RIGA TECHNICAL UNIVERSITY

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DYNAMICS OF URBAN RESILIENCE TO NATURAL HAZARDS

Summary of the Doctoral Thesis

RTU Press
Riga 2020

RIGA TECHNICAL UNIVERSITY
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RTU Press
Riga 2020

Feofilovs, M. Dynamics of Urban Resilience to Natural Hazards. Summary of the Doctoral Thesis. Riga: RTU Press, 2020. 39 p.

Published in accordance with the decision of the Promotion Council "RTU P-19" of 31 August 2020, Minutes No. 130.

The work has been developed in connection with the following projects:

- European Social Fund project "Strengthening the academic staff of Riga Technical University in the fields of strategic specialization" No.8.2.2.0 /18 /A /017;

- The European Union Erasmus + program supported project "Capacity Building for Resilience Education in Asia (CABARET)" No. 573816-EPP-1-2016-1- UK-EPPKA2-CBHE-JP

https://doi.org/10.7250/9789934225628
ISBN 978-9934-22-561-1 (print)
ISBN 978-9934-22-562-8 (pdf)

DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defense at the open meeting of RTU Promotion Council on __________________, 2020 at the Faculty of Electrical and Environmental Engineering of Riga Technical University, 12/1 Āzenes Street 12/1, Room ___.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Maksims Feofilovs ……………………………. (signature)

Date: ………………………

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 179, including appendices. The Bibliography contains 160 titles.

CONTENTS

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 indicator for resilience measurement (Fig. 1.)

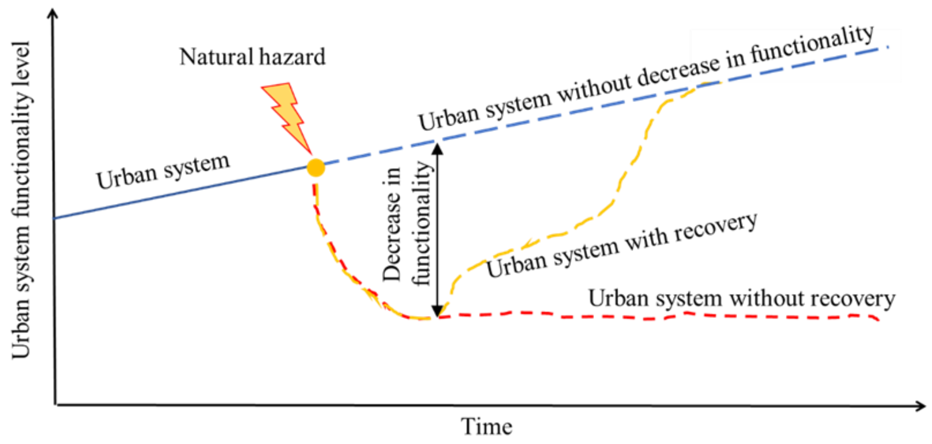

Fig. 1. Urban system functionality level as urban resilience measurement indicator.

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. Quantitative urban resilience measurement can be performed in two ways, as a measure of static urban system functionality level (inherent resilience) or dynamic change of functionality level over time (adaptive resilience). 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 made in the direction to provide a solution to an existing resilience measurement problem. The goal is to provide a better approach for measurement urban resilience and facilitate the pathways for overcoming knowledge gaps reported in literature and can support 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.

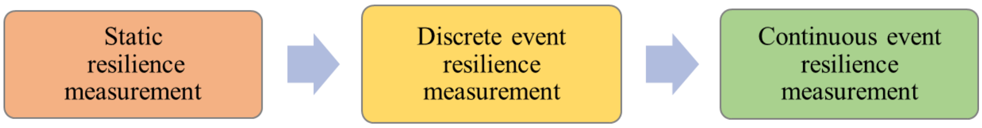

Fig. 2. Transition from static to continues event resilience measurement.

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 continues 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 a 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 dynamics model allows overcoming the limitations of the 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 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 approaches 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 urban resilience assessment to natural hazards that can support policy planning for building urban resilience at local level. The main objectives for achieving the goal are as follows:

- 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 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 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 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.

