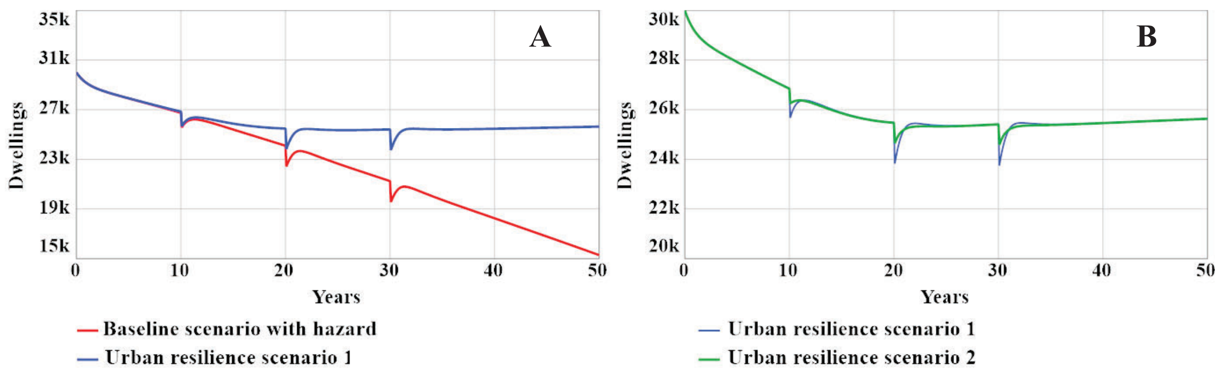


Fig. 3.27 A and B. Simulation outputs from dwellings component for urban resilience scenarios.

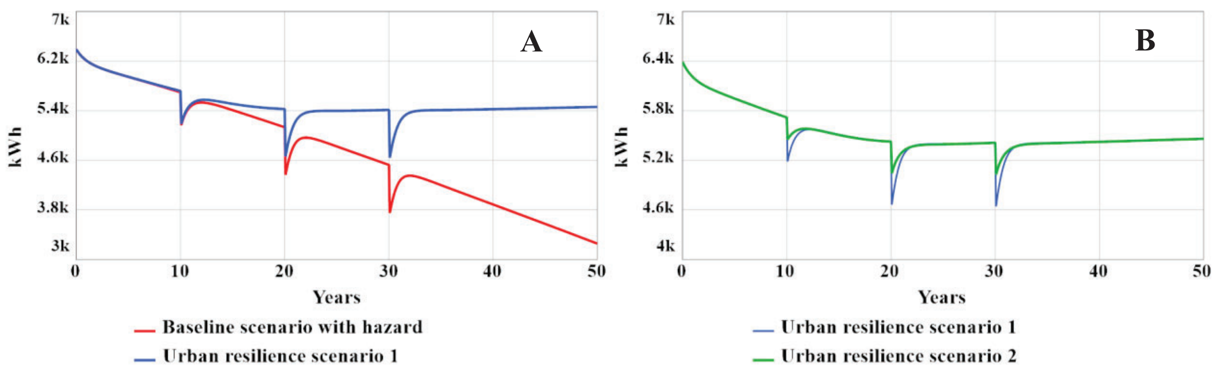


Fig. 3.28 A and B. Simulation outputs from heat supply component for urban resilience scenarios.

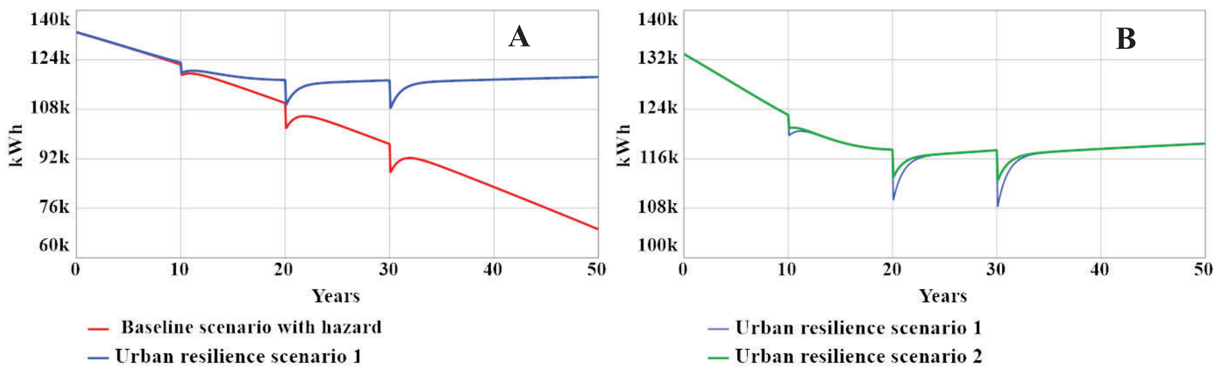


Fig.3.29 A and B. Simulation outputs from electricity supply component for urban resilience scenarios.

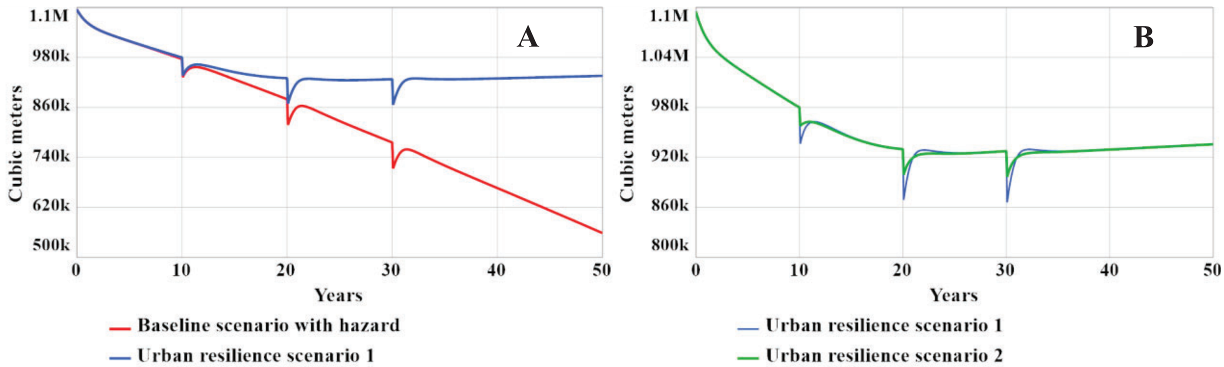


Fig. 3.30 A and B. Simulation outputs from water supply component for urban resilience scenarios.

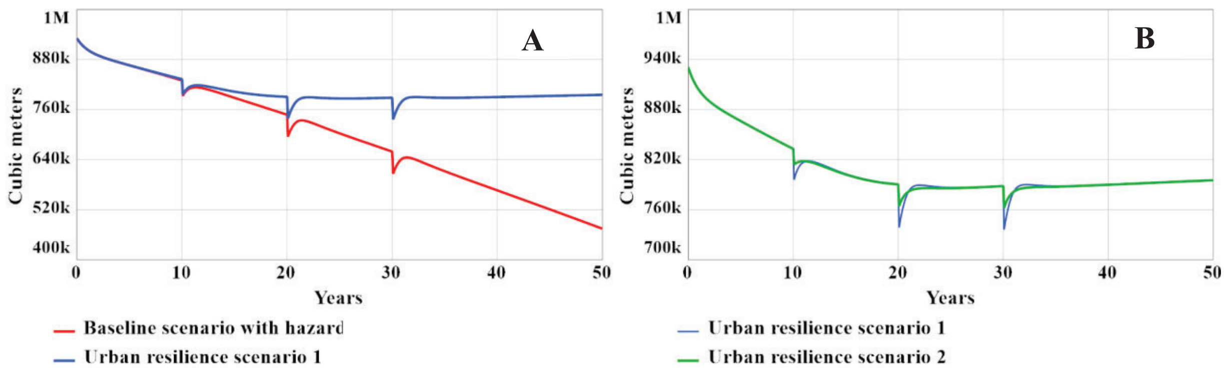


Fig. 3.31 A and B. Simulation outputs from sewage water treatment component for urban resilience scenarios.

The electricity and heat supply components of infrastructure dimension also have a feedback on the CO_2 emissions component, which is already considered when presented earlier in Fig. 3.23 A and B.

All of the components of infrastructure dimension services presented in this sub-chapter have a similar tendency within the same scenario. This shows that the created urban resilience SD model is consistent in terms of feedbacks also when changes are introduced in the predefined parameters, as reported in Table 3.3, and thus the model is considered appropriate for further urban resilience assessment with URI for different urban resilience scenarios.

Monte Carlo Simulations for Urban Resilience Scenarios

The comparison of urban resilience scenarios is performed by analysis of Monte Carlo simulation statistics for three defined scenarios: Baseline scenario with hazard, Urban resilience scenario 1 and Urban resilience scenario 2.

The results of comparison are presented in histogram type graphs as frequency of occurrence of specific cumulative URI score for predefined scenario and consequently evaluated probability of getting a certain cumulative URI score result. High probability of getting high URI score in the predefined scenario means that the scenario is more preferable.

The evaluated necessary number of trials that must be performed by Monte Carlo simulation for every scenario to achieve a 95 % confidence level of Monte Carlo simulation is equal to 286 samples according to Equation 2.4.2. The output of Monte Carlo simulation in the form of frequency of occurrence of certain cumulative URI score in Baseline scenario with hazard are shown in Fig. 3.32. The results show that the most frequent cumulative URI score in baseline scenario is from 0.761 to 0.786. Scores in period from 0.736 to 0.761 and period from 0.786 to 0.811 also occur frequently. Higher cumulative URI scores than 0.811 do not occur for Baseline scenario with hazard.

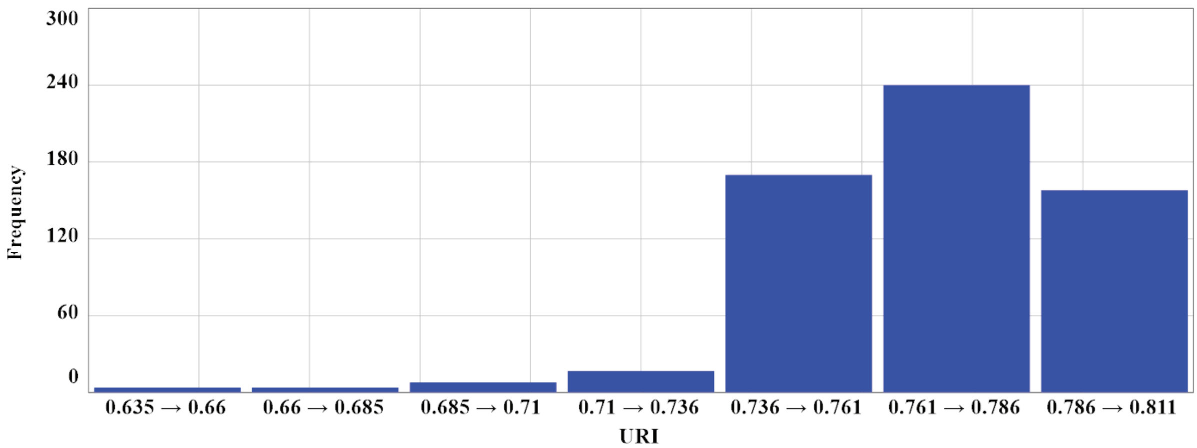


Fig. 3.32. Frequency of cumulative URI scores in Baseline scenario with hazard.

The probability of getting a certain URI score in Baseline scenario with hazard is computed from the frequency of cumulative URI score occurrence and shown in Fig.3.33. The results of statistics analysis of Monte Carlo simulations show that mean average of cumulative URI score for baseline scenario with hazard occurrence is 0.769 and the median is 0.767.

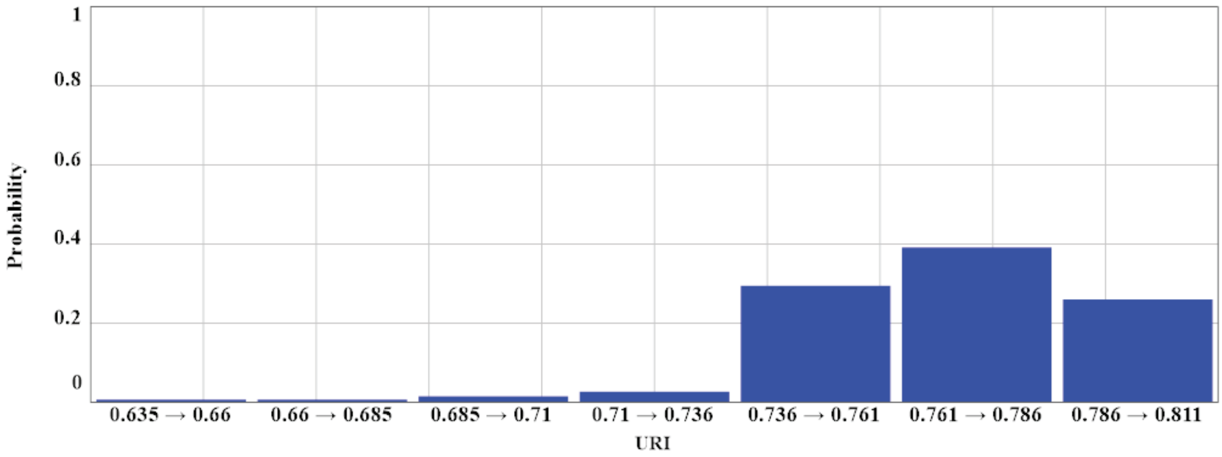


Fig. 3.33. Probability of cumulative URI scores in Baseline scenario with hazard.

The results of Monte Carlo simulation in Urban resilience scenario 1 in Fig. 3.34 show that most frequent cumulative URI score is in period from 0.761 to 0.786. Comparing Urban resilience scenario 1 to Baseline scenario with hazard, lower cumulative URI scores occur frequently for Baseline scenario with hazard than for Urban resilience scenario 1.

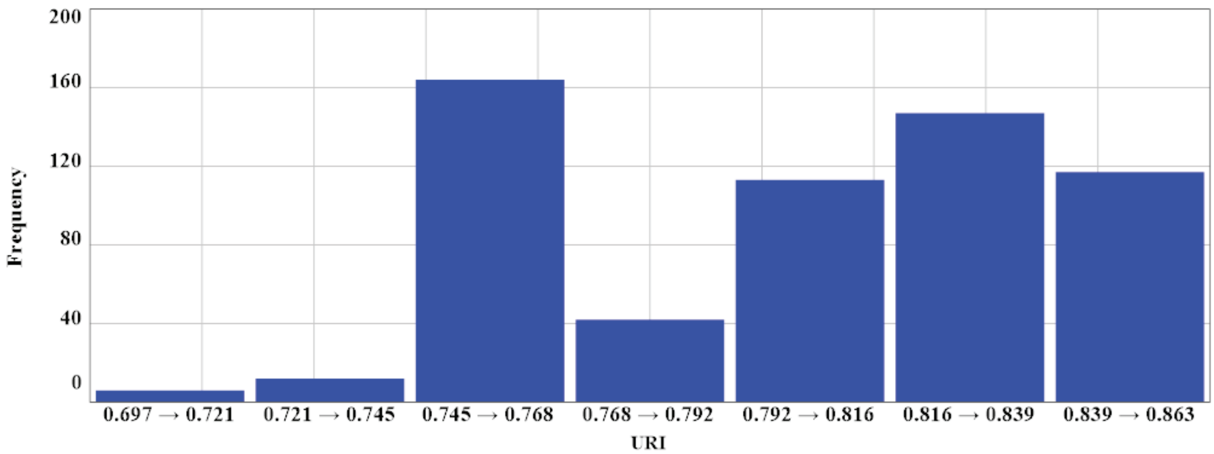


Fig. 3.34. Frequency of cumulative URI scores in Urban resilience scenario 1.

From the results presented in Fig. 3.34 the probability of getting a certain cumulative URI score in Urban resilience scenario 1 is computed and shown in Fig. 3.35. The results show that mean average of cumulative URI score in Monte Carlo simulations for Urban resilience scenario 1 is 0.802 and the median is 0.809. Thus, according to Monte Carlo simulation statistics there is a notable increase in cumulative URI score for Urban resilience scenario 1 compared to the Baseline scenario with hazard.

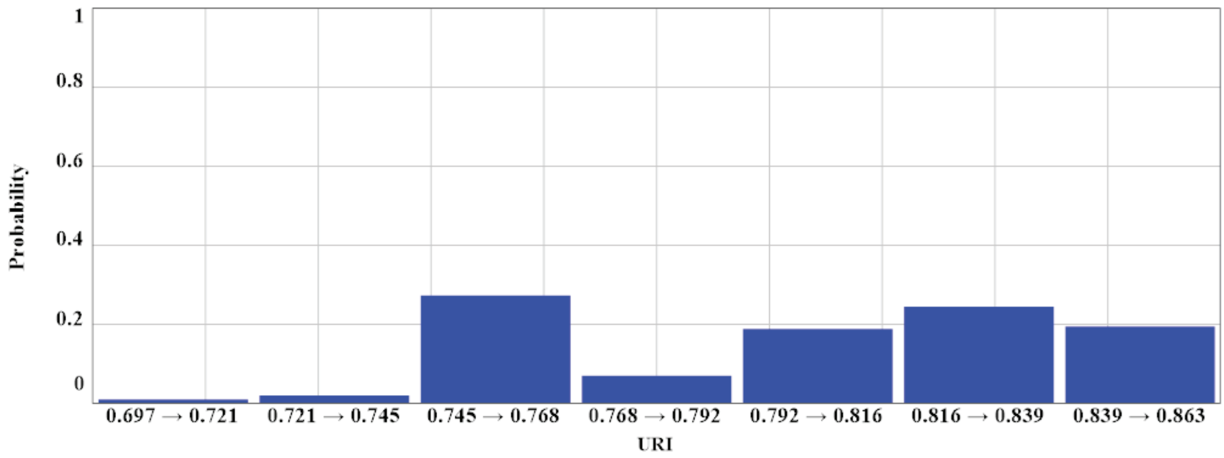


Fig. 3.35. Probability of cumulative URI scores in Urban resilience scenario 1.

The results of Monte Carlo simulation for frequency of occurrence of certain cumulative URI score in Urban resilience scenario 2 in Fig. 3.36. show that most frequent cumulative URI score in Urban resilience scenario 2 is from 0.754 to 0.772, which is lower than the most frequent score for Urban resilience scenario 1.

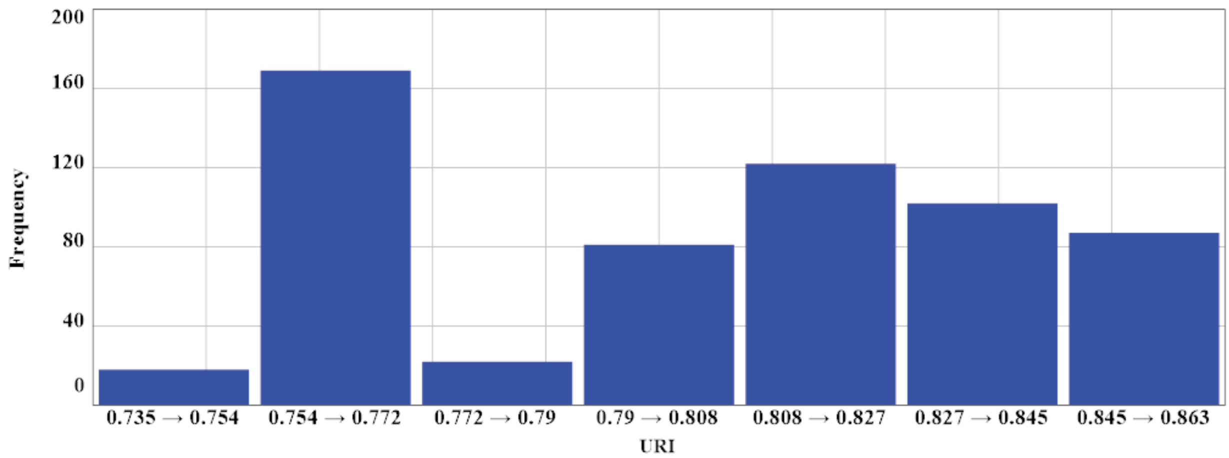


Fig. 3.36. Frequency of cumulative URI scores in Urban resilience scenario 2.

However, the statistics of probability of getting a certain URI score in Urban resilience scenario 2 is computed in Fig. 3.37 show. Mean average of cumulative URI score in Monte Carlo simulations for Urban resilience scenario 2 is 0.804 and the median is 0.811. Thus, there is a small increase in cumulative URI score for Urban resilience scenario 2 compared to Urban resilience scenario 1.

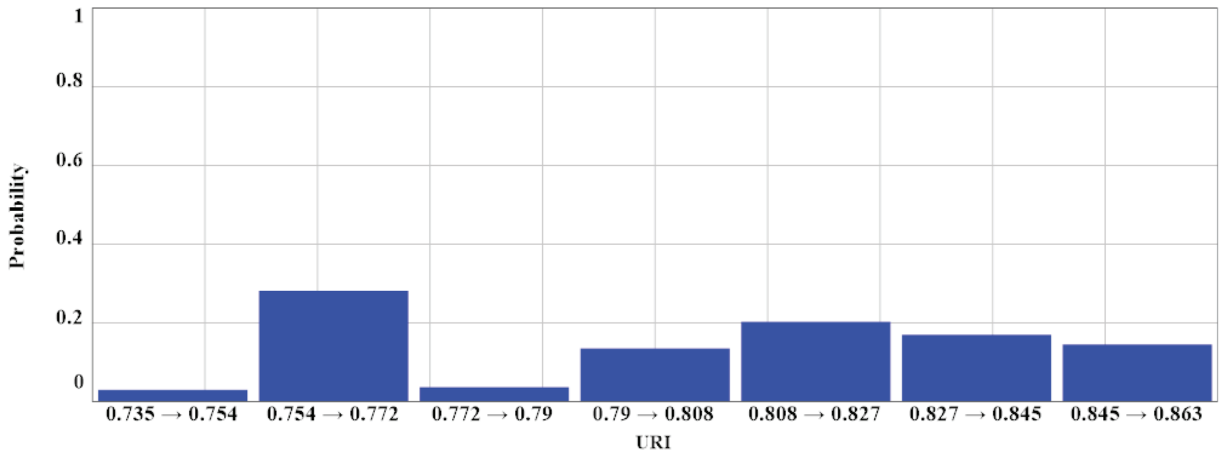


Fig. 3.37. Probability of cumulative URI scores in Urban resilience scenario 2.

The comparison of min, max, and mean average values of cumulative URI scores in Monte Carlo simulations with confidence level of 95 % for different scenarios is shown in Fig. 3.38, also presented in Article 7. The min, max, and mean average values are computed in the *Stela Architect* software with Monte Carlo simulation output. The summary of results shows that there is an increase in min, max, and mean average values of cumulative URI scores for Urban resilience scenario 1 and Urban resilience scenario 2 compared with Baseline scenario with hazard.

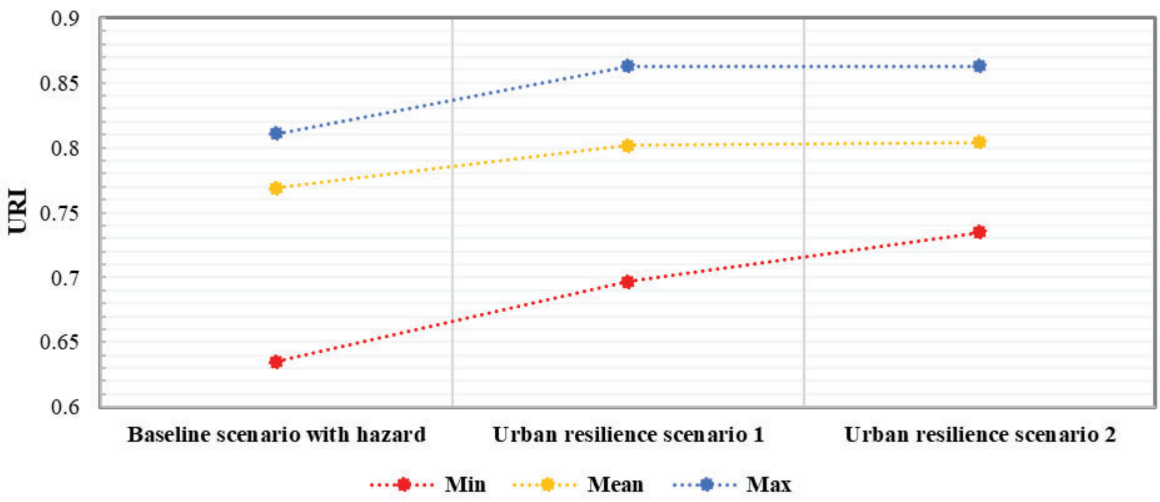


Fig. 3.38. Comparison of Monte Carlo simulation results for different scenarios.

There is a notable increase in cumulative URI score min value for Urban resilience scenario 2 compared to Urban resilience scenario 1, but only a small increase in mean average value and no increase in max value. In this case, the benefit of implementing Urban resilience scenario 2 lies in decreasing the low cumulative URI score occurrence, which is present in the probabilistic simulations with most of natural hazard events.

Summary of the Urban Resilience Scenario Comparison

The comparison of urban resilience scenarios with help of the developed tool is performed for a selected case study of Jelgava city. Three scenarios are compered: Baseline scenario with hazard, Urban resilience scenario 1, and Urban resilience scenario 2.

The Baseline scenario with hazard shows that due to the existing trend of emigration there is a decrease in the population over simulation time from 57 600 to 30 000. The used input for decreasing trend is validated according to historical data of 8 years and shows R^2 equal to 0.926694. The population emigration results in increasing social vulnerability, namely, youth and elderly dependency.

As a result of population decrease in the Baseline scenario with hazard there is also a decrease in infrastructure services (electricity supply, heating, water supply). However, the demand for services per capita remains the same and thus does not have a negative impact on Urban resilience and URI score. The GDP is increasing according to the predefined increase in productivity, also validated according to historical data of 5 years and shows R^2 equal to 0.955643. The URI score in baseline scenario shows a small decrease in the start of simulation due to increase of social vulnerability and increase in the long term mainly because of high increase in GDP. The mean average of URI score in Monte Carlo simulations for baseline scenario with hazard is 0.769.

Parameters for Urban resilience scenario 1 consider increase of renewable energy share and recycled waste ratio. According to the predefined CLD in Fig. 3.3 in section "Causal loop diagrams", this increases urban attractiveness, and thus emigration is decreased and immigration increases.

The results of Urban resilience scenario 1 show a smaller decrease in population over simulation time, from 57 600 to 51 300 compared to Baseline scenario. This results in a bigger increase of GDP due to more working age people that can be employed. In addition, the youth dependency in Urban resilience scenario 1 is decreasing over simulation time. This results in an increase in cumulative URI score. The mean average of cumulative URI score in Monte Carlo simulations for Urban resilience scenario 1 is 0.802.

The comparison of the simulated scenarios shows that there is an increase in urban resilience according to cumulative URI score due to decrease of social vulnerability, namely, youth and elderly dependency, and increase in GDP in the long term, which is the result of stopping the emigration by improving urban attractiveness. This suggests that policies aiming at increasing urban attractiveness through increase of renewable energy share, increase of waste recycling, and thus improving the environment have positive impact on urban resilience in the long term by decreasing the social vulnerability.

Parameters for Urban resilience scenario 2 besides already defined parameters in Urban resilience scenario 1 consider decrease of exposed infrastructure vulnerability. This results in additional increase in mean average of cumulative URI score up to 0.804 in Monte Carlo simulations for Urban resilience scenario 2. In addition, a notable increase in min value of cumulative URI score up to 0.735, which corresponds to the decrease in natural impact in simulated scenarios.

The comparison of Urban resilience scenarios 1 and 2 shows a rather small increase in urban resilience because the decrease of vulnerability affects the URI score in short term only when hazard event impact occurs. The result of this study suggests that strengthening urban resilience by decreasing vulnerability of infrastructure services shows a significant increase in urban resilience in terms of decreasing the worst-case scenario probabilities. The results are the output of proxy data used for impact and recovery process. The real benefits of decreasing infrastructure vulnerability can be even higher. For application of the tool for policy scenario planning in practice more precise data on response and recovery to disaster is necessary than currently available.

DISCUSSION

Composite indicator measures the inherent resilience by assessing different criteria and provides a holistic measurement in a single score. The main limitation is that inherent resilience does not allow to provide complete understanding of urban resilience according to its definition because it lacks the ability to evaluate the dynamic change in urban system over time. Also, as reported in literature, the data available for many of the criterions used in composite indicator is not up to date or is completely lacking in statistics databases.

Probabilistic method provides insight of system abilities to react and cope with certain hazard. It will provide a more complete overview about specific system or parts of system functionality over time than a generalized measurement of composite indicator. However, when used alone, probabilistic method is limited to provide a continuous event simulation. The method allows to capture systems performance as discrete events in time. Also, the probabilistic methods do not consider the feedback effects over time, and thus are not used for evaluating resilience of complex systems involving several infrastructure systems and socio-economic aspects.

System dynamics is a continuous event simulation method, which is suitable for modelling a dynamic change over time in a complex system such as urban area. The classic system dynamics model simulation provides a deterministic simulation output, which does not allow to capture all the probable scenarios of natural hazard events. The output of system dynamics models for a large system such as urban areas is hard to interpret because of the complexity of modelled system and large number of involved components.

The advantage of the developed tool is that based on system dynamics model it allows to replace existing linear models currently used for resilience assessment. The tool is appropriate to analyse dynamic change in urban area considering its multi dimensionality and looking at feedbacks between components of the multiple dimensions.

The structure of the urban system dynamics model includes social, economic, infrastructure, and environmental dimensions with two main feedback loops. The social, infrastructure and environmental dimensions feedback loop that includes the dynamic change in urban area is based on social factors and urban attractiveness factor. The social and economic feedback loop includes the feedback of social factors on economy.

The disruptive effect on urban systems is integrated in system dynamics model with probabilistic simulation. The disruptive effect considers loss of life in social dimension, disruption of infrastructure services in infrastructure dimension, and decrease in labor hours in economic dimension. The recovery from natural hazard impact can be considered with different recovery functions over time based on available data. This is important for precisely evaluating the disaster risk reduction policies. In the selected case study, only proxy data on disruptive effects and recovery is used because of unavailable information about such processes. This underlines that also the information gathering in disaster risk reduction field must be improved.

To perform a comparison of model output with multiple dimensions, a composite index approach is used. Indicators are selected in each of the dimensions to represent the dynamic change in urban functionality level occurring in the long term and short term. The long-term changes are mainly occurring in social and economic dimensions and thus are represented by social and economic dimension indicators. The short-term changes that are mainly occurring in infrastructure and environmental dimension are presented by dimension indicators.

The normalization of selected indicators is performed to bring them to a common scale. The output of composite indicator is urban resilience index (URI), which shows the urban resilience of urban area in a holistic way and in this way also allows to compare different urban resilience scenarios with help of a single score. However, due to probabilistic simulation the same scenario has different output in every simulation run. Thus, the Monte Carlo simulations are used to overcome the problem of different output in every simulation run. The Monte Carlo simulation provides probability statistics of getting a certain URI score for selected model input.

The analysis of the study of Monte Carlo simulations for different urban resilience scenarios used for Jelgava case shows that according to the defined causal loops in the model and the definition of URI, there is a notable increase in urban resilience in the long term, when the selected urban resilience strategy is to increase urban attractiveness by decreasing the emissions and increasing recycling. In the specific case, the increase of urban resilience occurs due to the positive effect on the decrease of social vulnerability, caused by increase of working age population, which according to the defined causal loop of the model migrates to the urban area due to higher urban attractiveness. Thus, the young population and elderly population dependency decreases, labour power increases, also enabling increase in employment rate and higher productivity and the rate of GDP growth.

The analysis of Monte Carlo simulations for urban resilience scenarios used for Jelgava case study shows that urban resilience strategy for decreasing the vulnerability increases the minimum URI score in simulations, but there is no increase in maximum URI scores compared to the strategy aiming at increase of urban attractiveness. According to the defined causal loops in the model and the definition of URI, such model behaviour shows that over the benefits of urban resilience increase in short term does not surpass the benefit of urban resilience increase in the long term, but are rather an added value to the long-term benefits.

Such output is reasonable considering that proxy data on disruptive effects and recovery are used for the case study and show that the model suits the intended purpose of evaluation of different urban resilience strategies, but for precise data on response and recovery processes of all types of infrastructure should be used with consideration of reference to time scale for urban resilience assessments in practice.

CONCLUSIONS

In the Thesis a novel tool for urban resilience to natural hazards assessment is developed. The tool integrates three quantitative methods that are used for resilience assessment: composite indicator, probabilistic simulation, and system dynamics. In order to integrate the methods in a single tool, methods are examined through a separate case studies in the context of Latvia. The findings of these case studies allow to understand the shortcomings of methods of resilience assessment. The content and structure of the tool is validated and different urban resilience scenarios are tested in a local case study of Jelgava city and defined for the natural hazard of spring floods.

The main conclusions of the Thesis are as follows.

- The integration of three methods – composite indicator, probabilistic simulation, and system dynamics, within the developed tool allows to overcome the limitations of every method, which are reported in literature. Specifically, the implementation of probabilistic simulation in system dynamics model with output in the form of index allows to capture all the possible outcomes of different urban resilience scenarios with consideration of the dynamic change in the urban system and perform comparison of these different urban resilience scenarios in a holistic way.
- The results of model validation and simulation in a case study show that the tool is suitable for different urban resilience scenario evaluation. The multi-dimensionality of the tool and feedbacks between the defined dimensions allow to capture the tradeoffs occuring in different dimensions of urban areas, as intended by the defined causal loops.
- The developed urban resilience tool is sensitive enough to capture the effects of different urban resilience strategies both in short term and long term, as shown by the summary of Monte Carlo simulation results for different urban resilience scenarios in the case study for Jelgava city. Thus, the tool can be used for comparison of different urban resilience strenthening strategies in order to understand the possible tradeoffs of the selected strategies.
- The analysis of different urban resilience scenarios shows that there is a notable increase in urban resilience in the long term when the selected urban resilience strategy is aiming at increase of urban attractiveness. Cosequently, such strategy has a possitive effect on the decrease of social vulnerability, and thus increases urban resilience.
- The analysis of different urban resilience scenarios shows that over long term the benefits of decreasing vulnerability of infrastructure in short term do not surpas the benefit of decreasing social vulnerability increase in the long term, but are rather an addedd value to the long-term benefits of social vulnerability decrease, and thus also the increase of urban resilience.

RECOMMENDATIONS

The developed tool has proved to serve the indented purpose. Future research in the direction of dynamic urban resilience to natural hazard assessment should consider the results of this study and following recommendations.

- The developed tool can be used for wider application in policy planning, taking into account that the tradeoffs between short-term and long-term urban resilience strategies are limited to the causal loops defined in the dynamic structure of the model.
- When performing the comparison of urban resilience scenarios to evaluate urban resilience strategies, additional system dynamics sub-models can be implemented to consider relevant tradeoffs for different urban resilience strategies. As an example, such sub-models can include additional infrastructure, like roads and telecomunications, or factors influencing social vulnerability, like education, hospitals, and different social groups.
- The effects of urban attractiveness considered in the developed tool should be studied in different areas. Additional factors that have effect on urban attactiveness should be studied.
- The simulation of natural hazard is made by probabilistic simulation, which has a certain sampling bias. The natural hazard events are predefined defined as random events with certain probability of occurance, which does not change in urban resilienc escenario. The dynamic change of natural hazard event probabilities can be introduced in a more advanced version of the developed tool.
- The developed tool strongly depends on the available data about urban areas. The availability of data for assessment of urban resilience in short term is an issue for performing precise comparison of different urban resilience scenarios. The data avilability on disaster response and recovery for different dimensions of urban areas should be improved, and thus the availability of indicators for normalization of URI scores to enable wider application the tool in policy planning.

REFERENCES

[1] U. Ranke, *Natural disaster risk management: Geosciences and social responsibility*. 2016.

[2] EM-DAT, CRED / UCLouvain, Brussels, Belgium – www.emdat.be (D. Guha-Sapir).

[3] A. Keating and S. Hanger-Kopp, “Practitioner perspectives of disaster resilience in international development,” *Int. J. Disaster Risk Reduct.*, vol. 42, 2020, doi: 10.1016/j.ijdrr.2019.101355.

[4] Gu, Danan. Exposure and vulnerability to natural disasters for world's cities. United Nations, Department of Economics and Social Affairs, Population Division, Technical Paper No. 4. 2019.

[5] CRED, “The Human Cost of Natural Disasters,” 2015.

[6] European Environment Agency, “Mapping the impacts of natural hazards and technological accidents in Europe”, technical report no. 13. 2010.

[7] P. Weyrich, A. Scolobig, and A. Patt, “Dealing with inconsistent weather warnings: effects on warning quality and intended actions,” *Meteorol. Appl.*, vol. 26, pp. 569–583, 2019, doi: 10.1002/met.1785.

[8] Asian Development Bank, “Global Increase in Climate-Related Disasters Evaluation,” p. 45, 2015.

[9] D. Paton, D. Johnston, and J. Rovins, *Disaster Resilience: An integrated approach (2nd Ed).* 2017.

[10] J. E. Suk, E. C. Vaughan, R. G. Cook, and J. C. Semenza, “Natural disasters and infectious disease in Europe: a literature review to identify cascading risk pathways,” *Eur. J. Public Health*, pp. 928–935, 2019, doi: 10.1093/eurpub/ckz111.

[11] Civil Protection and Disaster Management Law, 2016, [Online]. Available: https://likumi.lv/ta/en/id/282333-civil-protection-and-disaster-management-law.

[12] IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

[13] International Monetary Fund. Strategy, Policy, & Review Department;International Monetary Fund. Western Hemisphere Dept.;International Monetary Fund. Asia and Pacific Dept “Building Resilience in Developing Countries Vulnerable to Large Natural Disasters,” *Policy Pap.*, vol. 19, no. 020, June 2019, doi: 10.5089/9781498321020.007.

[14] A. H. Palermo Kuss, “Barriers To Climate Adaptation in Urban Areas: the Case of Water Crisis in the Metropolitan Region of São Paulo,” *Bras. J. Brazilian Stud.*, vol. 5, pp. 76–107, 2017, doi: 10.25160/v5i2.d4.

[15] “The natural disasters of 2018 in figures | Munich Re.” [Online]. Available: https://www.munichre.com/topics-online/en/climate-change-and-natural-disasters/natural-disasters/the-natural-disasters-of-2018-in-figures.html (accessed Oct. 14, 2020).

[16] WTO, “Natural Disasters and Trade: Study I,” *Third Symp. Nat. Disasters Trade*, 2019, [Online]. Available: https://www.wto.org/english/tratop_e/devel_e/study1_sympnaturaldisaster29112019_e.pdf. (accessed Oct. 14, 2020).

[17] L. Bevere, M. Gloor, and A. Sobel, “Natural catastrophes in times of economic accumulation and climate change,” *Swiss Re sigma*, no. 2, 2020.

[18] W. R. Berghuijs, S. T. Allen, S. Harrigan, and J. W. Kirchner, “Growing Spatial Scales of Synchronous River Flooding in Europe,” *Geophys. Res. Lett.*, vol. 46, pp. 1423–1428, 2019, doi: 10.1029/2018GL081883.

[19] G. Forzieri *et al.*, “Multi-hazard assessment in Europe under climate change,” *Clim. Change*, vol. 137, pp. 105–119, 2016, doi: 10.1007/s10584-016-1661-x.

[20] J. G. Carter, “Climate change adaptation in European cities,” *Curr. Opin. Environ. Sustain.*, vol. 3, pp. 193–198, 2011, doi: 10.1016/j.cosust.2010.12.015.

[21] G. Forzieri, L. Feyen, R. Rojas, M. Flörke, F. Wimmer, and A. Bianchi, “Ensemble projections of future streamflow droughts in Europe,” *Hydrol. Earth Syst. Sci.*, vol. 18, pp. 85–108, 2014, doi: 10.5194/hess-18-85-2014.