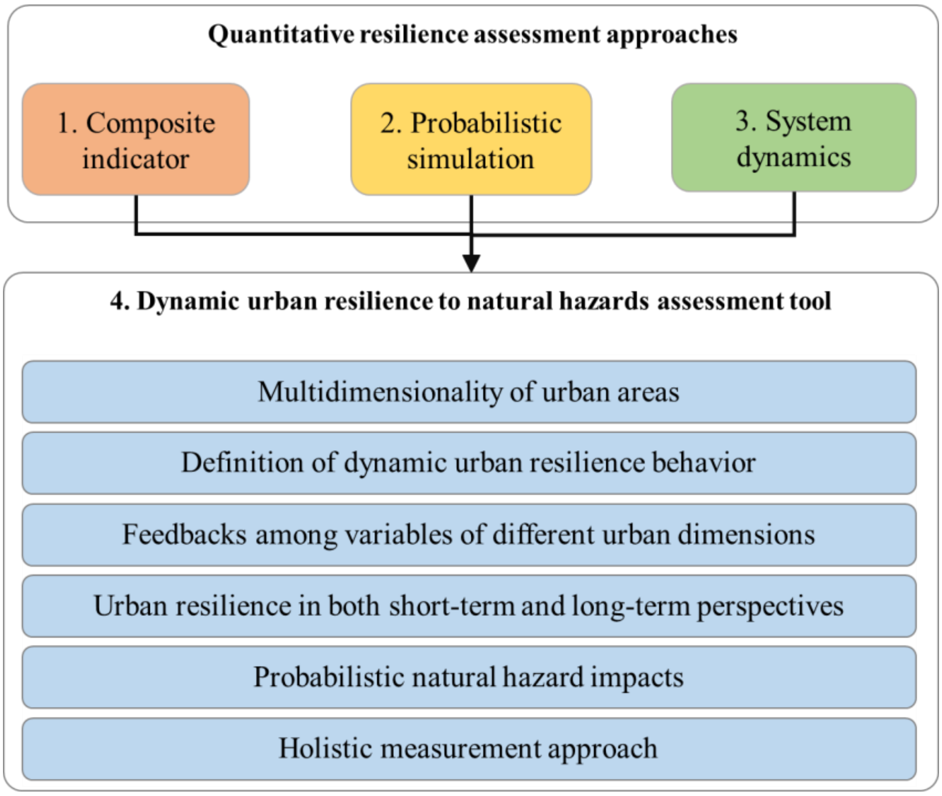

Fig. 3. Steps of methodology and characteristics of the developed tool.

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 the methodology is focused on a probabilistic simulation approach, presented in Article 2. The article presents the application results of probabilistic simulation for 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 the development of a dynamic urban resilience assessment tool specifically addressed to natural hazards. The hypothesis for such tool together with its causal loop diagram is 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.

The 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 including the feedbacks among different dimensions and captures 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 representing 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 could be used for comparison of different scenarios of strengthening 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 on 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 hazard, 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 were 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. METHODOLOGY

The objectives for the Thesis are set to reach the main aim, which is creating a novel tool for assessment of urban resilience to natural hazards. The overview of the Thesis is presented in Fig. 1.1 within four steps and corresponding with the predefined objectives of the Thesis.

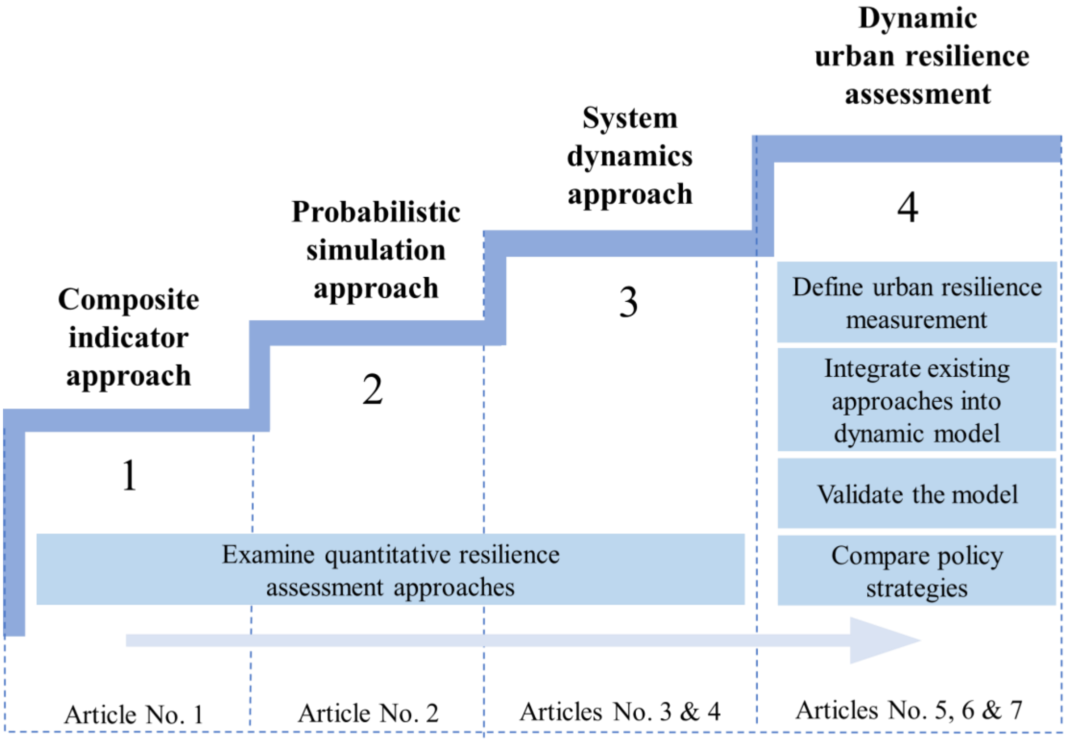

Fig. 1.1. Overview of the thesis structure.

The objectives for the Thesis are set to reach the main aim, which is creating a novel tool for assessment of urban resilience to natural hazards. For this purpose, separate case studies are performed to examine the strengths and weaknesses of different quantitative approaches used for evaluation of resilience (Steps 1, 2 and 3). These studies are reported in 4 publications that are published in international scientific journals.

One of the objectives is to overcome the weaknesses found in the existing quantitative approaches for resilience evaluation and integrate them into a single tool that is able to provide more advanced urban resilience assessment than other tools currently used in the research field of urban resilience to natural hazards (Step 4).

The development process of the dynamic urban resilience to natural hazard assessment tool is reported in 2 publications published in international scientific journals. Within publications, definition of urban resilience assessment measurement used for purpose of the developed tool, algorithm for integration of existing approaches into dynamic model and validation and testing of the tool is reported.

The development of dynamic urban resilience model allows to move from static resilience measurement and single infrastructure resilience measurement towards dynamic resilience measurement.

1.1. Composite Indicator Approach in Local Case Study

The study dedicated to composite indicator approach for community resilience assessment implements the concept of a multi-criteria analysis in the form of composite indicator-based index known as community disaster resilience index (CDRI) is presented in Article 1. The study aims to provide a holistic measure for community resilience 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 DRM. This link is implemented through a matrix consisting of community capitals in relation to disaster management phases. Within the matrix community capitals have indicators that are accounted for specific DRM phases according to their relevance. Indicators are brought to a common scale of measure with help of *z*-score method, also known as standard score method. The CDRI score is calculated as sum of the weighted capital scores:

$$CDRI = \frac{\sum_{i=1}^{n}(\omega \cdot capital\ score)}{n}, \quad (1.1)$$

where *capital score* – sum of *z*-scores for given capital;

ω – weight of capital;

n – number of capitals.

Validation of the obtained CDRIs was assessed with correlation and regression analysis respecting external criteria. For this purpose, social vulnerability index [6], the flood damage costs and risks from natural and man-made disaster were included.

1.2. Probabilistic Simulation Approach in Local Case Study

Probabilistic simulation is used for determination of resilience for infrastructural systems, because holistic approach does not allow to precisely determine resilience of an infrastructural system to specific natural hazard events. The study is presented in Article 2.