[22] Joshua J. LeMonte, *et al.* "Sea Level Rise Induced Arsenic Release from Historically Contaminated Coastal Soils" *Sparks Environmental Science & Technology.,* vol. 51, pp. 5913-5922, 2017, doi: 10.1021/acs.est.6b06152.
[23] B. Jongman *et al.*, "Increasing stress on disaster-risk finance due to large floods," *Nat. Clim. Chang.*, vol. 4, pp. 264–268, 2014, doi: 10.1038/nclimate2124.
[24] Poschlod, B., Ludwig, R., and Sillmann, J."Return levels of sub-daily extreme precipitation over Europe," *Earth Syst. Sci. Data Discuss.*, in review, 2020, https://doi.org/10.5194/essd-2020-145.
[25] S. Hochrainer-Stigler, R. Mechler, G. Pflug, and K. Williges, "Funding public adaptation to climate-related disasters. Estimates for a global fund," *Glob. Environ. Chang.*, vol. 25, pp. 87–96, 2014, doi: 10.1016/j.gloenvcha.2014.01.011.
[26] *Europe and Central Asia - Country risk profiles for floods and earthquakes (English).* Washington, D.C. : World Bank Group. http://documents.worldbank.org/curated/en/958801481798204368/Europe-and-Central-Asia-Country-risk-profiles-for-floods-and-earthquakes
[27] *Preliminary flood risk assessment for 2019-2024*. Latvian Environment, Geology and Meteorology Centre, 2019.
[28] Order No. 160/5000 of the Cabinet of Ministers of February 4, 2020 "On the National Energy and Climate Plan of Latvia for 2021–2030". Available: https://likumi.lv/ta/id/312423.
[29] *Sendai Framework for Disaster Risk Reduction 2015-2020*. Third UN World Conference on Disaster Risk Reduction in Sendai, Japan, on March 18, 2015.
[30] *Paris Agreement*. 2020 United Nations Framework Convention on Climate Change, 2015.
[31] *New Urban Agenda*. United Nations (Habitat III), 2017.
[32] "Climate Change Policy Brief," Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. June, 2016.
[33] UN, "Sustainability goal 13 'Take urgent action to combat climate change and its impacts," (Online). Available: https://unstats.un.org/sdgs/report/2020/goal-13. (accessed Oct. 14, 2020).
[34] UNDRR (2019), Global Assessment Report on Disaster Risk Reduction, Geneva, Switzerland, United Nations Office for Disaster Risk Reduction (UNDRR).
[35] Cepin, M. (Ed.), Bris, R. (Ed.). (2017). *Safety and Reliability. Theory and Applications*. London: CRC Press, https://doi.org/10.1201/9781315210469.
[36] European Commission Staff, "Action Plan on the Sendai Framework for Disaster Risk Reduction 2015-2030," p. 27, 2016, [Online]. Available: http://ec.europa.eu/echo/sites/echo-site/files/1_en_document_travail_service_part1_v2.pdf. (accessed Oct. 14, 2020).
[37] "Action Plan for Resilience in Crisis Prone Countries 2013-2020," *European Commission Staff Work. Doc.*, 2013.
[38] E. M. Stumpp, "New in town? On resilience and ' Resilient Cities,'" *Cities*, vol. 32, pp. 164–166, 2013, doi: 10.1016/j.cities.2013.01.003.
[39] A. Priority, G. Action, B. Dunford, and S. Jones, "Food Security and Resilience," April, 2018.
[40] "Facing Extreme Climate Events," *GCCA+ Rev. Clim. ISSUE*, vol. 1, no. 2, pp. 1–12, 2018, doi: 10.26418/jp2d.v1i2.28.
[41] "Clima East Policy Project: Overview of results" (Online). Available: https://www.euneighbours.eu/sites/default/files/publications/2017-05/Clima-East-Final-Brochure-2017-2.pdf (accessed Oct. 14, 2020).
[42] A. Rizzo, "Transparency of Climate Action in the ENPI South region. An assessment of the capacity of South Mediterranean countries to undertake Measurement, Reporting and Verification (MRV) and related challenges," pp. 1–52, 2016.
[43] Decision 1313/2013/EU of the European Parliament and of the Council of Dec. 17, 2013, revised by Decision 2019/420/EU of the European Parliament and of the Council of Mar. 13, 2019.
[44] F. Z. Giustiniani, "Something old, something new: Disaster risk reduction in international law," *QIL, Zoom-in*, vol. 49, 2018, pp. 7–27.
[45] Civil Protection and Disaster Management Law. Available: https://likumi.lv/ta/id/282333. (accessed Oct. 14, 2020).
[46] T. Aven, "How some types of risk assessments can support resilience analysis and management," *Reliab. Eng. Syst. Saf.*, vol. 167, pp. 536–543, 2017, doi: 10.1016/j.ress.2017.07.005.
[47] A. Rose, *Defining and Measuring Economic Resilience from a Societal, Environmental and*

Security Perspective. 2017.
[48] B. L. Turner, “Vulnerability and resilience: Coalescing or paralleling approaches for sustainability science?,” *Glob. Environ. Chang.*, vol. 20, pp. 570–576, 2010, doi: 10.1016/j.gloenvcha.2010.07.003.
[49] T. P. Bostick, T. H. Holzer, and S. Sarkani, “Enabling Stakeholder Involvement in Coastal Disaster Resilience Planning,” *Risk Anal.*, vol. 37, pp. 1181–1200, 2017, doi: 10.1111/risa.12737.
[50] R. Leichenko, “Climate change and urban resilience,” *Curr. Opin. Environ. Sustain.*, vol. 3, pp. 164–168, 2011, doi: 10.1016/j.cosust.2010.12.014.
[51] P. Romero Lankao and H. Qin, “Conceptualizing urban vulnerability to global climate and environmental change,” *Curr. Opin. Environ. Sustain.*, vol. 3, pp. 142–149, 2011, doi: 10.1016/j.cosust.2010.12.016.
[52] A. X Sanchez, J. van der Heijden, and P. Osmond, “The city politics of an urban age: urban resilience conceptualisations and policies,” *Palgrave Commun.*, vol. 4, 2018, doi: 10.1057/s41599-018-0074-z.
[53] D. E. Alexander, “Resilience and disaster risk reduction: an etymological journey,” *Nat. Hazards Earth Syst. Sci. Discuss.*, vol. 1, pp. 1257–1284, 2013, doi: 10.5194/nhessd-1-1257-2013.
[54] F. S. Brand and K. Jax, “Resilience as a Descriptive Concept and a Boundary Object,” *Ecol. Soc.*, vol. 12, p. art23, 2007, [Online]. Available: http://www.ecologyandsociety.org/vol12/iss1/art23/%0ASynthesis. (accessed Oct. 14, 2020).
[55] Y. Wu, W. Que, Y.-G. Liu, L. Cao, S.-B. Liu, and J. Zhang, “Is resilience capacity index of Chinese region performing well? Evidence from 26 provinces,” 2020, doi: 10.1016/j.ecolind.2020.106088.
[56] S. Libralato and D. Agnetta, “From ecological trade-offs to resilience: insights from exploited marine ecosystems,” *Curr. Opin. Syst. Biol.*, vol. 13, pp. 136–141, 2019, doi: 10.1016/j.coisb.2018.12.005.
[57] T. Li, Y. Dong, and Z. Liu, “A review of social-ecological system resilience: Mechanism, assessment and management,” *Sci. Total Environ.*, vol. 723, p. 138113, 2020, doi: 10.1016/j.scitotenv.2020.138113.
[58] A. Clare, R. Graber, L. Jones, and D. Conway, “Subjective measures of climate resilience: What is the added value for policy and programming?,” *Glob. Environ. Chang.*, vol. 46, pp. 17–22, 2017, doi: 10.1016/j.gloenvcha.2017.07.001.
[59] P. N. Lal *et al.*, *National systems for managing the risks from climate extremes and disasters*, vol. 9781107025. 2012.
[60] R. Friend and M. Moench, “What is the purpose of urban climate resilience? Implications for addressing poverty and vulnerability,” *Urban Clim.*, vol. 6, pp. 98–113, 2013, doi: 10.1016/j.uclim.2013.09.002.
[61] *Fiscal Resilience to Natural Disasters*. 2019.
[62] S. Shamsuddin, “Resilience resistance: The challenges and implications of urban resilience implementation,” *Cities*, vol. 103, p. 102763, 2020, doi: 10.1016/j.cities.2020.102763.
[63] P. Aldunce, R. Beilin, M. Howden, and J. Handmer, “Resilience for disaster risk management in a changing climate: Practitioners’ frames and practices,” *Glob. Environ. Chang.*, vol. 30, pp. 1–11, 2015, doi: 10.1016/j.gloenvcha.2014.10.010.
[64] M. Wolfram, N. Frantzeskaki, and S. Maschmeyer, “Cities, systems and sustainability: status and perspectives of research on urban transformations,” *Curr. Opin. Environ. Sustain.*, vol. 22, pp. 18–25, 2016, doi: 10.1016/j.cosust.2017.01.014.
[65] S. Basu, C. S. E. Bale, T. Wehnert, and K. Topp, “A complexity approach to defining urban energy systems,” *Cities*, vol. 95, p. 102358, 2019, doi: 10.1016/j.cities.2019.05.027.
[66] A. Botequilha-Leitão and E. R. Díaz-Varela, “Performance Based Planning of complex urban social-ecological systems: The quest for sustainability through the promotion of resilience,” *Sustain. Cities Soc.*, vol. 56, 2020, doi: 10.1016/j.scs.2020.102089.
[67] J. M. Diaz-Sarachaga and D. Jato-Espino, “Development and application of a new Resilient, Sustainable, Safe and Inclusive Community Rating System (RESSICOM),” *J. Clean. Prod.*, vol. 207, pp. 971–979, 2019, doi: 10.1016/j.jclepro.2018.10.061.
[68] S. Roostaie, N. Nawari, and C. J. Kibert, “Sustainability and resilience: A review of definitions,

relationships, and their integration into a combined building assessment framework," *Build. Environ.*, vol. 154, pp. 132–144, 2019, doi: 10.1016/j.buildenv.2019.02.042.
[69] C. Wamsler, E. Brink, and C. Rivera, "Planning for climate change in urban areas: From theory to practice," *J. Clean. Prod.*, vol. 50, pp. 68–81, 2013, doi: 10.1016/j.jclepro.2012.12.008.
[70] S. Meerow, J. P. Newell, and M. Stults, "Defining urban resilience: A review," *Landsc. Urban Plan.*, vol. 147, pp. 38–49, 2016, doi: 10.1016/j.landurbplan.2015.11.011.
[71] D. G. Angeler, C. R. Allen, A. S. Garmestani, L. H. Gunderson, and I. Linkov, "Panarchy use in environmental science for risk and resilience planning," *Environ. Syst. Decis.*, vol. 36, pp. 225–228, 2016, doi: 10.1007/s10669-016-9605-6.
[72] A. J. Imperiale and F. Vanclay, "Experiencing local community resilience in action: Learning from post-disaster communities," *J. Rural Stud.*, vol. 47, pp. 204–219, Oct. 2016, doi: 10.1016/j.jrurstud.2016.08.002.
[73] N. Gupta, C. T. Clavin, Z. E. Petropoulos, A. B. Mudd, R. Nek, and S. S. Tinkle, "Case Studies of Community Resilience Policy Case Studies of Community Resilience Policy," p. 114, 2016, [Online]. Available: http://dx.doi.org/10.6028/NIST.GCR.16-002. (accessed Oct. 14, 2020).
[74] A. Mullins and R. Soetanto, "Enhancing community resilience to flooding through social responsibility," *Int. J. Saf. Secur. Eng.*, vol. 1, pp. 115–125, 2011, doi: 10.2495/SAFE-V1-N2-115-125.
[75] D. G. Angeler, C. R. Allen, A. Garmestani, K. L. Pope, D. Twidwell, and M. Bundschuh, "Resilience in Environmental Risk and Impact Assessment: Concepts and Measurement," *Bull. Environ. Contam. Toxicol.*, vol. 101, pp. 543–548, 2018, doi: 10.1007/s00128-018-2467-5.
[76] A. Schardong, S. P. Simonovic, and H. Tong, "Use of quantitative resilience in managing urban infrastructure response to natural hazards," *Int. J. Saf. Secur. Eng.*, vol. 9, pp. 13–25, 2019, doi: 10.2495/SAFE-V9-N1-13-25.
[77] G. P. Cimellaro, A. M. Reinhorn, and M. Bruneau, "Framework for analytical quantification of disaster resilience," *Eng. Struct.*, vol. 32, pp. 3639–3649, 2010, doi: 10.1016/j.engstruct.2010.08.008.
[78] S. L. Cutter *et al.*, "A place-based model for understanding community resilience to natural disasters," *Glob. Environ. Chang.*, vol. 18, pp. 598–606, 2008, doi: 10.1016/j.gloenvcha.2008.07.013.
[79] A. J. Hickford, S. P. Blainey, A. Ortega Hortelano, and R. Pant, "Resilience engineering: theory and practice in interdependent infrastructure systems," *Environ. Syst. Decis.*, vol. 38, pp. 278–291, 2018, doi: 10.1007/s10669-018-9707-4.
[80] K. Kombiadou, S. Costas, A. R. Carrasco, T. A. Plomaritis, Ó. Ferreira, and A. Matias, "Bridging the gap between resilience and geomorphology of complex coastal systems," *Earth-Science Rev.*, vol. 198, p. 102934, 2019, doi: 10.1016/j.earscirev.2019.102934.
[81] R. J. Standish *et al.*, "Resilience in ecology: Abstraction, distraction, or where the action is?," *Biological Conservation*, vol. 177, pp. 43–51, 2014, doi: 10.1016/j.biocon.2014.06.008.
[82] A. M. A. Saja, A. Goonetilleke, M. Teo, and A. M. Ziyath, "A critical review of social resilience assessment frameworks in disaster management," *Int. J. Disaster Risk Reduct.*, vol. 35, p. 101096, 2019, doi: 10.1016/j.ijdrr.2019.101096.
[83] J. M. Cariolet, M. Vuillet, and Y. Diab, "Mapping urban resilience to disasters – A review," *Sustain. Cities Soc.*, vol. 51, p. 101746, 2019, doi: 10.1016/j.scs.2019.101746.
[84] C. W. Zobel, "Representing the multi-dimensional nature of disaster resilience," *8th Int. Conf. Inf. Syst. Cris. Response Manag. From Early-Warning Syst. to Prep. Training, ISCRAM 2011*, pp. 1–5, 2011.
[85] A. Chandra *et al.*, "Building Community Resilience to Disasters," *Rand Heal. Q.*, vol. 1, Mar. 2011.
[86] International Federation of Red Cross and Red Crescent Societies, *Resilience : saving lives today*. 2016.
[87] C. Rochas, T. Kuzņecova, and F. Romagnoli, "The concept of the system resilience within the infrastructure dimension: Application to a Latvian case," *J. Clean. Prod.*, vol. 88, pp. 358–368, 2015, doi: 10.1016/j.jclepro.2014.04.081.
[88] W. Solecki, R. Leichenko, and K. O'Brien, "Climate change adaptation strategies and disaster risk reduction in cities: Connections, contentions, and synergies," *Curr. Opin. Environ. Sustain.*,

vol. 3, pp. 135–141, 2011, doi: 10.1016/j.cosust.2011.03.001.
[89] D. Serre and C. Heinzlef, "Assessing and mapping urban resilience to floods with respect to cascading effects through critical infrastructure networks," *Int. J. Disaster Risk Reduct.*, vol. 30, pp. 235–243, 2018, doi: 10.1016/j.ijdrr.2018.02.018.
[90] J. Liang and Y. Li, "Resilience and sustainable development goals based social-ecological indicators and assessment of coastal urban areas ——A case study of Dapeng New District, Shenzhen, China," *Watershed Ecol. Environ.*, vol. 2, pp. 6–15, 2020, doi: 10.1016/j.wsee.2020.06.001.
[91] S. Scherzer, P. Lujala, and J. K. Rød, "A community resilience index for Norway: An adaptation of the Baseline Resilience Indicators for Communities (BRIC)," *Int. J. Disaster Risk Reduct.*, vol. 36, May 2019, doi: 10.1016/j.ijdrr.2019.101107.
[92] O. Cohen, D. Leykin, M. Lahad, A. Goldberg, and L. Aharonson-Daniel, "The conjoint community resiliency assessment measure as a baseline for profiling and predicting community resilience for emergencies," *Technol. Forecast. Soc. Change*, vol. 80, pp. 1732–1741, 2013, doi: 10.1016/j.techfore.2012.12.009.
[93] C. W. Zobel and L. Khansa, "Characterizing multi-event disaster resilience," *Comput. Oper. Res.*, vol. 42, pp. 83–94, 2014, doi: 10.1016/j.cor.2011.09.024.
[94] A. Fekete, "Urban Disaster Resilience and Critical Infrastructure," 2018.
[95] D. Serre, B. Barroca, M. Balsells, and V. Becue, "Contributing to urban resilience to floods with neighbourhood design: the case of Am Sandtorkai/Dalmannkai in Hamburg," *J. Flood Risk Manag.*, vol. 11, pp. S69–S83, 2018, doi: 10.1111/jfr3.12253.
[96] C. Apreda, "C Limate Change , Urban Vulnerability and Adaptation," vol. 1, pp. 233–256, 2016.
[97] W. Becker, M. Saisana, P. Paruolo, and I. Vandecasteele, "Weights and importance in composite indicators: Closing the gap," *Ecol. Indic.*, vol. 80, pp. 12–22, 2017, doi: 10.1016/j.ecolind.2017.03.056.
[98] A. Asadzadeh, T. Kötter, and E. Zebardast, "An augmented approach for measurement of disaster resilience using connective factor analysis and analytic network process (F'ANP) model," *Int. J. Disaster Risk Reduct.*, vol. 14, pp. 504–518, 2015, doi: 10.1016/j.ijdrr.2015.10.002.
[99] C. Chen, L. Xu, D. Zhao, T. Xu, and P. Lei, "A new model for describing the urban resilience considering adaptability, resistance and recovery," *Saf. Sci.*, vol. 128, p. 104756, 2020, doi: 10.1016/j.ssci.2020.104756.
[100] I. Kotzee and B. Reyers, "Piloting a social-ecological index for measuring flood resilience: A composite index approach," *Ecol. Indic.*, vol. 60, pp. 45–53, 2016, doi: 10.1016/j.ecolind.2015.06.018.
[101] S. L. Cutter, K. D. Ash, and C. T. Emrich, "The geographies of community disaster resilience," *Glob. Environ. Chang.*, vol. 29, pp. 65–77, 2014, doi: 10.1016/j.gloenvcha.2014.08.005.
[102] A. Ostadtaghizadeh, A. Ardalan, D. Paton, H. Jabbari, and H. R. Khankeh, "Community disaster resilience: A systematic review on assessment models and tools," *PLoS Curr.*, vol. 7, May 2015, doi: 10.1371/currents.dis.f224ef8efbdfcf1d508dd0de4d8210ed.
[103] Joseph Stephen Mayunga, "Measuring the Measure: A Multi-dimensional Scale Model to Measure Community Disaster," 2009.
[104] F. Z. Shabrina, I. Meilano, W. Windupranata, and N. R. Hanifa, "Measure coastal disaster resilience using community disaster resilience index (CDRI) in Mentawai Island, Indonesia," *AIP Conference Proceedings*, vol. 1987, doi: 10.1063/1.5047365.
[105] J. H. Shim and C. Il Kim, "Measuring resilience to natural hazards: Towards sustainable hazard mitigation," *Sustain.*, vol. 7, pp. 14153–14185, 2015, doi: 10.3390/su71014153.
[106] C. E. Kontokosta and A. Malik, "The Resilience to Emergencies and Disasters Index: Applying big data to benchmark and validate neighborhood resilience capacity," *Sustain. Cities Soc.*, vol. 36, pp. 272–285, 2018, doi: 10.1016/j.scs.2017.10.025.
[107] K. A. Campbell, F. Laurien, J. Czajkowski, A. Keating, S. Hochrainer-Stigler, and M. Montgomery, "First insights from the Flood Resilience Measurement Tool: A large-scale community flood resilience analysis," *Int. J. Disaster Risk Reduct.*, vol. 40, p. 101257, 2019, doi: 10.1016/j.ijdrr.2019.101257.
[108] T. Ijdrr, "The correlation between resilience and sustainability criteria regarding the environmental crisis management against Karaj ' s earthquake : The case of district one."

[109] S. Ainuddin and J. K. Routray, “Community resilience framework for an earthquake prone area in Baluchistan,” *Int. J. Disaster Risk Reduct.*, vol. 2, pp. 25–36, 2012, doi: 10.1016/j.ijdrr.2012.07.003.
[110] Project co-funded by the EU, Humanitarian Aid and Civil Protection, “INDRIX – Inclusive Disaster Resilience Index,” final report, 2018.
[111] R. Z. Zaidi, “International Journal of Disaster Risk Reduction Beyond the Sendai indicators : Application of a cascading risk lens for the improvement of loss data indicators for slow-onset hazards and small-scale disasters,” *Int. J. Disaster Risk Reduct.*, vol. 30, pp. 306–314, 2018, doi: 10.1016/j.ijdrr.2018.03.022.
[112] V. Gallina, S. Torresan, A. Critto, A. Sperotto, T. Glade, and A. Marcomini, “A review of multi-risk methodologies for natural hazards: Consequences and challenges for a climate change impact assessment,” *J. Environ. Manage.*, vol. 168, pp. 123–132, 2016, doi: 10.1016/j.jenvman.2015.11.011.
[113] Y. Tan, L. Jiao, C. Shuai, and L. Shen, “A system dynamics model for simulating urban sustainability performance: A China case study,” *J. Clean. Prod.*, vol. 199, pp. 1107–1115, 2018, doi: 10.1016/j.jclepro.2018.07.154.
[114] L. Zhou, X. Wu, Z. Xu, and H. Fujita, “Emergency decision making for natural disasters: An overview,” *Int. J. Disaster Risk Reduct.*, vol. 27, pp. 567–576, 2018, doi: 10.1016/j.ijdrr.2017.09.037.
[115] A. Sarwar, F. Khan, L. James, and M. Abimbola, “Integrated offshore power operation resilience assessment using Object Oriented Bayesian network,” *Ocean Eng.*, vol. 167, pp. 257–266, Nov. 2018, doi: 10.1016/j.oceaneng.2018.08.052.
[116] L. Galbusera and G. Giannopoulos, “On input-output economic models in disaster impact assessment,” *Int. J. Disaster Risk Reduct.*, vol. 30, no. November 2017, pp. 186–198, 2018, doi: 10.1016/j.ijdrr.2018.04.030.
[117] K. G. Tidball and A. Aktipis, “Feedback enhances greening during disaster recovery: A model of social and ecological processes in neighborhood scale investment,” *Urban For. Urban Green.*, vol. 34, pp. 269–280, 2018, doi: 10.1016/j.ufug.2018.07.005.
[118] A. Y. Grinberger and P. Samuels, “Modeling the labor market in the aftermath of a disaster: Two perspectives,” *Int. J. Disaster Risk Reduct.*, vol. 31, 2018, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2212420918306514.
[119] P. Amarasinghe, A. Liu, P. Egodawatta, P. Barnes, J. McGree, and A. Goonetilleke, “Quantitative assessment of resilience of a water supply system under rainfall reduction due to climate change,” *J. Hydrol.*, vol. 540, pp. 1043–1052, 2016, doi: 10.1016/j.jhydrol.2016.07.021.
[120] A. Blumberga, D. Lauka, A. Barisa, and D. Blumberga, “Modelling the Baltic power system till 2050,” *Energy Convers. Manag.*, vol. 107, pp. 67–75, Jan. 2016, doi: 10.1016/j.enconman.2015.09.005.
[121] R. Pant, K. Barker, and C. W. Zobel, “Static and dynamic metrics of economic resilience for interdependent infrastructure and industry sectors,” *Reliab. Eng. Syst. Saf.*, vol. 125, pp. 92–102, 2014, doi: 10.1016/j.ress.2013.09.007.
[122] R. Filippini and A. Silva, “A modeling framework for the resilience analysis of networked systems-of-systems based on functional dependencies,” *Reliab. Eng. Syst. Saf.*, vol. 125, pp. 82–91, 2014, doi: 10.1016/j.ress.2013.09.010.
[123] Borgomeo, Edoardo *et al*. "Risk-Based Water Resources Planning: Incorporating Probabilistic Nonstationary Climate Uncertainties," *Water Resources Research.* 50. (2014). doi: 10.1002/2014WR015558.
[124] M. Pishnamazzadeh, M. M. Sepehri, and B. Ostadi, “An Assessment Model for Hospital Resilience according to the Simultaneous Consideration of Key Performance Indicators: A System Dynamics Approach,” *Perioper. Care Oper. Room Manag.*, vol. 20, p. 100118, 2020, doi: 10.1016/j.pcorm.2020.100118.
[125] S. Khanmohammadi, H. Farahmand, and H. Kashani, “A system dynamics approach to the seismic resilience enhancement of hospitals,” *Int. J. Disaster Risk Reduct.*, vol. 31, pp. 220–233, 2018, doi: 10.1016/j.ijdrr.2018.05.006.
[126] G. Quitana, M. Molinos-Senante, and A. Chamorro, “Resilience of critical infrastructure to natural hazards: A review focused on drinking water systems,” *Int. J. Disaster Risk Reduct.*, vol.

48, p. 101575, 2020, doi: 10.1016/j.ijdrr.2020.101575.
[127] G. Watts, B. von Christierson, J. Hannaford, and K. Lonsdale, "Testing the resilience of water supply systems to long droughts," *J. Hydrol.*, vol. 414–415, pp. 255–267, 2012, doi: 10.1016/j.jhydrol.2011.10.038.
[128] A. Lagrange, M. de Simón-Martín, A. González-Martínez, S. Bracco, and E. Rosales-Asensio, "Sustainable microgrids with energy storage as a means to increase power resilience in critical facilities: An application to a hospital," *Int. J. Electr. Power Energy Syst.*, vol. 119, Jul. 2020, doi: 10.1016/j.ijepes.2020.105865.
[129] P. He, T. S. Ng, and B. Su, "Energy-economic resilience with multi-region input–output linear programming models," *Energy Econ.*, vol. 84, p. 104569, Oct. 2019, doi: 10.1016/j.eneco.2019.104569.
[130] W. Liu and Z. Song, "Review of studies on the resilience of urban critical infrastructure networks," *Reliab. Eng. Syst. Saf.*, vol. 193, 2020, doi: 10.1016/j.ress.2019.106617.
[131] O. Kammouh, P. Gardoni, and G. P. Cimellaro, "Probabilistic framework to evaluate the resilience of engineering systems using Bayesian and dynamic Bayesian networks," *Reliab. Eng. Syst. Saf.*, vol. 198, p. 106813, 2020, doi: 10.1016/j.ress.2020.106813.
[132] S. Kameshwar *et al.*, "Probabilistic decision-support framework for community resilience: Incorporating multi-hazards, infrastructure interdependencies, and resilience goals in a Bayesian network," *Reliab. Eng. Syst. Saf.*, vol. 191, p. 106568, 2019, doi: 10.1016/j.ress.2019.106568.
[133] A. Huck and J. Monstadt, "Urban and infrastructure resilience: Diverging concepts and the need for cross-boundary learning," *Environ. Sci. Policy*, vol. 100, pp. 211–220, 2019, doi: 10.1016/j.envsci.2019.05.008.
[134] D. Henry and J. Emmanuel Ramirez-Marquez, "Generic metrics and quantitative approaches for system resilience as a function of time," *Reliab. Eng. Syst. Saf.*, vol. 99, pp. 114–122, 2012, doi: 10.1016/j.ress.2011.09.002.
[135] M. Vona, M. Mastroberti, L. Mitidieri, and S. Tataranna, "New resilience model of communities based on numerical evaluation and observed post seismic reconstruction process," *Int. J. Disaster Risk Reduct.*, vol. 28, pp. 602–609, 2018, doi: 10.1016/j.ijdrr.2018.01.010.
[136] X. Lu *et al.*, "Quantification of disaster resilience in civil engineering: A review," *J. Saf. Sci. Resil.*, vol. 1, pp. 19–30, 2020, doi: 10.1016/j.jnlssr.2020.06.008.
[137] N. Komendantova, A. Scolobig, A. Garcia-Aristizabal, D. Monfort, and K. Fleming, "Multi-risk approach and urban resilience," *Int. J. Disaster Resil. Built Environ.*, vol. 7, pp. 114–132, 2016, doi: 10.1108/IJDRBE-03-2015-0013.
[138] C. Nan and G. Sansavini, "A quantitative method for assessing resilience of interdependent infrastructures," *Reliab. Eng. Syst. Saf.*, vol. 157, pp. 35–53, 2017, doi: 10.1016/j.ress.2016.08.013.
[139] W. Hein *et al.*, "Climate change and natural disasters: Government mitigation activities and public property demand response," *Land use policy*, vol. 82, pp. 436–443, 2019, doi: 10.1016/j.landusepol.2018.12.026.
[140] G. Papachristos, "System dynamics modelling and simulation for sociotechnical transitions research," *Environ. Innov. Soc. Transitions*, vol. 31, pp. 248–261, Oct. 2018, doi: 10.1016/j.eist.2018.10.001.
[141] Blumberga, A., Blumberga, D., Bažbauers, G., Davidsen, P., Moxnes, E., Dzene, I., Barisa, A., Žogla, G., Dāce, E., Bērziņa, A. *System Dynamics for Environmental Engineering Students.* Riga. 2011.
[142] N. Phonphoton and C. Pharino, "A system dynamics modeling to evaluate flooding impacts on municipal solid waste management services," *Waste Manag.*, vol. 87, pp. 525–536, 2019, doi: 10.1016/j.wasman.2019.02.036.
[143] R. Rehan, M. A. Knight, A. J. A. Unger, and C. T. Haas, "Financially sustainable management strategies for urban wastewater collection infrastructure - development of a system dynamics model," *Tunn. Undergr. Sp. Technol.*, vol. 39, pp. 116–129, 2014, doi: 10.1016/j.tust.2012.12.003.
[144] A. Macmillan and J. Woodcock, "Understanding bicycling in cities using system dynamics modelling," *J. Transp. Heal.*, vol. 7, pp. 269–279, 2017, doi: 10.1016/j.jth.2017.08.002.
[145] M. Zarghami and S. Akbariyeh, "System dynamics modeling for complex urban water systems:

Application to the city of Tabriz, Iran," *Resour. Conserv. Recycl.*, vol. 60, pp. 99–106, Mar. 2012, doi: 10.1016/j.resconrec.2011.11.008.
[146] Z. Li, L. Chunhui, X. Wang, C. Peng, Y. Cai, and W. Huang, "A Hybrid System Dynamics and Optimization Approach for Supporting Sustainable Water Resources Planning in Zhengzhou City, China," *J. Hydrol.*, vol. 556, Nov. 2017, doi: 10.1016/j.jhydrol.2017.11.007.
[147] G. Mavrommati, K. Bithas, and P. Panayiotidis, "Operationalizing sustainability in urban coastal systems: A system dynamics analysis," *Water Res.*, vol. 47, pp. 7235–7250, 2013, doi: 10.1016/j.watres.2013.10.041.
[148] Y. He, J. Jiao, Q. Chen, S. Ge, Y. Chang, and Y. Xu, "Urban long term electricity demand forecast method based on system dynamics of the new economic normal : The case of Tianjin," *Energy*, vol. 133, pp. 9–22, 2017, doi: 10.1016/j.energy.2017.05.107.
[149] H. Haghshenas, M. Vaziri, and A. Gholamialam, "Evaluation of sustainable policy in urban transportation using system dynamics and world cities data: A case study in Isfahan," *Cities*, vol. 45, pp. 104–115, Jun. 2015, doi: 10.1016/j.cities.2014.11.003.
[150] A. Gravelsins *et al.*, "Modelling energy production flexibility: system dynamics approach," *Energy Procedia*, vol. 147, pp. 503–509, Aug. 2018, doi: 10.1016/j.egypro.2018.07.060.
[151] Y. Y. Feng and L. Zhang, "System dynamics modeling for urban energy consumption and CO2 emissions: A case study of Beijing, China," *Ecol. Modell.*, vol. 252, pp. 44–52, Nov. 2013, doi: 10.1016/j.ecolmodel.2012.09.008.
[152] H. vafa arani, S. Jahani, H. Dashti, J. Heydari, and S. Moazen, "A system dynamics modeling for urban air pollution: A case study of Tehran, Iran," *Transp. Res. Part D Transp. Environ.*, vol. 31, pp. 21–36, Aug. 2014, doi: 10.1016/j.trd.2014.05.016.
[153] N. Tsolakis and L. Anthopoulos, "Eco-Cities: An Integrated System Dynamics Framework And A Concise Research Taxonomy," *Sustain. Cities Soc.*, vol. 17, Mar. 2015, doi: 10.1016/j.scs.2015.03.002.
[154] J. M. Links *et al.*, "COPEWELL: A Conceptual Framework and System Dynamics Model for Predicting Community Functioning and Resilience after Disasters," *Disaster Med. Public Health Prep.*, vol. 12, pp. 127–137, Feb. 2018, doi: 10.1017/dmp.2017.39.
[155] G. Li, C. Kou, Y. Wang, and H. Yang, "System dynamics modelling for improving urban resilience in Beijing, China," *Resour. Conserv. Recycl.*, vol. 161, p. 104954, 2020, doi: 10.1016/j.resconrec.2020.104954.
[156] B. Flanagan, E. Gregory, E. Hallisey, J. Heitgerd, and B. Lewis, "A Social Vulnerability Index for Disaster Management," *J. Homel. Secur. Emerg. Manag.*, vol. 8, Jan. 2011, doi: 10.2202/1547-7355.1792.
[157] "Getting Started with iThink and STELLA Copyright , Trademarks , and Conditions of Use."
[158] E. A. J. A. Rouwette, A. Größler, and J. A. M. Vennix, "Exploring influencing factors on rationality: A literature review of dynamic decision-making studies in system dynamics," *Syst. Res. Behav. Sci.*, vol. 21, pp. 351–370, 2004, doi: 10.1002/sres.647.
[159] D. Ozer, "Correlation and the Coefficient of Determination," *Psychol. Bull.*, vol. 97, pp. 307–315, Mar. 1985, doi: 10.1037/0033-2909.97.2.307.
[160] T. Yamane, *Statistics: An Introductory Analysis*. Harper & Row, 1967.

PUBLICATIONS ARISING FROM THIS THESIS

Article 1: Feofilovs, M., Romagnoli, F. Measuring Community Disaster Resilience in the Latvian Context: an Apply Case using a Composite Indicator Approach. (2017) Energy Procedia, 113, 12–14.

Article 2: Feofilovs, M., Romagnoli, F. Resilience of Critical Infrastructures: Probabilistic Case Study of a District Heating Pipeline Network in Municipality of Latvia. (2017) *Energy Procedia*, 128, 17–23.

Article 3: Feofilovs, M., Romagnoli, F. Gravelsins, A. System Dynamics Model for Natural Gas Infrastructure with Storage Facility in Latvia. (2018) *Energy Procedia*, 147, 549–557.

Article 4: Feofilovs, M., Gravelsins, A., Pagano, A., Romagnoli, F. Increasing Resilience of the Natural Gas System with Implementation of Renewable Methane in the Context of Latvia: A System Dynamics Model. (2019) *Energy Procedia,* 158, 3944–3950.

Article 5: Feofilovs, M., Romagnoli, F., Gotangco, C. K., Josol J. C., Jardeleza J. M., Campos J., Litam J., Abenojar K. Assessing Resilience Against Floods With A System Dynamics Approach: A Comparative Study Of Two Models. (2020) *International Journal of Disaster Resilience in the Built Environment,* vol. 11, no. 5, pp. 615-629.

Article 6: Feofilovs, M., Romagnoli, F. Assessment of Urban Resilience to Natural Disasters with a System Dynamics Tool: Case Study of Latvian Municipality. (2020) *Environmental and Climate Technologies*, vol. 24, no. 3, pp 249–264

Article 7: Feofilovs, M., Romagnoli, F. Dynamic Assessment of Urban Resilience to Natural Hazards. (2020) *International Journal Of Disaster Risk Reduction* (in review).

MEASURING COMMUNITY DISASTER RESILIENCE IN THE LATVIAN CONTEXT: AN APPLY CASE USING A COMPOSITE INDICATOR APPROACH

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 113 (2017) 43 – 50

Energy Procedia

International Scientific Conference "Environmental and Climate Technologies", CONECT 2016, 12–14 October 2016, Riga, Latvia

Measuring community disaster resilience in the Latvian context: an apply case using a composite indicator approach

Maksims Feofilovs*, Francesco Romagnoli

Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, Riga, LV–1048, Latvia

Abstract

Despite a growing and considerable interest and implementation of disaster resilience framework methods in research, policy programs and engineering design, metrics and standards for a quantitative measuring of resilience are still an open issue.
Recent literatures on hazard and disaster show that the resilience concept represents a guideline toward a valuable hazard risk management and mitigation. For the Latvian context this also represents a beneficial approach for the implementation of policy strategies based on (semi)quantitative framework aiming to enhance resilience within communities in order to properly and most efficient spend a limited availability of funds. In fact man-made and natural disasters are usually preceded by periods where communities develop toward increasing risk states until a loss occurred due to a specific disaster event. In regard to this aspect this study, principally based on the definition of the Community Disaster Resilience Framework (CDRF) developed by Mayunga, is aiming to evaluate the level of community resilience to disaster at the Latvian national level for a specific set of social, economic, human, physical, and environmental indicators. The method implements the concept of a composite-based, multi-criteria analysis aiming to measure baseline quantitative characteristics of the communities under investigation to potentially further enhance resilience within specific actions plans and/or policy mechanisms. The results are applied to the Latvian context and provide a tool to assess the variation in resilience in places giving a ranking from the most resilient region to the least.

Peer-review under responsibility of the scientific committee of the International Scientific Conference "Environmental and Climate Technologies".

Keywords: community disaster resilience; composite indicator; multi-criteria; indicator; building resilience

* Corresponding author. Tel.: +371 26733409; fax: +371 67089908.
E-mail address: maksims.feofilovs@edu.rtu.lv

Peer-review under responsibility of the scientific committee of the International Scientific Conference "Environmental and Climate Technologies".
doi:10.1016/j.egypro.2017.04.012

1. Introduction

The increase of disasters at EU and international levels due to both man-made (i.e. technological) and natural reasons (i.e. hazards due to extreme weather conditions induced by climate change or by other geological, oceanographic, hydrological biological conditions [1]) create important debates and questions within research and policy arenas [2].

The Swiss Re's report of year 2013 [3] encountered at world scale 308 disaster events in the year 2013 (of which 150 were natural catastrophes and 158 technological) with almost 26 000 lost lives. Europe has experienced a total amount of $ 33 billion of economic losses with about 50 % of insurance payments.

Figures from the UNISDR [4] show that the exposure of technological assets to earthquake with a 250 years return time is about US$ 71 trillion. In Europe economic loss per capita is higher than in the rest of the world due to the higher population density. According to UNISDR this trend "will probably continue to rise as natural disasters are expected to become more frequent and severe for Europe in the future". To increase society's resilience to disaster in Europe, ANDROID – an academic network was formed that aims to promote co-operation among European Higher Education institutions [5]. Nevertheless, further research is crucial to increase number of innovations on topic of disaster resilience.

According to the figures provided by the Centre of Research on the Epidemiology of Disasters (CRED) country profile of Latvia within the period from 1999 to 2016 storms caused 6 deaths and damages from around 450 thous. € in the year 1999 and around 300 mill. € in the year 2005 [6].

This situation indicates that communities, including Latvia, are not "resilient" enough to natural disasters. In other words, there is a lack of capacity to withstand disasters that require an in-sight effort from different key actors in fact including research, policy, and disaster risk reduction (DRR) fields of interests. This is the main target following the Sendai Framework for Disaster Risk Reduction to move to "building the resilience of nations and communities to disasters" within hazard planning and disaster risk reduction agenda [7].

The general definition of resilience can be identified as a system's ability to: i) withstand external and unexpected conditions within the minimum sustainable level performance, ii) further actively respond to these conditions and iii) recover after them [8] (see Fig. 1).

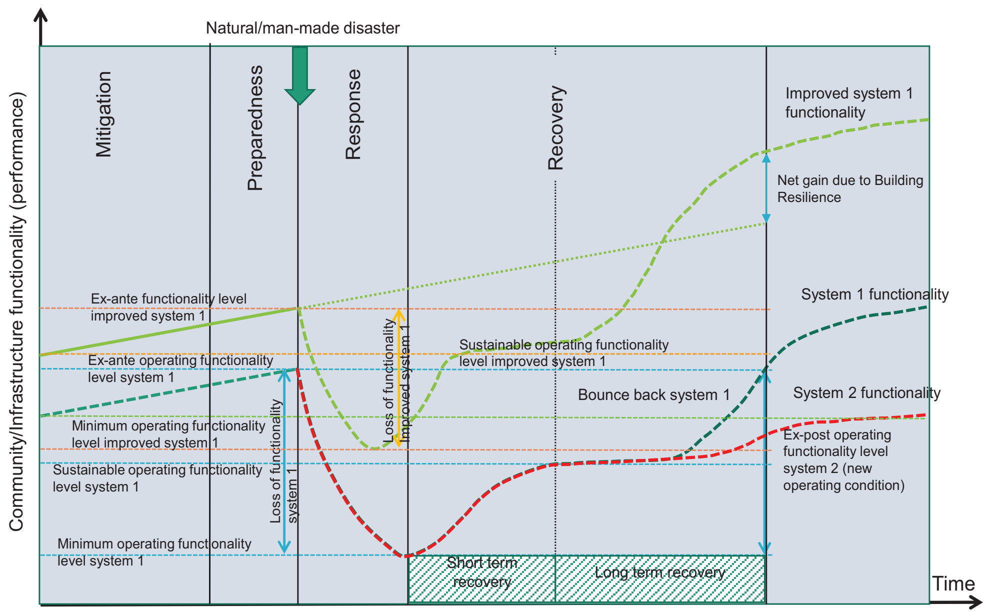


Fig. 1. The dotted dark green line represents the performance of a system (or society) without measures aimed to build resilience – i.e. system 1; the dotted light green line represents the performance of a system (or society) with measures aimed to build resilience – i.e. improved system 1; the dotted red line represents the performance of a system (or society) with low and a new operational level after the disaster – i.e. system 2.

Based on this concept different methods for resilience assessment have been developed and applied, both qualitative and quantitative like in Bruneau studies [9, 10] with the introduction of the "4Rs" (i.e. Robustness, Redundancy; Resourcefulness; and Rapidity) and Henry and Ramirez-Marquez [11] that expressed resilience more in terms of loss of delivered products or services within a system dependent by its recovery function.

Nevertheless, using the concept of recovery (or bounce-back) to an initial level it can be not always applicable as the recovery process might reach a lower but always stable state (see system 2 in Fig. 1). The resilience assessment is an important preventive measure oriented toward: i) the minimization of the total effect of a disaster (both on society and environment), ii) mitigation of the economic losses, iii) minimization of recovery time after a disaster thus speeding up the rate at which a community or system can regain its functionality. However, the field of resilience assessment is still in a development stage [9] and is lacking applied quantitative practical studies and holistic-comparative approaches. The practical task is now devoted to map regions with specific levels of resilience or scores [12] in order to more efficiently prioritize DRR strategies and management at the policy level.

It is this remarkable how the use of an indicator-based approach is going toward this direction. The proper and consistent selection of a set of indicators framed into a specific indicator-based evaluation approach that would offer the possibility of quantification among different places and over time [1] is not a trivial task. In fact, the selection of a specific set of indicators needs to deal with two critical factors: the large diversity and multi- (and inter-) dimensions of the community system (i.e. societal, human, economic, technical, and environmental) affected by an occurred disaster. In this approach the dynamic and non-linear perspective is still a lacking issue [13].

In the study of Ostadtaghizadeh et al. (2015) [14] the outcome was that, from around 675 papers reviewed focused on the key word "community resilience," only 17 papers provided a way to measure the community resilience. This aspect was interpreted as a lack within a systematic assessment process.

In order to offset the gap toward the real application of quantitative methods for community resilience assessment to be used by stakeholders (e.g. in regional planning or disaster management) this study is proposing the application of Mayunga method [15] specifically adapted to the Latvian condition. Specifically, an overall evaluation through the final definition of a composite index score able to aggregate different dimensions within the application of Mayunga method is performed. The Mayunga method (described in section 2) is oriented to providing a holistic composite index score for the measure of a community's disaster resilience taking into account both the different phases of a disaster (i.e. mitigation, preparedness, response, and recovery) and the potential dimensions of resources (so called "capitals") that can be mobilized (i.e. social, human, economic, physical, environmental) or affected by an occurred hazard.

2. Methodology

For this study the approach of Mayunga [15] has been selected to assess community disaster resilience. This is taking into account a capital based approach including five major forms of capital: Social, Economic, Physical, Human, and Environmental, in fact selecting specific indicators also relevant for development of a sustainable community economy. Fig. 2 shows the proposed conceptual framework via the definition of on overall Community Disaster Resilience Index (CDRI). The final CDRI index is thus the final result of a conceptual model based on the theory of the composite indicators [16] and involving the following main steps: i) Definition of the main capital domains with specific sub-indicators selected in a function of the disaster phase and capital domains; ii) Standardization of the sub-indicators; iii) Weighting (both at sub-indicator levels and capital domain level); iv) Definition of Community disaster resilience index (CDRI); v) Reliability and validity assessment of the set of indicator selected and the obtained scores.

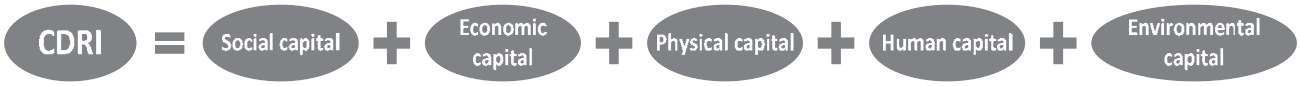


Fig. 2. CDRI relation to community capital [16].

2.1. Capital domains and sub-indicators identification

The 5 main domains of Mayunga's method are described below:

- Social capital: It indicates the level of social cooperation. This can be represented by links and networks established within a community as beneficial resource in terms to go beyond collective worries through community cooperation. A total number of 9 indicators were identified like – among others – trust, norm types and networks able to facilitate the cooperation and coordination;
- Economic capital: it indicates the direct financial resources of a community necessary to reach its level of livelihoods. The effect on mobilizing economic capital to building a community's resilience is directly connected to the increased ability and capacity of individuals to easily cope against disaster towards the 4 main disaster phases and fastening the recovery process. A total number of 6 indicators were identified among others – incomes, savings and investment, in fact ability to increase wellbeing and the capacity of insured both goods and lives;
- Physical capital: it is devoted to the built environment (e.g. buildings and all the main life and critical infrastructures) and represents a key resource for enhancing resilience. This is mainly identified as those infrastructures essential on favouring evacuation following a disaster and increase the level of safety always guaranteeing a minimal level of functioning. A total number of 35 indicators were identified (e.g. number of hospitals, shelters, housing units, etc.);
- Human capital: it mostly addressed support to economic production. This is defined as the capabilities in the working population to fruitfully work together sharing with other forms of capital. Within the Mayunga method, the main identified sub-indicators aimed at reinforcing the knowledge capacity on risk assessment and risk reduction strategies. A total number of 25 indicators were identified;
- Environmental (natural) capital: it refers to natural resources, such as water, minerals and oil, land which provides space on which to live and work, and the ecosystems that maintain clean water, air and a stable climate. Indicators such as resource stocks and environmental ecosystems, among others were identified.

Within the Mayunga method a total number of 75 sub-indicators were selected. This selection initially did not include the environmental capital for which has been considered within the case study the selection of indicator from the DROP model proposed by Cutter [17]. The detailed description of the specific indicators selected for the Latvian case study is reported within the master thesis study of Feofilovs [18].

2.2. Standardization of the sub-indicators

The standardization of indicators, necessary to use and compare indicators in different unit measure, was performed according to the z-score method [20], also known as standard score method (see Eq. (1)).

$$z_i = \frac{(x_i - \mu)}{\sigma} \tag{1}$$

where

z_i	z-score for a given indicator;
x_i	actual value of a given indicator;
μ	mean value of a given indicator values for a specific value distribution;
σ	standard deviation for a specific value distribution.

2.3. Weighting (both at sub-indicator levels and capital domain level)

Each capital has a different number of indicators, thus if indicators are simply added together the final score will tend to be highly influenced by the sub-indices with the highest numbers of indicators. The following equation shows a proposed mathematical formula for combining sub-indicators to generate individual indices for each capitals of the community identified in reference based on relative weights among indicators [19].

$$y_i = \sum_{i=1}^{n} (\omega_1 x_1 + \omega_2 x_2 + \omega_2 x_2 + ... + \omega_n x_n) \quad (2)$$

where
y_i score for each capital domain;
x_i standardized sub-indicators;
ω_i weight;
n number of indicators or weight considered;
i indicator number.

Within this case study the implemented weights were considered equal in fact moving toward the use of an average method.

2.4. Definition of Community Disaster Resilience Index (CDRI)

Mayunga's method is based on a conceptual model defining a matrix involving the four disaster phases (i.e. mitigation, preparedness, response and recovery) as columns and the five types of capital domains as rows. Each identified indicator is considered where relevant for a specific disaster phase creating the final CDRI and avoiding that indicators would be accounted for more than once. Based on that the overall score was calculated as a mean value of the obtained score for each capital domain [19].

$$CDRI = \sum_{i=1}^{5} y_i / 5 \quad (3)$$

where
y_i score for each capital domain.

2.5. Reliability and validity assessment of the set of indicator selected and the obtained

The reliability assessment was employed to assess the internal consistency of the indicators as well as to facilitate the selection of indicators. Indicators were selected based on their performances in terms of the overall internal consistency (Cronbach's alpha level) and inter-item correlations. The Cronbach's alpha coefficients can vary from zero to one; where one denotes perfect reliability and zero a very unreliable measure. A Cronbach's alpha coefficient close to 0.70 is considered acceptable [21]. The final step of the evaluation methods was devoted to assess the validity of the selected set of indicators for the CDRI determination as a measure of disaster resilience.

Specific content and construct validity assessment are considered within the proposed method. Content validity is connected to the measure to capture the theoretical concept of the items measured [15] in other words showing that the proposed set of indicators is indeed a picture of the actual community resilience. The construct validity is the degree to which a measure relates to other variables as expected within a system of theoretical [22, 23]. The Construct validity is made by a correlational analysis (i.e. Pearson's product-moment correlation) to examine the degree to which the CDRI is correlated with external criteria calculated within other evaluation approaches. In the case study this has been evaluated as the correlation among the CDRI and the Social Vulnerability index (SVI) [24] as well as the overall damage from floods.

3. Case study

Through the application of Mayunga's methods the proposed case study aims to comparatively evaluate community resilience to natural hazards among six macro regions of Latvia (Fig. 3), namely Riga region, Around Riga region and Kurzeme, Vidzeme, Latgale and Zemgale. The aim is thus to map the patterns of the CDRI scores within the territory investigated. The whole Latvian territory represents a good case study since it provides a scheme for planners and emergency managers toward enhancing local community coping capacities and promotes disaster resilience evaluation methods.

Thus this study emphasis more the changes of what is defined as CDRI type 1 (CDRI1 score) and is focused more on the assessment of the validity and utility of the CDRI scores community capitals rather than on the insight analysis associated with the disaster phases.

In this study the "regional" scale is considered as a unit of the analysis mainly because local decisions on community mitigation measures and risk reduction programs can be directly organized and proposed at this level. The main data source was the Central Statistical Bureau (CSB) of Latvia. Most of the indicators were collected for the year 2012 except some of the Human capital indicators which were collected from the year 2011 [17].

4. Results and Conclusions

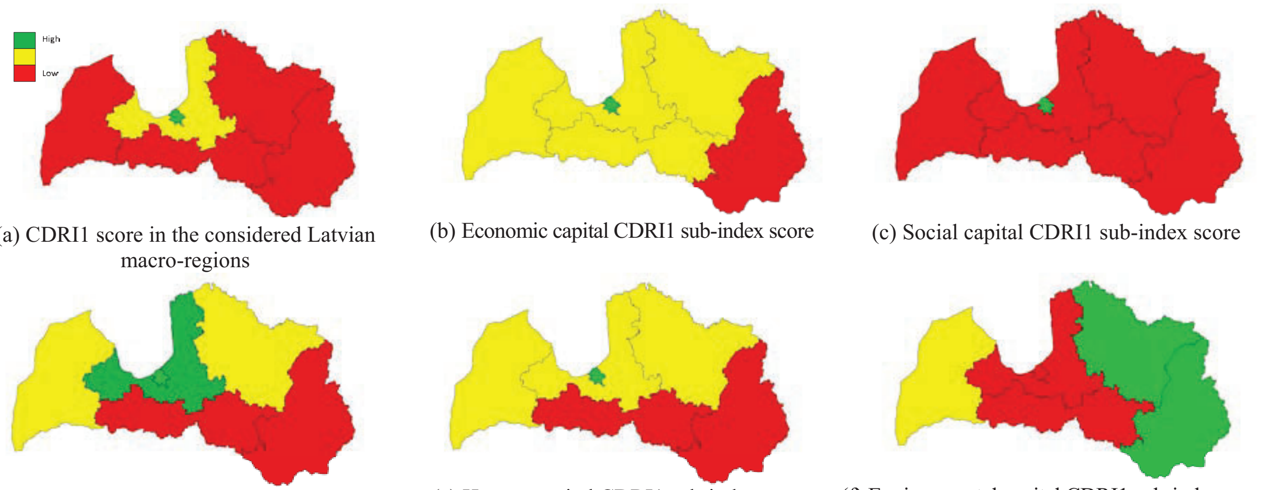
The results were addressed to show and analyse the spatial distribution of the CDRI1 scores and their components by mapping community resilience across the investigated Latvian regions.

A reliability assessment – prior normalization of the data used – was implemented to assess the internal consistency of the set of selected indicators based on a Cronbach's alpha control and thus screen the proper set of indicators to be selected within the CDRI score. Finally, 55 indicators were employed for each analysed region.

A final validation of the obtained CDRI score was assessed consisting of the construct and content validation as described in section 2. The construct validation has been implemented with correlation and regression analyses in respect to external criteria, in specific the SVI [24], the flood damage costs and the risks from natural and man-made disaster (according to figures from the Latvian Civil Protection Department [25].

As mentioned the results reported in this paper are only referenced to the CDRI1 scores, where basically all the five capital dimensions (i.e. social, economic, physical, human and natural) were selected among the four disaster phase (i.e. mitigation, preparedness, response, recovery).

The final maps for the CDRI final are displayed in Fig. 3 and classified into 3 classes (low, medium, low) obtained from the overall distribution of the CRDI1 scores within each region.



(a) CDRI1 score in the considered Latvian macro-regions

(b) Economic capital CDRI1 sub-index score

(c) Social capital CDRI1 sub-index score

(d) Physical capital CDRI1 sub-index score

(e) Human capital CDRI1 sub-index score

(f) Environmental capital CDRI1 sub-index score

Fig. 3. CDRI1 sub-index score for each capital dimensions respect to low, medium and high grades (namely red, yellow and green colours).

According to the patterns observed there is a relevant correlation among specific capitals in CDRI1, namely between economic and physical capitals and social and human capitals, this is "a priori" predictable and expected if we can assume that areas with more developed infrastructure (referred to physical capital) and high population with bigger human capital tend to have higher CDRI1 scores. This justifies that for Riga region the CDRI1 score is higher than other regions for its higher density population and economic activity that follow and relied on more developed infrastructures and more important social capitals that can be mobilized.

The CDR1 of the Around Riga is the second one due to a direct connection and dependency to the Riga region within the social and economic dimensions. For other regions the resilience level remains relatively low compared to the two main regions (see Fig. 1). This situation in Latvia is relied on the different levels of urbanization among the Riga Region (in fact presenting a higher and relevant contribution within the economic development of the country) and the other regions in the country.

The community capitals sub-index scores are displayed in the map (Fig. 3(a)). By comparing social capital and economic capital in Fig. 3(b) and Fig. 3(c), it is obvious that Riga region shows high scores in both capitals in agreement with the real situation of the economic development in Latvia. In Fig. 3b social capital sub-index show low scores except for Riga region. According to this study the higher social capital sub-index is also located in Riga region.

Fig. 3(d) shows CDRI1 for physical sub-capital index scores. Physical capital sub-index score is providing an important part on overall the overall CDRI1 final score of both Riga and Around Riga regions. Average sub-index scores for Kurzeme and Vidzeme and low score for Zemgale and Latgale are also observed.

As mentioned in section 3 the human capital is difficult to be estimated due to a complicated research required for the selection of a consistent and reliable set of indicators. Nevertheless, based on the assumed indicator results show (according to Fig. 3(e)) low human capital sub-index scores observed for Zemgale and Latgale regions. Exept the region around Riga, this fits with the score depicted for physical capital sub-index (Fig. 3(d)), in fact providing a confirmation about the strong connection among physical and human capital (as shown and commented in Fig. 2).

The environmental capital sub-index score illustrated in Fig. 3(f) presents different trends in respect to the previous sub-index score patterns observed for other capitals. In fact, this is mainly due to the lower amount of natural resources that can be mobilized in urbanized regions (i.e. Riga and Around Riga regions). A low score is also for Zemgale region, an average for Kurzeme region while high sub-index scores are observed in regions of Vidzmeme and Latgale. This is mainly due to the large forest area (including national parks and natural reserves), farm land, lake surface, protected mammal species and biological farming characterisristic of Vidzmeme and Latgale regions and included in the set of the sub-indicators for the environmental capital score.

For the construct validation of the CDRI1 the SVI [24] was used together with damage cost due to floods according to the figures obtained by the Latvian Civil Defence department [25] with reference to the year 2013.

Within the regression analysis made by the Statgraphics software, CDRI1 and SVI were considered the independent variables while damage cost is the dependent one. The results from the equation of the best -fitting model are reported in formula below:

$$Damage\_cost = -38774.3 + 583052 \bullet SVI - 410245 \bullet CDRI1 \tag{4}$$

Model Eq. (4) shows a relation of variables, where for any increase in CDRI1 there is an important decrease in total damage costs, as well as there is confirmation that for a higher SVI (thus higher vulnerability) there is an increase of the damage costs. The adjusted R^2 statistic is 62.312 %. Since the P-value is greater than 0.05 there is evidence of a not statistically significant relationship between the variables at the 95.0 % or higher confidence level.

The outcomes of this study represent a promising valuable tool to provide information to planners, emergency managers, and infrastructure managers on how and where to potentially implement measures for enhancing resilience. Nevertheless, further research must be conducted to better evaluate potential feedback effects among the considered set of indicators as well as conducting a further in-depth validation of the measures provided.

Acknowledgements

The work has been supported by the National Research Program “Energy efficient and low-carbon solutions for a secure, sustainable and climate variability reducing energy supply (LATENERGI)”.

References

[1] Birkmann J. Measuring vulnerability to natural hazards : towards disaster resilient societies. Tokyo: United Nations University Press; 2006.
[2] International Bank for Reconstruction and Development/The World Bank. Building resilience. Integrating Climate and Disaster Risk into Development; 2013.
[3] Swiss Re. Natural catastrophes and man-made disasters in 2013; 2014. Available: http://www.swissre.com/media/news_releases/nr_20131218_sigma_natcat_2013.html

[4] UNISDR (The United Nations International Strategy for Disaster Reduction). Global Assessment Report on Disaster Risk Reduction: From Shared Risk to Shared Value –The Business Case for Disaster Risk Reduction. Geneva; 2013.
[5] Knezic S, Scudeller M, Indirli M, Romagnoli F, Kuzņecova T, Perdikou S. The ANDROID case study; Venice and its territory: identification of hazards and impact of multi-hazard scenarios. Procedia Economics and Finance 2014;18:465– 472.
[6] Centre for Research of Epidemiology of disasters. Latvia risk profile. Riga; 2013.
[7] UNISDR (The United Nations International Strategy for Disaster Reduction). Sendai Framework for Disaster Risk Reduction 2015–2030. Geneva; 2015.
[8] Rochas C, Kuzņecova T, Romagnoli F. The concept of the system resilience within the infrastructure dimension: Application to a Latvian case. J. Clean. Prod. 2015;88:358–368.
[9] Tierney K, Bruneau M. A Key to Disaster Loss Reduction. TR News; 2007;14–18.
[10] Bruneau M, Chang S, Eguchi R, Lee G, O'Rourke T, Reinhorn A, Shinozuka M, Tierney K,Wallace W, von Winterfelt D. A framework to quantitatively assess and enhance the seismic resilience of communities. EERI Spectra J. 2003;19(4):733–752.
[11] Henry D, Ramirez-Marquez JE. Generic metrics and quantitative approaches for system resilience as a function of time. Reliab. Eng. Syst. Saf. 2012;99:114–122.
[12] UNISDR (The United Nations International Strategy for Disaster Reduction). Disaster Resilience Scorecard for Cities. Geneva; 2014.
[13] Toseroni F, Romagnoli F, Marincioni F. Adapting and reacting to measure an extreme event: a methodology to measure disaster community resilience. Energy Procedia 2016;95:491–498.
[14] Ostadtaghizadeh A, Ardalan A, Paton D, Jabbari H, Khankeh HR. Community disaster resilience: A systematic review on assessment models and tools. PLoS Curr. 2015;7(DISASTERS).
[15] Mayunga J. Measuring the measure: A multi-dimensional scale model to measure community disaster resilience in the US Gulf Coast region. Dissertation; Texas A&M University; 2009.
[16] Birkmann J. Measuring vulnerability to promote disaster-resilient societies : Conceptual frameworks and definitions. Meas. Vulnerability to Nat. Hazards; Towar. Disaster Resilient Soc. 2006;1:9–54.
[17] Cutter SL, Barnes L, Berry M, Burton C, Evans E, Tate E, Webb J. A place-based model for understanding community resilience to natural disasters. Glob. Environ. Chang. 2008;18(4):598–606.
[18] Feofilovs M. Infrastructure and community resilience metrics: application of holistic method within the Latvian context. Riga Technical University: Institute of Energy Systems and Environment; 2016.
[19] Mayunga JS. Understanding and Applying the Concept of Community Disaster Resilience : A capital-based approach. Landsc. Archit. 2007;7:22–28.
[20] Freudenberg M. Composite indicators of country performance: a critical assessment. OECD Sci. Technol. Ind. Work. Pap. 2003;16:35.
[21] Hair JF, Black W, Babin B, Anderson R, Tatham R. Multivariate Data Analysis, vol. 6. Upper Saddle River, NJ: Pearson Prentice Hall; 2006.
[22] Babbie ER. The Practice of Social Research, vol. 17. Belmont, CA: Thomson Wadsworth; 2007.
[23] Carmines EG, Zeller RA. Reliability and Validity Assessment, vol. 17. Beverly Hills, London: SAGE Publications; 1979.
[24] Flanagan BE, Gregory EW, Hallisey EJ, Heitgerd JL, Lewis B. A Social Vulnerability Index for Disaster Management. J. Homel. Secur. Emerg. Manag. 2011;8(1):1–22.
[25] Ministry of the Interior of the Republic of Latvia – State Fire and Rescue Service – Department Civil Protection. The 2013 floods and flood damage caused by the municipalities and planned social assistance to the population. Informative report. Riga; 2014.

RESILIENCE OF CRITICAL INFRASTRUCTURES: PROBABILISTIC CASE STUDY OF A DISTRICT HEATING PIPELINE NETWORK IN MUNICIPALITY OF LATVIA

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 128 (2017) 17–23

Energy Procedia

www.elsevier.com/locate/procedia

International Scientific Conference “Environmental and Climate Technologies”, CONECT 2017, 10–12 May 2017, Riga, Latvia

Resilience of critical infrastructures: probabilistic case study of a district heating pipeline network in municipality of Latvia

Maksims Feofilovs*, Francesco Romagnoli

Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, Riga, LV–1048, Latvia

Abstract

The effects of disasters on communities is a critical issue to be considered in terms of growing exposure of infrastructures to natural hazards. The significant role of the infrastructure systems – and thus their interconnections – is a key for the current urbanization development expected to increase within the next years. Thus, the role of infrastructures should guarantee the support of urban life standards to guarantee public welfare. This aim can only be designed with an enhanced level of infrastructural resilience within the field of crisis management.

The concept of infrastructure resilience is normally linked with the ability to cope with severe disruptions, guaranteeing a minimal level of a specific function of infrastructure itself. This framework provides a useful tool to enable stakeholders to effectively assess resilience strategies that are a key factor for building a resilient infrastructures. Considering this, the aim of this research is to present a resilience evaluation tool addressed to evaluate potential scenarios for enhancing the resilience of a specific infrastructure network and to further identify the most sensitivite assets of that critical infrastructure network.

The case of a real system was examined by the application of probabilistic methods applied to infrastructure network to generate statistical data for the calculation of the district heating (DH) pipeline network resilience of a municipality in Latvia. The study clarifies how resilient the district heating system is to a specific hazard and what could be the effect of specific investment scenarios aimed to enhance resilience. It will also identifies the most resilient assets of the DH network system and thus determine the main features of a DH systems that are important to ensure overall infrastructure resilience.

Peer review statement - Peer-review under responsibility of the scientific committee of the International Scientific Conference “Environmental and Climate Technologies”.

Keywords: district heating system; probabilistic simulation; network modelling; case study

* Corresponding author. Tel.: +371-26733409.
E-mail address: maksims.feofilovs@edu.rtu.lv

1876-6102
Peer review statement - Peer-review under responsibility of the scientific committee of the International Scientific Conference “Environmental and Climate Technologies”.
10.1016/j.egypro.2017.09.007

1. Introduction

Safe environment is a necessity for community development and critical infrastructure is vital for sustaining the 21st century community as they support most human needs. Critical infrastructure is usually considered as energy, water/sewage, telecommunication, transportation infrastructures [1–3]. Failure of any type of critical infrastructure can result in a cascade of failures in other infrastructures [4]. Unfortunately, with a growing population, urbanization, resource consumption, waste production and pollution, we keep on creating potential risks to natural and manmade disasters [5].

On this matter, the Sendai framework for disaster risk reduction 2015–2030 [6] was developed by United Nations Office for Disaster Risk Reduction and adopted in Third UN World Conference to fight disaster risks world-wide. It defines global targets like the reduction of disaster risk as an expected outcome; the goals are focused on preventing new risks, reducing existing risks, strengthening resilience, in an all-of-society and all-of-State institutions engagement. The Sendai framework introduces the goals, but solutions still must be developed step by step as the 21st century unfolds, an increasing majority of the world's population will live in cities. By 2050, the UN expects 80 % of the world's population to live in urban areas. Half of these are in small- and medium-sized cities [7].

There is an underlying assumption that resilient cities are far less vulnerable to hazards and disasters than less resilient places. But for this assumption to be validated and useful, knowledge of how resilience is determined, measured, enhanced, maintained, and reduced is vital. Specifically, it is not obvious what leads to resilience within coupled human-environment systems or what variables should be utilised to measure it. Several studies have attempted to highlight the fundamental aspects of resilience [8, 9], but because of the multi-dimensional and cross-disciplinary nature of resilience, a broad model of resilience has yet to be empirically tested at the community or city level [10, 11].

Human wellbeing in cities relies on a complex web of interconnected institutions, infrastructure and information. People are drawn to cities as centres of economic activity, opportunity and innovation. But cities are also places where disruptive events such as a disaster may result in social breakdown, physical collapse or economic deprivation. In the next decades, the major driver of the increasing damages and losses from disasters will be the growth of people and assets in harm's way, especially in urban areas [12].

Information about a city's susceptibility to disruption from hazards that is based on the status of a city's institutions, economy, and physical and social structures is already a topical issue [13]. Comparable information on cities is particularly useful, as it gives characteristics of urban development and provides confidence for policy directions that lead to better resilience [14]. This information is useful to many stakeholders, from residents and planners to national governments and international agencies.

Nevertheless, the term resilience is still indistinct as there is little regarding what it means to society, what factors are describing it and how cities might achieve greater resilience to increasing threats from natural and human induced hazards.

Findings suggest that different resilience systems have been developed of which some have been applied in real life, none of those are applicable on a regional or global scale as they are developed considering only a specific case [15–17]. A major challenge is the creation of a joint model for cities that implies identification of the metrics that can support policy action on a global scale and to develop action-relevant metrics that can be applied to hazards in cities with radically different geographical, infrastructural, economic, social, political and cultural characteristics.

The concept of infrastructure resilience is usually linked to an ability to maintain the functionality of the network through shocks and disruptions [18]. Some studies have introduced metrics for evaluation of the networked infrastructure resilience [19, 20]. In research of Leon F. G. Alanis et al. [21] a probabilistic method is carried out to evaluate the resilience of a water distribution network that is considered a critical part of infrastructure. According to Leon F. G. Alanis this method can be used for other types of networked infrastructure, like energy infrastructure. However, that study does not take into account customer based solutions for building resilience in disaster mitigation and preparedness phase [22], as for example of energy infrastructure, those would be energy efficiency measures [23, 24].

This study applies the Gay Alanis methodology to investigate a district heating (DH) system in a municipality in Latvia (i.e. Ludza). With the application of this method, the performance of the DH system can be determined under a specific damage and recovery time with respect to a well-functioning state. This information is a valuable tool for investors to find the solutions that will improve resilience of an infrastructure.

2. Methodology

According to findings in literature, probabilistic method is applied for a district heating network. For this study, extreme cold temperatures are considered as a hazard.

The probabilistic method used within this study involves several steps of implication:

- Definition of network asset that are used further for calculation of possible failures in time of hazard;
- Ranking the assets according to parameters that are notable to understand the asset performance in time of hazard;
- Assigning failure probabilities to assets per rank;
- Generating network failure matrix;
- Evaluating resilience of district heating network;
- Varying the variables used in resilience evaluation to find a more resilient state of system.

For this study, only the DH system distribution network of pipelines is considered as assets. To determine asset failure probability, a simplified analytical ranking system is proposed and described hereafter: pipelines are ranked in five categories that are considered most notable to describe character of a pipeline (Table 1) in the network. Higher rank means a less probability for this pipeline to fail. The description of pipeline systems is observed from DH network map and data gained from the municipality.

Table 1. Ranking of assets.

Category	Ranking
Type of pipeline	Major pipeline rank is *5*, Minor pipeline rank is *1*
Distance from boiler house	Asset locations are divided in five ranks according to specific distance. Assets group close to boiler house rank *5*, further *4*, *3*, *2* and so on to farthest asset rank *1*
Length of pipeline	Lengths of pipelines are divided in five ranks. Shortest assets rank *5*, longer *4*, then *3*, *2* and so on to longest asset rank *1*
Nodes	Number of nodes for pipelines are divided in five specific ranks. Assets with most count of nodes are ranked as *1*, less nodes *2*, then *3*, *4* and so on to asset rank *5* with smallest count of nodes
Diameter of pipeline	Inner diameters of pipelines have five specific ranks. Assets with largest diameter rank *5*, smaller *4*, then *3*, *2* and so on to asset rank *1* with smallest diameter

Rank distribution is explained in the way that major pipelines are considered more protected and supervised; pipelines close to the boiler house will be considered less likely to fail as they are better supervised; short pipelines have less space to be affected; more nodes are considered as more vulnerable because higher numbers of them have more probability to fail than small numbers; pipelines with a larger diameter will be more robust to low outside air temperatures.

These ranks (N) are summed up to evaluate a total score (S):

$$S = \sum_{i=1} N_i \tag{1}$$

where

S score;

N_i rank of asset for category;

i category.

Probabilities of failures are considered in five groups (Table 2) from high score with 20 % failure probability to low score with 1 % of failure probability. These kinds of ranking and probabilities are assessed from literature and considered for this specific case with the help of experts and civil engineer specialists.

Table 2. Asset probabilities of failure.

Score (S)	Probability of failure	Asset group
$S \le 5$	20 %	1
$5 < S \le 10$	15 %	2
$10 < S \le 15$	10 %	3
$15 < S \le 20$	5 %	4
$20 < S$	1 %	5

Probability of failure are assigned to asset in specific group (Table 2) with biased sampling method of Wallenius' probability distribution as suggested in literature [19]. This simplifies univariate problem in a sampling process. From the gathered data, a matrix is generated to simulate possible scenarios for asset damage with assigned failure probability:

$$M = \begin{pmatrix} S_{11} & S_{12} & S_{1n} \\ S_{21} & S_{22} & S_{2n} \\ S_{k1} & S_{k2} & S_{kn} \end{pmatrix} \quad (2)$$

where
M matrix;
S_k scenario;
S_n asset.

Within the matrix, a number of scenarios are generated (S_k) with asset (S_n) failures. This matrix is made using software and it assigns failures to assets randomly, with no intervention from the designer of the matrix. This way random scenarios are generated with total count of 1000 for this study. The output of the scenario matrix consists of failed assets, assets out of order and working assets. Assets out of order are considered as the assets that do not function in the network because of connection to the failed assets and the failed assets

The scenario of asset failures is considered resilient for this study when the number of failed assets does not exceed the limits of critical functioning level and the system recovers to a normal functioning state in reasonable time so that consumers are not exposed to extreme cold temperatures. The critical level of DH network functioning is considered as the state when the recovery to normal functioning state is not possible in a reasonably short time to avoid heat losses and negative side-effects on consumers, that can be being exposed to extreme cold temperatures. According to the proposed method, this occurs when the ratio of assets out of order is so high that critical level of functioning is exceeded, the network is brought out of resilience limits.

The concept of methodology gives a representation of probabilistic resilience level of a given networked infrastructure. Results of this method are given with implication of three dimensions that describe a resilient system: the ratio of assets out of order, recovery time and recovery costs, for this reason the output of this simulation is illustrated in a graph within these dimensions. Information on values of critical limits of these variables is gained from experts in the field and approximate estimations.

The ratio of assets out of order is also considered as resistance of networked infrastructure to a given natural hazard.

Different types of recovery time function can be applied in this method: linear, exponential, and trigonometric. This way a more complete calculation of resilience can be assessed, but in this case also more precise information is needed on resources and locations. For this case study, the recovery time function is linear as there was no information on previous recovery rates of failures in this DH network.

Probabilistic resilience is calculated as a ratio of scenarios that are in the range of available recovery costs and recovery time to overall number of scenarios simulated and the outcome is given as a percentage:

$$R = \frac{S_\alpha}{S_\beta} \quad (3)$$

where
R calculated resilience, %;
S_α number of scenarios in the resilience limits;
S_β total number of scenarios.

This method provides insight of system abilities to react and cope with a certain hazard, in this case it is extreme cold temperatures. Further this method is important to bring out the possibilities of improving systems resilience. This is done by varying the investment thus affecting recovery cost and recovery time. To improve low level of resilience higher investment should be considered for measures like attracting more specialists and technologies that will help to locate failure and deal with it. It is considered that this way recovery time will be cut. For this research it is considered that raising investment two times will also reduce the recovery time two times. This is an approximate calculation that will help to observe the possible benefits of investment in recovery of network.

3. Case study

For this study, the methodology proposed is applied to a case study on a district heating network of Ludza municipality that has went through several technical improvements in the past [25]. It is a city with a population of 8,700 thousand, located in the eastern part of Latvia, the region of Latgale. Ludza is in the continental part of Latvia and thus extreme temperatures are more likely to occur here. For this reason, DH system is crucial for resilience of community and infrastructure.

According to mapping of DH distribution, some buildings have minor pipelines connected directly to major pipeline, and others are linked to minor pipelines through secondary nodes. The total number of the assets for this study is 121. Recovery costs and recovery time are bound to the number of failed assets. Table 3 shows the recovery cost and recovery time used in this study for different cases of damaged pipes with consultancy of engineering experts in the field. Suggested recovery time for one asset in normal conditions would take 1–2 days. Three parts of the recovery process are considered: 1) identifying and 2) locating the damage 3) repair of the ripped pipe within damage range. Within the repair part three phases were reported by experts: i) digging up the area in approximately 3-meter range around the major pipeline, ii) repair works, iii) backfilling the area. Hence in this case study recovery time for a failure of major pipeline in extreme situation is considered to be no longer 1 day as there is threat of reaching critical functioning level of the system. For 10-meter damage of major pipeline 2 days of recovery time are assumed as there must be more work done on excavation and repairing per the size of damage.

For a minor pipeline the part of recovery process of locating the damage (part 2) is very specific for each damage case and sometimes would take more time than for a major pipeline. And on the opposite, repair work phases can take more time for major pipeline than for minor pipeline. Damage of 10-meters would be located faster than damage of 1-meter, but the recovery of 10-meter damage takes longer time. For minor pipeline recovery, the length of damage of the pipeline does not affect the recovery time to extent as for major pipeline. Thus, the recovery time of minor pipeline is taken into account as 2 days for all lengths of damage (Table 3).

Table 3. Pipeline recovery costs and recovery time.

Length of damage for pipelines, meters	Major pipeline recovery cost, EUR	Major pipeline recovery time, days	Minor pipeline recovery cost, EUR	Minor pipeline recovery time, days
1	2000	1	1500	2
5	10000	1.5	7500	2
10	20000	2	15000	2

The recovery cost calculations are assumed in the way that if the failed asset number grows, the specific recovery time of disruption scenario will gradually decline, as the repair work will go on bigger scale with and attract more recovery work specialists. For this research the recovery time function was considered in a way that for number 10 asset disruption the recovery time would decline by a certain level. For 10 asset disruption the recovery decline was considered two times bigger and for 20 asset disruption – three times.

For this study, the critical recovery limit is considered 6 days from occurrence of failure in the district heating, as in this period it is possible to partly sustain processes in community in severe winter conditions without centralized district heating in case when the residents have followed best energy efficiency measures (thermal isolation, ventilation) up to best standards to avoid heat loss from the building. This means a scenario that takes to recover in more than 6 days is below critical functioning level and is considered non-resilient.

Recovery cost limit is the amount of available financial resources that can be used to recover to normal functioning level of heating network in 6 days' period. It is considered that investment in terms of increase of available financial resources for recovery will lead to faster recovery thus scenarios with more assets failed will be in resilience boundaries. This way overall resilience of network should also increase.

If the extreme cold temperature occurs long enough and heat supply is not restored, there is a risk that water will freeze within these pipelines. Thus, pipes that are from metal can be torn apart by expansion of density when water crystalizes. For this reason, the effect of investment in faster recovery is introduced in this study and calculation of case with double financial investment in recovery measures is made.

4. Results and Conclusions

Based on the number of the disruptive scenarios, the statistical scenario distribution per failures assigned to scenario matrix M can be defined. From the random scenario generated with the excel tool it is shown that most have 5 failed assets. This case occurs in 170 scenarios of the total 1000 scenarios. Similarly, scenarios with 4 and 6 assets failed are observed in 166 and 169 scenarios. The scenario with the largest number of assets to fail is 13, which is observed only in four scenarios.

In the output of the matrix, it is possible to observe that scenarios with the same number of failed assets have different effect on network performance. This means that scenarios with failed assets have different number of assets out of order. The higher the ratio of assets out of order, then the network is closer to critical functioning level. This also corresponds to findings in literature and confirms validity of output given by the excel tool.

Cases when network is completely out of order only 4 to 8 assets are failed. This is since major pipeline failure in the start of DH network at the boiler house is the ‘trigger point’ to bring down the functioning of entire network. This is also a place where the failure is easy to locate. Thus this asset is an important part of the network and attention must be paid on supervising it.

Considering outputted information gained from scenarios the probabilistic resilience for a three-dimensional graph is made with “Ratio of assets out of order”, “Recovery time” and “Recovery costs” to understand the differences between scenarios and determine the resilience. The output consists of 1000 scenarios that are simulated regarding worst case when all damaged assets recovery is related to 10 m asset.

Regarding the matrix output data distribution in three-dimensional graph, most of the scenarios (90 %) that represent specific disruptive scenarios are not over the ratio 0.69 of assets out of order and total number of assets and more scenarios are distributed in the zone with lower ratio. This zone is defined in literature as high probability low consequence zone, thus, results gained by excel tool are considered reliable and are taken to evaluate probabilistic resilience of DH network of Ludza municipality.

The results show that most of the scenarios are not in the limit of the critical recovery time of 6 days. Total scenarios are obtained in recovery time resilience limits. 73 of these scenarios are also not over 30 000 Euro recovery costs. According to the results the probabilistic resilience of the Ludza DH network is considered 7.3 %.

Further results of double investment in recovery showed that scenarios that enter the limit of 6 days and with costs under 30 000 euros are minority, as most of scenarios are located over this limit. Within limit of 60 000 euro recovery costs there are more output scenarios. When investment is doubled, total of 313 scenarios are within the limit of 6 days, so for this case probabilistic resilience can be considered 31.3 %.

To sum it all up, in this case study investigation of Latvian municipality district heating network was performed. Case study contains significant information for stakeholders, pointing out importance of investment in recovery of infrastructure. It showed that investment in recovery of DH network improves the resilience. However, consideration according to results conclude that network with several heating sources (boiler houses) resulting as more major pipelines routes theoretically would continue to provide the heat supply when one major pipeline is out of order if network is equipped with the right technology to switch off certain parts of the network. In other means the diversification of heat supply should be considered for building more resilient infrastructure network.

Acknowledgements

The work has been supported by the National Research Program “Energy efficient and low-carbon solutions for a secure, sustainable and climate variability reducing energy supply (LATENERGI)”.

References

[1] Zio E. Challenges in the vulnerability and risk analysis of critical infrastructures. Reliability Engineering & System Safety 2016;152:137–150.
[2] Ferrario E, Pedroni N, Zio E. Evaluation of the robustness of critical infrastructures by Hierarchical Graph representation, clustering and Monte Carlo simulation. Reliability Engineering and System Safety 2016;155:78–96.
[3] Genge B, Haller P, Kiss I. A framework for designing resilient distributed intrusion detection systems for critical infrastructures. International Journal of Critical Infrastructure Protection; 2016.
[4] Stergiopoulosa G, Kotzanikolaoub P, Theocharidouc M, Lykoua G, Gritzalisa D. Time-based critical infrastructure dependency analysis for large-scale and cross-sectoral failures. International Journal of Critical Infrastructure Protection 2016;12:46–60.
[5] UN Secretary-General Ban Ki-moon. Resolution. New York; 2015.
[6] UN. Sendai framework for disaster risk reduction 2015–2030. Available: http://www.preventionweb.net/files/43291_sendaiframeworkfordrren.pdf
[7] UN. World urbanization prospects. New York, 2014. Available: https://esa.un.org/unpd/wup/Publications/Files/WUP2014-Highlights.pdf
[8] Berkes F, Colding J, Folke C. Navigating Social-Ecological Systems: Building Resilience for Complexity and Change. Cambridge: Cambridge University Press; 2003.
[9] Plummer R, Armitage D. A resilience-based framework. Ecological Economics 2007;61:62–74.
[10] Cutter LS, Barnes L, Berry M, Burton C, Evans E, Tate E, Webb J. A place-based model for understanding community resilience to natural disasters. Global Environmental Change 2008;18:598–606.
[11] Ainuddin S, Routray J. Community resilience framework for an earthquake prone area in Baluchistan. International Journal of Disaster Risk Reduction 2012;2:25–36.
[12] IFRC. World disasters report 2010 – Urban Risk.Available: http://www.ifrc.org/en/publications-and-reports/world-disasters-report/wdr2010/
[13] Henry D, Ramirez-Marquez JE. Generic metrics and quantitative approaches for system resilience as a function of time, Reliability Engineering & System Safety 2012;99:114–122.
[14] Toseroni F, Romagnoli F, Marincioni F. Adapting and reacting to measure an extreme event: a methodology to measure disaster community resilience. Energy Procedia 2016;95:491–498.
[15] Reed DA, Kapur KC, Christie RD. Methodology for Assessing the Resilience of Networked Infrastructure. Systems Journal, IEEE 2009;3(2):174–180.
[16] Tokgoz BE, Gheorghe AV. 114 Resilience Quantification and Its Application to a Residential Building Subject to Hurricane Winds. Int. J. Disaster Risk Sci. 2013;4(3):105–114.
[17] Francis R, Bekera B. A metric and frameworks for resilience analysis of engineered and infrastructure systems. Reliability Engineering & System Safety 2014;121:90–103.
[18] Omer M. Systems Research Series: Volume 3. The Resilience of Network Infrastructure Systems. World Scientific; 2013.
[19] Zhao S, Liu X, Zhuo Y. Hybrid Hidden Markov Models for Resilience Metric in a Dynamic Infrastructure System. IFAC-Papers On Line 2016;49–12:343–348.
[20] Kuznecova T, Romagnoli F, Rochas C. Energy Metabolism for Resilient Urban Environment: A Methodological Approach, 4th International Conference on Building Resilience. Building Resilience United Kingdom, Salford Quays, 8–10 September. 2014. Procedia Economics and Finance 2014;18:780–788.
[21] Alanis LFG. Development of a Resilience Assessment Methodology for Networked Infrastructure Systems using Stochastic Simulation, with Application to Water Distribution Systems; 2013.
[22] Measuring Community Disaster Resilience in the Latvian Context: An Apply Case Using a Composite Indicator Approach. Energy Procedia 2017;113:43–50.
[23] Miezis M, Zvaigznitis K, Stancioff N, Soeftestad L. Climate Change and Buildings Energy Efficiency – the Key Role of Residents. Environmental and Climate Technologies 2016;17(1):30–43.
[24] Latosov E, Volkova A, Siirde A, et al. Methodological Approach to Determining the Effect of Parallel Energy Consumption on District Heating System. Environmental and Climate Technologies 2017;19(1):5–14.
[25] Vigants G, Galindoms G, Veidenbergs I, Blumberga D. Energy efficiency of DH system with wood chip boiler and flue gas condensing unit. The 2013 International Conference on Energy, Environment, Ecosystems and Development, Greece, Rhodes Island, July 16–19, 2013.

SYSTEM DYNAMICS MODEL FOR NATURAL GAS INFRASTRUCTURE WITH STORAGE FACILITY IN LATVIA

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 147 (2018) 549–557

Energy Procedia

www.elsevier.com/locate/procedia

International Scientific Conference "Environmental and Climate Technologies", CONECT 2018

System dynamics model for natural gas infrastructure with storage facility in Latvia

Maksims Feofilovs*, Francesco Romagnoli, Armands Gravelsins

Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, Riga, LV-1048, Latvia

Abstract

Considering the recent happenings in the energy market of Latvia, future strategies for natural gas market and infrastructure remain unclear. For policy planners and gas market stakeholders it is crucial to deal with this uncertainty and aim for exploitation of existing natural gas infrastructure. In this case a model that allows to explore opportunities for renewable energy applications in natural gas infrastructure and at the same time provides information about security of energy supply can be highly desirable. Therefore, this paper presents a System Dynamics model made for natural gas infrastructure with storage facility in the Latvian context. The model incorporates the specific parts of the Latvia's natural gas infrastructure (transmission system and storage facility) and their characterizing parameters: natural gas transmission system capacities, storage facility capacities, working regimes, processes performed by transmission system operator for transmission system balancing based on natural gas flows. Model has potential to be used as a tool in energy policy planning processes for evaluation of different RES strategies and natural and technogenic risks of gas supply disruption. For this purpose, model must be upgraded with aspects that show gas market dynamics.

Keywords: natural gas infrastructure; system dynamics; sustainable energy; infrastructure development; natural gas storage; renewable gas

* Corresponding author.
E-mail address: maksims.feofilovs@edu.rtu.lv

1876-6102 © 2018 The Authors. Published by Elsevier Ltd.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)
Selection and peer-review under responsibility of the scientific committee of the International Scientific Conference 'Environmental and Climate Technologies', CONECT 2018.
10.1016/j.egypro.2018.07.070

1. Introduction

Energy sector is changing under the strives for efficient and clean energy production to achieve carbon emission reduction. Studies refer to power-to-gas and gas-to-power technologies to have a major role in transition to more flexible and resilient energy systems [1, 2] and contribute to environmental impact reduction in terms of CO_2 decreasing [3, 4]. This also means that new perspectives for natural gas infrastructure use arise with the need of an in-depth analysis. As power-to-gas technologies give opportunity to use gas infrastructure in combination with renewable energy sources (RES) [5], Blanco et al. [6] suggests that models must be created for case studies to evaluate the performance of entire gas supply system together with different renewable energy technologies.

Zoss et al. [7] in their study reported that in existing power-to-gas technologies can be used to produce and store 22.6 TWh of gas in existing natural gas storage in Latvia creating a model for the evaluation of power grid balancing options with power-to-gas system [8]. According to model of Blumberga et al. [9], the potential of natural gas use for electricity production in Latvia will diminish form 35 % in 2020 to 11 % in 2050 and wind energy can potentially become dominant in the Baltic region. This addresses the changes that natural gas infrastructure must undergo after 2020 to be used together with different renewable energy technologies.

The scientific literature analyzed on system dynamics models for Latvia left specific aspects of the natural gas infrastructure like transmission system capacities and working regimes outside the proposed models. In fact, these are important aspects for defining the future role of existing natural gas infrastructure in combination with renewable energy technologies. Moreover, another important the aspect of security of energy supply was also not fully explored in SD models for Latvia.

To undertake the development of future energy infrastructure and avoid not profitable investments, the approach of resilient energy infrastructure development must be analyzed in areas that are subject to investment decisions. This underlines the need for a modelling tool that allows to plan the application of natural gas infrastructure for supply of renewable gas and at the same time gives support for policy planning as for energy systems as for one whole system towards resilient energy sector in Latvia.

System dynamics (SD) modelling can be considered a valuable approach for an in-depth assessment of a complex system [10,11]. For this reason, the first step is oriented towards the creation of a SD model, which further can be used in energy policy planning in order to evaluate the resilience and flexibility of the Latvian natural gas system and how the implementation of a higher use of RES can bring beneficial effects. Specifically, in this study the structure of a SD model, which includes technical aspects of natural gas infrastructure and that can be used for the assessment of security of energy supply is proposed for the natural gas infrastructure with existing underground storage facility in Latvia [12]. The hypothesis of this study considers that it is possible to create SD model based on information in novel literature about existing models, historical data on natural gas flows and infrastructure available in number of sources and the statistical analysis.

2. Literature review on simulation models for natural gas infrastructure

Different methods from a literature review analysis can be used to create models of natural gas infrastructure depending on the targets of research, which are either gas demand/consumption forecasting or simulation of gas supply. Recent trends have also shown that advanced models that can provide information on several aspects of gas market and infrastructure are becoming more actual.

2.1. Models for gas demand forecasting and simulation of gas supply

Findings in literature suggest that models for daily gas demand forecasts involving the distribution system and yearly gas demand for the transmission systems (TS) are using regression analysis of historical data [13–16]. A case study evaluating the consistence of static or adaptive models for short-term residential natural gas forecasting in Croatia [17] concluded that non-linear regression provides a most suitable approach when dealing with adaptive models such as the case of natural gas infrastructure.

Grey System theory [18] models are often mentioned in novel literature and can be used instead of a regressive analysis based on stochastic simulation of gas demand forecasting [19, 20]. The combinations of Grey models with other modelling methods like Bernoulli differential equations [21], Bayesian probabilities [22] and Neural networks [23, 24] give promising results for forecasts of natural gas demand. Fagiani et al. [25] studied different Neural network techniques and concluded that they have different performance with a different time resolution.

Recently, even more advanced self-adapting intelligent models to forecast natural gas demand were reported [26, 27]. Karadede et al. [28] presented a natural gas demand forecasting model based on breeder hybrid algorithm (BHA) that includes breeder genetic algorithm, which is inspired by natural selection, and simulated annealing algorithm. According to BHA the model continuously provides updated best solution for gas demand forecasting model based on gross national product, population and the growth rate.