A self-developed probabilistic simulation tool for generating statistical data of infrastructure network failures is developed for resilience assessment and applied in the case study on district heating (DH) pipeline network of a municipality in Latvia. The tool implies resilience assessment by measuring three infrastructure system resilience aspects: the 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, making it almost impossible to evaluate all the scenarios. 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:

$$M = \begin{pmatrix} S_{11} & S_{12} & S_{1n} \\ S_{21} & S_{22} & S_{2n} \\ S_{k1} & S_{k2} & S_{kn} \end{pmatrix}, \quad (1.2)$$

where *M* – matrix;

S_k – scenario;

S_n – pipeline.

Random failures for assets (S_n) are generated with certain failure probability, which is predefined according to the failure mode probability distribution function (Fig. 1.2) for a specific disaster.

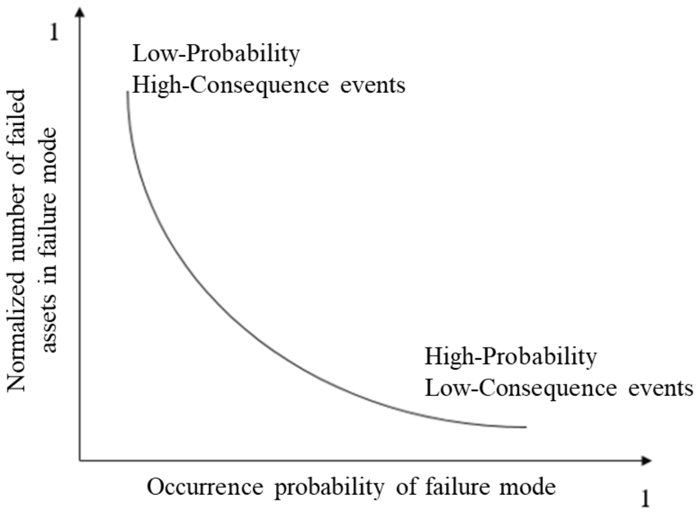

Fig. 1.2. Failure mode distribution.

Within matrix asset failures during the simulation are assigned to asset according to the 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. The proposed method for evaluation of resilience considers the definition of threshold of available recovery costs, maximum recovery time and critical damage ratio (Fig. 1.3)

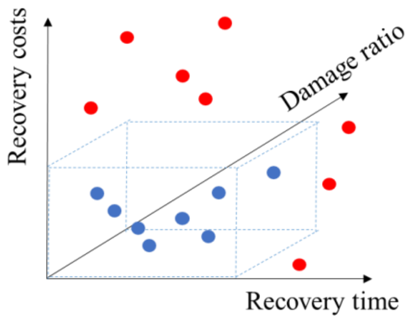

Fig. 1.3. Resilience described by three dimensions.

The simulated scenarios that exceed thresholds are considered to be outside system resilience limits, therefore the resilience of DH network system is calculated as ratio of scenarios that are in the range of available recovery costs and recovery time to overall number of scenarios simulated.

1.3. System Dynamics Approach for Complex Systems

More advanced approach that can recognize the feedbacks between multiple elements of a complex system to show non-linear and dynamic behaviour of the systems known as system dynamics (SD) [6] is examined in studies on infrastructural systems and presented in Articles 4 and 5.

SD model for natural gas transmissions system with storage facility is developed as a homogenous system with endogenous variables that influence the behaviour of the system. The main components of SD model are imports of gas, exports of gas, domestic supply and flows into and out of storage.

SD modeling approach is based on application of three components used for definition of variables 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 (1.3) [7]:

$$Stock\ X_t = Stock\ X_{(t-\mathrm{d}t)} + Inflows_{(t-\mathrm{d}t)} - Outflows_{(t-\mathrm{d}t)}, \tag{1.3}$$

where *Stock* X_t – the level of *Stock X* at simulation time *t*;

Stock $X_{(t-\mathrm{d}t)}$ – the level of *Stock X* at time $t - \mathrm{d}t$;

d*t* – time interval used as a step of model simulation over which this equation spans;

$Inflows_{(t-\mathrm{d}t)}$ – the sum of inflows into *Stock X* at the simulation time $t - \mathrm{d}t$;

$Outflows_{(t-\mathrm{d}t)}$ – the sum of outflows out of *Stock X* at the simulation time $t - \mathrm{d}t$.