Models for simulation of a gas supply are mainly based on thermo-fluid dynamics principles to describe natural gas quality distribution for pipeline systems [29, 30]. Such models are physics-based considering technological and physical properties as main data input for the modelling phase (i.e. pressure, density and mass of gas components, pipeline surface roughness, frictions factor). There is a belief that physics-based models cannot be used for a big scale, for example, country-wide models, as not all the physical processes in TS have been studied on long distances [31]. However, models to forecast gas velocity, pressure and temperature on long distances in TS have been reported [32, 33].

2.2. Advanced models for gas market and infrastructure

Models for demand forecast and simulation of supply mentioned above can be used to forecast future work regimes for the system operator, but they do not provide enough information for policy planning of energy sector. The problem in this case often is that existing models are used separately as they capture only one aspect concerning the energy sector. Several specified models have been reported to determine the effects of price fluctuations on demand [34–39], assess the potential of disruption of supply [40] and the economic consequences [41], but only few studies mention about a possible expansion or combination of models to provide a holistic and consistent information about energy policy planning. For example, model utilizing mixed integer linear programming approach, like mentioned by Wang et al. [42] and Mikolaikova et al. [43], can be easily reformulated to provide the needed information on primary energy use, carbon emissions and environmental impact. As a good example of a model that provides aggregate information, model NANGAM can be mentioned for the context of North America [44]. Model includes capacity expansion criteria for suppliers, storage and TS, and allows to change scenarios for imports and local production and considers the costs for these scenarios.

Combining several energy planning programs [45] or merging modelling techniques is mentioned in literature [46]. Erdener et al. [47] in his study provided a list of approaches – Agent-based, Economic theory, Topological network-based, Functional network-based and Empirical modelling – and categorized by their scope: Economic, Technical and Security perspective. As a result, he presented a fine integrated simulation model that possibly served as a base for development of SAInt [48], which is an advanced model created to analyze the interdependence and cascading failures between the natural gas and electric power system with integrated renewable energy sources. The available data for Latvia in this tool is limited to major gas-fired CHP plants, leaving out many small-scale power plants distributed across the country outside of scope the model. SAInt is an important tool that can help energy policy planning on EU level, however, national energy policy planning in long term requires more detailed information.

SD models already exist for several aspects of the Latvian energy sector including energy efficiency planning [49, 50], RES support policies [11, 51], development of 4^{th} generation district heating [52] and overall development of energy sector [53]. Nevertheless, at the moment energy transmission aspects were not deeply investigated within the structure of the proposed SD models.

Based on this background information, the aim of this study is to create a SD structure for a model considering the natural gas infrastructure technical characteristics, the dynamics changes of natural gas flows and storage regimes. Such SD model potentially can be merged together with existing SD models for Latvia to assess the development of energy sector with help of renewable gas supply through existing natural gas infrastructure. To provide a more information for policy planners, the structure of the proposed SD model can incorporate the risks of disruption of gas supply through natural gas infrastructure.

3. Methodology

The methodology adopted for this study consists of several parts described below, which can be summarized as:

- Historical data collection on gas flows, storage, TS capacities, gas supplies in Latvia for creation of SD model;
- Statistical analysis of historical data to identify internal variables for equations in SD model;
- Explanation of SD model with casual loop diagram.

3.1. Historical data collection

The data for natural gas flows into and out of the country are gathered from the International Energy Agency gas trade flow database for Europe [54] from January 2010 to December 2017. Data for natural gas consumption per month for the Latvian condition was obtained from Central Statistics Bureau [55] for the same period. Other information, including the data about the flows per month into and out of gas storage facility (SF) for year 2010, transmission pipeline volume and maximal technical pressure is collected from TS operator reports.

3.2. Statistical analysis of historical data

Statistical analysis of gas flows in and out of the SF is performed to define the relationship of variables describing gas injection from TS into SF and gas injection from SF into TS in relation to gas main flows in Latvia. The analysis consists of:

- Assessing the correlations of gas flows and injection processes to find the relationships of between gas flows;
- Regression analysis to explain missing data on the relationships between variables for SD model.

Pearson product-moment correlation [56] are assessed between all the gas flows distinguished in data collection part, namely:

- Gas injection from TS into SF;
- Gas injection from SF into TS;
- Gas flow into the country;
- Domestic gas supply;
- Gas flow out of the country.

To include the gas injection from TS into SF and from SF into TS as variables in the SD model, an equation is obtained with regression analysis for description of gas injection processes. Data sets for regression analysis are chosen based on the results of correlations to avoid unnecessary analysis of all the possible equations that can be formed from the given set of data. Specifically, historical data on gas injection is subjected different regression analysis (linear regression, multi-variable regression, polynomial regression) in statistics software as dependent variables to determine which type of equation is the best to describe the injection processes into and out of the SF. This is determined by comparing which equation from different regression analysis output has the P-value of variables lower than 0.5 and the highest R squared.

3.3. Model construction

In general, natural gas infrastructure is a complex system, which works in specific regimes that are determined by technical aspects of gas infrastructure regarding the gas flows, transmission system capacities, amount of gas in the storage, and social aspects, like demand and consumption, that are directly influenced by energy policies. It is difficult to capture a set of variety of these aspects in one tool or method. To deal with this SD modelling is introduced.

SD modelling aims to analyze systems behavior and its structure together, by distinguishing flows that can accumulate in stocks, in this way creating the dynamic effect [57]. Flows in SD model can be distinguished as material values, in this case gas, and non-material values, for example, effects of support policy. This study, however, does not present social effects in SD at this development stage of the model. Also, the thermo-dynamic effects of changes in gas flow directions occurring in the pipelines due to different gas velocity and composition were not studied, as physics-based software tools for thermo-dynamics process modelling are more suitable for this purpose then SD modelling. However, equation that defines the amount of gas injected from SF into TS describes the isochoric process, which occurs in SF.

Model includes fuzzy-logic, which is set to compare different variables in model and switch the regimes of gas flows, in this way imitating the balancing process performed by TS operator. In fact, the process of regime switch of gas flows in TS is representing the feedback loops in SD model that are causing the dynamic effect.

4. Results

4.1. Results of statistical analysis of historical data

The Pearson's correlation coefficients of gas injection from TS into SF and from SF into TS with data on gas flows in Table 1 show the level of relation between the selected set of data. P-values of all correlations are below 0.05 and indicate statistically significant non-zero correlations.

Table 1. Correlation coefficients of gas injection from TS into SF and from SF into TS with data on gas flows.

Simulation period	Gas flow into the country	Domestic gas supply	Gas flow out of the country	Gas injection from TS into SF
Domestic gas supply	–0.84419			
Gas flow out of the country	–0.74842	0.92578		
Gas injection from TS into SF	0.96410	–0.76108	–0.65546	
Gas injection from SF into TS	–0.84269	0.97030	0.97488	–0.73289

According to the interpretation of Pearson correlation coefficient standards, there is very high positive correlation for gas injection from TS into SF with gas flow into the country; for domestic gas supply with gas flow out of the country; for gas injection from SF into TS with domestic gas supply and gas flow out of the country. This can be interpreted as following:

- Gas injection from TS into SF is performed according to the gas flow into the country;
- Gas injection from SF into TS is performed according to domestic gas supply and gas flow out of the country.

Other correlations coefficients underline these relations, for example, the high negative correlation coefficient of gas flow into the country and gas injection from SF into TS can be explained by fact that when there is large amount of gas flowing into the country, there is no need to supply the gas from the SF. Moreover, gas injection from TS into SF and gas injection from SF into TS cannot be performed at the same time by the existing technology in this TS.

From the correlations presented in Table 1 a set of variables with very high correlation is chosen to define the gas injection from TS into SF and gas injection from SF into TS as independent variables for regressions analysis. The highest P-value of variables (not including the intercept) and for highest order term and coefficient of determination R squared for performed linear regression, multi-variable regression, polynomial regression with different variables are shown in Table 2.

Table 2. Summary of different regression assessed for gas injection from TS into SF and gas injection from SF into TS.

Dependent variable	Form of regression	P-value on the highest order term/ variable	R squared	Independent variables considered		
				Gas flow into the country	Domestic gas supply	Gas flow out of the country
Gas injection from TS into SF	Linear	$P < 0.05$	0.85839	Yes	No	No
	Multi-variable	$P \geq 0.05$	0.93920	Yes	Yes	No
	2nd order polynomial	$P < 0.05$	0.98131	Yes	No	No
	3rd order polynomial	$P < 0.05$	0.99037	Yes	No	No
	4th order polynomial	$P \geq 0.05$	0.99108	Yes	No	No
Gas injection from SF into TS	Linear	$P < 0.05$	0.95039	No	No	Yes
	2nd order polynomial	$P \geq 0.05$	0.96229	No	No	Yes
	Linear	$P < 0.05$	0.94139	No	Yes	No
	2nd order polynomial	$P \geq 0.05$	0.96100	No	Yes	No
	Multi-variable	$P < 0.05$	0.98248	No	Yes	Yes

According to R squared and P-value of highest order term, gas injection from TS into SF can be described best by polynomial Eq. (1), with R squared of 0.99037.

$$\alpha = 2.10148 - 0.7307 \cdot \mu + 0.00611877 \cdot \mu^2 - 0.0000058443\ 5 \cdot \mu^3 \quad (1)$$

where

α gas injection from TS into SF;

μ gas flow into the country.

Gas injection from SF into TS is mainly dependent on gas demand and outflow and is described best by multi-variable Eq. (2) with R squared of 0.98248 and P-value of variables lower than 0.05. Eq. (1) and Eq. (2) are used as variables in the SD model presented below.

$$\beta = 1.09924 \cdot \gamma + 1.24246 \cdot \rho - 74.8471 \quad (2)$$

where

β gas injection from SF into TS;

γ domestic gas supply;

ρ gas flow out of the country.

4.2. Construct of the SD model

The relationship of different aspects of natural gas transmission system and storage facility in Latvia is shown in Fig. 1 in casual loop diagram. The casual loop diagram consists mainly of positive reinforcing loop 1 (i.e. R1), negative reinforcing loop (i.e. R2), and three balancing loops (i.e. B1, B2, B3). Loop R1 ensures that more gas can flow into the country through gas injection from TS into SF and out of the country through gas injection from SF back into TS under influence of domestic gas demand and gas demand in neighbor countries. Balancing loos ensure that reinforcing loops are balanced.

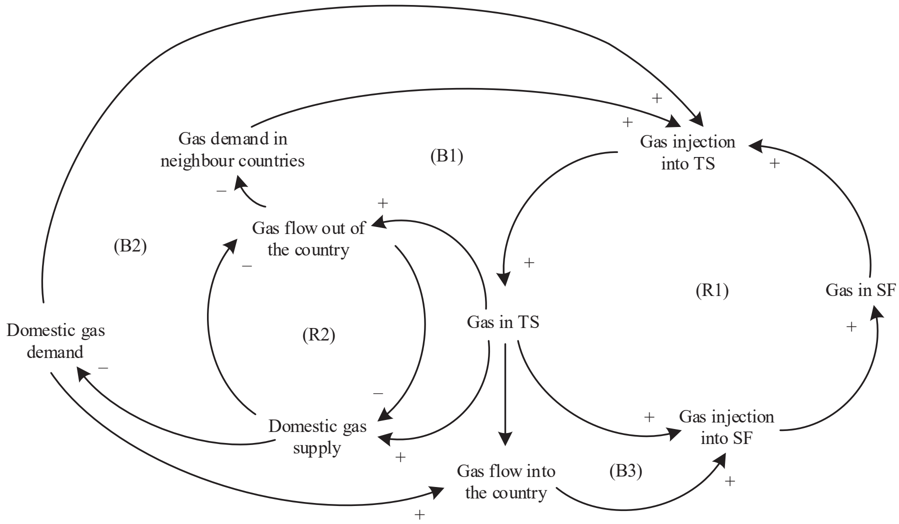


Fig. 1. Casual loop diagram for SD model of natural gas transmission system with storage facility in Latvia.

5. Conclusions

Natural gas infrastructure in Latvia can have an important role in RES implementation in the future. Assessing the insights of natural gas infrastructure exploitation to determine the possible implication of it together with the renewable gas can be desirable for many stakeholders. The results of statistical analysis performed are reliable and casual loop diagram explains the construct of the model appropriately. The hypothesis of the study is proved and the SD model presented in this study can be used for research of technological and social aspects for energy policy planning. Potential combinations of existing SD models for Latvia with the model presented in this study must be evaluated for extended studies on energy sector of Latvia. Based on available information for input and the necessary information in the output, different types of simulations can be performed. Model can be used to determine the effects of changes of gas flow into the country on the amount of gas in the storage in different seasons, or the effects of the gas amount in the storage on gas from out of the country and domestic supply. Moreover, the possible effects renewable gas injection into natural gas grid on storage regimes can be assessed and evaluated. The next task is to perform validation of this model. Also, regarding the findings from novel literature about self-adapting intelligent models, incorporation of such algorithm should be considered in the next development stage of this model.

Acknowledgements

"This work is partially based on the statistics of gas flows in Europe developed by the International Energy Agency, © OECD/IEA [2018] but the resulting work has been prepared by Riga Technical University and does not necessarily reflect the views of the International Energy Agency".

References

[1] Gotz M, Lefebvre J, Mors F, McDaniel-Koch A, Graf F, Bajohr S, Reimert R, Kolb T. Renewable Power-to-Gas: A technological and economic review. Renew. Energy 2016;85:1371–90.

[2] McKinnon MA, Brouwer J, Samuelsen S. The role of natural gas and its infrastructure in mitigating greenhouse gas emissions, improving regional air quality, and renewable resource integration. Prog. Energy Combust. Sci. 2018;64:62–92.

[3] Parra D, Zhang X, Bauer C, Patel MK. An integrated techno-economic and life cycle environmental assessment of power-to-gas systems. Appl. Energy 2017;193:440–54.

[4] Li G, Zhang R, Jiang T, Chen H, Bai L, Li X. Security-constrained bi-level economic dispatch model for integrated natural gas and electricity systems considering wind power and power-to-gas process. Appl. Energy 2017;194:696–704.

[5] Walker SB, van Lanen D, Mukherjee U, Fowler M. Greenhouse gas emissions reductions from applications of Power-to-Gas in power generation. Sustain. Energy Technol. Assessments 2017;20:25–32.

[6] Blanco H, Faaij A. A review at the role of storage in energy systems with a focus on Power to Gas and long-term storage. Renew. Sustain. Energy Rev. 2018;81:1049–86.
[7] Zoss T, Karklina I, Blumberga D. Power to gas and pumped hydro storage potential in Latvia. Energy Procedia 2016;95:528–35.
[8] Zoss T, Dace E, Blumberga D. Modeling a power-to-renewable methane system for an assessment of power grid balancing options in the Baltic States' region. Appl. Energy 2016;170:278–85.
[9] Blumberga A, Lauka D, Barisa A, Blumberga D. Modelling the Baltic power system till 2050. Energy Convers. Manag. 2016;107:67–75.
[10] Ziemele J, Gravelsins A, Blumberga A, Vigants G, Blumberga D. System dynamics model analysis of pathway to 4th generation district heating in Latvia. Energy 2016;110:85–94.
[11] Romagnoli F, Barisa A, Dzene I, Blumberga A, Blumberga D. Implementation of different policy strategies promoting the use of wood fuel in the Latvian district heating system: Impact evaluation through a system dynamic model. Energy 2014;76:210–22.
[12] European Comission. Innovation and Networks. Incukalns underground gas storage – study of increased flexibility and use as strategic gas storage, 2016.
[13] Ozmen A, Yilmaz Y, Weber G-W. Natural gas consumption forecast with MARS and CMARS models for residential users. Energy Econ. 2018;70:357–81.
[14] Oliver R, Duffy A, Enright B, O'Connor R. Forecasting peak-day consumption for year-ahead management of natural gas networks. Util. Policy 2017;44:1–11.
[15] Sanchez-Ubeda EF, Berzosa A. Modeling and forecasting industrial end-use natural gas consumption. Energy Econ. 2007;29(4):710–42.
[16] Sabo K, Scitovski R, Vazler I, Zekic M. Energy Conversion and Management. 2011;52:1721–7.
[17] Simunovic G, Saric T, Jeromen A. Comparison of static and adaptive models for short-term residential natural gas forecasting in Croatia. 2014;129:94–103.
[18] Julong D. Introduction to Grey System Theory. J. Grey Syst. 1989;1:1–24.
[19] Wang J, Jiang H, Zhou O, Wu J, Qin S. China's natural gas production and consumption analysis based on the multicycle Hubbert model and rolling Grey model. Renew. Sustain. Energy Rev. 2016;53:1149–67.
[20] Ma X, Liu Z. Application of a novel time-delayed polynomial grey model to predict the natural gas consumption in China. J. Comput. Appl. Math. 2017;324:17–24.
[21] Shaikh F, Ji O, Hameed P. Forecasting China' s natural gas demand based on optimised nonlinear grey models. Energy 2017;140:941–51.
[22] Zhang W, Yang J. Forecasting natural gas consumption in China by Bayesian Model Averaging. Energy Reports 2015;1:216–20.
[23] Liu X, Moreno B, Garcia AS. A grey neural network and input-output combined forecasting model. Primary energy consumption forecasts in Spanish economic sectors. Energy 2016;115:1042–54.
[24] Panapakidis IP, Dagoumas AS. Day-ahead natural gas demand forecasting based on the combination of wavelet transform and ANFIS/genetic algorithm/neural network model. Energy 2017;118:231–45.
[25] Zeng B, Li C. Forecasting the natural gas demand in China using a self-adapting intelligent grey model. Energy 2016;112:810–25.
[26] Ceperic E, Zikovic A, Ceperic V. Short-term forecasting of natural gas prices using machine learning and feature selection algorithms. Energy 2017;140:893–990.
[27] Fagiani M, Squartini S, Gabrielli L, Spinsante S, Piazza F. A review of datasets and load forecasting techniques for smart natural gas and water grids: Analysis and experiments. Neurocomputing 2015;170:448–65.
[28] Karadede Y, Ozdemir G, Aydemir E. Breeder hybrid algorithm approach for natural gas demand forecasting model. Energy 2017;141:1269–84.
[29] Chaczykowski M. Simulation of natural gas quality distribution for pipeline systems. Energy 2017;134:681–98.
[30] Guandalini G, Colbertaldo P, Campanari S. Dynamic modeling of natural gas quality within transport pipelines in presence of hydrogen injections. Appl. Energy 2017;185:1712–23.
[31] Ahmadian-Behrooz H, Boozarjomehry RB. Dynamic optimization of natural gas networks under customer demand uncertainties. Energy 2017;134:968–83.
[32] Lopez-Benito A, Bolado-Lavin R. A case study on global sensitivity analysis with dependent inputs: The natural gas transmission model. Reliab. Eng. Syst. Saf. 2017;165:11–21.
[33] Lopez-Benito A, Elorza Tenreiro FJ, Gutierrez-Perez LC. Steady-state non-isothermal flow model for natural gas transmission in pipes. Appl. Math. Model. 2016;40(23–24):10020–37.
[34] Pambour KA, Bolado-Lavin R, Dijkema GPJ. An integrated transient model for simulating the operation of natural gas transport systems. J. Nat. Gas Sci. Eng. 2016;28:672–90.
[35] Dyachenko SA, Zlotnik A, Korotkevich AO, Chertkov M. Operator splitting method for simulation of dynamic flows in natural gas pipeline networks. Phys. D Nonlinear Phenom. 2017;361:1–11.
[36] Linn J, Muehlenbachs L. The heterogeneous impacts of low natural gas prices on consumers and the environment. J. Environ. Econ. Manage. 2018;89:1–29.
[37] Aolin H, Qing D. On natural gas pricing reform in China. Nat. Gas Ind. B. 2015;2(4):374–82.
[38] Giziene V, Zalgiryte L. The Assessment of Natural Gas Pricing. Procedia – Soc. Behav. Sci. 2015;213:111–6.
[39] Zeng S, Chen ZM, Alsaedi A, Hayat T. Price elasticity, block tariffs, and equity of natural gas demand in China: Investigation based on household-level survey data. J. Clean. Prod. 2018;179:441–9.
[40] Badea AC, Rocco SCM, Tarantola S, Bolado R. Composite indicators for security of energy supply using ordered weighted averaging. Reliab. Eng. Syst. Saf. 2011;96(6):651–62.
[41] Bouwmeester MC, Oosterhaven J. Economic impacts of natural gas flow disruptions between Russia and the EU. Energy Policy 2017;106:288–97.

[42] Wang B, Yuan M, Zhang H, Zhao W, Liang Y. An MILP model for optimal design of multi-period natural gas transmission network. Chem. Eng. Res. Des. 2018;129:122–31.
[43] Mikolajkov M, Sax H, Pettersson F. Linearization of an MINLP model and its application to gas distribution optimization. Energy 2018;146:156–68.
[44] Feijoo F, Huppmann D, Sakiyama L, Siddiqui S. North American natural gas model: Impact of cross-border trade with Mexico. Energy 2016;112:1084–95.
[45] Golara A, Esmaeily A, Asce M. Quantification and Enhancement of the Resilience of Infrastructure Networks. Journal of Pipeline Systems Engineering and Practice 2016;8:04016013.
[46] Zio E, Sansavini G. Modeling interdependent network systems for identifying cascade-safe operating margins. IEEE Trans. Reliab. 2011;60(1):94–101.
[47] Erdener BC, Pambour KA, Lavin RB, Dengiz B. An integrated simulation model for analysing electricity and gas systems. Int. J. Electr. Power Energy Syst. 2014;61:410–20.
[48] Pambour KA, Cakir Erdener B, Bolado-Lavin R, Dijkema GPJ. SAInt – A novel quasi-dynamic model for assessing security of supply in coupled gas and electricity transmission networks. Appl. Energy 2017;203:829–57.
[49] Asere L, Blumberga A. Government and municipality owned building energy efficiency system dynamics modelling. Energy Procedia 2015;72:180–7.
[50] Locmelis K, Blumberga A, Bariss U, Blumberga D. Energy policy for energy intensive manufacturing companies and its impact on energy efficiency improvements. System dynamics approach. Energy Procedia 2017;128:10–6.
[51] Bazbauers G, Repele M, Udrene L. Support mechanism for biomethane production and supply. Energy Procedia 2017;113:304–10.
[52] Ziemele J, Gravelsins A, Blumberga A, Blumberga D. Combining energy ef fi ciency at source and at consumer to reach 4th generation district heating: Economic and system dynamics analysis. Energy 2017;137:595–606.
[53] Blumberga D, Blumberga A, Barisa A, Rosa M, Lauka D. Modelling the Latvian power market to evaluate its environmental long-term performance q. Appl. Energy 2016;162:1593–600.
[54] Based on IEA data from Montly gas statistics. Modified by Riga Technical University. Available: www.iea.org/statistics
[55] Based on Central statistical bureau of Latvia data from Environment and energy statistics section. Modified by Riga Technical University. Available: http://www.csb.gov.lv/en/dati
[56] Wikipedia. Pearson correlation coefficient. Available: https://en.wikipedia.org/wiki/Pearson_correlation_coefficient
[57] Blumberga A, Bazbauers G, Daviddsen P, Blumberga D, Gravelsins A, Prodanuks T. System dynamics modelling in bioeconomy sector. Scientific monography. Riga: RTU publisher; 2016.

INCREASING RESILIENCE OF THE NATURAL GAS SYSTEM WITH IMPLEMENTATION OF RENEWABLE METHANE IN THE CONTEXT OF LATVIA: A SYSTEM DYNAMICS MODEL

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 158 (2019) 3944–3950

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

Increasing resilience of the natural gas system with implementation of renewable methane in the context of Latvia: a system dynamics model

Maksims Feofilovs[a], Armands Gravelsins[a], Andrea Jonathan Pagano[b], Francesco Romagnoli[a*]

[a]Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, LV-1048, Latvia
[b]Turiba University, Law faculty, Graudu iela 68, Riga, LV- 1058, Latvia

Abstract

Implementation of renewable energy sources while ensuring security of energy supply is a pressing issue in energy policy planning. Findings in literature suggest that biomethane and power-to-gas applications together with natural gas systems can have great benefits in terms of carbon emission reduction, contribution to local economies and circular economy and important impact to the phasing of fossil fuel-based energy systems. Moreover, according to theoretical background the diversification of supplies in natural gas system will enhance the infrastructural system resilience and contribute to the security of energy supplies. In this light the study presents a system dynamic model for biomethane and power-to-gas application in natural gas system in Latvia with the existing underground storage facility. The natural gas infrastructure technical characteristics, natural gas flow and storage regime dependence on the seasonal gas demand are considered in the model. The model presented in this study can help policy planners to determine the necessary steps for implementation of RES support policy in Latvia to reach goals of EU low carbon economy. This system dynamic model has a potential to be used for energy policy planning together with other system dynamic models developed within the context of Latvia to cover a range of issues in energy sector.

Peer-review under responsibility of the scientific committee of ICAE2018 – The 10th International Conference on Applied Energy.

Keywords: Energy system resilience; Biomethane injection; Renewable energy sources; Natural gas system; System dynamics

* Corresponding author. *E-mail address:* francesco.romagnoli@rtu.lv

1876-6102
Peer-review under responsibility of the scientific committee of ICAE2018 – The 10th International Conference on Applied Energy.
10.1016/j.egypro.2019.01.848

1. Introduction

1.1. Biomethane and power-to-gas application with natural gas systems

Natural gas has a high share in final energy consumption in European Union (EU) and most of the gas is imported, and is estimated to reach 85 % by 2030 [1]. This stresses the security of energy supply [2] in light of EU low carbon economy goals [3][4]. As to deal with this, findings in novel literature suggest that biomethane can be used as a substitute of natural gas and contribute to achievement of the EU low carbon economy goals [5]. In specific, life-cycle analysis of biomethane shows greenhouse gas (GHG) emission reduction of 85 % compared with natural gas [6] and according to the estimations of Koornneef et.al. [7] the global biomethane technology deployment in combination with carbon capture and storage would remove up to 3.5 Gt CO_2-eq of GHG emissions from the atmosphere by 2050 and additionally save 8 Gt CO_2-eq if biomethane is used to substitute natural gas. In addition, the use of biomethane contributes to the development of circular economy by recovering wide range of waste [8].

Other findings in novel literature suggest that power-to-gas technologies will play an important role in future energy systems [9],[10] to maximize the use of renewable energy sources (RES) like wind and solar, while ensuring the reduction of the environmental impact with carbon capture and storage [11]. Power-to-gas technologies give opportunity to use natural gas infrastructure in combination with renewable energy sources [12], reduce the natural gas consumption, emissions [13] and overall cost for combined electricity and natural gas systems [14].

Case studies about biomethane and power-to-gas application potential effects on national energy market of Latvia has not been studied enough. Results from the study for other EU countries show that one third of annual GHG emission can be avoided in UK and 15 % in Germany till 2030 [15]. Estimations of Fubara et.al. [16] show that even more significant results can be achieved in UK. Up to 72 % of natural gas can be substituted and reduction of GHG emissions up to 84 % can be achieved with help of different technological, economic and environmental mechanisms. Results of Thema et.al. [17] study showed that application of power-to-gas in long-term leads to cost savings of up to EUR 19 billion in Germany. The case study on potential utilization of CO_2 sources with help of power-to-gas in Ireland showed that there is a potential to produce approximately 396 GWh of methane [18].

In terms of security of energy supply the use of biomethane ensures diversification of bioenergy sector, which allows to promote bioenergy on local and national level: biogas and biomass usually is used on local level, but biomethane injected into natural gas transmission system can contribute to renewable energy production anywhere [19]. The use of biomethane can ensure flexibility for electricity by allowing flexible power generation in a RES-based electricity sector and balancing energy production among cogeneration and storage in the gas grid [20]. For heating sector, the use of biomethane can ensure cross-sectoral integration with renewables-based heating grids. Similar benefits are reported in literature for power-to-gas technology application [21]. However, high penetration of renewables would put more stress on the gas transmission system to respond quickly to changes in power-to-gas production and the gas demand [22], therefore measures to reduce security risks would be required [23].

These findings in literature give perspective for natural gas infrastructure in Latvia regarding the EU low carbon economy goals, however, security of energy supply in such energy systems must be studied more in-depth to ensure prompt and consistent national energy strategy. Studies suggest that incorporating the concept of resilience can be useful to describe the trade-off and regime shifts in energy systems [24],[25].

1.2. Context of natural gas in energy policy of Latvia

Natural gas in Latvia is used to fulfil the base load demand and its consumption accounts approximately for 25 % in final energy consumption by fuel [26]. Natural gas infrastructure of Latvia includes natural gas storage facility of volume of 4 billion cubic meters [27]. The natural gas is used in utility scale combined heat and power plants, industrial power plants and in households for heating and cooking.

Edvins Karnitis, expert of the Sustainable Energy Committee of the United Nations Economic Commission for Europe, in his paper *Improvement of natural gas supply reliability in Latvia: strategy and tools* [28] noted that natural gas is an important strategic resource, which cannot be replaced, and underlined the need for diversification of gas supplies. However, ensuring more routes for natural gas supplies to ensure the security of gas supplies while replacing oil in accordance to EU low carbon economy goals [29] can lead to higher dependency on natural gas imports. Furthermore, in light of climate challenges and development of RES, smart grids and decentralization of energy systems that leads to technological advancement, the basic elements of energy security should be requisitioned and revised [30]. Thus, this study aims to create a model that will help to find accordance between two issues of national energy policy planning in Latvia: security of energy supplies and EU low carbon energy goals. For that purpose, a system dynamics approach is applied to describe the implementation of biomethane and renewable methane from power-to-gas effect on the natural gas systems in Latvia.

The carbon reduction from biomethane and power-to-gas applications is promising, however, creating policy strategies for multiple technology deployment can be complicated. Findings in literature suggest that in order to explain and provide more information about energy systems for policy planning, novel tools are emerging, which incorporate several perspectives [31]-[33], for example economic, environmental and security. Using state-of-art approach, this study aims to create a system dynamics model that will explain the interaction tendencies of biomethane and renewable methane injections into natural gas system with the seasonal regimes of natural gas system in Latvia. Such model will help to determine the quantitative parameters that are necessary for planning national energy strategy that will ensure technology transition.

2. Methodology

System dynamics approach is commonly used to describe the nonlinear behavior of complex systems that include social and technical aspects by using stocks, flows and internal feedback loops [34]. The interrelation of different variables in system dynamics models are explained with casual loop diagram, which consist of nodes and edges. Nodes present the variables, and edges are the links that present a connection. A link marked positive represents a positive relation, on the contrary, link marked negative indicates the negative relation. Positive link means the nodes change in the same direction, whereas a negative link means that two nodes are changing in the opposite directions. The loops in diagram are closed cycles, which either reinforces the initial deviation of variable (variable value increases in closed cycle – also called reinforcing loop) or balances the initial deviation of variable (variable value decreases in closed cycle – also called counterbalancing or more simply balancing loop) [35].

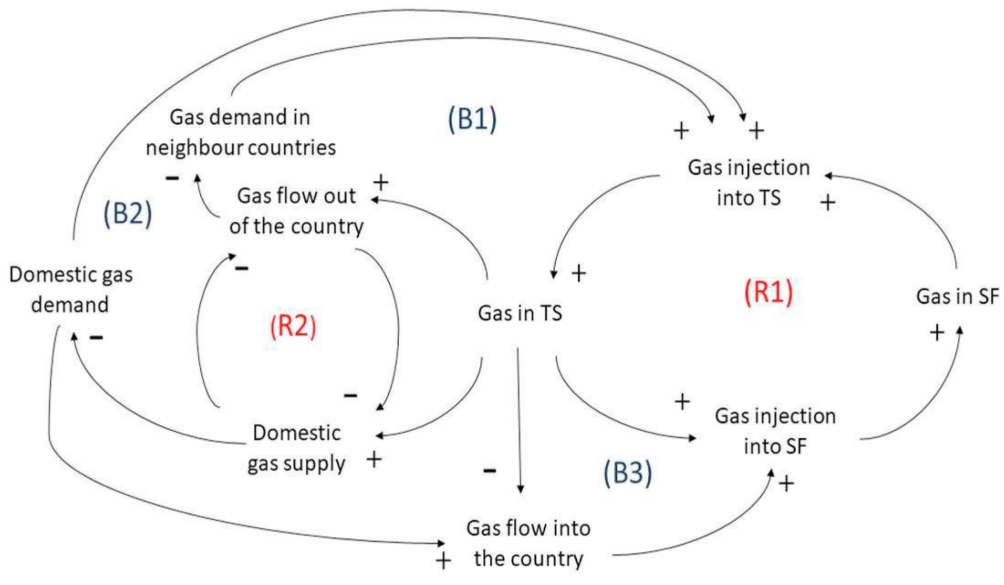


Fig. 1. Casual loop diagram for natural gas system with storage facility where are represented the Transmission system (TS) and the Storage facility (SF)

For this study, the methodology adopts existing system dynamics model for natural gas system infrastructure in Latvia with the storage facility reported in the casual loop diagram in fig.1. This model is built based on the information about natural gas transmission system and storage capacities, historical data on gas flows [36] into and out of the country and domestic gas supplies [26]. The casual loop diagram consists of positive reinforcing loop 1 (i.e. R1), negative reinforcing loop (i.e. R2), and three balancing loops (i.e. B1, B2, B3). Loop R1 ensures that the gas injection from the transmission system into the storage facility allows more gas flow into the country, and that more gas can flow out of the country, by performing the gas injection from the storage facility back into the transmission system. Loop R2 shows the competition for transmission capacities between domestic gas supply and gas flow out of the country due to limits of natural gas system capacities. Specifically, it shows that growth of the domestic gas supply will result as decrease in gas flow out of the country, and vice versa.

The hypothesis for describing the resilience of energy system within system dynamic model model is based on a concept presented in study of Roege et.al. [37], where resilience is increased by diversity and interconnectedness, while limiting or decreasing system efficiency. According to this concept, the resilience of energy systems will be increased by diversification of natural gas systems with the biomethane and renewable methane from power-to-gas, thus will increase the security of energy supplies. For this purpose, the system dynamics model considers RES support policy effects on subsidies for biomethane, which effect biomethane production, and investment in renewable technologies, which effect renewable methane production in power-to-gas applications. In this way, the economic perspective can be evaluated for these technologies. The resulting system dynamics model is explained with casual loop diagram that will be presented in fig.2.

3. Results and analysis

The system dynamics model of biomethane and renewable methane from power-to-gas implementation in natural gas system in the context of Latvia is presented in fig.2. The processes in natural gas system in this casual loop diagram is represented with: Gas in transmission system, Gas injection into storage facility, Gas in storage facility, Gas injection into transmission system, Natural gas flow into the country, Domestic gas supply, Gas flow out of the country. The loop (R1) is the reinforcing loop for gas storage, (R2) is the reinforcing loop for gas supplies. Both reinforcing loops are balanced by balancing loops (B1), (B2) and (B3).

To create a model that would help to study the possible effects of renewable methane implementation in natural gas system in Latvia two loops are added to the existing model: (B4) and (B5). Both loops start from RES support policy, which must be implemented to achieve the EU low carbon economy goals. In loop (B4) RES support policy increases the subsidies for biomethane, which increases biomethane production and consequently the renewable methane injection into transmission system. The share of renewable methane in transmission system increases with renewable methane injection into transmission system. Thus, share of natural gas in transmission system reduces. As the increase of the share of natural gas in the transmission system stimulates the RES support policy increase, with the decrease of the share of natural gas in transmission system, the RES support policy will decrease.

Similar process is represented for the loop (B5) as for loop (B4). The loop starts with RES support policy which increases the investment in renewable energy technologies and consequently the power-to-gas production. Thus, the renewable methane injection into transmission system increases, share of renewable methane in transmission system increases and share of natural gas decreases and RES support policy decreases.

Overall, loops (B4) and (B5) ensure the increase of gas in transmission system with the renewable methane injection into transmission system. According to the casual loop diagram of natural gas system, in case the gas amount increase in transmission system from renewable methane injection into transmission system, the loop (B3) will ensure decrease of the natural gas flow into the country. This ensures reduction of the share of natural gas in transmission system and enables renewable methane injection into storage.

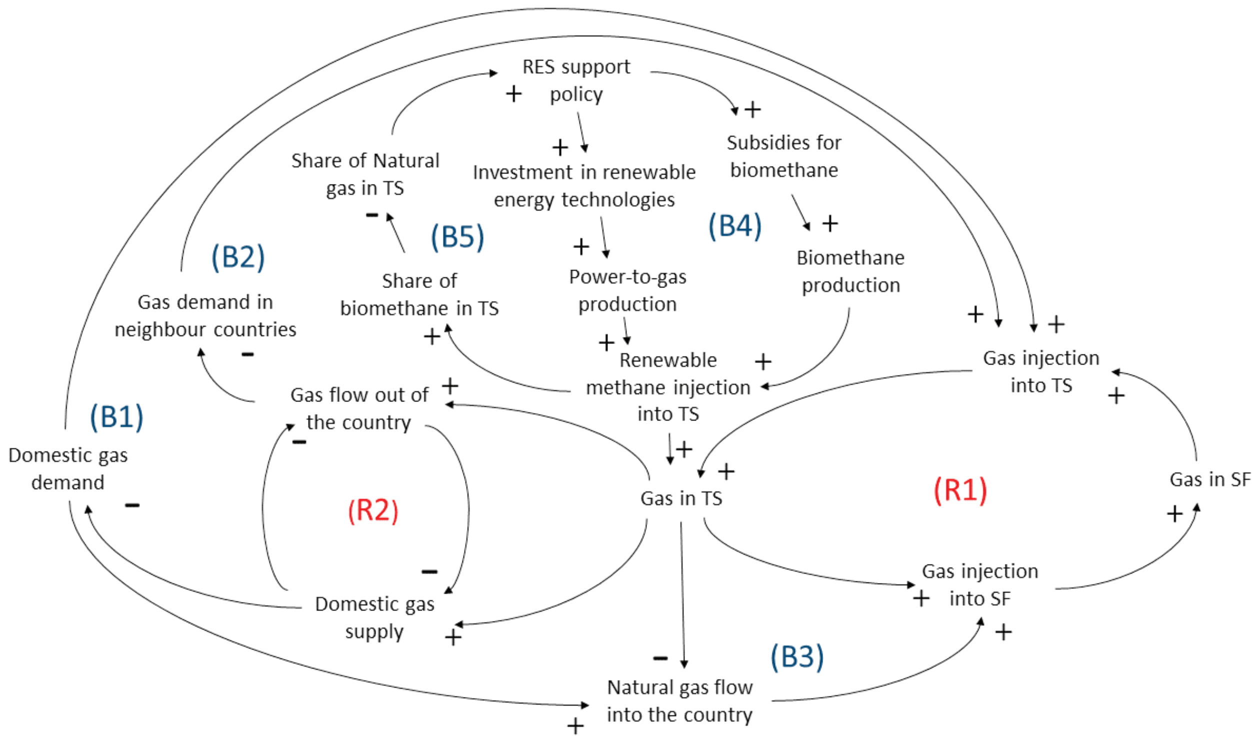


Fig. 2. Casual loop diagram of biomethane and power-to-gas application for natural gas system with storage facility

4. Conclusions

The system dynamics model, presented in this study with casual loop diagram, shows the dynamics of substitution of natural gas in Latvia with locally produced biomethane and renewable methane from power-to-gas by injecting it into natural gas system infrastructure. The model considers RES support policy, which enables the subsidies for biomethane and investment into power-to-gas technologies. According to the concept of resilience presented in literature, the diversification of gas sources will increase the resilience of natural gas system in Latvia, thus will contribute to the security of energy supplies.

In the economic perspective, the model can be used as a tool by policy planners and other stakeholders to assess quantitative parameters of RES support policy implementation. Moreover, the model has potential for improvements that will allow quantitative evaluation of security of gas supply with diversified gas sources. The model can be combined with other system dynamics models for energy sector in Latvia. Further, the model development should aim on adding the aspects of market, like natural gas price volatility, taxes, consumer side structure and location.

Acknowledgements

The research has been supported by European Regional Development found & European Neighbourhood Instrument in the frame of the Interreg Baltic Sea Region Programme 2014-2020 project “Low Temperature District Heating for the Baltic Sea Region”.

References

[1] M. Flouri, C. Karakosta, C. Kladouchou, and J. Psarras, “How does a natural gas supply interruption affect the EU gas security? A Monte Carlo simulation,” *Renew. Sustain. Energy Rev.*, vol. 44, pp. 785–796, 2015.

[2] O. G. Austvik, “The Energy Union and security-of-gas supply,” *Energy Policy*, vol. 96, pp. 372–382, 2016.

[3] C. Guivarch and S. Monjon, "Identifying the main uncertainty drivers of energy security in a low-carbon world: The case of Europe," *Energy Econ.*, vol. 64, pp. 530–541, 2017.

[4] D. K. Jonsson, B. Johansson, A. Månsson, L. J. Nilsson, M. Nilsson, and H. Sonnsjö, "Energy security matters in the EU Energy Roadmap," *Energy Strateg. Rev.*, vol. 6, pp. 48–56, 2015.

[5] D. M. Wall, S. McDonagh, and J. D. Murphy, "Cascading biomethane energy systems for sustainable green gas production in a circular economy," Bioresour. Technol., vol. 243, no. July, pp. 1207–1215, 2017.

[6] M. Adelt, D. Wolf, and A. Vogel, "LCA of biomethane," J. Nat. Gas Sci. Eng., vol. 3, no. 5, pp. 646–650, 2011.

[7] J. Koornneef, P. Van Breevoort, P. Noothout, C. Hendriks, L. Luning, and A. Camps, "Global potential for biomethane production with carbon capture, transport and storage up to 2050," Energy Procedia, vol. 37, pp. 6043–6052, 2013.

[8] F. Cucchiella and I. D'Adamo, "Technical and economic analysis of biomethane: A focus on the role of subsidies," Energy Convers. Manag., vol. 119, pp. 338–351, 2016.

[9] M. Götz, J. Lefebvre, F. Mörs, A. McDaniel Koch, F. Graf, S. Bajohr, R. Reimert, and T. Kolb, "Renewable Power-to-Gas: A technological and economic review," Renew. Energy, vol. 85, pp. 1371–1390, 2016.

[10] M. A. Mac Kinnon, J. Brouwer, and S. Samuelsen, "The role of natural gas and its infrastructure in mitigating greenhouse gas emissions, improving regional air quality, and renewable resource integration," Prog. Energy Combust. Sci., vol. 64, pp. 62–92, 2018.

[11] D. Parra, X. Zhang, C. Bauer, and M. K. Patel, "An integrated techno-economic and life cycle environmental assessment of power-to-gas systems," Appl. Energy, vol. 193, pp. 440–454, 2017.

[12] S. B. Walker, D. van Lanen, U. Mukherjee, and M. Fowler, "Greenhouse gas emissions reductions from applications of Power-to-Gas in power generation," Sustain. Energy Technol. Assessments, vol. 20, pp. 25–32, 2017.

[13] G. Li *et al.*, "Security-constrained economic dispatch for integrated natural gas and electricity systems," *Energy Procedia*, vol. 88, pp. 330–335, 2016.

[14] L. He, Z. Lu, J. Zhang, L. Geng, H. Zhao, and X. Li, "Low-carbon economic dispatch for electricity and natural gas systems considering carbon capture systems and power-to-gas," *Appl. Energy*, vol. 224, no. May, pp. 357–370, 2018.

[15] T. Horschig, P. W. R. Adams, M. Röder, P. Thornley, and D. Thrän, "Reasonable potential for GHG savings by anaerobic biomethane in Germany and UK derived from economic and ecological analyses," *Appl. Energy*, vol. 184, pp. 840–852, 2016.

[16] T. Fubara, F. Cecelja, and A. Yang, "Techno-economic assessment of natural gas displacement potential of biomethane: A case study on domestic energy supply in the UK," Chem. Eng. Res. Des., no. 2017, pp. 1–21, 2018.