Links can connect stocks to flows, 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 a natural gas infrastructure with storage facility includes fuzzy-logic based on logical function, which is set to compare different variables in the model and switch the regimes of gas flows, in this way imitating the balancing process performed by transmission system operator.

The relationship of different aspects of natural gas transmission system and storage facility in Latvia is shown with casual loop diagrams (CLD). The reinforcing loop is identified with 'R' and the balancing loop with 'B'. The feedbacks are considered in CLD and interaction of feedback loop interaction of the causing counteraction to the change in initial component output value.

1.4. Dynamic Urban Resilience Model

The integration of three previously discussed approaches – composite indicator, probabilistic simulation and system dynamics (SD) are applied for creating a tool suitable to describe the dynamics of urban resilience to natural hazards and deal with the existing knowledge gaps on the topic of urban resilience measure. The process of creating the tool and performing assessment can be summarized in analytical graph (Fig. 1.4) and presented in Article 7.

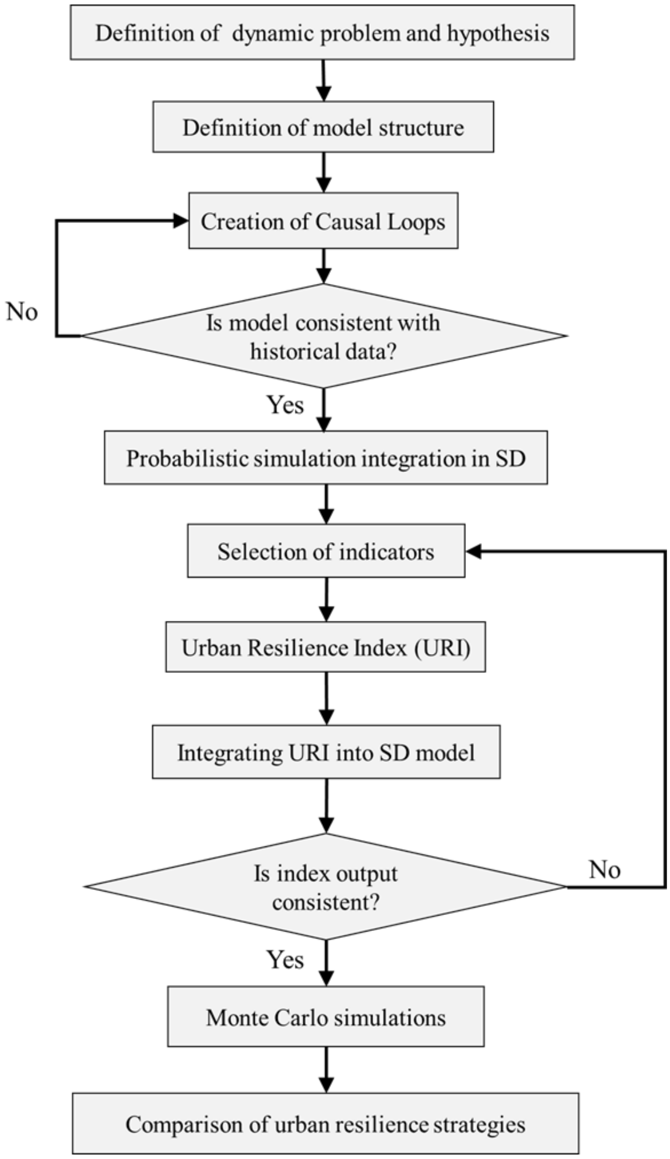

Fig. 1.4. Analytical graph for tool development and assessment of urban resilience.

Structure of Dynamic Urban Resilience Model

Behaviour of an urban system is best described by non-linear dynamics, which is the result of many feedbacks between multiple elements of urban system. Therefore, the developed urban resilience assessment model to natural hazards is made with SD approach, which enables dynamic modeling of urban areas with help of internal feedback loops between different components of urban areas. The study distinguishes different dimensions of urban areas to set the scope at which urban area performance is captured in the model.