[17] M. Thema, M. Sterner, T. Lenck, and P. Götz, "Necessity and Impact of Power-to-gas on Energy Transition in Germany," *Energy Procedia*, vol. 99, no. March, pp. 392–400, 2016.

[18] R. O'Shea, D. M. Wall, S. McDonagh, and J. D. Murphy, "The potential of power to gas to provide green gas utilising existing CO2 sources from industries, distilleries and wastewater treatment facilities," *Renew. Energy*, vol. 114, pp. 1090–1100, 2017.

[19] A. Purkus, *Concepts and Instruments for a Rational Bioenergy Policy*, vol. 55. 2016.

[20] N. Scarlat, J.-F. Dallemand, and F. Fahl, "Biogas: developments and perspectives in Europe," Renew. Energy, 2018.

[21] A. Mazza, E. Bompard, and G. Chicco, "Applications of power to gas technologies in emerging electrical systems," *Renew. Sustain. Energy Rev.*, vol. 92, no. May, pp. 794–806, 2018.

[22] J. Devlin, K. Li, P. Higgins, and A. Foley, "The importance of gas infrastructure in power systems with high wind power penetrations," *Appl. Energy*, vol. 167, pp. 294–304, 2016.

[23] Z. Qiao, Q. Guo, H. Sun, Z. Pan, Y. Liu, and W. Xiong, "An interval gas flow analysis in natural gas and electricity coupled networks considering the uncertainty of wind power," *Appl. Energy*, vol. 201, pp. 343–353, 2017.

[24] J. Hodbod and W. N. Adger, "Integrating social-ecological dynamics and resilience into energy systems research," *Energy Res. Soc. Sci.*, vol. 1, pp. 226–231, 2014.

[25] S. Erker, R. Stangl, and G. Stoeglehner, "Resilience in the light of energy crises – Part I: A framework to conceptualise regional energy resilience," *J. Clean. Prod.*, vol. 164, pp. 420–433, 2017.

[26] Based on Central statistical bureau of Latvia data from Environment and energy statistics section, http://www.csb.gov.lv/en/dati; as modified by Riga Technical University.

[27] Natural gas transmission system operator yearly report of 2014. https://em.gov.lv/files/energetika/eus/zinojums_2014.pdf [15.05.2018]

[28] E. Karnītis, "Dabasgāzes ap gādes drošuma paaugstināšana Latvijā; stratēģija un instrumenti," 2010.

[29] European Commission, Energy roadmap 2050, Luxembourg: Publications Office of the European Union, ISBN 978-92-79-21798-2 doi:10.2833/10759

[31] L. Proskuryakova, "Updating energy security and environmental policy: energy security theories revisited," *J. Environ. Manage.*, vol. 223, no. December 2017, pp. 203–214, 2017.

[32] F. Feijoo, D. Huppmann, L. Sakiyama, and S. Siddiqui, “North American natural gas model: Impact of cross-border trade with Mexico,” Energy, vol. 112, pp. 1084–1095, 2016.

[33] K. A. Pambour, B. Cakir Erdener, R. Bolado-Lavin, and G. P. J. Dijkema, “SAInt – A novel quasi-dynamic model for assessing security of supply in coupled gas and electricity transmission networks,” Appl. Energy, vol. 203, pp. 829–857, 2017.

[34] A.Blumberga, G.Bazbauers, P.Daviddsen, D.Blumberga, A.Gravelsins, T.Prodanuks, “System dynamics modelling in bioeconomy sector”, Scientific monografy. Riga:RTU publisher, pp.67-99, 2016

[35] Sterman, John. (2000). Business Dynamics, System Thinking and Modeling for a Complex World. http://lst-iiep.iiep-unesco.org/cgi-bin/wwwi32.exe/[in=epidoc1.in]/?t2000=013598/(100). 19.

[36] Based on IEA data from Monthly gas statistics © OECD /IEA, www.iea.org/statistics, Licence: www.iea.org/t&c; as modified by Riga Technical University.

[37] Roege, Paul & Collier, Zachary & Mancillas, James & A. McDonagh, John & Linkov, Igor. (2014). Metrics for energy resilience. Energy Policy. 72. 249–256. 10.1016/j.enpol.2014.04.012.

ASSESSING RESILIENCE AGAINST FLOODS WITH A SYSTEM DYNAMICS APPROACH: A COMPARATIVE STUDY OF TWO MODELS

Assessing Resilience Against Floods With A System Dynamics Approach: A Comparative Study Of Two Models

Maksims Feofilovs[1], Francesco Romagnoli[1], Charlotte Kendra Gotangco[2,3], Jairus Carmela Josol[2,3,] Jean Meir Jardeleza[2,3,] Joaquin Campos[2,] Joseph Litam[2,] Katrina Abenojar[2]

[1] Institute of Energy Systems and Environment, Riga Technical University, Latvia
[2] Dept. of Environmental Science, Ateneo de Manila University, Philippines
[3] Ateneo Institute of Sustainability, Ateneo de Manila University, Philippines

ABSTRACT

This paper presents the concepts of two different ways of generating a dynamic structure of the urban system in order to further allow to understanding specific urban behavior facing against flood and further evaluate the potential effect of specific resilience strategies aiming to decrease the exposure and/or vulnerability of the system. Within the approach, the purpose is to properly, and more efficiently evaluate, the effect of different and/or diversified Flood Risk Management strategies, i.e., prevention, defence, mitigation, preparation, and recovery, as requirement for consistent and resilient flood governance plans including different type of enhancing resilient scenarios.
Two system dynamics models structures are presented as results Casual Loop Diagrams (CLDs) as first step needed for the application in real case studies trough modelling simulation. The main differences among the tow approach are the time horizon and in the approach that regulate the assessment of the resilience trough a dynamic composite indicator: the first model refers to baseline at initial simulation time, while the second is more focused on the ratio service supply to demand.
The need for such tool is underlined by a lack on the assessment of urban resilience to flood as whole, considering the physical and social dimensions and the complex interaction among their main components. There are several assessment tools based on an indicator approach that have been proposed to meet this need. Nevertheless, indicator-based approach has the limitation to exclude the complexity of the system and its systemic interaction in terms of feedbacks effects among the identified components or variables selected for the system description. This peculiarity can be provided by System Dynamics modelling.

INTRODUCTION

The growing challenge for urban scale policy-makers and implementers to follow sustainable development pathways is becoming critical under the increasing number and severity of natural hazard events, increase in environmental impacts and exposure to natural hazards due to world population growth [1]. In this light, increasing resilience of communities against disasters became paramount for sustainable development goals. The analysis of community frameworks proposed by J. M. Diaz-Sarachaga and D. Jato-Espino [2] concluded that resilience and sustainability are complementary properties necessary to jointly enhance urban development. However, the sustainability and resilience are terms of high complexity with different definitions and areas of applicability [3] and therefore the task to integrate these two concepts when performing urban resilience assessment for policy planning of city or municipality scale is not simple.

The concept of resilient city can be described as combination of sustainable networks of physical systems and human communities, capable of managing extreme events and able to survive and function under extreme stress [4], but there is no unitary definition of urban resilience. In research, three basic perspectives of resilience can be distinguished: ecological, engineering and socio-ecological [5], [6]. In engineering perspective resilience is result oriented, whereas in socio-ecological perspective resilience is viewed as ability to persist by responding to, recovering from, and in other means transforming in order to adapt to new conditions [4]. This transformability aspect in socio-ecological resilience best fits social, economic and/or political systems embodied in urban system [6]. However, often socio-ecological resilience is often left out of urban resilience studies due to the complex relation of the different dimensions of urban environment and as a result more approaches are applying only engineering resilience to urban environment [7]. Such approach does give a certain level of accuracy for characterization of individual component, but increasing the resilience of one given type of infrastructure cannot guarantee the optimal resilience of urban community [8]. One of the most used approach to model engineering resilience of infrastructural systems is the loss triangle method. This method considers the time it takes the system to recover after a disruption to a normal functioning state [9]. This allows to deal with particular risks in the short to medium-term impacts [10], but do not enough information about urban environment over longer term, where sustainability perspective takes place. To strengthen the urban resilience, while dealing with the growing challenge of sustainable development pathways, the diversity and evolutionary dynamics of system can be considered in context of Socio-ecological resilience.

Socio-ecological resilience was developed to shift the perspective from studying only natural systems or only infrastructure, by including aspects that are governed by relationships between human made and natural components [11]. The formal definition for socio-ecological resilience is "*the capacity of a system to absorb disturbance and organize while undergoing change so as to retain essential same the function, structure, identity, and feedbacks*" [12]. Socio-ecological resilience is a key component of urban or city resilience, which according to Meerow et al., [13] is formulated as: "*The ability of an urban system and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales to maintain or rapidly return to desired functions in the face of disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity*". Within the context of both definitions, this study investigates how different the aspects of urban areas can be presented within resilience assessment model. This study undertakes the system dynamics approach for creation of the main structure of an urban resilience assessment tool.

Over the last decade several studies implement system dynamics approach to understand and analyse specific challenges and problems in urban areas. The study proposed by Mavrommati et al. (2013) [14] presented system dynamic model for sustainability of urban coastal systems. The study introduced the use of an index for estimation of the systems condition for an assessment of specific policy measures. Different type of model presented in the study of Tsolakis N. [15] on eco-cities included several sub-models: population, housing, business, energy consumption, environmental pollution. Each sub-models results are presented in sector relevant reference units unlike the previously mentioned index approach.

The study of Zarghami M. [16] showed how system dynamics can be used to understand the need for water supply, under growing population background conditions, and what are the shortage thresholds. The water balance in the model was defined as a stock governed by supply and demand flows that are affected by variables included in the model. The interdisciplinary approach for modelling sustainable water resources planning with system dynamics model is shown in study of Li C. et al. [17]. The model included sub-models of population, economic, water supply and water demand. This model showed that system dynamics approach is rational to support water resources management in cities as provides a good reference for decision makers to weight the cost, target amount and systems risk.

System dynamics approach is often found in literature to be a widely used tool for energy sector models for different scale: national [18], urban [19] and single actor energy producer [20]. Energy sector modelling methodology was presented in the study of Y. He et al. [19], which similarly to approach of G. Mavrommati [14] used index to show how urban electricity demand forecasting can be made with system dynamics. Another study adopting system dynamics approach for energy sector by Y. Y. Feng et al. [21] showed how energy consumption and emission trends for urban area can be modelled for long term. Study suggested an in-depth sensitivity analysis to make results more robust and reliable for policy making. There are other cases reported in literature on sensitivity analysis for example with help of system dynamics urban water management model found how sensitive is the water demand output to the change in population, per capita demand, and temperature [22].

The study proposed by R. Rehan [23] presents conceptual frameworks for modelling financially self-sustaining water and wastewater networks that involved system dynamics model and explained it with causal feedback loops. The conclusion suggested that traditional management tools used in the area are deemed inadequate and that system dynamics model can be used for developing both short-term and long-term management plans, also suggested by H. Vafa-Arani et al. [24].

The findings in literature review are responsive to the context of this study and are considered for the definition of two system dynamics models.

METHODOLOGY

General methodology for the study

An in-depth study on urban resilience and community resilience [26] concluded that the interactive combination of different physical and non-physical factors leads to the formation and transformation of cities. According to A. Shari [27], any analysis of urban form resilience should not be conducted in isolation from other determining factors considering a comprehensive integrated approach. Therefore, system dynamics approach is chosen as consistent quantitative assessment method for integrating different physical and non-physical aspects of different systems. The approach is based on linear dynamics and feedback control theory and is explaining the behaviour of system through structure that drives the behaviour of the system itself [28].

System dynamics approach allows focusing on different socio-technological, political, and behavioural aspects and provides a basis for modelling these aspects into endogenous structure. System dynamic models are using three components known as stocks, flows and variables [29]. The visualization of the model composed of stocks, flows and variables, and their loops - as direct or feed-back - is known as Causal Loop Diagrams (CLDs). The reinforcing and disrupting drivers within system can be described in the following way: the change in the originating component is cause for change in other components that after a certain time has strengthening effect also in the initial component, then this loop is reinforcing loop. If there is an opposite case, when the response of other components in the loop decreases the original effect of the loop and thus the change in system, the loop is a balancing loop. Usually a system has multiple feedback loops that interact with each other and is the main cause for the complex dynamic behaviour. [23]

This study undertakes three steps of system dynamics modelling: 1) definition of the dynamic problem and 2) creation of the dynamic hypothesis and 3) building the structure of the model with help of CLD. The study shows generalized version of causal loop diagram to explain the urban system from perspective of the topic "urban resilience", while the sensitivity of the variables should be calibrated for specific case studies depending on the local conditions. Both system dynamics models measure resilience in terms of Composite Resilience Indexes is proposed.

Model 1: Urban Resilience Index approach with four urban dimensions

The dynamic hypothesis for urban resilience model is defined from previous study on composite indicators for disaster resilience [30]. The model of this study should be able to fit all the necessary aspects urban environment to describe the dynamics of urban system performance represented in Fig. 1. The dynamic hypothesis for model 1 can be explained as following: the urban systems is developing and increasing its level of functionality, but under the effects of an occurred natural hazard decreases its level of functionality, both in short-term and long-term, in this way the urban system either recovers to the pre-disaster performance level and continues its development or is going to face a final collapse. The model to be implemented in a CLD must be able to show how different mitigation, preparedness, response and recovery measures would affect the performance of urban environment in short term and long term.

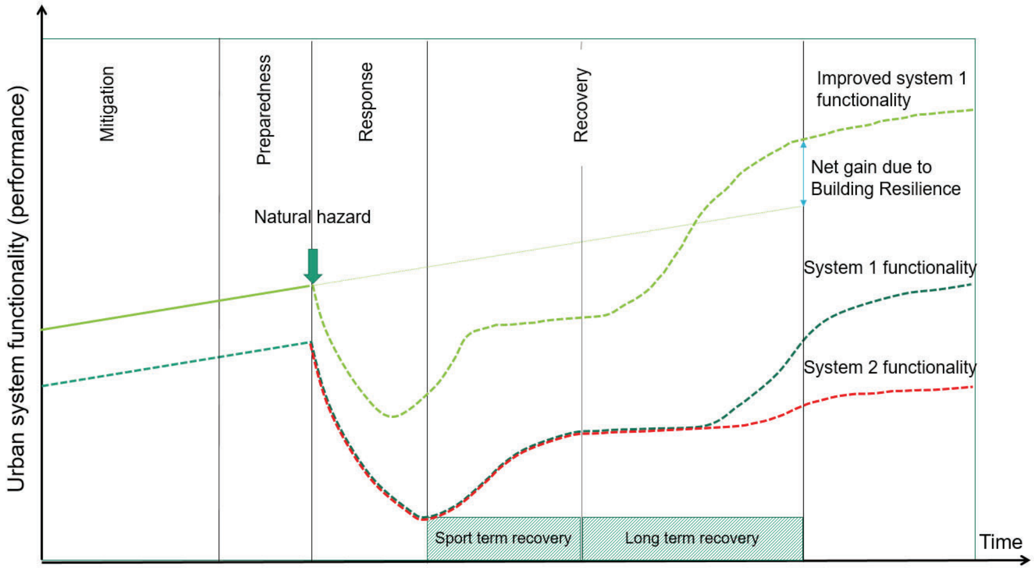


Fig. 1. Dynamic hypothesis for model 1- the dotted blue line represents the performance of an urban system without measures aimed to build resilience (system 1); the dotted light green line represents the performance of a system with measures aimed to build resilience (improved system 1); the dotted red line represents a system with low operational level after disaster.

The purpose of the model 1 is to allow estimation of urban resilience, considering the dynamic interactions of various aspects affecting the function level of urban area. The concept for the urban resilience in model 1 (shown in Fig.2.), with a reference measure called Urban resilience index using indicators (URI-I). This reference measure is an output of performance of four urban dimensions or so called capital: social, economic, infrastructural, and environmental.

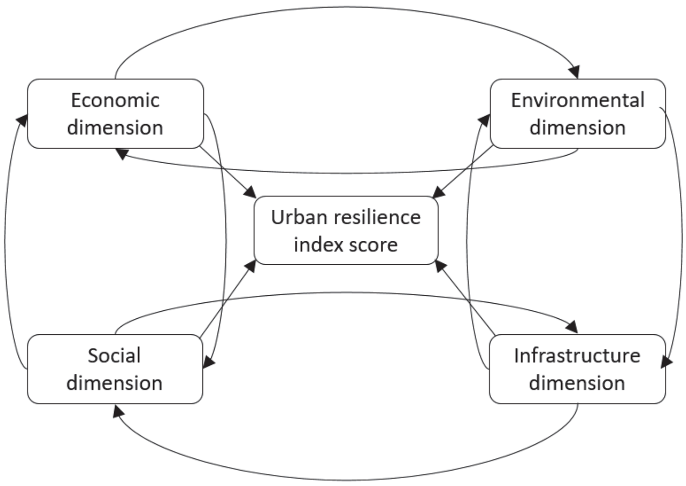


Fig.2. Concept of system dynamics model 1.

The given definition of four urban dimensions allows distinguishing the aspects of urban areas that provide different most necessary functions to society. In the model URI-I is a dimensionless index composed of indicators from different dimensions measured over a period of time. The indicators are normalized to their reference value and standardized to their initial values at the start of the simulation time. Therefore, the final URI is actually not coming from indicator values, but from the change in indicator value. The change in indicators is estimated for given moment (*t*) of the simulation time imposed to the initial value of the indices at the start of the model simulation time (equation 1):

$$\Delta URI - I = \frac{URI - I_t}{URI - I_{t,init}} \tag{1}$$

Where the *ΔURI-I* showing the change (increase or decrease) in indicator; $URI\text{-}I_t$ is the indicator value in moment (*t*) of simulation time; $URI\text{-}I_{t,init}$ is the indicator value in the initial time of simulation.

The choice of indicators for each urban dimension is a result of the sub-model modelling process. The indicators are chosen by their significance to measure urban resilience according to the dynamic hypothesis and with consideration of feedbacks between the sub-models.

Model 2: Urban Resilience Index approach using services

The second model is created based on concept of services approach. The dynamic hypothesis employed is similar to that of URI-I in Model 1, but with "functionality" defined specifically as the capacity to provide needed social-economic and ecosystem services. In the short-term, this capacity maybe compromised by the occurrence of hazards, but the impact may be mitigated by preparedness measures, similar to the dynamic hypothesis in Fig. 3.

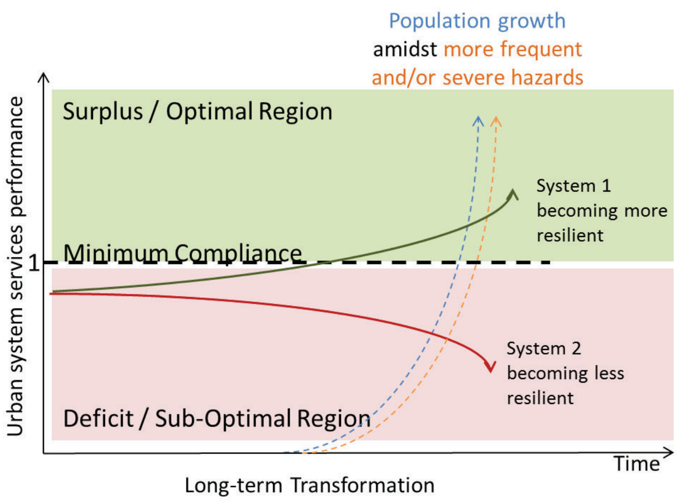


Fig.3. Dynamic hypothesis for the system dynamics model 2.

In the long-term, this capacity may be eroded by increasing pressures of population growth in the urban area compounded by increasing frequency or severity of hazards. The inability to adapt and transform over time to enable the continuous delivery of services leads to a less sustainable and less resilient city; whereas the improvement of services over time to accommodate the mounting pressures leads to a more sustainable and more resilient city, as illustrated in Fig. 4.

Using this approach, the Urban Resilience Index is based on the ratios of the supply of the services vs. the demands for them, given the growing population of the city, the way that this population modifies its physical environment, and given disturbances such as climate- and weather-related hazards and geophysical hazards. This model is developed to represent categories of services, or different sectors tasked to provide such services, and how they interconnect to influence the overall urban area performance, and trends in this performance over the long-term. The indices representing the extent to which each service is fulfilled can be combined to produce an overall resilience index, particularly for characterizing socio-ecological resilience (SER), as seen in the equation below in equation 3:

$$URI - S = \frac{\sum_{i=1}^{n} r_i}{n}$$

(3)

where $r_{1 \ldots n}$ refers to the ratios of supply and demand (or actual conditions over ideal conditions) for the different services considered in the scope of the model. Each ratio is normalized such that a score of <1 represents deficit or sub-optimal conditions, =1 means that supply just means demand, while >1 represents surplus or optimal/buffer conditions (also seen in Figure 3). The URI-S is thus the mean score of all the ratios, assuming equal weights are assigned. These ratios will be dynamic over time considering the changes in demand in the process of urbanization accompanied by potential changes in the supply of the services given environmental changes, hazards, and efforts to build resilience.

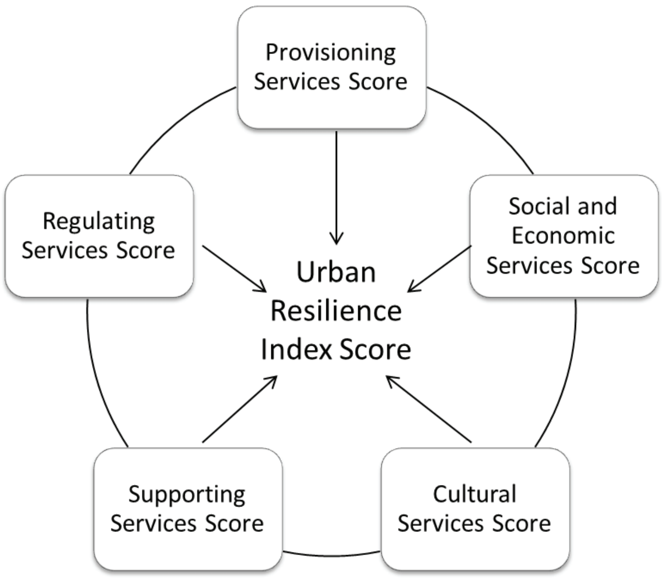


Fig.4. Concept of system dynamic model 2.

This services approach with a supply-demand structure has potential to measure socio-ecological resilience by reframing it in terms of ecosystem services approach. Ecosystem services are categorized into four types based on their functions: provisioning, regulating, cultural and supporting services. Contextualizing ecosystem services in the urban setting has been analysed in the review by Gómez-Baggethun and Barton [31]. The concept of ecosystem services has been adapted to include man-made modifications such as urban cooling, peri-urban agriculture, noise reduction, and runoff mitigation.

The method of deriving resilience by comparing a quantified supply of service against a quantified demand can also further be extended to characterizing quality in a system or sub-systems – i.e. by comparing the actual quality experienced to the ideal or prescribed state. All of these services and/or conditions interact with one another through synergies and trade-offs to contribute to urban resilience.

RESULTS

Model 1

The created model 1 for estimation of urban resilience index depends from four dimensions (also called capitals) as described in methodology: social, economic, infrastructure and environmental. The generalized version of CLDs is presented in Fig. 5. to provide information about the model construct. Due to complexity of the model only the most important feedback loops for model 1 are reported here.

The main part of the social dimension is the population model with reinforcing loop R1 for births, balancing loop B1 for deaths and R2 and B2 loops for immigration and emigration due to effect of urban attractiveness variable. The increase of population is occurring due to births and immigrations. The decrease of population is occurring due to deaths and emigration. Vulnerable social groups have a notable effect on the resilience of urban area and therefore the variable Vulnerable social groups are the main output of the social sector for calculation of URI-I. Urban attractiveness is creating the dynamics in social sector by influencing emigration and immigration, because urban attractiveness is considered to be a feedback loops of several indicators from other sectors and is affecting the immigration and emigration variables. These feedback loops can be tracked through variables linked with connector step by step in Fig. 5.

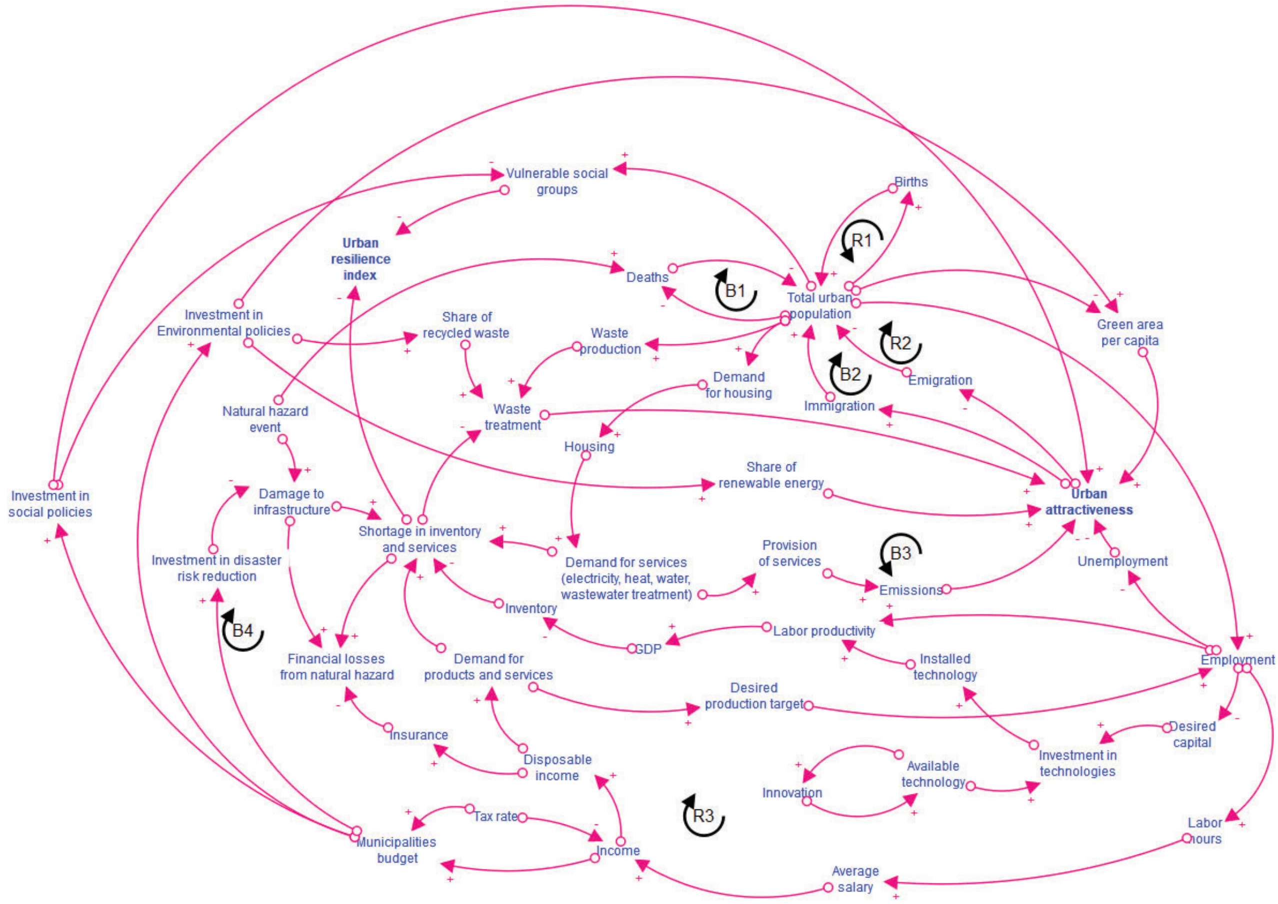


Fig.5. Generalized causal loop diagram of system dynamic model 1.

The economic dimension has key aspects of the urban economy in terms of: productivity and labor, capital and technology, wages, etc. The main output of the economic sector for URI-I estimation is a shortage in the inventory and services, which depends on the demand-supply balance. Economic dimension has a reinforcing loop R3, which is influenced by change in variable of total urban population from social dimension. Therefore, the changes in social sector are the main influencing factor for changes in economic dimension through employment variable.

The infrastructure dimension in the model is presented in sector divided into five sub-sectors: housing, electricity, heating, water supply and wastewater treatment. Sub-sector of housing has an important role for other sectors, because through the demand of housing the amount of infrastructure services provision is defined. There is also a feedback loop B3 from service provision on emissions variables in environmental dimension, which again influences urban attractiveness. The stressor on supply-demand balance in provision of infrastructure service is the natural hazard, which causes damage to infrastructure and thus shortage in inventory and service provision.

Similarly, to shortage in infrastructure dimension for environmental dimension waste treatment supply-demand balance is modelled and used indicator for URI. The other part of environmental dimension of the model is set to represent emissions of infrastructure services. The emission factors are estimated for the respective transport and energy services.

Though feedback loop B4 the effect of disaster risk reduction policies can be assessed in this model. The effects of social policies and environmental policies can be assessed on emigration and immigration through urban attractiveness in loops B2 and R2, which can have crucial role for increasing resilience of urban area. Overall, the dynamic effect in this model is caused by changes in many variables over time period. This model allows to track the influences of changes in variables in specific urban dimensions and understand their effect on the overall urban resilience, allowing to utilize the model 1 concept presented in Fig. 1.

Model 2

This causal loop diagram is shown in Figure 6. The diagram describes how medium- to long-term urban resilience is aligned with development needs, and how a city's long-term development plans can likewise contribute towards the adapt/transform aspect of resilience. Following the connector arrows, the main cause of the dynamic effect in model 2 can be described in following way: As the population in the city grows, there is pressure to provide basic services and meet needs for an acceptable quality of life (e.g. needs for food, water, energy, housing, mobility, education, health services, etc.). Service shortage occurs when current supplies or levels of service delivery cannot meet the demand. This increases the necessity to construct and develop additional infrastructure that can ensure the demanded level of services. Ability to provide basic services contributes to overall resilience. The means by which the services are provided might affect environmental quality (e.g. the consumption of water resources, the degradation of land), which influences urban attractiveness and immigration. By immigration again urban population is affected, and thus step by step the loop is occurring due to the effects of the change in variables. An important variable of the model is Urban attractiveness. Urban attractiveness influences business investments and expansion, which contributes to the economic growth of the city. Economic growth of the city determines the resources available to spend for public services. On the leadership side, adaptive governance approaches can help mitigate adverse impacts on environmental quality, implement responsible public spending and manage hazard and risks for long-term sustainability of the city.

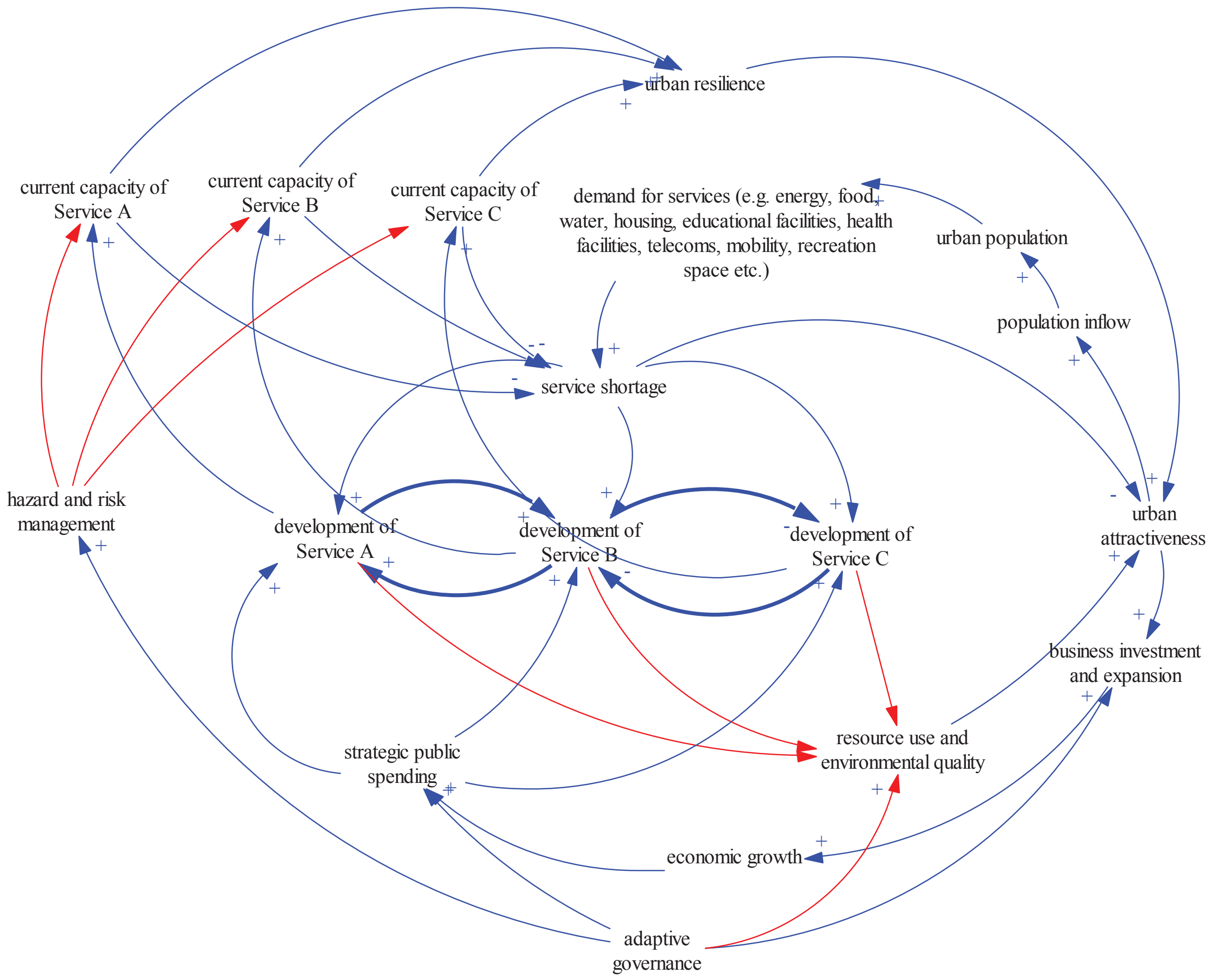


Fig. 6. Causal Loop Diagram representing a General Template of the Services Approach to Urban Resilience Index Development (Arrows in red are those whose polarities are not indicated as they would depend on the specific services and decisions being considered. Arrows in bold represent where synergies (Services A&B) and tradeoffs (Services B&C) are occurring.)

However, limited resources will result in prioritization of some services over other. Thus, this model also considers potential trade-offs as well as synergies in enhancing service capacities. An example of a limited resource is a city is the land. A specific trade-off is that as more land is allocated to green spaces, less land becomes available for infrastructure such as housing. However, there are also potential synergies. Green spaces contribute not only to the recreational and health aspects of citizens, but also to flood regulation. This sample situation is illustrated in Figure 7, which is an adaptation of the template in Figure 6 for these specific services and their trade-offs.

In Figure 7, sample loop R1 represents the population inflow that eventually leads to increased demands for housing. If the current capacity is not sufficient, then a housing shortage exists, which drives construction and augments housing capacity. This strengthens urban resilience and enhances urban attractiveness. However, at the same time, the housing construction requires resource consumption and waste generation, which detracts from urban attractiveness. This is a balancing loop B1. The housing construction also means more built-up areas, which increases runoff that contributes to flooding. This has an adverse impact on flood regulation services. In the same diagram, we have the population inflow also resulting in a demand for green spaces. Similarly, if the available green space is not sufficient, more must be allocated to augment current capacities, and increase urban resilience. This will attract more populations to the area, resulting in a reinforcing loop R2a. The green spaces also have the effect of reducing runoff and enhancing flood regulation capacities, as seen in R2b. But while there is synergy between the implementation of flood mitigation measures and green spaces, since land is limited, the allocation of land to green space necessarily means that less land can be allocated to housing, or vice versa, which is a common trade-off in urban areas.

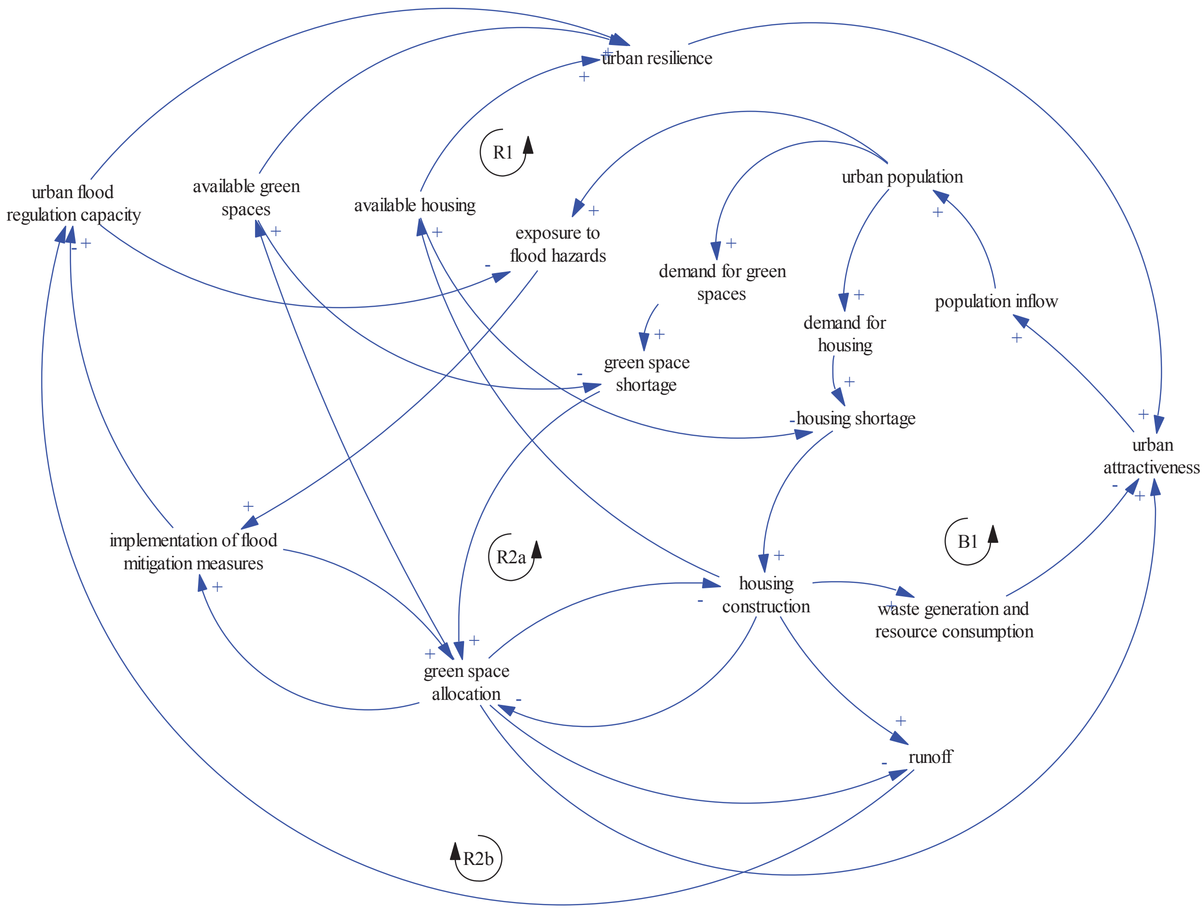


Fig. 7. Causal Loop Diagram illustrating the application of the general template for specific services: flood regulation, green space allocation, housing. (Variables pertaining the economic and governance aspects were omitted from the diagram only to simplify the figure and highlight the synergies and trade-offs.)

Similar trade-offs can be identified when it comes to the allocation of land among the different possible uses, e.g. for urban farming, or for commercial/industrial areas. Another major limitation is the local government budget that would limit the funding allocation for the development of education services vs. public health services vs. ICT vs. mobility vs. energy vs. waste management and treatment capacities. The scope of the approach is flexible, and users may opt to include as many services as practical considerations may permit, as long as the trade-offs and synergies are clearly articulated. This will make the derivation of the service ratios over time, as adaptive governance adjusts to the needs of their contexts and prioritize specific services over others at specific time.

DISCUSSION

The study gives an analysis of system dynamics model building for urban systems and two models, which included many urban system aspects that are found to be causes for different behaviours of urban system. Both models developed in this study allow to simulate simultaneous interactions between different aspects of urban system. Number of similar solutions used to model urban system resilience can be found in both models. This includes the application of index for urban resilience assessment, identification of services in urban area and interactions between them, use of supply-demand and service shortage and also the urban attractiveness aspect. As a result, both models provide a dynamic urban resilience index, which allows comparison of urban system functionality in time of stressors like natural hazards for different scenarios and response to these stressors.

Model 1 is created in way to show interaction of the service shortage to meet the demand of population in urban area will influence resilience considering the social vulnerability effect on resilience. In this sense, the concept of URI-S, the services approach is also used in URI-I. The chosen approach allows to capture the interaction of several services and interaction of their shortage, making the estimation for service shortage at time of hazard more adequate. For example, when dwellings are destroyed by the hazard, the demand of for such infrastructure services like electricity supply and water supply will decrease, thus there will be no additional burden on provision of these services and only the shortage for dwellings in urban area will be indicated when estimating URI-I. This is a strong side of the model for estimating the resilience in short term with consideration of multi-dimensional interactions in urban systems. Model must be studied with applied case studies for in-depth analysis of the model behaviour, which would also allow the calibration of feedback strengths between the chosen variables and assigning weights to the existing indicators used in URI-I.

Similarly, as in model 1, model 2 defined the interactions of different services in form of trade-offs and synergies, but highlighting more the socio-ecological aspect. Model 2 also does not define a limit to the dimensions of urban system that may be included in the scope. While categories of services are suggested, following the types of ecosystem services (provisioning, regulating, cultural and supporting), and including social and economic services, the user is given the flexibility to define the scope for as long as the performance of each sector can be expressed as a ratio of supply to demand (or actual to ideal quality/conditions) for the purposes of calculating the overall URI-S. However, the trade-off of this flexibility is the lack representation of important dynamic processes that are not as easily represented in terms of a "service" such as the building of economic capital or the evolution of social networks.

Given the similarities in supply-demand concept between Model 1 and Model 2 (URI-I and URI-S), there are two main differences. The first main different is the time horizon. Model 1 (URI-I) more explicitly recognizes the short-term impacts on system performance, while Model 2 (URI-S) is intended more to describe long-term processes for enhancing the delivery of services within the urban ecosystem. The second main difference is in the calculation of the overall urban resilience index. In URI-I, the final URI is based on the change in indicator value relative to a baseline, whereas in URI-S, the final URI is the mean of all ratios of service performance across the different categories. This means that in URI-I, the value of the index will always be relative to conditions at the initial time, without any judgment or assessment of how "good" system performance was at that initial time. This has implications for interpretation of the index, and for comparability across contexts. Normalization of indicators is a higher concern for model 1. While this approach would be useful for tracking the performance of a specific system over time, it would make comparison across systems more difficult.

In contrast, Model 2 employing the URI-S approach, would maintain some comparability across cities given the normalization scheme of generating ratios for each sector in the range of 0 to 1 or better than 1. A value of, say "0.8", regardless of city, would mean that only 80% of the demand being considered is being fulfilled by the services provided. Given these, Model 1 might be more useful for cities that generally already fulfil basic needs and comply with environmental and health standards and regulations, and want to increase urban resilience to stressors in terms of strengthening existing institutions and services, and utilizing these towards adaptation and transformation of urban system towards sustainable development pathways. Model 2 would be more useful for cities in a developing country context where the lack of basic services is a priority to be addressed.

CONCLUSIONS

The output of this study is the described of two models with help of causal loop diagrams. Although system dynamics approach was applied for creation of both models and many aspects in chosen modelling methods are similar (e.g. the use of a supply-demand approach), the models have key differences in the quantification of "resilience" across time horizons.