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

Composite indicator-based index allows to have an output of complex model structure in the form of a single number. For the purpose of creating composite indicator-based index, indicators that best represent the dynamic changes in urban dimensions are selected from the urban resilience SD model.

To make indicator values comparable over the simulation time, a normalization of indicators is made based on reference data set outside the SD model. The problem of using such an approach is that the indicators most of the time must be selected based on available data sets of statistics to have this reference data set. This makes it hard to define indicators, as they must be consistent with both urban resilience SD model structure, to be meaningful for urban resilience assessment, and at the same time have a reference data set in order to have a meaningful measurement over all simulation period of the urban resilience SD model.

Validation of Dynamic Urban Resilience Model

Validation of the urban resilience SD model was performed for the model structure and content. Model structure was 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 a balanced equilibrium simulation is linear behaviour without any changes over time. After finding balanced equilibrium, extreme values are checked that drive the model to a 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 the historical trend from statistics. For this purpose, coefficient of determination R^2 is used according to Equation (1.4) [8]:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}, \tag{1.4}$$

where R^2 – coefficient of determination;

n – number of measurements in the 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.

When value of R^2 is close to 1, it shows that the model is making a good perdition. The model is considered valid for the cases when R^2 value is over 0.9.

The validation of urban resilience index (URI) consistency with dynamic change in SD model structure is performed. The validity of URI is verified when all normalized indicators in index i) have the same scale of measure, thus have the same impact on the final URI score when equally weighted and ii) aggregated in composite URI present the dynamic changes occurring in short term and long term in urban SD model with the probabilistic simulation of hazards considered.

Assessment of Urban Resilience in a Local Case 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 national flood risk assessment [9] is used in this study. The probability-impact curve is defined according to predefined information based on historical data of hazard events.

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

Classic deterministic simulation of system dynamics model presents a single result based on fixed set of data. The urban resilience model, however, runs a stochastic simulation due to probabilistic input from command RANDOM, which changes the output for every simulation. Thus the Monte Carlo method is used to replicate a large number of simulation runs with varying input number in probability-impact curve during every simulation step of one simulation. The results of Monte Carlo simulations show likelihood of different outcomes. This allows to have an understanding of statistical nature of the systems performance and make decisions accordingly to the statistical output. The number of trials for Monte Carlo simulation is distinguished by Equation (1.5) [10]:

$$Z = \frac{N}{1 + N(E)^2}, \quad (1.5)$$

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 urban resilience index value scale. The parameters of the urban resilience index are shown in chapter “Integration of the urban resilience index in the system dynamics model” and are taken into account when determining N and the number of attempts for Monte Carlo simulations.

2. RESULTS

2.1. Quantitative Resilience Assessment Approaches

According to the methodology of study, quantitative approaches used for community and infrastructure resilience are examined in separate case studies to identify their advantages and limitations. The overview of the results of these three quantitative approaches – composite indicator, probabilistic simulation and system dynamics is reported this summary. The results of each approach can be found in the respective scientific articles presented in at the end of the Thesis.

Case Study of Composite Indicators

Different indicators of community resilience are aggregated into a holistic community resilience measurement with an output in the form of a single score. The created composite indicator-based index – community disaster resilience index (CDRI) is assessed for the macro regions of Latvia. The study is presented in Article 1. The study showed that according to the definition of CDRI, urbanized areas can gather higher values for community capitals and thus will show higher level of disaster resilience.

The validation of the obtained CDRI scores was performed by correlation and regression analysis in respect to external criteria. For this purpose, the social vulnerability index and the flood damage costs from natural floods were used. The results of CDRI correlation with social vulnerability index show weak correlation. Also the multi variable regression analysis with social vulnerability index and CDRI as independent variables and damage costs as dependent variable showed no statistically significant relationship between CDRI and damage cost.

CDRI approach is appropriate for the study that is meant to measure city, country or region disaster resilience. It allows to compare levels of resilience for different DRM phases among communities with a static, but comparable measure. However, it does not provide information about resilience to specific disaster, for this reason it is considered a holistic method.

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

1. Better evaluation of the assumptions made and higher quality data should be used. A lot of statistical data was found not up to date and lack of specific indicators that can be used for describing the inherent resilience was observed.
2. Implementation of system dynamics would be useful in order to replace linear models with the dynamic non-linear model in order to analyse complex systems and take into account resilience variations over time.