Model 1 was created with consideration of urban systems different dimensions and composite index method, which resulted as a dynamic index, showing the performance of urban system under stress of natural hazard over time. The dynamic index is relative to the specific studied case and therefore useful for benchmarking city's performance over time. Model 2 similarly focuses on the aggregation of supply-demand of services in an urban system, recognizing trade-offs and synergies between different services, but framing the approach for long-term development and adaptation. None of these models have been applied across multiple case studies and therefore normalization and weighting of indicators is still obscure.

Each approach has strengths and weaknesses, which can be studied through case studies. This would help to calibrate and validate the models, or even create another improved model by merging two existing models.

REFERENCES

[1] A. X. Sanchez, P. Osmond, and J. Van Der Heijden, "Are some forms of resilience more sustainable than others ?," vol. 180, pp. 881–889, 2017.

[2] J. M. Diaz-sarachaga and D. Jato-espino, "Development and application of a new Resilient , Sustainable , Safe and Inclusive Community Rating System (RESSICOM)," J. Clean. Prod., vol. 207, pp. 971–979, 2019.

[3] S. Roostaie, N. Nawari, and C. J. Kibert, "Sustainability and resilience : A review of definitions , relationships , and their integration into a combined building assessment framework," vol. 154, no. February, pp. 132–144, 2019.
[4] K. Rus, V. Kilar, and D. Koren, "Resilience assessment of complex urban systems to natural disasters : A new literature review," International Journal of Disaster Risk Reduction, vol. 31, no. January, pp. 311–330, 2018.
[5] D. M. Nunes, M. D. Pinheiro, and A. Tomé, "Does a review of urban resilience allow for the support of an evolutionary concept ?," J. Environ. Manage., vol. 244, no. April, pp. 422–430, 2019.
[6] M. Abdulkareem and H. Elkadi, "From engineering to evolutionary , an overarching approach in identifying the resilience of urban design to flood," International Journal of Disaster Risk Reduction vol. 28, no. February, pp. 176–190, 2018.
[7] C. G. Mathieu Feagana, Marissa Matsler, Sara Meerow, Tischa A.Muñoz-Erickson, Robert Hobbins, "Environmental Science and Policy," Environ. Sci. Policy, vol. 101, pp. 358–363, 2019.
[8] C. W. Zobel and M. Baghersad, "Socio-Economic Planning Sciences Analytically comparing disaster resilience across multiple dimensions," no. April 2018, 2019.
[9] N. Goldbeck, P. Angeloudis, and W. Y. Ochieng, "Resilience assessment for interdependent urban infrastructure systems using dynamic network flow models," Reliab. Eng. Syst. Saf., vol. 188, no. January, pp. 62–79, 2019.
[10] E. Torabi, A. Dedekorkut-howes, and M. Howes, "Adapting or maladapting : Building resilience to climate-related disasters in coastal cities," vol. 72, no. December 2016, pp. 295–309, 2018.
[11] Galderisi, A., "Urban resilience: A framework for empowering cities in face of heterogeneous risk factors," ITU J Faculty Arch, vol. 11, no. 1, pp. 36-58, 2014.
[12] Walker, B., Holling, C., Carpenter, S., & Kinzig, A., "Resilience, Adaptability and Transformability in Social–ecological Systems," Ecology and Society. vol. 9, no. 2 article 5, 2004.
[13] Meerow, S., Newell, J., & Stults, M. (2016), "Defining urban resilience: A review," Landscape and Urban Planning, vol.147, March 2016, pp 38-49
[14] G. Mavrommati, K. Bithas, and P. Panayiotidis, "Operationalizing sustainability in urban coastal systems : A system dynamics analysis," Water Res., vol. 47, no. 20, pp. 7235–7250, 2013.
[15] N. Tsolakis and L. Anthopoulos, "Eco-cities : An integrated system dynamics framework and a concise research taxonomy," Sustain. Cities Soc., vol. 17, pp. 1–14, 2015.
[16] M. Zarghami and S. Akbariyeh, "System dynamics modeling for complex urban water systems : Application to the city of Tabriz , Iran," "Resources, Conserv. Recycl., vol. 60, no. 2012, pp. 99–106, 2020.
[17] Z. Li, C. Li, X. Wang, C. Peng, Y. Cai, and W. Huang, "A hybrid system dynamics and optimization approach for supporting sustainable water resources planning in Zhengzhou City , China," J. Hydrol., vol. 556, pp. 50–60, 2018.
[18] D. Lund et al., "Modelling energy production flexibility: system dynamics approach" Scientific Conference ' Environmental and Climate Technologies ', CONECT 2018
[19] Y. He, J. Jiao, Q. Chen, S. Ge, Y. Chang, and Y. Xu, "Urban long term electricity demand forecast method based on system dynamics of the new economic normal : The case of Tianjin," Energy, vol. 133, pp. 9–22, 2017.
[20] A. Tukulis, I. Pakere, A. Gravelsins, and D. Blumberga, "Methodology of system dynamic approach for solar energy integration in district heating," Energy Procedia, vol. 147, pp. 130–136, 2018.

[21] Y. Y. Feng, S. Q. Chen, and L. X. Zhang, "System dynamics modeling for urban energy consumption and CO 2 emissions : A case study of Beijing , China," vol. 252, pp. 44–52, 2013.
[22] T. Wei, I. Lou, Z. Yang, and Y. Li, "A system dynamics urban water management model for," JES, vol. 50, pp. 117–126, 2016.
[23] R. Rehan, M. A. Knight, A. J. A. Unger, and C. T. Haas, "Financially sustainable management strategies for urban wastewater collection infrastructure – development of a system dynamics model," vol. 39, pp. 116–129, 2014.
[24] H. Vafa-arani, S. Jahani, H. Dashti, J. Heydari, and S. Moazen, "A system dynamics modeling for urban air pollution : A case study of Tehran , Iran," vol. 31, pp. 21–36, 2014.
[25] C. Qi and N. Chang, "System dynamics modeling for municipal water demand estimation in an urban region under uncertain economic impacts," vol. 92, 2011.
[26] A. Sharifi, "A critical review of selected tools for assessing community resilience," Ecol. Indic., vol. 69, pp. 629–647, 2016.
[27] A. Shari, "Resilient urban forms : A macro-scale analysis," vol. 85, no. November 2018, pp. 1–14, 2019.
[28] G. Papachristos, "System dynamics modelling and simulation for sociotechnical transitions research," vol. 31, no. September 2018, pp. 248–261, 2019.
[29] Gravelsins, A., "Bazbauers, G., Blumberga, A., Blumberga, D., Bolwig, S., Klitkou, A., & Lund, P. D., Modelling energy production flexibility: system dynamics approach," Energy Procedia, no. 147, pp. 503-509, 2018.
[30] M. Feofilovs, F. Romagnoli, and A. Gravelsins, "System dynamics model for natural gas infrastructure with storage facility in Latvia," Energy Procedia, vol. 147, pp. 549–557, 2018.
[31] Gómez-Baggethun, E., & Barton, D., "Classifying and valuing ecosystem services for urban planning," Ecological Economics, vol. 86, February, pp. 235-245, 2013.

ASSESSMENT OF URBAN RESILIENCE TO NATURAL DISASTERS WITH A SYSTEM DYNAMICS TOOL: CASE STUDY OF LATVIAN MUNICIPALITY

Environmental and Climate Technologies
2020, vol. 24, no. 3, pp. 249–264
https://doi.org/10.2478/rtuect-2020-0101
https://content.sciendo.com

Assessment of Urban Resilience to Natural Disasters with a System Dynamics Tool: Case Study of Latvian Municipality

Maksims FEOFILOVS[1]*, Francesco ROMAGNOLI[2]

[1–2]*Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, Riga, LV-1048, Latvia*

Abstract **– Research focuses on linking climate adaptation and disaster risk reduction strategies. The aim of the research is to test an urban resilience assessment tool through a local case study. The tool is based on integrating two methods. Multi-criteria analysis and system dynamics model is used to create a dynamic Urban Resilience Index. For the case study a local medium sized town is chosen in Latvia that is subject to flood risk. The results of the model simulation show that the model is suitable for both short term and long term resilience assessment. Future studies must focus on the precision of such a tool, which in this study could not be evaluated. Overall, the tool presented can contribute to offsetting the existing knowledge gaps between climate adaptation and disaster risk reduction for better policy planning and strengthening urban resilience on the local level.**

Keywords **– Climate adaptation; infrastructure; risk reduction; sustainability**

1. INTRODUCTION

1.1. Lack of resilience against natural disaster

In light of the world's growing population, the increasing level of urbanization from 29 % to 49 % between 1950 and 2005 and the increase in global carbon emissions from fossil-fuel burning during the same time period by almost 500 % [1], the actual consequences of climate-related disasters have increased tremendously [2]. Climate-related disasters between 1998 and 2017 accounted for 91 % of all recorded events and the losses from extreme weather events rose by 251 %. In this period, the disaster-hit countries reported losses from climate-related disasters equal to more than two billion dollars, while the real costs of disasters to the global economy are assumed to be up to EUR 429 billion per year. The build-up of urban infrastructure around the world has led to more capital exposure to disasters and consequently increase in disaster losses. Thus, the integration of climate change adaptation and disaster risk reduction policies is crucial for decreasing the vulnerability to disasters of urban areas.

Furthermore, review [3] of progress made on Priority 2 of the Sendai Framework for strengthening disaster risk governance concluded that progress was made for planning and implementation at the international, regional and national levels, however, the available capacity and information for decision making on the local level that would enable synergies

* Corresponding author.
E-mail address: maksims.feofilovs@rtu.lv

between disaster risk reduction and climate adaptation and overall sustainable strategies is still lacking.

The topicality of this study is also underlined by the current state on the local level in the context of Latvia. According to the predictions reported in Latvia's Adaptation Plan to Climate Change for the Time Period to 2030 [4], the evidence of the recent increase in precipitation in Latvia will grow even more, by 10 % to 21 % until the end of the 21st century, which means floods will occur more often than ever before. Other changes include significant increase in the air temperature; there will be a significant increase in the number of summer days as well as a significant increase in the number of tropical nights. The periods of heat and drought and their frequency will increase. Altogether there is increasing vulnerability of the population in terms of health risks, economic in terms of loss or damage of capital, environmental problems in terms of ecosystem degradation, or even all together. Therefore, the main objective of this study is to contribute to offsetting the knowledge gaps of local governments (i.e. cities, municipalities) on the topic of climate adaptation and disaster risk reduction towards the concept of urban resilience. The study aims to present and test an urban resilience assessment tool through a case study on one of urban areas in Latvia to find the most optimal scenario for local policy planners considering the multi-dimensional nature of urban resilience.

1.2. Multi-dimensional nature of the research field

Urban policy making requires careful weighting and evaluation of alternative decisions or policies, but the aspect of multi-dimensional nature and adaptivity of urban systems is causing a real challenge for planning and decision-making regarding climate adaptation and disaster risk reduction. Findings in literature suggest that there is a lack of engagement with complex challenges in urban policy, especially when addressing resilient urban communities and ecosystems. According to [5], the terminological variety and epistemological disjunctions of the research field seem to have made urban policy making even more difficult, because of lack of recognition and reflection, while the existing knowledge gaps have not been reduced or filled.

The urban areas are highly complex systems which develop and change rapidly and have been acknowledged as complex socio-ecological-technical systems [6]. Considering the rapid change and a multi-dimensional nature urban areas are also defined as complex adaptive systems with multiple elements and relationships having an unstable, transformative character, which is hard to fully understand. The interrelationships between elements include natural and social processes, which involve people, nature and culture. Complex adaptive systems behaviour can only be described by non-linear dynamics, which is the result of many feedbacks of multiple elements [7]. Therefore, a framework for evaluating the urban resilience firstly should consider the complexity of the multidimensional nature of urban areas to aid urban policy and decision making [8].

The concept of resilience itself is also of a very comprehensive, multifaceted nature and for this reason can have even several evaluation perspectives, this is very confusing and misleading when attempting to measure it. In recent years resilience has been of great interest for many research areas including engineering and environmental science, which lead to distinguish of engineering resilience, ecological resilience and evolutionary resilience. Depending on the perspective, resilience can have a different focus on system characteristics like recovery, robustness or adaptive capacity, and therefore also a different approach towards measuring resilience, for example, speed of return to steady state, magnitude of disturbance that can be absorbed or coupled systems capacity to co-evolve [9].

Recent study on definition of urban resilience concluded that the term itself has not been defined well and proposed a better definition, which addresses urban resilience recognizing it as both socio-ecological and socio-technical networks (including their ability to transform) and considers temporal and spatial scales, in this way capturing multiple possible pathways of looking at urban resilience, [10] considering the ability to return to the desired functions in the face of disturbance as the main parameter. For such definition of urban resilience, the concept of evolutionary resilience is crucial. The concept defines the link between urban planning and adaptation, embedding vulnerability and adaptive capacity over both short-term and long-term [11], thus introducing the connection between resilience to sustainability [12].

Considering the complexity of the given term urban resilience it can be difficult to quantify, but any of the assessment tools can strongly help to increase the understanding and learning, especially when dynamic change in system is described [13].

1.3. Assessment of urban resilience against natural hazards

The challenge of assessing urban resilience lies in creation of a consistent methodology that can consider all the uncertainties related to multi-dimensionality of urban areas and complexity of urban resilience. In practice, the theoretical concepts that are difficult to interpret in a measure state are synthesized into a single number with the help of an indicator approach [10]. Through such an approach, usually different criteria can be included into a simple decision-making tool for policy makers, allowing them the comparison between different measurements. Such an approach is very common across climate vulnerability and impact assessments of urban systems, because the use of different criteria can capture the multi-dimensionality of the chosen complex system. Examples of indicator-based approaches for measuring resilience are found in [14] and [15].

Despite the recognition of indicator-based methods in climate relate studies, disadvantages are often reported in literature due to the complexity of the given concept of resilience. One of the most recognized indicators in the research field are Sendai Framework indicators to determine global trends in the reduction of risk and losses, which according to [16] at the current state of use serve for calculating the impact of short-term realized risks, but do not provide enough information to create risk reduction and disaster prevention strategies over the long-term. The lack of research addressing long-term effects in the field of climate change and natural hazards was also mentioned in the study of [17].

Study of [18] reviewed social resilience framework focusing on indicators and found that process oriented indicators that are based on dynamic properties have been largely neglected, and the existing social resilience frameworks are limited for interpreting the actual resilience status of a community. The indicators do not reflect the interactions among the variables in the chosen system and for that reason cannot provide indications for future scenario development. This also means that such approach will lack the definition of a link between socio-economic and environmental aspects in the assessment [19]. Similar flaws of the existing methods was found earlier in methodologies assessing risks to natural hazards [20], where focus lies on static vulnerability, without looking at changes in time or space.

Regarding spatial changes, [21] found that integration of spatial reference to indicator-based measures will not help to fully reflect the concept of resilience if the capacity to adapt or to transform studied systems is not embedded in the indicators. Moreover, it is hard to apply relevant variables or indicators that are practical for every city, therefore, a way to integrate a systemic approach into urban resilience measures should be developed. Similar conclusions found in study of [22] about seeing resilience as a complex of social processes. This view is in line with the socio-ecological perspective, which addresses urban resilience as a complex of social processes that allow local communities to self-organize and ensure positive collective action for community survival and wellbeing, instead of seeing urban resilience just as a set of community capacities, assets or capitals, which are often used in indicator based methods.

Among several other methods found in literature that are used to assess processes considering the interrelationship of system variables and having a time reference (Bayesian networks [23]; Input-Output economic model [24]; Agent based model [25], [26]), the system dynamics approach was found to be the most appropriate to analyse the causal relationships among various factors. This approach is based on systemic thinking and is extensively applied in many research fields including in social, economic, ecological, and resource and policy assessment systems.

The System Dynamics (SD) approach has been widely used when modelling complex systems to aid policy planning and decision making. In the study of [19] system dynamics approach was used for creation of a model with integrated economic-social-environmental resource dimensions and indicator index is used to evaluate the urban sustainability performance of each dimension. The results of the model simulation include scenarios for different policies and strategies that can be implemented to guide the development of urbanization. Another study of [27] also found that the SD approach has all the tools offering a useful modelling approach to simulate scenarios in a wide array of disciplines and presented a system dynamics based tool for understanding the system behaviour of sophisticated public utility services and to evaluate the external impact from natural hazards. Study of [28] used a SD model to help optimize water supply strategies considering the economic, social and environmental factors in the short, medium and long-term.

With the consideration of background information in the research field of urban resilience and the current state of the urban resilience assessment tools, this paper is structured in the following way: Methodology part describes the steps performed for a creating the novel urban resilience tool and validating its applicability through a case study; Results part presents the outcomes of the case study; Conclusions are made at the end of the paper.

2. Methodology

The research methodology developed for this study is proposed to finally contribute to change in urban resilience measures by providing a tool that allows to discard the assessment of urban resilience of single disciple/dimension within the short-term and move towards the multi-dimensional urban resilience assessment, which includes socio-economic and environmental aspects over both a short-term and long-term perspective. The methodology used for the purpose of this study can recognize the feedbacks between multiple elements of urban area to show the non-linear dynamics behaviour of the socio-ecological and socio-technical systems, thus addressing urban resilience through the perspective of socio-ecological (evolutionary) resilience.

The main methods included in the methodology are SD approach and Multi Criteria Analysis (MCA). The feedbacks modelled within a SD model are suitable for the evaluation of dynamic change in complex systems over time, but, specifically for the purpose of measuring resilience, there is a need to refer to resilience as a quantitative value. The value (expressed as single resilience indicator) is not defined by a SD approach and therefore the MCA approach should be included in terms of an indicator-based index. Such methodology favours transition from conventional indicator-based resilience measures to dynamic indicator-based urban resilience assessment with a SD model.

The summary of methodology for creating and testing the urban resilience tool is presented in Fig. 1. The methodology is divided in four parts for achieving the main goal of the study. The first part is performed to create the background and define the structure and purpose of the following steps of this study: literature review, definition of the urban resilience and assessment methods and the definition of dynamic problem and hypothesis. Part 2 addresses the selection of indicators, creation of reference index for MCA, integration of MCA into SD model. In Part 3 the SD model is validated for: i) consistency of indicators, ii) consistency of index output; and iii) explanation of the dynamic problem. When the model is validated, the results of urban resilience assessment are presented as the final output.

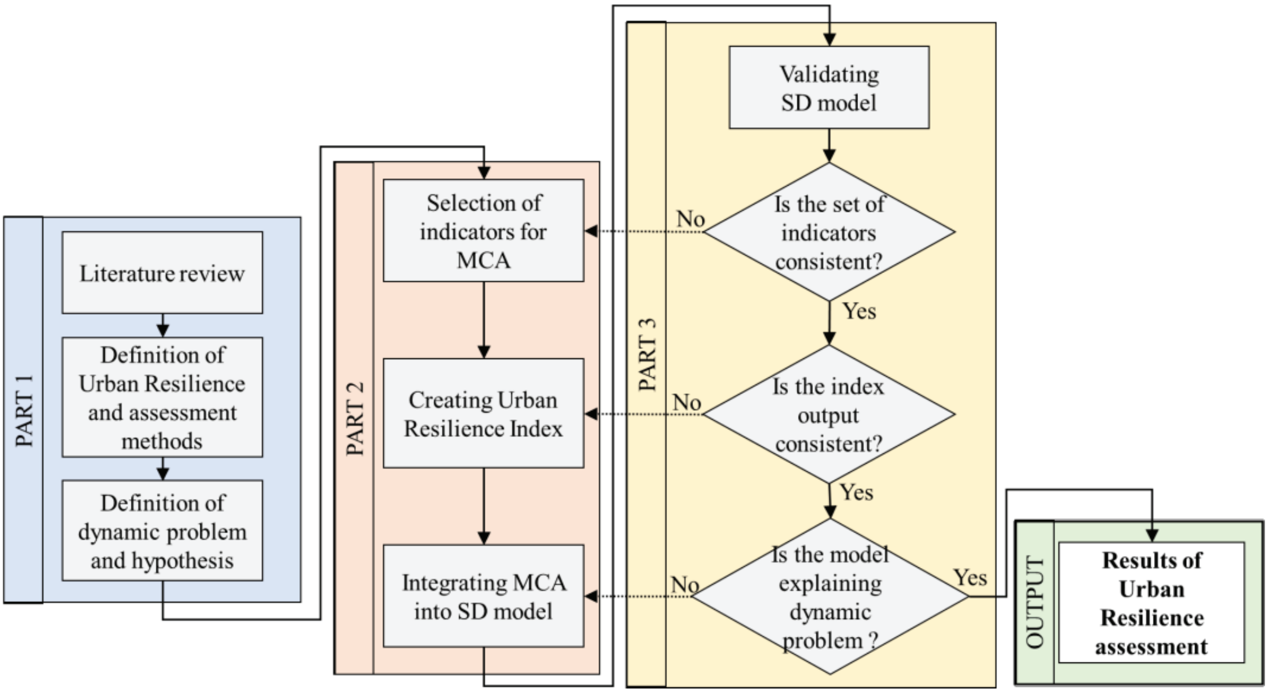


Fig. 1. Summary of methodology of the study.

The methodology chapter of the paper follows the structure: definitions, assessment methods, dynamic problem and hypothesis is introduced in sub-chapter 2.1.; Selection of indicators for MCA and creation of Urban Resilience Index and integration of MCA into SD model in sub-chapter 2.2.; Part 3 on validation of SD model in sub-chapter 2.3. Outputs are presented in the Results Chapter.

2.1. Definitions, assessment methods, dynamic problem and hypothesis

According to literature the definition of Urban Resilience was proposed by [10] and refers to the ability of urban systems "…to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity". The definition of urban resilience best fits the application of two methods – SD approach and MCA.

SD approach is commonly used to describe the nonlinear behaviour of complex systems that include social and technical aspects by using stocks, flows and internal feedback loops [29]. This approach can be used to model dynamics and metabolism of systems dealing with interconnections among and between the different factors of the environment in societal, technological, governance and ecological dimensions. SD models allow to understand the reason of specific system behaviour and have the potential (when applied on a modelling tool) to hypothesize, test, and refine resilience strategies. The approach is based on linear dynamics and feedback control theory and explains the behaviour of a system through structure that drives the behaviour of the system itself and therefore the feedback loops are the basis of explanation of system behaviour [30].

Complex definition of urban resilience was synthesized into SD model through MCA, which addressed four dimensions of urban areas to create a robust structure for analysis of urban area. Based on the adopted definition of urban resilience, indicators were selected for four distinguished dimensions of urban areas: social, economic, infrastructure and environmental. The given classification of urban area in four dimensions was found to be comprehensive to distinguish the main processes taking place in urban areas in respect to socio-ecological and socio-technological contexts, as presented by concept of urban resilience SD model in a comparative study of two models [31].

Within the context of the selected dimensions for SD model, the study aims to measure urban resilience. The dynamic problem is the change of urban system functionality level over time due to the background structure of the urban system and the way it reacts to an external stressor, represented by Fig. 2. The problematic behaviour is the loss of functionality level in urban systems (Urban system), after which the system can either get back to the normal functionality level thus showing a certain resilience (Urban system with recovery) or maintain a lower functionality level in fact presenting a lower resilience (Urban system without recovery). The hypothesis is that problematic behaviour can be solved by increasing or decreasing the strengths of feedback loops embedded in the urban SD model in order to increase the recovery rate to the normal function level or even have almost no loss of the functionality level (Urban system without loss of functionality level).

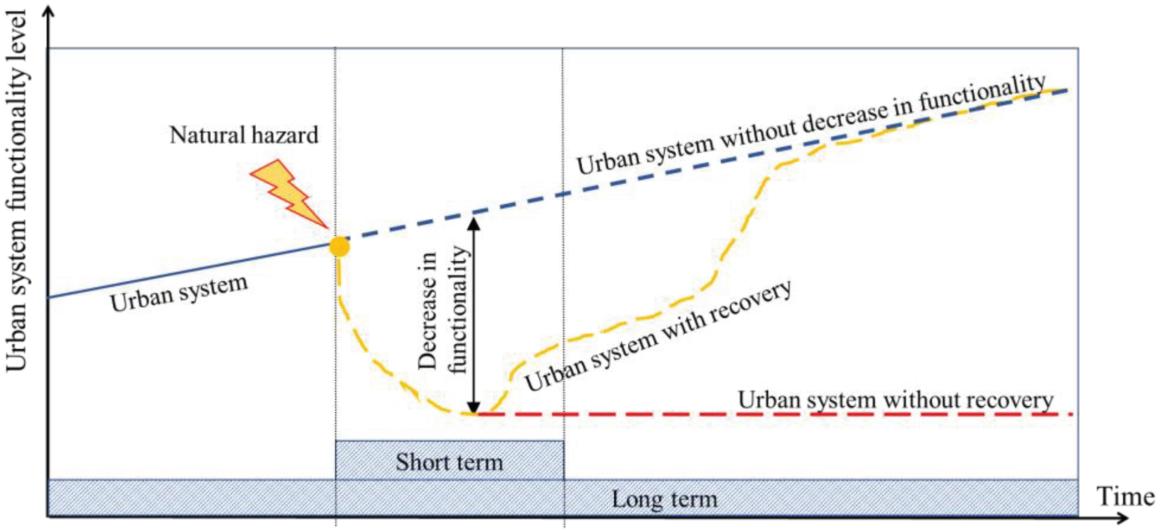


Fig. 2. Dynamic problem that study intends to solve (Urban system: Blue line; Urban system without loss of functionality level: Blue dotted line; Urban system with recovery: Orange dashed line; Urban system without recovery: Red dotted line).

For the purpose of this study, long term and short term are also considered. Short-term addresses the systems behaviour after the natural hazard occurrence, including the response (loss of functionality level) to natural hazards and recovery phase. Long term addresses the system functionality level over a period before and after short term recovery. Study also considers the long-term recovery that can occur due to delay in indirect effects of natural hazard on socio-economical aspects. The inclusion of both time references allows to understand what the key feedbacks between dimensions of urban areas are and how changes in different variables affect urban resilience.

2.2. Selection of indicators, creation of Index and MCA integration into SD model

To have measurable output of SD model describing the urban resilience, a measure is necessary that is able to distinguish how high or low the resilience of the given urban area. For this purpose, MCA is used with a single value output in the form of Urban Resilience Index (*URI*). *URI* is composed of indicators referring to characteristics of urban resilience in each dimension. Indicators must have a reference scale that distinguish if the value of this indicator is low or high for the specific urban area. To understand this relative value of indicator, it can be compared to the same indicator value in other areas. In this study, EUROSTAT data was used to create a reference scale for each indicator.

Next step is to deal with different scale of measure of each indicator by performing normalization of indicators. Several normalization methods were tested in validation of the Urban Resilience Index consistency. Normalized indicators are then used for evaluation of Urban Resilience Index as described by Eq. 1.

$$URI = \frac{\sum_{i=1}^{n}\left(x_i \cdot w_i\right)}{n}, \quad (1)$$

where

x_i normalized indicator;
w_i weight of indicator;
i indicator number;
n number of indicators.

Urban Resilience Index is defined as the mean average of weighted normalized indicators. Equal weights were assigned to all the indicators in this case study. The indicators were integrated into SD model for evaluation of *URI* as shown in Fig. 3. The lines linking dimensions represent the feedbacks considered in the model.

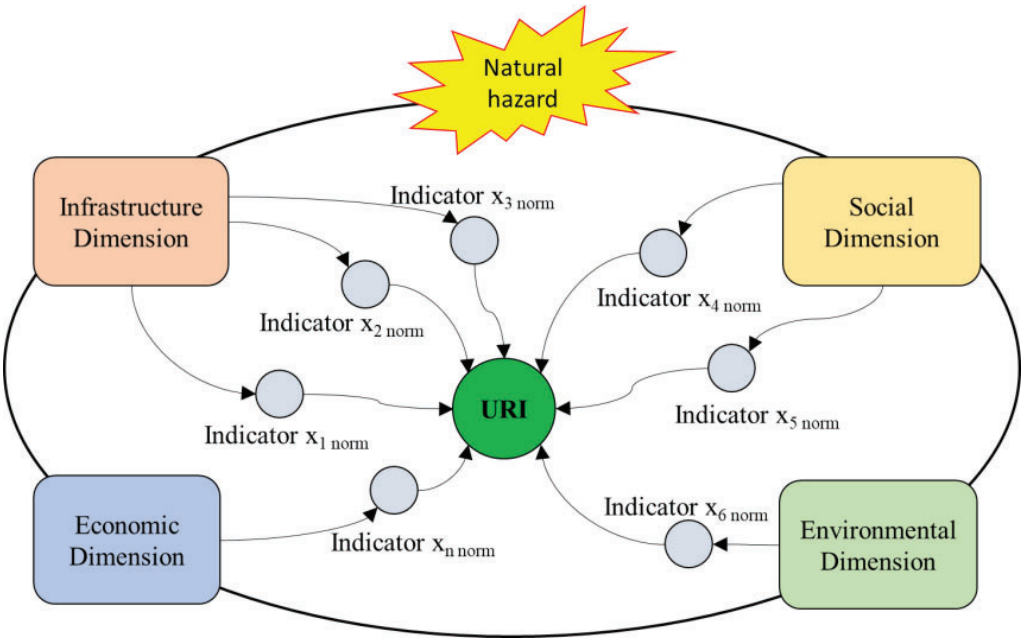


Fig. 3. MCA integration into SD.

The event disturbing functioning level of the urban area is the natural hazard defined within the SD model as a shock occurring to exposed population and services. The structure of this SD model is created in order to show how urban systems can rapidly return to desired functions in the face of a disturbance or maintain the level of functioning without loss in ideal scenario in the short and long term.

For purpose of this study floods of different magnitudes were considered as natural hazards. The magnitude of floods was defined as flooded area depending on likelihood of occurrence once in 10 years, once in 100 years and 200 years, according to data on national flood risk assessment by the Latvian Environment, Geology and Meteorology Centre for the chosen urban area. The hazard event during the simulation is created by a built-in function RANDOM (0.100) that foresees uniformly distributed generation of number between 0,1, which is then used as the probability of likelihood of occurrence. The hazard intensity is estimated based on RANDOM number according to logical functions in Eq. (2).

$$\text{Hazard intensity} = \text{If}\left(\text{RANDOM}\right) \geq 99.5\ \text{Then}\left(200\right)$$

$$\text{Else If}\left(\text{RANODM}\right) \geq 99\ \text{Then}\left(100\right)$$

$$\text{Else If}\left(\text{RANDOM}\right) >= 90\ \text{Then}\left(10\right)\ \text{Else}\left(0\right) \tag{2}$$

For example, if during the simulation step RANDOM >= 99.5 then the hazard equivalent to magnitude of once in 200 years is used as a shock. In this way, RANDOM function generates a random number every step of the simulation and model transforms into hazard intensity according to likelihood of occurrence of the hazard. This hazard is then transformed into shock to specific variables in dimensions of the urban area.

A brief explanation of causal loops embedded in the urban resilience SD model is presented in Fig. 4. In this illustration, only the main feedbacks between dimensions important for description of the model are shown. Not all the variables included in the model are shown in Fig. 4. The links from variables in four dimensions to indicators (as described by Fig. 3) are not included in Fig. 4.

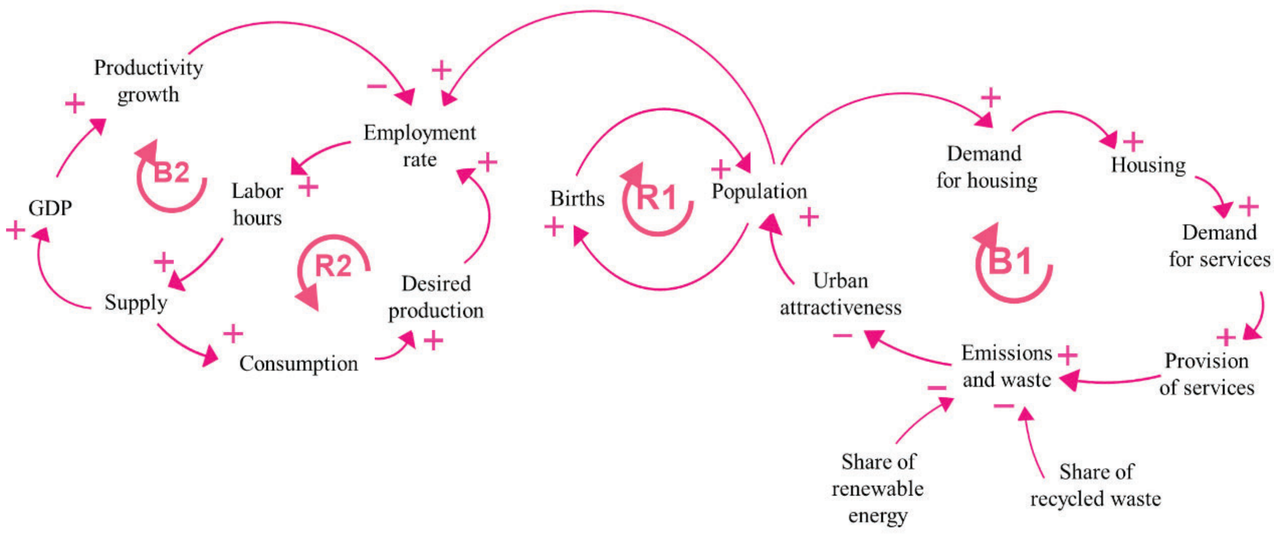


Fig. 4. Causal loop diagram for main feedbacks loops in Urban Resilience SD model.

The urban resilience SD model structure starts with the definition of urban population in social dimension. Urban population is the core aspect of the urban area, which drives the demand for services that the urban area can provide. To model the link between urban population infrastructure services in infrastructure dimension, a supply-demand balance is created within the structure of the model with the help of flows and stocks. The infrastructure services included in the infrastructure dimension are housing, water supply, wastewater treatment, heat supply, electricity supply. Similarly, environmental dimension services for waste treatment are also defined within the structure of the model with supply-demand balance. Economic dimension includes supply-demand balance structure between supply from inventory, which depends on GDP and imports and demand, which depends on disposable income.

The first important feedback loop is reinforcing loop R1, which governs the population growth. Balancing loop B1 includes variables of social, infrastructure and environmental dimensions. When the value of Urban population variable increases, the Demand for infrastructure services also increases, which leads to higher Emissions and lower Urban attractiveness and consequently the decrease of Urban population through Migration variable. The second important feedback loop is balancing loop R2, which includes the variables of social and economic dimensions. When value of Urban population variable increases, the stock of working age population will increase and thus the Share of employed population can increase under the simulation of economic loop R2. Loop B2 balances the economic sector by satisfying the Demand for consumption through the Supply from inventory.

2.3. Validation of SD model

The validation of the created SD model with *URI* index and indicators was performed in three steps: validation of indicators, validation of index and validation of SD model structure. First indicator consistency was checked with the structure of the model and with the available data for reference scale in EUROSTAT. Indicators that did not have reference data were excluded from this study, because no quantitative reference to low or high value of indicators existed for normalization and *URI* evaluation.

URI is created from validated indicators. Normalization methods known as Z-score, Minmax and Ranking were tested for this purpose. Normalization of validated indicators was performed in order to put indicators on the same scale. *URI* is considered validated for consistency when all normalized indicators in index have the same scale of measure, thus have the same scale of impact on the final *URI* score when equally weighted according to Eq. (1).

Validation of the Urban Resilience SD model was performed in two parts. First, balanced equilibrium simulation was performed for each dimension separately, without any feedbacks on other dimensions and changes of variables over time. Such approach was chosen to validate the consistency of the model structure. The expected output is a linear behaviour without any changes over time. When each dimension included in the model can provide such a consistent output alone, the model is considered to have a consistent structure and further changes of variables over time and feedback loops between separate dimensions can be linked for simulation of the dynamic behaviour.

Second part of the validation is performed within a local case study. To validate the model during the simulation, it is expected that model will show the dynamic behaviour as described in dynamic problem and hypothesis. Such output would be the result of interaction among all the feedbacks loops between variables in different dimensions.

The validation has used input data taken from a real, medium-sized town exposed to potential flooding in Latvia. Due to the lack of all the local level statistics needed as input data for the model, it is not possible to validate the model according to historical data. The available statistics data was used for most of the variables in the model, but some parts of the model required use of proxy data and therefore, only the tendencies of the dynamic behaviour could be validated without validating the precision of the output. The input values for this simulation are reported in Table A1 in the Annex. A 50-year-long simulation period is used to see how the model captures the feedbacks over the short and long term. It is assumed that the model that can show a consistent output considering all the feedbacks for a 50-year simulation period without errors and has a robust enough structure to be used for future research when more precise data is collected.

3. RESULTS

The validation of the model was performed for consistency of indicators. Together 26 indicators were proposed to be included in the MCA for the definition of the SD model. After validating the set of indicators, only 12 indicators were found suitable for application in the final Urban Resilience SD model. These indicators are presented in Table 2.

TABLE 2. INDICATORS SELECTED FOR FINAL URBAN RESILIENCE SD MODEL

Social dimension	**Economic dimension**	**Infrastructure dimension**	**Environmental dimension**
Share of unemployed population	GDP per capita	Share of population experiencing housing deprivation	Waste produced vs treated
Youth dependency		Share of population with electricity supply	
Elderly dependency		Share of households with inability to keep house warm	
Share of population at poverty risk		Share of population with access to water supply	
Share of immigrants		Share of population with wastewater treatment	

For *URI* evaluation data gathered from EUROSTAT for chosen indicators was normalized according to Minmax normalization.

$$x_{i\ \mathrm{norm}} = \frac{x_i - \min(x_i)}{\max(x_i) - \min(x_i)}\ , \tag{3}$$

where

$x_{i\ \mathrm{norm}}$	the normalized indicator;
x_i	the indicator value before normalization;
min (x_i)	the minimum value of indicator in EUROSTAT data set;
max (x_i)	the maximum value of indicator in EUROSTAT data set.

Besides Minmax normalization, other normalization methods were considered, but did not fit the specifics of index evaluation over time in the SD model. The Z-core method could not be used as after indicator normalization the Z-score values have different scales for each indicator. Ranking approach would be similar to the Minmax method, but with a smaller scale of measure, for example 5 ranks. Therefore, the model would not be as sensitive as with the Minmax method, which linearly transforms x_i to $x_{i\ norm}$ and provides output values on a scale of 0 to 1. According to the Eq. (1) *URI* is the mean average of weighted normalized indicators and thus also has a scale of 0 to 1.

During balanced equilibrium validation of Urban Resilience SD model, all four dimensions were separately tested. The model showed that it is possible to have a balanced equilibrium in all parts of the model.

To validate the full urban resilience SD model with feedbacks between four dimensions as described in Fig. 4, simulation was performed using input data derived from the Annex over 50 years without the occurrence of hazards. The output of the simulation for indicators used in *URI* assessment is presented in Fig. 5.

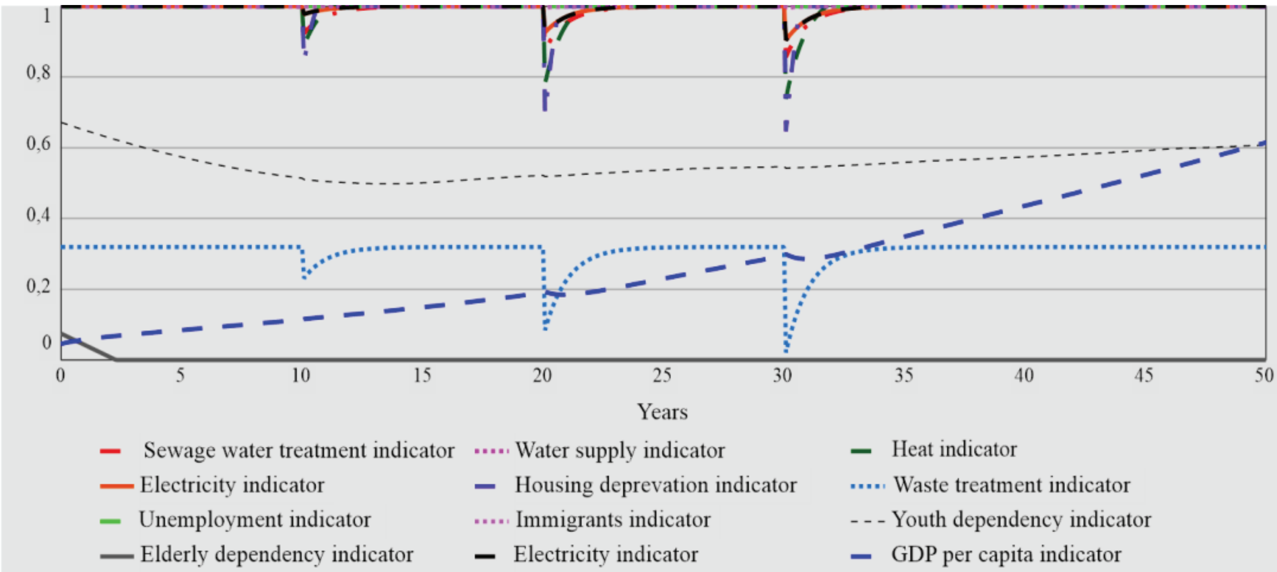


Fig.5. Output of indicators for Urban Resilience SD model simulation without occurrence of natural hazard.

Natural hazard variable is added to the simulation as describe by Eq. (2), however for purpose of presenting the results during the simulation the hazard was generated manually 3 times by at years 10, 20 and 30 and respective results for indicators were received as an outcome.

According to Fig. 5, only some of the selected indicators show change over long term and other over short term. Long term changes are mainly occurring in social and economic indicators: unemployment, youth dependency and elderly dependency, GDG per capita.

The main cause for the trend in Youth dependency and Elderly dependency is the changes of urban population. The number of adults in the area decreases due to migration tendency and thus the youth dependency increases, and youth dependency indicator shows low values. Also, due to migration the number of elderly people decreases, and so the Elderly dependency indicator shows higher value. Values of indicators are not affected by decrease of urban population. For example, decrease of population does not affect the indicators of infrastructure dimension. Also, some of the social dimension indicators like share of population with disabilities and share of population at poverty risk do not change with decrease of population according to this model.

Long term changes also occur in the GDP per capita indicator shows increase in value, while unemployment indicator does not show any change over simulation time while. This is in line with the feedbacks considered in model structure. GDP increases with productivity growth. The unemployment does not increase, since there is a decrease of working age population due to migration. Thus, the working age population stock is fully employed.

The Fig. 5. Also shows that it is hard to understand output all the indicators together. The changes in infrastructure indicators occur in short term and overlay. Over the short term it is possible to observe the impact of the hazard on specific parts of the urban system that were not subjected to changes over the long term. The magnitude of the hazard and vulnerability of each urban system defines the severity of impact on urban system and thus on the indicator values. This underlines the need of a single score output. The output of the case study simulation without natural hazard in form of *URI* is presented in Fig. 6.

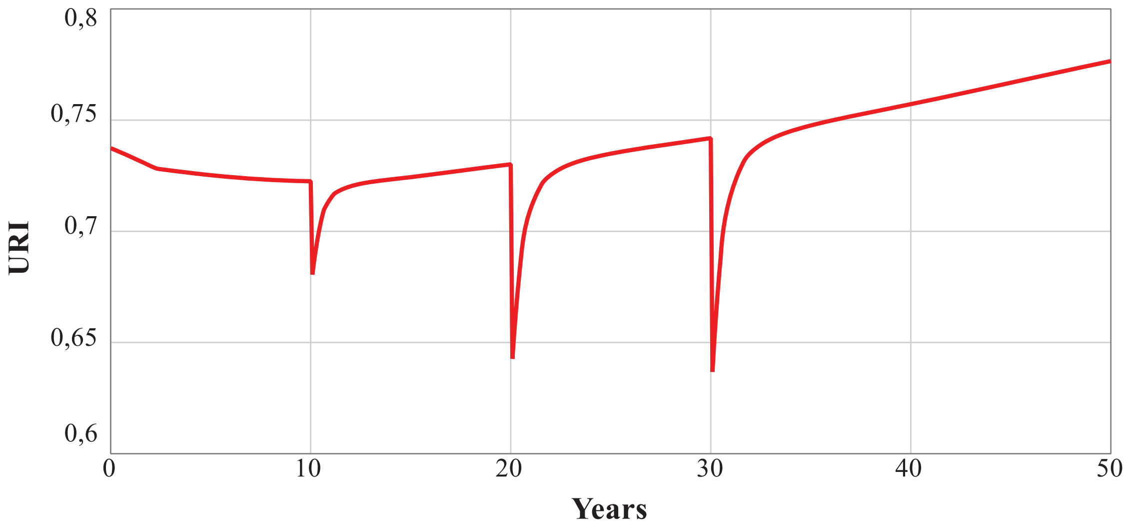


Fig. 6. Output of *URI* for Urban Resilience SD model simulation without occurrence of natural hazard.