The findings and problems in creation of composite indicator-based index are considered further in the development of dynamic urban resilience assessment tool. Full results are reported in Article No. 1.

Probabilistic Simulation Case Study

Probabilistic method is applied for simulation of failures in a DH infrastructure of a Latvian municipality. The study is presented in Article 2. The study clarifies how district heating system resilience to a specific hazard can be assessed within the context of adaptive resilience. 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. The output of such simulation helps to understand the robustness, recovery time and possible costs of damage for different pipeline network disruption magnitudes.

The results of probabilistic simulations show a pattern that corresponds to probability-consequence function, where high probability disruptions have low consequences and low probability disruptions have high consequences. This method provides a more complete overview than holistic resilience measurement with an indicator-based approach.

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

Case Studies of System Dynamics Approach

The relationship of different aspects of natural gas transmission system and storage facility in Latvia are determined based on the results of correlations and regressions, a definition for gas injection from transmission system into storage facility and gas injection from storage facility into transmission system is set. The study is presented in Article 3 and 4. As a result of this analysis, an SD model is created for natural gas transmission system and storage able to present the dynamic changes in this system. Causal loops are used to describe the feedbacks included in the model.

The model is used to study possible effects of renewable methane implementation in natural gas system in Latvia with help of support policy to diversify gas supplies. The diversification of gas sources will increase the resilience of natural gas system in Latvia according to the definition of energy resilience.

The study of system dynamics approach shows that SD models can be used as tools by policy planners and other stakeholders to assess quantitative parameters of different policy implementation.

2.2. Dynamic Urban Resilience Assessment Tool

The SD modeling approach combined with probabilistic simulation and composite based simulation has potential for framing a new integrated approach for urban resilience assessment. The results of building, validating and testing a dynamic urban resilience to natural hazard tool are reported in this sub-chapter in respect to algorithm reported in the methodology chapter in Fig. 1.4. and presented in Articles 5, 6 and 7.

Definition Selected for Urban Resilience

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. The defined dynamic problem (Fig. 2.1) is the decrease of urban system functionality level over time, both long-term and short-term after natural hazard impact occurring, and the way in which system reacts to an external stressor: a) Urban system X without recovery; b) Urban system X with recovery; c) Urban system X without decrease in functionality. The dynamic problem is discussed more in-depth in Articles 5.

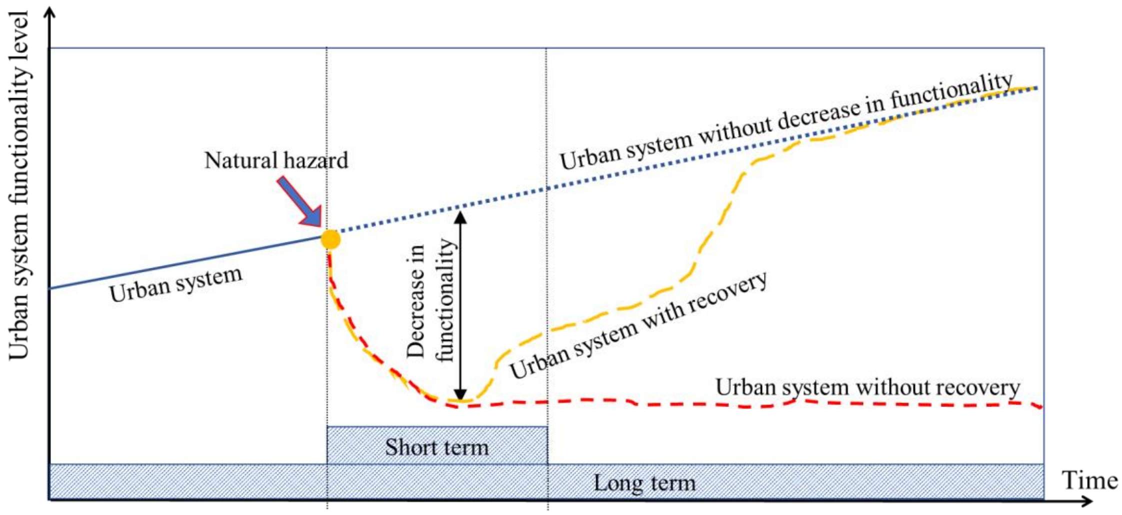

Fig. 2.1. Dynamic problem that study intends to solve.