The increase of *URI* value over simulation time occurs due to increase in GDP per capita indicator value. The decrease of *URI* value at the start of simulation occurs due to increase of Youth dependency and Elderly dependency.

The indicators represent the hazard shock in graph as the “resilience triangle”. Also, this effect of “resilience triangle” is reflected in *URI* (Fig. 6.), thus capturing all aspects of urban resilience in the long and short term.

Overall, the results show that effects of the feedback loops are well represented in the results in terms of dynamic output graphs, and the model can provide an output for *URI* in long term simulation based on historical data. The output of this simulation for *URI* index can be considered as a baseline for further simulation and testing of different urban resilience scenarios.

4. Conclusions

The complex definition of urban resilience was synthesized into a SD model through MCA to create an assessment tool suitable for urban resilience assessment to natural disasters over the short and long term. Based on the adopted definition of urban resilience, indicators were selected for four distinguished dimensions of urban areas: social, economic, infrastructure and environmental. These dimensions were used to create the structure of the SD model.

The study showed that the most appropriate normalization method for purpose of integrating *URI* into SD model is Minmax. The balanced equilibrium simulation of dimensions without feedbacks shows consistency in the output. The results of the local case study showed that the model has the appropriate capacity to present a consistent output over both the short and long term considering the complex feedback loops embedded in the structure of the model. The main causes for dynamic behaviour of the model are the changes in population, that effect demand for infrastructure services in infrastructure dimension and demand in economic dimension.

The model is suitable for modelling the scenarios for policy planning aiming at the increase of urban resilience both in the short and long term. For improving urban resilience in long-term, scenarios should focus on improving changes in population, while for improving urban resilience in the short term, the scenarios must focus on improving the "resilience triangle".

Future studies addressing such an approach must focus on precision of simulation, which mainly depends on the availability of the statistics for local case studies. Unfortunately, due to the application of proxy data in some of the variables, the precision of outputs of this study can be considered imperfect. Availability of local statistics for the long-term period with high granularity would be needed to fully validate the Urban Resilience SD model for local level.

Annex

TABLE A1. INPUT DATA FOR URBAN RESILIENCE SD MODEL FOR CASE STUDY OF TOWN IN LATVIAN CONTEXT

Name of variable	Type	Initial value	Unit
Social dimension			
Births	Flow	4329.96	People/year
Young population	Stock	9447	People
Growing up	Flow	4329.96	People/year
Mature population	Stock	36 083	People
Ageing	Flow	4329.96	People/year
Migration	Flow	400	People/year
Elderly population	Stock	12024	People
Births per mature person	Variable	0.12	Per Person
Children deaths	Flow	3.599307	People/year
Mature people deaths	Flow	186.90994	People/year
Elderly deaths	Flow	532.639152	People/year
Children death rate	Variable	0.000381	Per Person
Mature people death rate	Variable	0.00518	Per Person
Elderly death rate	Variable	0.044298	Per Person
Exposure of population	Variable	0	People
Deaths from natural hazard	Variable	0	People
Youth dependency	Variable	0.261813042	Unitless
Elderly dependency	Variable	0.333231716	Unitless
Share of immigrants	Variable	0	%
Share of population at poverty risk	Variable	0.285	%
Share of population with disabilities	Variable	0.597182	%
Share of unemployed	Variable	2.77	%
Infrastructure dimension			
Commissioning of the dwellings	Flow	0	Dwellings/year
Unoccupied dwellings	Stock	0	Dwellings
Moving out	Flow	1223	Dwellings/year
Moving in	Flow	0	Dwellings/year
Occupied dwellings	Stock	30 000	Dwellings
Damage to occupied dwellings	Flow	0	Dwellings/year
Recovery of occupied dwellings	Flow	0	Dwellings/year
Damaged dwellings	Stock	0	Dwellings

Name of variable	**Type**	**Initial value**	**Unit**
Construction rate	Variable	1.060235658	Dwellings
Desired occupied dwellings	Variable	28 777	Dwellings
Desired persons per dwelling	Variable	0.5	Persons per Dwelling
Shortage of housing per capita	Variable	−0.021249609	Dwellings per Person
Occupied dwellings per capita	Variable	0.521249609	Dwellings per Person
Exposure of occupied dwellings	Variable	0	Dwellings
Water supply	Flow	1 095 000	m^3/year
Water for consumption	Stock	1 095 000	m^3
Water demand per capita	Variable	19.02561073	m^3 per person
Water consumption	Flow	1 095 000	m^3/year
Exposure of water supply	Variable	0	m^3
Shortage in water supply	Variable	0	m^3
Disruption of water supply	Flow	0	m^3/year
Shortage in water supply per capita	Variable	0	m^3 per capita
Wastewater production	Flow	93 0750	m^3/year
Wastewater	Stock	93 0750	m^3
Wastewater treatment	Flow	93 0750	m^3/year
Exposure of wastewater treatment	Variable	0	m^3
Wastewater disruption	Flow	0	m^3/year
Wastewater treatment demand	Variable	93 0750	m^3
Wastewater treatment shortage	Variable	0	m^3
Share of population with wastewater treatment	Variable	100	%
Electricity supply	Flow	132 949.74	MWh/year
Available electricity	Stock	132 949.74	MWh
Electricity consumption	Flow	132 949.74	MWh/year
Disruption of electricity supply	Flow	0	MWh/year
Electricity demand	Variable	132 949.74	MWh
Exposure of electricity infrastructure	Variable	0	MWh
Shortage in electricity supply	Variable	0	MWh
Shortage of electricity per capita	Variable	0	MWh per Person
Heat production	Flow	6390	MWh/year
Heat for consumption	Stock	6390	MWh
Heat consumption	Flow	6390	MWh/year
Disruption of heat supply	Flow	0	MWh/year
Heat demand	Variable	6390	MWh
Heat demand per capita	Variable	0.111026167	MWh per Person
Exposure of DH infrastructure	Variable	0	MWh
Shortage in heat supply	Variable	0	MWh
Shortage in heat supply per capita	Variable	0	MWh per Person
Inability to keep house warm	Variable	0	%
Environmental dimension			
Waste production	Flow	63 309.4	kg/year
Waste	Stock	63 309.4	kg
Waste treatment	Flow	63 309.4	kg/year
Waste recycling	Variable	0	kg
Waste production factor	Variable	63 309.4	kg
Waste vs treated Waste	Variable	1	unitless
Waste exposure	Variable	0	kg
CO_2 Heat	Variable	115 020	tons/MWh
CO_2 Electricity	Variable	53 179 896	g/kWh
CO_2 emission factor for heat	Variable	18	Tons
CO_2 emission factor for electricity	Variable	400	g
CO_2 emission	Flow	60 049 532.46	g/year
CO_2 stock	Stock	60 049 532.46	g
NO_2 emissions	Flow	1 986 715.8	g/year
NO_2 stock	Stock	1 986 715.8	g
NO_2 emission factor for heat	Variable	0.01	g/kWh
PM emissions	Flow	996 520.95	g/year

Name of variable	Type	Initial value	Unit
PM stock	Stock	996 520.95	g
PM Heat	Variable	3195	g
PM emission factor for heat	Variable	0.5	g/kWh
Economic dimension			
Employed	Stock	29 000	People
Employment rate	Flow	0	People/year
Not employed	Stock	1000	People
Desired employment	Variable	14 167.18044	People
Hours per worker	Variable	2000	hr/person
Desired labour hours	Variable	86 334 360.88	hr
Labour hours	Variable	58 000 000	hr
Labour exposure	Variable	0	hr
GDP	Variable	590 440 000	EUR
Supply	Flow	1 039 826 642	EUR/year
Inventory	Stock	959 355 217.7	EUR
Consumption	Flow	590 000 000	EUR/year
Export	Flow	369 355 217.7	EUR/year
Aggregated demand	Stock	590 000 000	EUR
Income	Flow	510 000 000	EUR/year
Desired production	Variable	878 883 793.8	EUR
Import	Flow	449 386 641.6	EUR/year

REFERENCES

[1] UN-HABITAT. Urbanization and development. Emerging Futures. Nairobi: UN-HABITAT, 2016.
[2] Wallemacq P., UNISDR, CRED. Economic Losses, Poverty and Disasters 1998–2017, 2018.
[3] Djalante R. & Lassa S. Governing complexities and its implication on the Sendai Framework for Disaster Risk Reduction priority 2 on governance. *Progress in Disaster Science* 2019:2:100010. https://doi.org/10.1016/j.pdisas.2019.100010
[4] Cabinet of Ministers. Latvian National Plan for Adaptation to Climate Change until 2030. No. 380, 2019.
[5] Wolfram M., Frantzeskaki N. & Maschmeyer S. Cities, Systems and Sustainability: status and perspectives for research on urban transformations. *Current Opinion in Environmental Sustainability* 2017:22:18–25. https://doi.org/10.1016/j.cosust.2017.01.014
[6] Basu S., Bale C. S. E., Wehnert T., and Topp K. A complexity approach to defining urban energy systems. *Cities* 2018:95:102358. https://doi.org/10.1016/j.cities.2019.05.027
[7] Botequilha-leitão A. and Díaz-varela E. R. Performance Based Planning of complex urban social-ecological systems: The quest for sustainability through the promotion of resilience. *Sustainable Cities and Society* 2020:56:102089. https://doi.org/10.1016/j.scs.2020.102089
[8] Apreda C., Ambrosio V. D., and Di Martino F. A climate vulnerability and impact assessment model for complex urban systems. *Environmental Science & Policy* 2018:93:11–26. https://doi.org/10.1016/j.envsci.2018.12.016
[9] Nunes D. M., Pinheiro M. D., and Tomé A. Does a review of urban resilience allow for the support of an evolutionary concept? *Journal of Environmental Management* 2017:244:422–430. https://doi.org/10.1016/j.jenvman.2019.05.027
[10] Meerow S., Newell J. P., and Stults M. Defining urban resilience: A review. *Landscape and Urban Planning* 2016:147:38–49. https://doi.org/10.1016/j.landurbplan.2015.11.011
[11] Dhar T. K. and Khirfan L. A multi-scale and multi-dimensional framework for enhancing the resilience of urban form to climate change. *Urban Climate* 2017:19:72–91. https://doi.org/10.1016/j.uclim.2016.12.004
[12] Diaz-Sarachaga J. M., & Jato-Espino D. Do sustainable community rating systems address resilience? *Cities* 2018:93:62–71. https://doi.org/10.1016/j.cities.2019.04.018
[13] Wardekker A. *et al.* A diagnostic tool for supporting policymaking on urban resilience. *Cities* 2020:101:102691. https://doi.org/10.1016/j.cities.2020.102691
[14] Scherzer S., Lujala P., & Ketil Røda J. A community resilience index for Norway: An adaptation of the Baseline Resilience Indicators for Communities (BRIC). *International Journal of Disaster Risk Reduction* 2018:36:101107. https://doi.org/10.1016/j.ijdrr.2019.101107
[15] Fekete A. Societal resilience indicator assessment using demographic and infrastructure data at the case of Germany in context to multiple disaster risks. *International Journal of Disaster Risk Reduction* 2018:31:203–211. https://doi.org/10.1016/j.ijdrr.2018.05.004

[16] Zaidi R. Z. Beyond the Sendai indicators: application of a cascading risk lens for the improvement of loss data indicators for slow-onset hazards and small-scale disasters. *International Journal of Disaster Risk Reduction* 2017:30:306–314. https://doi.org/10.1016/j.ijdrr.2018.03.022

[17] Hein W., Wilson C., Lee B., Rajapaksa D., and De Moel H. Climate change and natural disasters: Government mitigation activities and public property demand response. *Land use policy* 2018:82:436–443. https://doi.org/10.1016/j.landusepol.2018.12.026

[18] Saja A. M. A., Goonetilleke A., Teo M., & Ziyath A. M. A critical review of social resilience assessment frameworks in disaster management. *International Journal of Disaster Risk Reduction* 2018:35:101096. https://doi.org/10.1016/j.ijdrr.2019.101096

[19] Tan Y., Jiao L., Shuai C., and Shen L. A system dynamics model for simulating urban sustainability performance: A China case study. *Journal of Cleaner Production* 2018:199:1107–1115. https://doi.org/10.1016/j.jclepro.2018.07.154

[20] Gallina V., Torresan S., Critto A., Sperotto A., Glade T., & Marcomini A. A review of multi-risk methodologies for natural hazards: Consequences and challenges for a climate change impact assessment. *Journal of Environmental Management* 2016:168:123–132. https://doi.org/10.1016/j.jenvman.2015.11.011

[21] Cariolet J., Vuillet M., & Diab Y. Mapping urban resilience to disasters – A review. *Sustainable Cities and Society* 2019:51:101746. https://doi.org/10.1016/j.scs.2019.101746

[22] Imperiale A. J., & Vanclay F. Experiencing local community resilience in action: Learning from post-disaster communities. *Journal of Rural Studies* 2016:47:204–219. https://doi.org/10.1016/j.jrurstud.2016.08.002

[23] Zhou L., Wu X., Xu Z., & Fujita H. Emergency decision making for natural disasters: An overview. *International Journal of Disaster Risk Reduction* 2018:27:567–576. https://doi.org/10.1016/j.ijdrr.2017.09.037

[24] Galbusera L., & Giannopoulos G. On input-output economic models in disaster impact assessment. *International Journal of Disaster Risk Reduction* 2018:30:186–198. https://doi.org/10.1016/j.ijdrr.2018.04.030

[25] Tidball K. G., & Aktipis A. Feedback enhances greening during disaster recovery: A model of social and ecological processes in neighborhood scale investment. *Urban Forestry and Urban Greening* 2018:34:269–280. https://doi.org/10.1016/j.ufug.2018.07.005

[26] Grinberger A. Y., & Samuels P. Modeling the labor market in the aftermath of a disaster: Two perspectives. *International Journal of Disaster Risk Reduction* 2018:31:419–434. https://doi.org/10.1016/j.ijdrr.2018.05.021

[27] Phonphoton N., & Pharino C. A system dynamics modeling to evaluate flooding impacts on municipal solid waste management services. *Waste Management* 2019:87:525–536. https://doi.org/10.1016/j.wasman.2019.02.036

[28] Xu Z., Yao L., & Chen X. Computers & Industrial Engineering Urban water supply system optimization and planning: Bi-objective optimization and system dynamics methods. *Comput. Ind. Eng*. 2019:142:106373.

[29] Blumberga A., Blumberga D., Bažbauers G., Davidson P., Moxnes E., Dzene I., Barisa A., Žogla G., Dāce E., & Bērziņa A. *System Dynamics for Environmental Engineering Students*. Riga: Riga Technical University, 2011.

[30] Papachristos G. System dynamics modelling and simulation for sociotechnical transitions research. *Environmental Innovation and Societal Transitions* 2018:31:248–261. https://doi.org/10.1016/j.eist.2018.10.001

[31] Feofilovs M. *et al*. Assessing resilience against floods with a system dynamics approach: a comparative study of two models. *International Journal of Disaster Resilience in the Built Environment* 2020:11(5):615–629. https://doi.org/10.1108/IJDRBE-02-2020-0013

DYNAMIC ASSESSMENT OF URBAN RESILIENCE TO NATURAL HAZARDS

DYNAMIC ASSESSMENT OF URBAN RESILIENCE TO NATURAL HAZARDS

Maksims FEOFILOVS*, Francesco ROMAGNOLI
Institute of Energy Systems and Environment, Riga Technical University,
Azenes iela 12/1, Riga, LV-1048, Latvia
Maksims.Feofilovs@rtu.lv
Francesco.Romagnoli@rtu.lv
**Corresponding author*

ABSTRACT

The current urbanization and increase of intensity and likelihood of natural hazard events underlines that particular attention must be addressed to strengthening urban resilience to natural hazards. Urban resilience assessment tools based on indicator approach have certain disadvantages, which do not allow considering systemic interaction in terms of feedbacks effects among the urban system components selected for urban resilience assessment. This peculiarity can be provided by system dynamics modelling. Within this study the purpose is to introduce a dynamic urban resilience to natural hazards assessment tool that is able to compare different urban resilient scenarios, considering the multi-dimensionality of urban systems and short term and long term time reference. This paper presents the structure of novel tool and comparison of urban resilience scenarios performed for a local case study with the given tool. Specifically, the implementation of probabilistic simulation in system dynamics model with output inform of index allows capturing all the possible outcomes of different urban resilience scenarios. The results of model validation and simulation show that the tool is suitable for different urban resilience scenario evaluation, thus has the potential to be used in urban policy planning for development of urban resilience strategies.

Keywords: Causal loops, Disasters, Modelling, Monte Carlo, Probabilistic simulations, System dynamics

Introduction

The number of natural disasters has increased tremendously in the last 60 years and thus have the amount of loss and damage from natural disasters [1]. This has made the disaster risk reduction policies an inalienable part of social welfare, economic growth and environmental protection. Within the context of disaster risk reduction policies, the term "resilience" is used in international policy agreements such as Sendai Framework [2] and Paris Agreement on Climate Change [3] to describe the complex behaviour of a system that is able to withstand natural disasters. The term has also gained increasing attention in scientific community [4].

There is an importance for resilience term practical use in the urban context [5]. Resilience and complex systems thinking can add to policy planning new ways of dealing with poverty, vulnerability, and governance by highlighting the diversity of components influencing these social problems. This is especially important with the consideration that European cities will face more challenges. In the near future, urban growth and climate change will influence social and economic aspects [6]. The increasing intensity of hazard activity caused by climate change together with the growth of population in urban areas will lead to higher risk in urban areas [7].

Studies of future disaster risk in Europe underline the need to adapt infrastructure, economy and communities in order to decrease socio-economic and environmental damage in the future [8]. According to [9], due to climate change, sea-level will rise by 0.8 meters in the next century, causing floods to coastal areas and along rivers, leading to chemical and mineralogical changes in coastal soils and threatening human life.

Study of [10] applied computer models for climate change and socio-economic development up to the year 2050, referring to floods of 2013, which had a high impact. The study concluded that floods such as in 2013 with a return rate of 16 years might increase to once every 10 years by 2050, with annual average economic losses of EUR 23.5 billion by 2050, while in period 2000 to 2012 losses accounted for EUR 4.6 billion.

The importance of including socio-economic aspects when planning disaster risk reduction (DRR) in the long term is underlined by the results of the study [11], which suggested that by the 2080 floods could have annual losses up to EUR 98 billion.

The study of [12] assessed 186 countries for potential losses to natural hazards and found that developed nations cannot deal with highly destructive, but less frequent events. At the same time, they are able to cover the costs of relief for less damaging or catastrophic recurring events. Latvia and Lithuania are mentioned in the list of the countries having a resource gap for high-frequency natural hazard events with a period below 25 years. The country risk profiles of World Bank [13] show that floods pose a very high risk for the Baltic States with annual average affected GDP of EUR 6.42 billion and average affected population of 800 000 inhabitants.

Over the years, studies report that there is a lack of tools on resilience [14], [15] and there is the need for a decision support system can assist city authorities in planning adaptation measures [16]. This identified gap underlines an opportunity for developing quantitative simulations tools based on urban systems theory for the application of ecological, social, and technical resilience in policy planning [17]. Thus, this work aims to show that tool based on system dynamics approach integrating probabilistic simulation and composite index can be used for comparison in of urban system resilience strategies.

1. Literature review

1.1 A conceptualisation of urban resilience

Currently, urban resilience policy is under high uncertainties due to political pressures, emergent nature of threats, speed of change, and the level of complexity of networks that form cities [18]. In the field of risk reduction policies, the term urban resilience s a topic of discussion due to a lack of clarity on how to apply this concept in practice [19]. The terminological varieties and epistemological disjunctions sometimes make it difficult to use the term urban resilience in policy planning due to lack of recognition and reflection [20]. The long-term planning horizon and holistic context make resilience policies different from traditional hazard mitigation policies [21].

Some existing methods for resilience assessment describe resilience with characteristics as redundancy, diversity, efficiency, autonomy, robustness, adaptability, and collaboration, and even sometimes vulnerability is assigned to be related to resilience as an opposite term [22]. The term resilience was a topic of discussion in the scientific arena due to subjectivity and inability to define the relationship between the system components, and lack of the inter- and trans-disciplinary perspective [19].

Summarizing many definitions of resilience, the term is used to describe how systems functionality is affected by certain level of stress, or shock. This concept relies on the maximal capacity of the system to cope against a particular hazard – i.e. the concept of capacity thresholds. Therefore, disaster risk assessment is also connected to resilience [23], [24]. Risk is a static metric that does not change over time and represents the severity of impact on a given system, social or technological in a specific reference time. Risk is often a part of metric used in engineering system resilience.

Many resilience studies focus on infrastructural system resilience as they provide essential services that support economic prosperity and quality of life [25]. Another type of resilience interpretation is linked to ecosystem resilience, where multiple equilibrium states exist, also known as alternative regimes [26]. Ecosystem resilience tends to measure an equilibrium state of system [27] and represents a dynamic metric of system performance over the disaster event [28], [29]. This approach underlines the non-linear spatial-temporal interaction of components in a complex adaptive system and is consistent with Holling's definition of thresholds that ecosystem can withstand [30]. Finally, recent definition of urban resilience provided by [31] is in line with socio-ecological resilience, which emerged from the definition of ecosystem resilience and recognised the dynamic nature of urban systems in different scales.

1.2 Challenges in urban resilience assessment

Based on the review of social resilience studies [32] concluded that different tools of different purposes towards resilience measuring are found in literature, but these tools are not yet capturing the dynamic interactions between social and other dimensions. The current studies applying multiple equilibrium regimes in models with socio-economic aspects are still limited [33].

Often quantitative indicators are used because they are easy to use and compare with each other [34]. To capture the multi-dimensionality indicators presenting different aspects of urban areas are synthesized into a single number called 'index' [35], known as a composite indicator-based method. The composite indicator-based method is known as multi-criteria analysis (MCA) and uses a set of indicators to present different criteria within selected resilience dimensions [24].

Composite indicators methods are often used for assessing the performance of human development, sustainability, corruption, innovation, competitiveness [36]. One of the most recognised Sendai Framework indicator problems is that they are used to determine global trends in the reduction of risk and losses at the current state of use [37]. They serve for calculating the impact of short term risks, but do not provide enough information to create a risk reduction and disaster prevention strategies over the long term.

The study of [38] found that it is challenging to apply relevant variables or indicators that are practicable and implementable for every urban system, and therefore suggested to integrate a systemic approach into urban resilience mapping should be developed.

In this direction, computer simulation tools for resilience assessment are created based on models created with quantitative methods that describe the interrelationship of system variables. Practical and precise models in the short term usually are those that are made for single systems like for hospitals [39], [40], water supply systems [41], [42] and energy supply [43], [44]. However, at the current state of development, these models seem unable to quantify the resilience of the whole urban system, leaving resilience as a separate measure for sub-parts of urban system.

More models found in the literature [41], [45]–[47] show that computer simulation tools for resilience assessment are mainly applied to infrastructural systems, leaving socio-economic aspects outside the scope of resilience studies. The social resilience assessments capturing dynamic interactions within and between different social dimensions are not found in literature [32]. For a tool capable of urban resilience assessment including the socio-economical approach is a very important aspect, but linking social and technical resilience faces enormous challenges [48].

1.3 System dynamics approach in urban research

The interactive combination of different physical and non-physical factors leading to the formation and transformation of cities makes the urban environment a dynamic system of systems[49]. Therefore any analysis of urban form resilience should not be conducted in isolation from determining factors and must consider a comprehensive, integrated approach[50]. In this direction, the system dynamics approach is used to model the dynamics and metabolism of all urban systems. The method allows explaining the behaviour of a system through a structure that drives the behaviour of the system itself with the help of feedback loops as the basis of an explanation of system behaviour[51].

The scale and scope of research applying system dynamics approach to study urban areas differ and cover a wide range of investigated aspects: some of them are focused at urban area in general; others are focused on specific aspects of the urban area and therefore mainly addressed to one type of discipline, like technological, economic, environment, health and other. Urban system dynamics models in the literature relate to topics such as: urban sustainability, energy sector of urban areas, urban transport, urban water supply system, urban economy.

In specific, the study [52] presents the results from a system dynamics model for urban passenger transport sector, including an economy subsystem, population subsystem, transport subsystem. The dynamics regulating energy consumption and CO_2 emissions provide the mechanism to prioritise technological and regulatory solutions to achieve significant energy and emissions reductions.

The study of [53] showed how causal loop diagrams can explain the effect of a selection of a specific set of policy recommendations and strategies implementable in different countries. This would enhance the generalisation of causal loop diagrams on this topic, while the sensitivity of the variables could be calibrated for specific case studies depending on the local conditions.

Study of [54] evaluated sustainable policy in urban transportation by using as inputs precise data form comprehensive databases. For this model nine urban sustainable transportation indicators were used divided into three indicators for each key group of environmental, economic and social sustainability and together aggregated into composite index. The study suggested that such model could be used for comparing various combinations of policies by their costs and achieved effects. In this case, the use of statistics as input data can be a partial solution for better sensitivity of the model, however, the effects of the interaction of variables in the model cannot be fully included by using only historical data.

The study of [55] focused on urban water sector presents conceptual framework for modelling financially self-sustaining water and wastewater networks. Framework involves system dynamics modelling and explanation of the created model with causal feedback loops. The conclusion suggested that feedback loops might demonstrate that management of wastewater collection networks constitutes a complex dynamic system for which traditional management tools used in the area are deemed inadequate. The study shows the adequacy of system dynamics model to be used for developing both short term and long term management plans.

One more aspect of system dynamics modelling was found in the model reported in [56] . The model focuses on a long term quantification of air pollution in urban areas considering non-linear interactions and time delays within different sub-models for industrial sectors with the aim to find the most efficient air pollution reduction strategy in a short term and long term perspectives. Therefore, the inclusion of time delays would play an important role when modelling urban resilience in order to show the long term and short term changes in the behaviour of a studied urban system.

The main findings from literature review on system dynamics models for urban areas can be summarized as following:

1) Urban system dynamic models can be grouped into three groups:
   a) Models that can be considered to be developed for a general description of urban area performance [57];
   b) Models that have been developed for a specific sector of the urban area, but have incorporated parts or variables from other sectors [58]–[60];
   c) Models that have been developed for a specific sector of the urban area with a very high detail to show precisely the dynamics of every sector [56], [61];
2) It is possible to use a single index in system dynamics model for evaluation of systems performance [54], [58], [62];
3) Models can be made for different time scale [63], short term, long-term or both.

The findings presented here are responsive to the context of this study and are considered for the development of dynamic assessment tool of urban resilience to natural hazards. The methodology section describes the creation of model in detail.

Methodology

Tool suitable to describe the dynamics of urban resilience to natural hazards and deal with the existing knowledge gaps on topic of urban resilience measurement is created by integrating three methods into a single model for performing the assessment. The development of this model can be summarized in an algorithm (see figure 1). The definition of the dynamic problem and hypothesis for the purpose of such tool follows the definition is provided in [64].

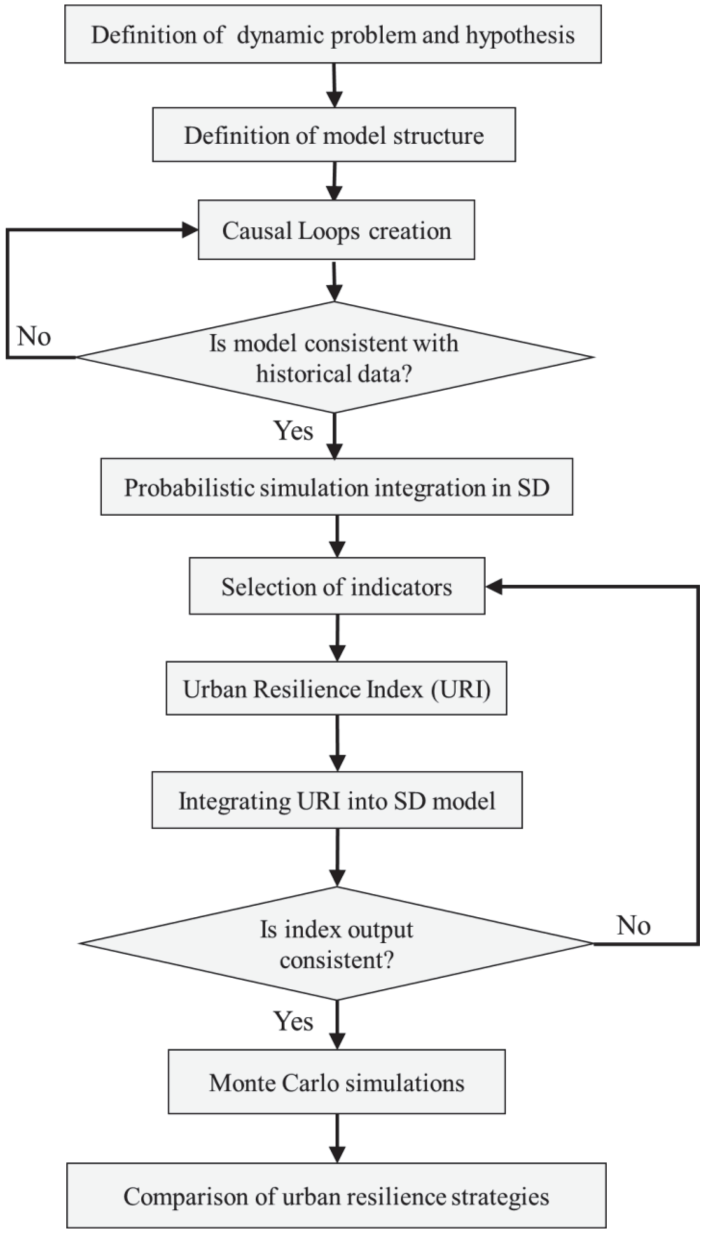


Figure 1. Model development algorithm.

Within this study urban resilience assessment is performed for a medium-sized city of Jelgava, which is exposed to flood risk related to spring floods due to snow melting and rain, ice congestion and partly also to wind floods. For natural hazard definition information on spring floods in Jelgava city prepared by "Latvian Environment, Geology and Meteorology Centre" for Preliminary flood risk assessment for 2019-2024 is used in this study [65].

2.1 Definition of tool structure

The structure of the tool that enables dynamic urban resilience to natural hazard assessment includes system dynamics approach with integrated probabilistic simulation and composite indicator index. System dynamics model considers endogenous structure of urban system, which is created with help of feedbacks between dimensions that represent the dynamic change occurring in urban areas. The urban system in the model is defined through urban dimensions that are included in the model as separate sectors. The defined dimensions of urban system are social dimension, infrastructure dimension, environmental dimension, economic dimension. The concept for dynamic urban resilience assessment tool structure is presented in figure 2.

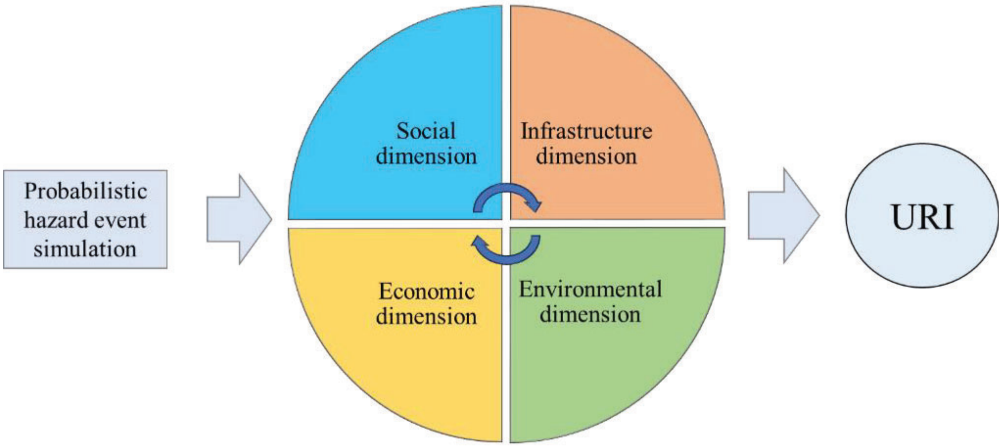


Figure 2. Concept of dynamic urban resilience assessment tool structure.

Urban systems behaviour is best described by non-linear dynamics, which are the result of many feedbacks between urban systems multiple elements. Therefore, the developed urban resilience assessment model to natural hazards is made with system dynamics approach, which enables dynamic modelling of urban areas with the help of internal feedback loops between different, and well identified, components of urban areas. System dynamic models is based on using three components applicable known as stocks, flows and variables [66].The model is used for simulation of the changes in the components over a simulation period.

The study distinguishes different dimensions of urban areas to set the scope at which urban area performances are captured in the model. The visualisation of the model composed of stocks, flows and variables, and their loops - as direct or feedback - is known as Causal Loop Diagrams (CLD). The CLD diagrams aim to identify the interactions within the component of the model [51].

The CLD consist of the reinforcing and disrupting drivers within system can be described in the following way: the change in the originating component is cause for change in other components that after a certain time have strengthening effect also in the initial component. This feedback loop is considered a self-reinforcing, identified with "R" in the CLD. If there is an opposite case, when the response of other components in the loop decreases the original effect of the initial component and thus the change in system, it is called a balancing loop, identified with "B" in the CLD. Usually a system has multiple feedback loops that interact with each other and are the main cause for the complex dynamic behaviour [55].

The probabilistic simulation is integrated in the developed urban resilience system dynamics model generating a random impact from a given probability-impact curve and assigns the defined impact to a model variable (i.e. dwellings, electricity supply, heating, water supply etc.).

The composite indicator based index for the urban resilience assessment allows having dynamic output in the form of single number or score. This enables to represent the dynamic changes within the representative urban dimensions directly selected from the urban resilience system dynamics model. To make indicator values comparable over the simulation time, a normalisation of indicators is made based on reference scale. Thus, indicators are selected from available data sets of statistics to provide a definition for reference scale.

2.2 Validation of dynamic urban model

The validation of model content is performed within a local case study by comparing the model output for each dimension with historical trend from statistics. This is performed before integrating probabilistic simulation into model. For this purpose, the coefficient of determination R^2 is used according to equation 1 [68]:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad (1)$$

where
R^2 – coefficient of determination,
n – number of measurements in selected data set,
y_i – value of the i^{th} observation in the validation dataset,
$\bar{y}$ – is the average value of the validation dataset,
$\hat{y}_i$ – predicted value of the i^{th} observation.

In Equation 1, the fraction is the ratio of the residual sum of squares to the total data sum of squares. Value R^2 allows understanding how close the data is to historical trend. The value of R^2 close to 1 shows that the model is making a good perdition. Model is considered valid for cases when R^2 value is over 0.9, which is considered a very precise model output. The formal hypothesis F-test is not necessary for purpose of system dynamics model, because the structure of the model is a "white box" based on deterministic equations and knowledge instead of statistics as in case of regression models.

2.3 Probabilistic natural hazard event simulation

Natural hazard in the system dynamics model is defined as an event with a specific impact on the population and provision of services. For natural hazard, the definition for the selected case study is based on information prepared by “Latvian Environment, Geology and Meteorology Centre” for national flood risk assessment is used in this study [65]. The hazard probability and magnitude in terms of flooded area for spring floods in Jelgava city (see figure 3) is based on historical data of hazard events occurring once in 200 years (0,5% probability), once in 100 years (1% probability), and every 10 years (10% probability).

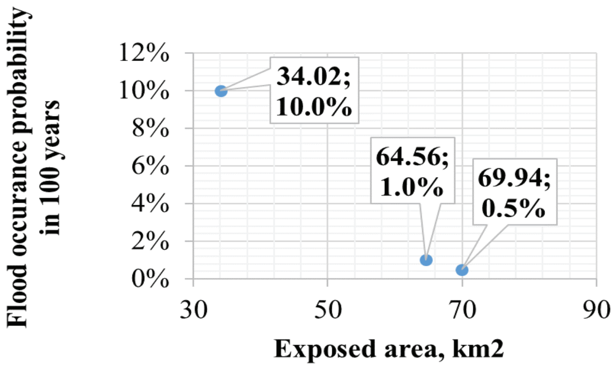


Figure 3. Probability and magnitude of spring floods.

The impact of hazard event for specific component is described by Equation (2):

$$Hazard\ impact_i = Hazard_j * Exposure_i * Vulnerability_i \quad (2)$$

Where
Hazard $impact_i$ is the effect of hazard on model component *i* of the considered system,
$Hazard_j$ is the hazard magnitude for a hazard of occurrence probability *i*,
$Exposure_i$ is the exposure of model component *i* to hazard,
$Vulnerability_i$ is the vulnerability of component *i*.

For the assessment of $Exposure_i$ and $Vulnerability_i$ components in connection to a specific Hazard intensity, in the proposed system dynamics model, proxy data are used due to lack of historical records. The exposure is determined according to the exposed population in the flooded area in Jelgava city during spring floods as shown in figure 4.

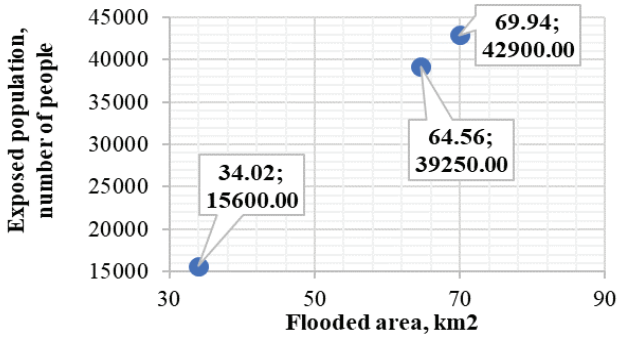


Figure 4. Exposed population to spring floods in Jelgava city.

The proxy data for $Exposure_i$ component is based on the exposed population. The $Exposure_i$ of specific components is determined as components value per capita. The higher number of exposed population, the higher the $Exposure_i$.

The $Vulnerability_i$ of components is defined by vulnerability coefficient from 1 to 0, where 1 equals to the full amount of impact assigned by $Exposure_i$ per capita and 0 means no assigned by $Exposure_i$ per capita. This allows determining the decrease of specific service depending on magnitude of natural hazard.

The defined model components in system dynamics model that have input from Hazard impact are reported in table 1.

Table 1. Defined components in system dynamic model with hazard impact

Components	**Hazard impact, units**
Social dimension	
Young population	Deaths (number of people)
Working age population	Deaths (number of people)
Elderly population	Deaths (number of people)
Economic dimension	
Labour hours	Decrease in labour hours (hours)
Infrastructure dimension	
Dwellings	Damage to dwellings (number of dwellings)
Electricity supply	Decrease in electricity supply (kWh)
Heating	Decrease in heating (kWh)
Water supply	Decrease in water supply (cubic meters)
Environmental dimension	
Wastewater treatment	Decrease in wastewater treatment (cubic meters)
Waste treatment	Decrease in waste treatment (kg)

The model structure allows incorporating different recovery functions (Linear, S-shaped, Exponential) for each component after hazard impact occurrence during model simulation. However, there is no historical data available on the recovery process from the hazard event for the selected case study area, thus only S-shaped recovery function is used for case study of Jelgava city.

2.4 Indicator selection and URI definition

The indicators that fit model structure and have reference data in EUROSTAT database are reported in [67]. The positive and negative effect of selected indicators on urban resilience is identified and considered in index creation. The different scales of indicators are normalised to a common scale of 0 to 1 with Min-Max method.

The indicators are used for creation of composite indicator based index – urban resilience index (URI), which is able to present the dynamic change of urban resilience in short term and long term. The index allows capturing the dynamics of urban resilience to natural hazard as estimation based on normalized indicators from different urban dimensions of the created system dynamics model and presenting the dynamic change as a single value measurement.

For the comparison of different urban resilience scenarios URI in form of converter in system dynamics model is not suitable, because different URI scores for every time step of the simulation will be presented. A more comprehensive way for comparison is to have a URI score for simulation in a single value at the end of the simulation. This is achieved by making URI as stock component in system dynamics model.

URI score during the simulation of urban resilience system dynamic model is used as an inflow into URI score stock. At the end of simulation, the value of stock for URI score is cumulative value of URI scores over simulation time. To make the cumulative value of URI score comprehensive for comparison of different scenarios, it is normalized to scale from 0 to 1, by dividing the URI value in stock at the end of simulation by whole simulation time period.

2.5 Assessment of urban resilience through probabilistic simulation

The urban resilience model runs a stochastic simulation with probabilistic input from command RANDOM. In other words, this makes the output for every simulation run different even when the same input data is used, because urban resilience system dynamics model simulation is probabilistic instead of deterministic. Thus, for simulation of the model Monte Carlo method is applied.

Monte Carlo method is used in the evaluation of complex problems involving random phenomena occurring in probabilistic simulations. The results of Monte Carlo simulations show likelihood of different outcomes of events, in this case different outcomes in dynamic change of urban area functionality over time under uncertainty of natural hazard event occurrence, which is measured by URI score. This allows having an understanding of statistical nature of the systems performance and making decisions accordingly to the statistical output. The number of trials for Monte Carlo simulation is distinguished by Equation 3 [69]:

$$Z = \frac{N}{1+N(E)^2} \tag{3}$$

Where
Z – number of samples,
N – all possible model output values for the urban resilience index in one scenario,
E – maximum permissible error in calculating Z.

The maximum permissible error in this study is considered as ±5%. All possible model output values for the urban resilience index in one scenario depend on the urban resilience index value scale. The *Stella Architect* software used to create the model derives the value of the cumulative urban resilience index from 0 to 1 after Monte Carlo simulations with an accuracy of up to three decimal places. Thus, the maximum number of different values of the city's resilience index is 1000. This number N is taken into account when calculating the Z number of samples in Monte Carlo simulations.

2.6 Comparison of different urban resilience scenarios

Within the case study of Jelgava, two different urban resilience scenarios were selected for comparison with the Baseline scenario. Both comparative urban resilience scenarios foresee the potential effects of policy strategies aiming at the increase of urban resilience by increasing the urban attractiveness. In addition, one of the scenarios includes policy strategies aiming at decreasing infrastructure service vulnerability to natural hazards. The changes in input parameters used for urban resilience system dynamics model to present the effects of policy planning strategies are reported in table 2.

Table 2. Parameters for selected urban resilience scenarios

Scenario	Parameters		
	CO_2 emissions	Waste recycling	Hazard effect component
Baseline scenario with hazard	18 g CO_2/kWh for heat and 400 g CO_2/kWh for electricity	0 for waste recycling factor	Coefficient of 1 for $Vulnerability_i$
Urban resilience scenario 1	S-type function decrease from 18 g/kWh to 9.6 g/kWh for heat and 400 g CO_2/kWh to 215 g/kwh over simulation time 1 to 30 years	S-type function increase from 0 to 1 for waste recycling factor from simulation year 15 to 30 years	Coefficient of 1 for $Vulnerability_i$
Urban resilience scenario 2	S-type function decrease from 18 g/kWh to 9.6 g/kWh for heat and 400 g/kWh to 215 g/kWh over simulation time 0 to 30 years	S-type function increase from 0 to 1 for waste recycling factor from simulation year 15 to 30 years	Coefficient of 0.5 for $Vulnerability_i$

The input parameter values for Environmental dimension component CO_2 emissions in Urban resilience scenario 1 and Urban resilience scenario 2 are selected based on the estimates of 80% decrease in of CO_2 emissions by 2050 compared to 1990. The selected S-type function describes a gradual decrease in CO2 emissions over simulation years 0 to 30, which is equivalent to time period of 2020 to 2050. Similarly, S-type function describes a gradual decrease in waste recycling factor value, but in a different time period, from simulation year 15 to 30 years. Such definition of scenarios allows to test if the tool is sensitive, enough to consider effect of policy strategies that have different time reference. Both components CO_2 emissions and waste recycling factor in urban resilience strategies affect urban attractiveness, which, according to CLD in "Model structure" section, would affect other components used in the model.

The Urban resilience scenario 2 in addition to the reduction of CO_2 emissions and the increase of recycled waste foresees the reduction of hazard effect. This is considered by changing hazard effect coefficient $Vulnerability_i$ from 1 to 0.5. This results as decrease in disruption amount in all the infrastructural services.

The expected result of implementing the urban resilience scenarios is increase in urban resilience to natural hazard. This increase measured by comparing URI score probabilities and their distribution in output of Monte Carlo simulations.

3. Results

3.1 System dynamics model structure

The created urban resilience system dynamics model includes four dimensions as described in methodology: social, economic, infrastructure and environmental. This section presents the CLD for each dimension to provide a description of the model structure and the feedbacks considered between model components. Each dimension is included in the model as separate sector, linked with respective influencing component of another sector. These linking variables are reported in CLDs with quotation marks in the title when used from another sector.

The social dimension CLD in figure 5 has several balancing loops representing the effects in ageing and deaths, and one reinforcing loop, representing the effect of births. The model is constructed in a way that it includes the age of population groups in order to have components responding for working-age population for economic dimension components and consider social vulnerability in terms of youth and elderly dependency.

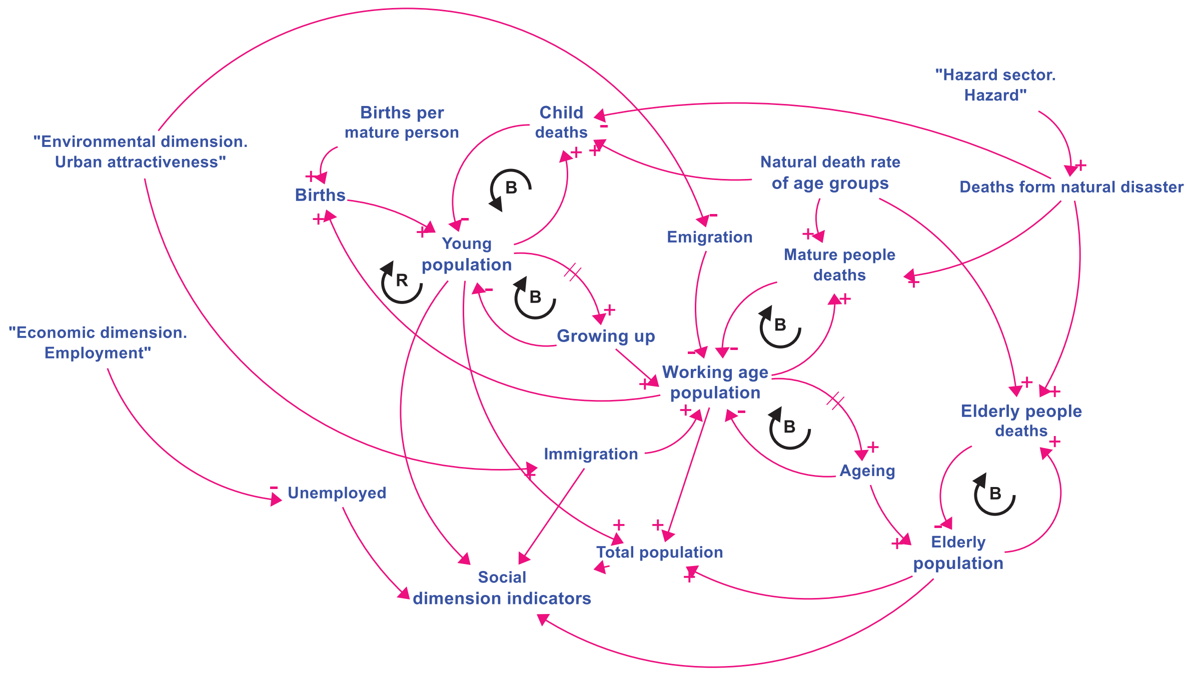


Figure 5. Causal loop diagram for social dimension.

The two strokes on the link between different age population is mark for time delay, which considers the aging effect of the population group. Working age population accounts population from 16 to 65 years old. The model is set in a way that young population grows up 16 years after birth and working age population ages after 59 years (from 16 years after births).

The increase of population is occurring due to births and immigrations. The decrease of population is occurring due to deaths and emigration. Deaths are the result of natural deaths and deaths from occurred disaster. The model considers different death rate for every age group of population. The balancing loops between respective age population deaths show that when population increases, the number of deaths also increase. This dynamic will cause a decline in the population and a consequential decline in the number of deaths as balancing loop.

Social dimension of urban area has a certain effect on the resilience of urban area and therefore the main output of the social sector model for calculation of URI. Another important factor in the developed model for creating the dynamic effect in social dimension is urban attractiveness. Urban attractiveness represents the feedback effect from environmental dimension. Urban attractiveness in the social sector is affecting the immigration and emigration in urban area.

The economic dimension in figure 6 includes key aspects of the urban economy in terms of productivity, labour, GDP, employment, etc. The main output of the economic sector for URI estimation is GDP. Another loop in economic dimension is the balancing loop of the employment. The interaction of these the two loops leads to a dynamic change in GDP component. Over the simulation time the value in GDP component is growing due to the effect of the reinforcing loop. This growth is then balanced by the employment rate, which is also dependent on working age population component in social dimension.

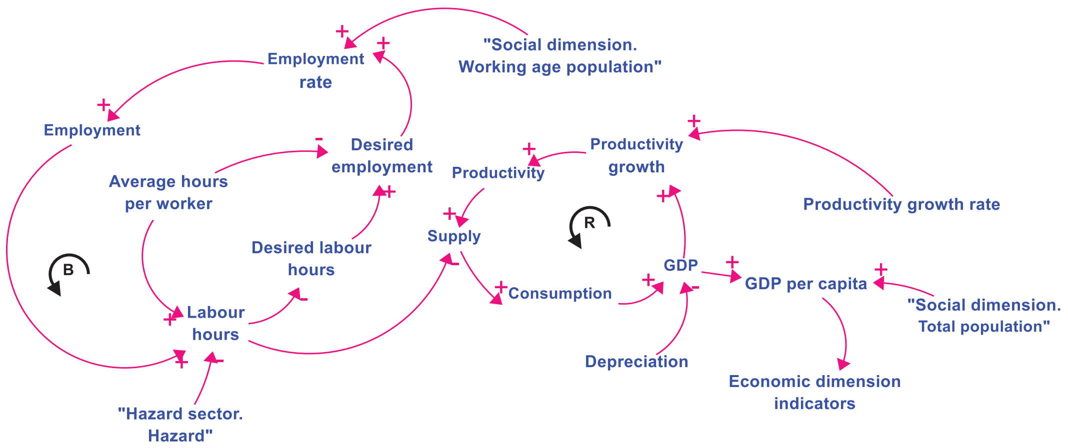


Figure 6. Causal loop diagram for economic dimension.

The infrastructure dimension of model shown in figure 7 is presented by dwellings, electricity supply, heating, water supply. The part of model representing processes concerning the dwellings has an essential role for other sectors, because through the occupied dwellings component, the level of demand for heating and water supply is defined.

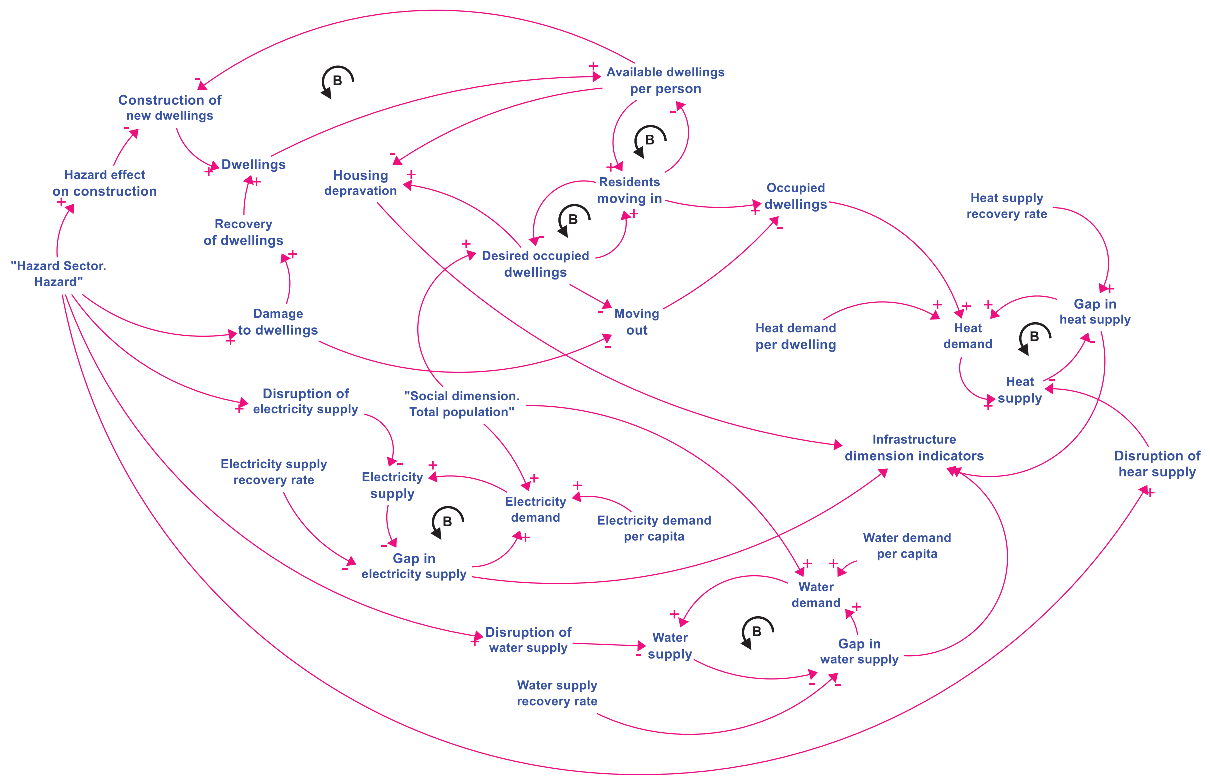


Figure 7. Causal loop diagram for infrastructure dimension.

The desired occupied dwellings component depends on total population variable from social dimension. Number of occupied dwellings will increase if desired occupied dwellings increase and decrease the number of available dwellings due to interaction of two balancing loops. For the model it is considered that when the available number of dwellings per person increases, the need for construction of new dwellings decreases and thus the construction of dwellings will accordingly decrease.

The CLD shows that the construction of new dwellings is exposed to a hazard. A negative effect on the construction of new dwellings is also considered in the model at time when the hazard occurs.

The effect of hazard on existing dwellings, with respective exposure and vulnerability is considered. Reconstruction of damaged dwellings is also considered in the developed model.

The variable occupied dwellings is used to define the amount of demanded water supply and heating services provided. The supply of services in the model is considered as a balancing loop. The supply of services decreases when the hazard affects on the provision of services, with respective exposure and vulnerability is considered. The gap in the provision of services is used as an indicator for URI calculation.

The CLD for environmental dimension in figure 8 shows that model includes waste treatment and wastewater treatment as balancing loops, similarly as used in the provision of heating, electricity supply and water supply in infrastructure dimension. Also, the impact of natural hazard is considered in a similar way for these loops. In addition, the environmental dimension includes CO_2 emissions, linked to electricity supply and heating components in the infrastructure dimension. The CO_2 emissions are linked to urban attractiveness component.

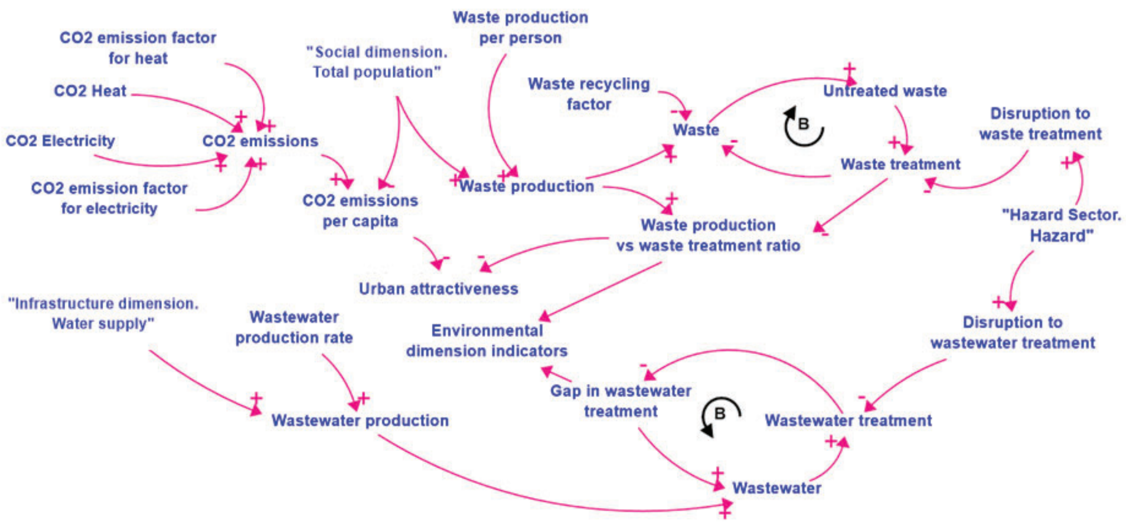


Figure 8. Causal loop diagram for environmental dimension.

The overview of the model structure in terms of interactions between the defined urban dimensions is shown in figure 9. The links between the dimensions create additional feedback loop. The balancing loop between social, infrastructure and environmental dimension, linked by urban attractiveness that influences population migration, and consequently the amount of services provided in the urban area and thus the impact on the environment in terms of CO_2 emissions and waste amount.

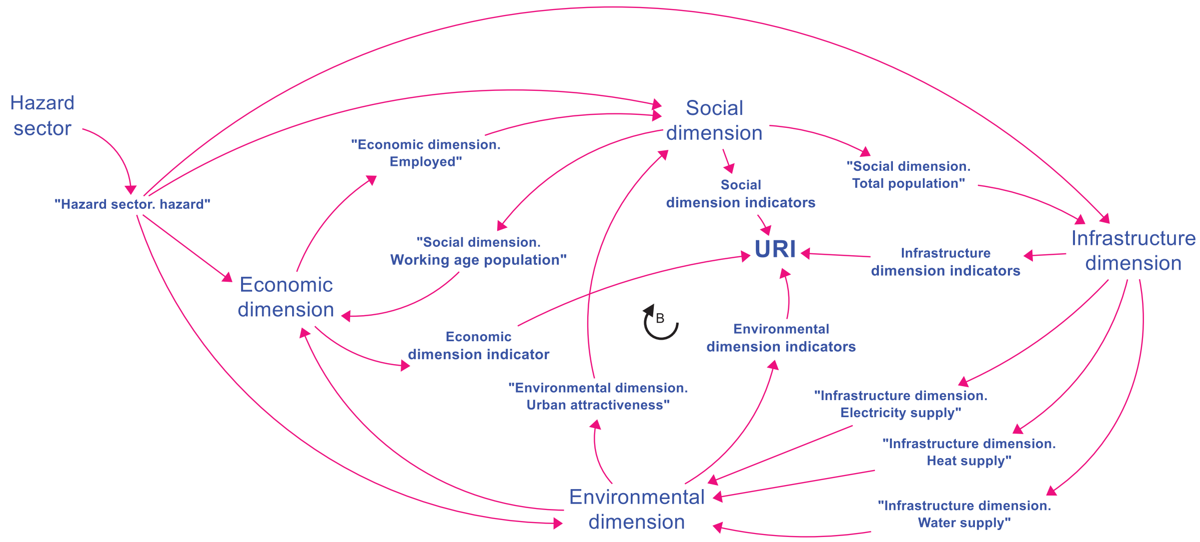


Figure 9. Causal loop diagram for interactions between the dimensions.

3.2. Results of model validation for case study

The urban resilience system dynamic model is validated based on historical data for a selected urban area of a case study. Despite a significant lack of available historical data for areas of urban scale, specific data are found from the Latvian Central Statistics Bureau appropriate for validation of the Population and GDP components.

Data set for Jelgava population is used for period years 2011-2018. The results of the validation in figure 10 show the comparison to historical data set for Population of Jelgava with the model output. For purpose of this validation an initial value of population as for statistical data in 2011 is set in the model.

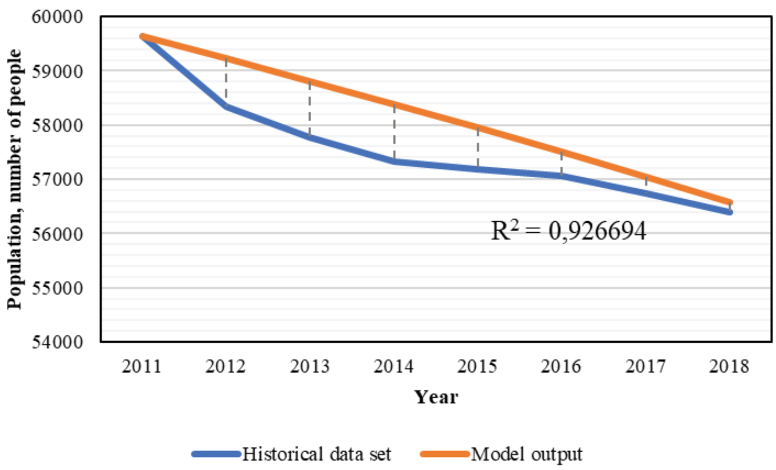


Figure 10. Results of population component validation.

The results of the validation show that model output for population component fits historical data of population with a coefficient of determination R^2 equal to 0,92669. This is considered as a very high relationship between real data and model data, and the model is valid to provide a consistent output for population component in urban resilience assessment.

The validation of model output for GDP of Jelgava is performed for years 2013-2017. For GDP component validation, the change in population component given in figure 10 is considered for the respective years of historical GDP data set. No data on GDP for a longer period is available for Jelgava city in Central Statistics Bureau. The results of GDP component validation are presented in figure 11.

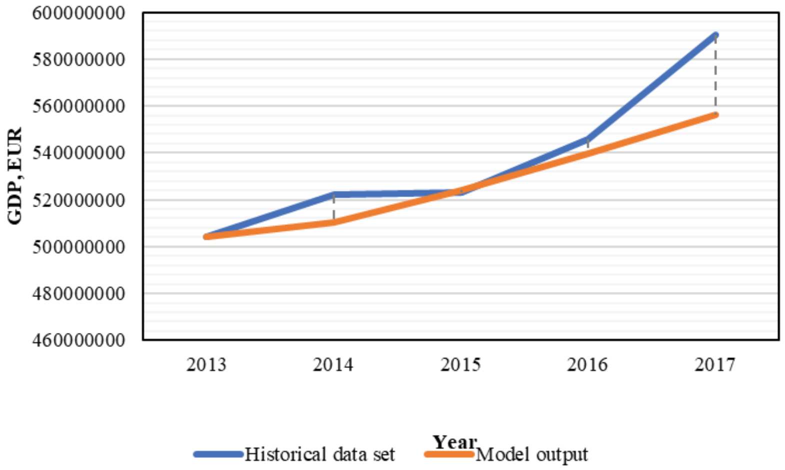


Figure 11. Results of GDP component validation.

The model output for GDP component fits historical data of GDP with coefficient of determination R^2 equal to 0,95564. This is considered as a very high relationship between real data and model data and the model is valid to provide a consistent output for GDP component in further urban resilience assessment.

The rest of the model components do not have a historical data set presenting a trend over a more extended period then few years. Inputs for the rest of components during the validation at the start of the simulation are used based on average statistics for Latvia or found in literature sources for Jelgava city.

3.3. Results of urban resilience scenario comparison

The comparison of urban resilience scenarios is performed by analysis of Monte Carlo simulation statistics for three defined scenarios: Baseline scenario with hazard, Urban resilience scenario 1 and Urban resilience scenario 2. The necessary evaluated number of trials that must be performed by Monte Carlo simulation for every scenario to achieve a 95% confidence level of Monte Carlo simulation is equal to 286 samples according to equation 2.4.2. High frequency of high URI score in the predefined scenario means that the scenario is more preferable.

The results show that most frequent cumulative URI score in baseline scenario is from 0,761 to 0,786. Cumulative URI scores in period from 0,736 to 0,761 and period from 0,786 to 0,811 also occur frequently. Higher cumulative URI scores than 0,811 do not occur for Baseline scenario with hazard. The results of statistics analysis of Monte Carlo simulations show that mean average of cumulative URI score for baseline scenario with hazard occurrence is 0,769 and the median is 0,767.

The results of Monte Carlo simulation in Urban resilience scenario 1 show that most frequent cumulative URI score is in period from 0,761 to 0,786. Urban resilience scenario 1 shows a higher cumulative URI respect the scores of the baseline scenario with hazard. The results show that mean average of cumulative URI score in Monte Carlo simulations for Urban resilience scenario 1 is 0,802 and the median is 0,809.

The results of Monte Carlo simulation for the frequency of occurrence of specific cumulative URI score in Urban resilience scenario 2 show that most frequent cumulative Urban resilience scenario 2 is from 0,754 to 0,772. The statistics of URI score in Urban resilience scenario 2 show that mean average of cumulative URI score in Monte Carlo simulations for Urban resilience scenario 2 is 0,804 and the median is 0,811. Thus, there is a small increase in cumulative URI score for Urban resilience scenario 2 compared to Urban resilience scenario 1.

The min, max and mean average values, together with other statistics parameters that can be used for comparison of urban resilience scenarios are computed in the Stela Architect software with Monte Carlo simulation output. The comparison of min, max, and mean average values of cumulative URI scores in Monte Carlo simulations with confidence level of 95% for different scenarios is shown in figure 12.

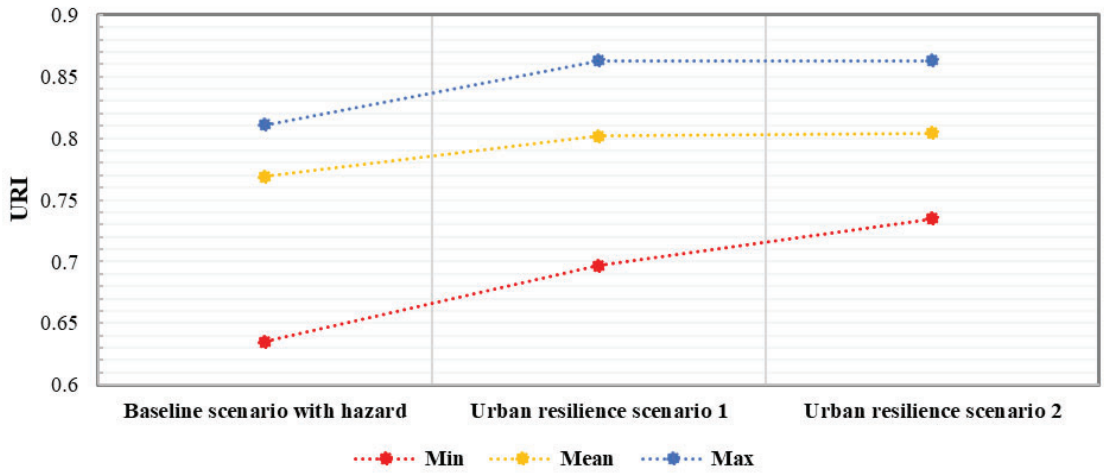


Figure 12. Summary of Monte Carlo simulation results for different scenarios.

Baseline scenario with hazard has the lowest min, average mean and max scores. There is an increase in cumulative URI score min value for Urban resilience scenario 1 and Urban resilience scenario 2 compared Baseline scenario with hazard. There is small increase in mean average value and no increase in max value Urban resilience scenario 2 compared with Urban resilience scenario 1. In this case, benefit of implementing Urban resilience scenario 2 lies in decreasing the low cumulative URI score occurrence, which are present in the probabilistic simulations in which large number of natural hazard events has occurred.

Conclusions

A novel tool for dynamic assessment of urban resilience to natural hazards is developed. The tool provides urban resilience measurement that suits the complexity of urban resilience definition. For this purpose, three quantitative methods are integrated into the tool: system dynamics, probabilistic simulation and composite indicator. The content and structure of the tool is validated and different urban resilience scenarios are tested in a local case study on a Jelgava city with natural hazard of spring floods.

The integration of three methods composite indicator, probabilistic simulation and system dynamics within the developed tool allows overcoming the limitations of every method for resilience assessment. The results of model validation and simulation show that the tool is suitable for different urban resilience scenario evaluation in case studies.

The analysis of different urban resilience scenarios in case study shows that there is a notable increase in urban resilience in the long term when the selected urban resilience strategy is aiming at increasing of urban attractiveness. Consequently, such a strategy has a positive effect on the decrease of social vulnerability in social dimension and thus increases urban resilience. In addition, analysis shows that the benefits of decreasing vulnerability of contribute to urban resilience increase, but do not surpass the benefit of decreasing social vulnerability in the long term.

The developed urban resilience tool captures the effects of different urban resilience strategies both in the short term and long term, as shown by summary of Monte Carlo simulation results for different urban resilience scenarios in case study for Jelgava city. The multi-dimensionality of the tool and feedbacks between the defined dimensions allows capturing the trade-offs occurring in different dimensions of urban areas, as intended by the defined causal loops in system dynamics model.

The developed tool has proved to serve the indented purpose and can be used for wider application in policy planning. The developed tool allows to consider the trade-offs between the short and the long terms of urban resilience strategies within the causal loops defined in the dynamic structure of the model. Additional system dynamics sub-models for infrastructure, such as roads and telecommunications, or factors influencing social vulnerability, like education, hospitals, and different social groups, can be implemented to consider relevant other trade-offs urban resilience strategies.

The simulation of natural hazard made by probabilistic simulation has a certain sampling bias for probability of occurrence, which does not change over defined scenario simulation time. The dynamic change of natural hazard event probabilities can be introduced in the future.

For more precise assessment of urban resilience with such dynamic tool also the data availability on response and recovery to disasters for different dimensions of urban areas should be improved and the availability of indicators for normalization of URI scores to enable wider application of the tool in policy planning.

REFERENCES

[1] U. Ranke, *Natural disaster risk management: Geosciences and social responsibility*. 2016.

[2] 2015 Third UN World Conference on Disaster Risk Reduction, *Sendai Framework for Disaster Risk Reduction 2015-2020*, in Sendai, Japan, on March 18.

[3] 2020 United Nations Framework Convention on Climate Change, *Paris Agreement*. 2015.

[4] A. Keating and S. Hanger-Kopp, “Practitioner perspectives of disaster resilience in international development,” *Int. J. Disaster Risk Reduct.*, vol. 42, 2020, doi: 10.1016/j.ijdrr.2019.101355.

[5] R. Friend and M. Moench, “What is the purpose of urban climate resilience? Implications for addressing poverty and vulnerability,” *Urban Clim.*, vol. 6, pp. 98–113, 2013, doi: 10.1016/j.uclim.2013.09.002.

[6] J. G. Carter, “Climate change adaptation in European cities,” *Curr. Opin. Environ. Sustain.*, vol. 3, pp. 193–198, 2011, doi: 10.1016/j.cosust.2010.12.015.

[7] P. N. Lal *et al.*, *National systems for managing the risks from climate extremes and disasters*, vol. 9781107025. 2012.

[8] G. Forzieri, L. Feyen, R. Rojas, M. Flörke, F. Wimmer, and A. Bianchi, “Ensemble projections of future streamflow droughts in Europe,” *Hydrol. Earth Syst. Sci.*, vol. 18, pp. 85–108, 2014, doi: 10.5194/hess-18-85-2014.

[9] Joshua J. LeMonte, "Sea level rise induced arsenic release from historically contaminated coastal soils" *Environmental Science & Technology*, vol. 51, 2017.

[10] B. Jongman *et al.*, “Increasing stress on disaster-risk finance due to large floods,” *Nat. Clim. Chang.*, vol. 4, pp. 264–268, 2014, doi: 10.1038/nclimate2124.

[11] B. Poschlod, R. Ludwig, and J. Sillmann, “Return levels of sub-daily extreme precipitation over Europe,” *Earth Syst. Sci. Data*, pp. 1–35, 2020.

[12] S. Hochrainer-Stigler, R. Mechler, G. Pflug, and K. Williges, “Funding public adaptation to climate-related disasters. Estimates for a global fund,” *Glob. Environ. Chang.*, vol. 25, pp. 87–96, 2014, doi: 10.1016/j.gloenvcha.2014.01.011.

[13] Country risk profiles for floods and earthquakes by World Bank, 2016.

[14] W. Solecki, R. Leichenko, and K. O’Brien, “Climate change adaptation strategies and disaster risk reduction in cities: Connections, contentions, and synergies,” *Curr. Opin. Environ. Sustain.*, vol. 3, pp. 135–141, 2011, doi: 10.1016/j.cosust.2011.03.001.

[15] D. Serre and C. Heinzlef, “Assessing and mapping urban resilience to floods with respect to cascading effects through critical infrastructure networks,” *Int. J. Disaster Risk Reduct.*, vol. 30, pp. 235–243, 2018, doi: 10.1016/j.ijdrr.2018.02.018.

[16] C. Wamsler, E. Brink, and C. Rivera, “Planning for climate change in urban areas: From theory to

practice," *J. Clean. Prod.*, vol. 50, pp. 68–81, 2013, doi: 10.1016/j.jclepro.2012.12.008.

[17] E. M. Stumpp, "New in town? On resilience and ' Resilient Cities,'" *Cities*, vol. 32, pp. 164–166, 2013, doi: 10.1016/j.cities.2013.01.003.

[18] A. X Sanchez, J. van der Heijden, and P. Osmond, "The city politics of an urban age: urban resilience conceptualisations and policies," *Palgrave Commun.*, vol. 4, 2018, doi: 10.1057/s41599-018-0074-z.

[19] P. Aldunce, R. Beilin, M. Howden, and J. Handmer, "Resilience for disaster risk management in a changing climate: Practitioners' frames and practices," *Glob. Environ. Chang.*, vol. 30, pp. 1–11, 2015, doi: 10.1016/j.gloenvcha.2014.10.010.

[20] M. Wolfram, N. Frantzeskaki, and S. Maschmeyer, "Cities, systems and sustainability: status and perspectives of research on urban transformations," *Curr. Opin. Environ. Sustain.*, vol. 22, pp. 18–25, 2016, doi: 10.1016/j.cosust.2017.01.014.

[21] N. Gupta, C. T. Clavin, Z. E. Petropoulos, A. B. Mudd, R. Nek, and S. S. Tinkle, "Case Studies of Community Resilience Policy Case Studies of Community Resilience Policy," p. 114, 2016, [Online]. Available: http://dx.doi.org/10.6028/NIST.GCR.16-002.

[22] A. Rose, *Defining and Measuring Economic Resilience from a Societal, Environmental and Security Perspective*. 2017.

[23] A. Mullins and R. Soetanto, "Enhancing community resilience to flooding through social responsibility," *Int. J. Saf. Secur. Eng.*, vol. 1, pp. 115–125, 2011, doi: 10.2495/SAFE-V1-N2-115-125.

[24] T. P. Bostick, T. H. Holzer, and S. Sarkani, "Enabling Stakeholder Involvement in Coastal Disaster Resilience Planning," *Risk Anal.*, vol. 37, pp. 1181–1200, 2017, doi: 10.1111/risa.12737.

[25] A. J. Hickford, S. P. Blainey, A. Ortega Hortelano, and R. Pant, "Resilience engineering: theory and practice in interdependent infrastructure systems," *Environ. Syst. Decis.*, vol. 38, pp. 278–291, 2018, doi: 10.1007/s10669-018-9707-4.

[26] K. Kombiadou, S. Costas, A. R. Carrasco, T. A. Plomaritis, Ó. Ferreira, and A. Matias, "Bridging the gap between resilience and geomorphology of complex coastal systems," *Earth-Science Rev.*, vol. 198, p. 102934, 2019, doi: 10.1016/j.earscirev.2019.102934.

[27] D. G. Angeler, C. R. Allen, A. Garmestani, K. L. Pope, D. Twidwell, and M. Bundschuh, "Resilience in Environmental Risk and Impact Assessment: Concepts and Measurement," *Bull. Environ. Contam. Toxicol.*, vol. 101, pp. 543–548, 2018, doi: 10.1007/s00128-018-2467-5.

[28] A. Schardong, S. P. Simonovic, and H. Tong, "Use of quantitative resilience in managing urban infrastructure response to natural hazards," *Int. J. Saf. Secur. Eng.*, vol. 9, pp. 13–25, 2019, doi: 10.2495/SAFE-V9-N1-13-25.

[29] G. P. Cimellaro, A. M. Reinhorn, and M. Bruneau, "Framework for analytical quantification of disaster resilience," *Eng. Struct.*, vol. 32, pp. 3639–3649, 2010, doi: 10.1016/j.engstruct.2010.08.008.

[30] R. J. Standish *et al.*, "Resilience in ecology: Abstraction, distraction, or where the action is?," *Biological Conservation*, vol. 177. Elsevier Ltd, pp. 43–51, 2014, doi: 10.1016/j.biocon.2014.06.008.

[31] S. Meerow, J. P. Newell, and M. Stults, "Defining urban resilience: A review," *Landsc. Urban Plan.*, vol. 147, pp. 38–49, 2016, doi: 10.1016/j.landurbplan.2015.11.011.

[32] A. M. A. Saja, A. Goonetilleke, M. Teo, and A. M. Ziyath, "A critical review of social resilience assessment frameworks in disaster management," *Int. J. Disaster Risk Reduct.*, vol. 35, p. 101096, 2019, doi: 10.1016/j.ijdrr.2019.101096.

[33] S. L. Cutter *et al.*, "A place-based model for understanding community resilience to natural disasters," *Glob. Environ. Chang.*, vol. 18, pp. 598–606, 2008, doi: 10.1016/j.gloenvcha.2008.07.013.

[34] A. Asadzadeh, T. Kötter, and E. Zebardast, "An augmented approach for measurement of disaster resilience using connective factor analysis and analytic network process (F'ANP) model," *Int. J. Disaster Risk Reduct.*, vol. 14, pp. 504–518, 2015, doi: 10.1016/j.ijdrr.2015.10.002.

[35] C. Apreda, "C Limate Change , Urban Vulnerability and Adaptation," vol. 1, pp. 233–256, 2016.

[36] W. Becker, M. Saisana, P. Paruolo, and I. Vandecasteele, "Weights and importance in composite indicators: Closing the gap," *Ecol. Indic.*, vol. 80, pp. 12–22, 2017, doi: 10.1016/j.ecolind.2017.03.056.

[37] R. Z. Zaidi, "International Journal of Disaster Risk Reduction Beyond the Sendai indicators : Application

of a cascading risk lens for the improvement of loss data indicators for slow-onset hazards and small-scale disasters," *Int. J. Disaster Risk Reduct.*, vol. 30, pp. 306–314, 2018, doi: 10.1016/j.ijdrr.2018.03.022.

[38] J. M. Cariolet, M. Vuillet, and Y. Diab, "Mapping urban resilience to disasters – A review," *Sustain. Cities Soc.*, vol. 51, p. 101746, 2019, doi: 10.1016/j.scs.2019.101746.

[39] M. Pishnamazzadeh, M. M. Sepehri, and B. Ostadi, "An Assessment Model for Hospital Resilience according to the Simultaneous Consideration of Key Performance Indicators: A System Dynamics Approach," *Perioper. Care Oper. Room Manag.*, vol. 20, p. 100118, 2020, doi: 10.1016/j.pcorm.2020.100118.

[40] S. Khanmohammadi, H. Farahmand, and H. Kashani, "A system dynamics approach to the seismic resilience enhancement of hospitals," *Int. J. Disaster Risk Reduct.*, vol. 31, pp. 220–233, 2018, doi: 10.1016/j.ijdrr.2018.05.006.

[41] G. Quitana, M. Molinos-Senante, and A. Chamorro, "Resilience of critical infrastructure to natural hazards: A review focused on drinking water systems," *Int. J. Disaster Risk Reduct.*, vol. 48, p. 101575, 2020, doi: 10.1016/j.ijdrr.2020.101575.

[42] G. Watts, B. von Christierson, J. Hannaford, and K. Lonsdale, "Testing the resilience of water supply systems to long droughts," *J. Hydrol.*, vol. 414–415, pp. 255–267, 2012, doi: 10.1016/j.jhydrol.2011.10.038.

[43] A. Lagrange, M. de Simón-Martín, A. González-Martínez, S. Bracco, and E. Rosales-Asensio, "Sustainable microgrids with energy storage as a means to increase power resilience in critical facilities: An application to a hospital," *Int. J. Electr. Power Energy Syst.*, vol. 119, Jul. 2020, doi: 10.1016/j.ijepes.2020.105865.

[44] P. He, T. S. Ng, and B. Su, "Energy-economic resilience with multi-region input–output linear programming models," *Energy Econ.*, vol. 84, p. 104569, Oct. 2019, doi: 10.1016/j.eneco.2019.104569.

[45] W. Liu and Z. Song, "Review of studies on the resilience of urban critical infrastructure networks," *Reliab. Eng. Syst. Saf.*, vol. 193, 2020, doi: 10.1016/j.ress.2019.106617.

[46] O. Kammouh, P. Gardoni, and G. P. Cimellaro, "Probabilistic framework to evaluate the resilience of engineering systems using Bayesian and dynamic Bayesian networks," *Reliab. Eng. Syst. Saf.*, vol. 198, p. 106813, 2020, doi: 10.1016/j.ress.2020.106813.

[47] S. Kameshwar *et al.*, "Probabilistic decision-support framework for community resilience: Incorporating multi-hazards, infrastructure interdependencies, and resilience goals in a Bayesian network," *Reliab. Eng. Syst. Saf.*, vol. 191, p. 106568, 2019, doi: 10.1016/j.ress.2019.106568.

[48] A. Huck and J. Monstadt, "Urban and infrastructure resilience: Diverging concepts and the need for cross-boundary learning," *Environ. Sci. Policy*, vol. 100, pp. 211–220, 2019, doi: 10.1016/j.envsci.2019.05.008.

[49] A. Sharifi, "Urban form resilience: A meso-scale analysis," *Cities*, vol. 93, pp. 238–252, 2019, doi: 10.1016/j.cities.2019.05.010.

[50] A. Shari, "Resilient urban forms : A macro-scale analysis," vol. 85, pp. 1–14, 2019, doi: 10.1016/j.cities.2018.11.023.

[51] G. Papachristos, "System dynamics modelling and simulation for sociotechnical transitions research," *Environ. Innov. Soc. Transitions*, vol. 31, pp. 248–261, Oct. 2018, doi: 10.1016/j.eist.2018.10.001.

[52] W. Bonelá, G. De Lorena, D. Chaves, and G. Mattos, "The Brazilian urban mobility policy : The impact in São Paulo transport system using system dynamics," *Transp. Policy*, vol. 73, pp. 51–61, 2019, doi: 10.1016/j.tranpol.2018.09.014.

[53] A. Macmillan and J. Woodcock, "Understanding bicycling in cities using system dynamics modelling," *J. Transp. Heal.*, vol. 7, pp. 269–279, 2017, doi: 10.1016/j.jth.2017.08.002.

[54] H. Haghshenas, M. Vaziri, and A. Gholamialam, "Evaluation of sustainable policy in urban transportation using system dynamics and world cities data: A case study in Isfahan," *Cities*, vol. 45, pp. 104–115, Jun. 2015, doi: 10.1016/j.cities.2014.11.003.

[55] R. Rehan, M. A. Knight, A. J. A. Unger, and C. T. Haas, "Financially sustainable management strategies for urban wastewater collection infrastructure - development of a system dynamics model," *Tunn. Undergr. Sp. Technol.*, vol. 39, pp. 116–129, 2014, doi: 10.1016/j.tust.2012.12.003.

[56] H. vafa arani, S. Jahani, H. Dashti, J. Heydari, and S. Moazen, "A system dynamics modeling for urban air pollution: A case study of Tehran, Iran," *Transp. Res. Part D Transp. Environ.*, vol. 31, pp. 21–36, Aug. 2014, doi: 10.1016/j.trd.2014.05.016.

[57] N. Tsolakis and L. Anthopoulos, "Eco-Cities: An Integrated System Dynamics Framework And A Concise Research Taxonomy," *Sustain. Cities Soc.*, vol. 17, Mar. 2015, doi: 10.1016/j.scs.2015.03.002.

[58] Y. He, J. Jiao, Q. Chen, S. Ge, Y. Chang, and Y. Xu, "Urban long term electricity demand forecast method based on system dynamics of the new economic normal : The case of Tianjin," *Energy*, vol. 133, pp. 9–22, 2017, doi: 10.1016/j.energy.2017.05.107.

[59] Y. Y. Feng, S. Q. Chen, and L. X. Zhang, "System dynamics modeling for urban energy consumption and CO 2 emissions : A case study of Beijing , China," vol. 252, pp. 44–52, 2013.

[60] L. Liu, B. Zheng, and K. Bernard, "Quantitative analysis of carbon emissions for new town planning based on the system dynamics approach," *Sustain. Cities Soc.*, vol. 42, pp. 538–546, 2018, doi: 10.1016/j.scs.2018.08.006.

[61] M. Zarghami and S. Akbariyeh, "Resources , Conservation and Recycling System dynamics modeling for complex urban water systems : Application to the city of Tabriz , Iran," *"Resources, Conserv. Recycl.*, vol. 60, pp. 99–106, 2020, doi: 10.1016/j.resconrec.2011.11.008.

[62] G. Mavrommati, K. Bithas, and P. Panayiotidis, "Operationalizing sustainability in urban coastal systems: A system dynamics analysis," *Water Res.*, vol. 47, pp. 7235–7250, 2013, doi: 10.1016/j.watres.2013.10.041.

[63] C. Qi and N. Chang, "System dynamics modeling for municipal water demand estimation in an urban region under uncertain economic impacts," vol. 92, 2011, doi: 10.1016/j.jenvman.2011.01.020.

[64] M. Feofilovs *et al.*, "Assessing resilience against floods with a system dynamics approach: a comparative study of two models," *International Journal of Disaster Resilience in the Built Environment*, vol. 11, pp.615-629, Jan. 2020, doi: 10.1108/IJDRBE-02-2020-0013.

[65] Latvian Environment, Geology and Meteorology Centre, "Preliminary flood risk assessment for 2019 - 2024," 2019.

[66] A. Gravelsins *et al.*, "Modelling energy production flexibility: system dynamics approach," *Energy Procedia*, vol. 147, pp. 503–509, Aug. 2018, doi: 10.1016/j.egypro.2018.07.060.

[67] M. Feofilovs, F. Romagnoli, "Assessment of Urban Resilience to Natural Disasters with a System Dynamics Tool: Case Study of Latvian Municipality," *Environmental and Climate Technologies* 2020, vol. 24, pp. 249–264 https://doi.org/10.2478/rtuect-2020-0101

[68] D. Ozer, "Correlation and the Coefficient of Determination," *Psychol. Bull.*, vol. 97, pp. 307–315, Mar. 1985, doi: 10.1037/0033-2909.97.2.307.

[69] T. Yamane, *Statistics: An Introductory Analysis*. Harper & Row, 1967.

Maksims Feofilovs graduated from Riga Technical University and obtained a Master's degree in Environmental Science in 2016; he holds a Double Master's degree in Environmental Engineering from Vilnius Gediminas Technical University. Since 2016, Maksims Feofilovs has been with the Institute of Energy Systems and Environment of RTU. Participation in international programs, conferences and Erasmus+ project have enriched his experience in research on topics within the field of environmental science. He has participated in national and international research projects supported by the Latvian Government and EU. His main scientific interest is modelling complex system processes with system dynamics approach and life cycle analysis.