The problematic behaviour is the decrease of functionality in urban systems, after which a system can either get back to the normal functionality level, thus showing a certain resilience, or maintain a lower functionality level in fact presenting a lower resilience. It is important to note that a system showing resilience 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" can fully recover only in long term. The desired state of system is having no decrease in functionality. The inclusion of both time references allows to understand the key feedbacks between the dimensions of urban areas.

The dynamic hypothesis defines the purpose of creating a specific model structure, considering that preferable state of system is having minimum decrease in system functionality under stress of natural hazard. The dynamic hypothesis urban SD model is that problematic behaviour can be solved both in long term and short term by increasing or decreasing the strengths of feedback loops between urban dimensions embedded in the urban SD model.

Structure of Urban Resilience Model

The structure of dynamic urban resilience model represents the urban areas through social, economic, infrastructure and environmental dimensions that are included in SD model as separate sectors. The structure of the model is discussed more in-depth in Articles 6 and 7. Urban resilience model considers 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. 2.2.

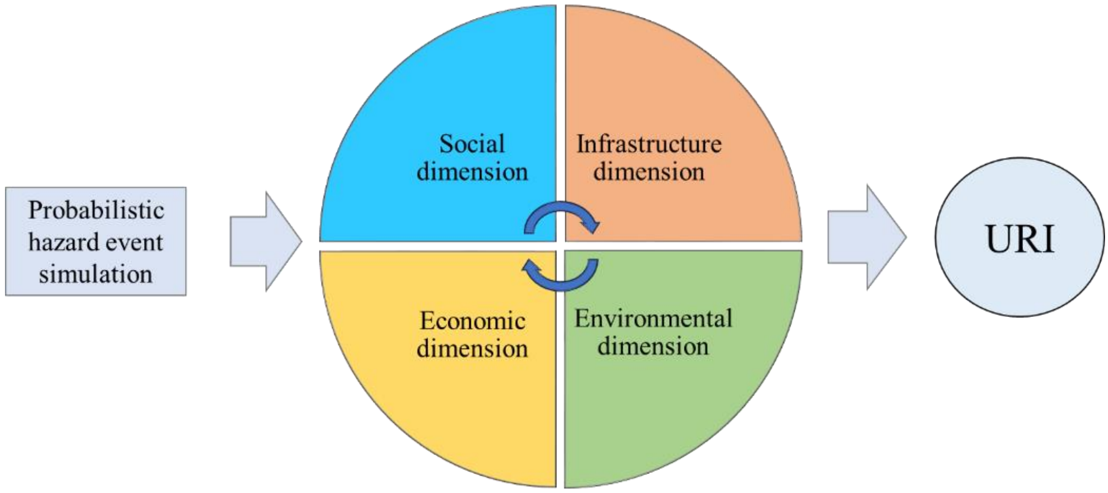

Fig. 2.2. Concept of urban resilience SD model structure.

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 certain predefined probability.

The composite indicator-based index in SD model allows to present the multi-dimensional and complex dynamic problem measurement of urban resilience to natural hazards as a single value in the output of SD model simulation. For this purpose, urban resilience index (URI) is composed of indicators referring to characteristics of urban resilience in urban dimensions.

Causal Loop Diagrams

Specific causal loops are defined in the model for each dimension. Full set of causal loops considered in creation of the model for each dimension and feedbacks between them is introduced in Article 7.

Figure 2.3 shows the summary of main CLDs of the urban resilience SD model with four main feedback loops R1, B1, R2 and B2.

Births and population are the main components of social dimension in the SD model. Births and population are linked with reinforcing feedback loop R1. This loop presents reinforcing effect of the population growth depending on the number of people living in the urban area.

Urban population also depends on urban attractiveness variable, 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. The amount of supplied services provided in the model depends on the occupied dwellings component, which again depends on population. This forms a feedback loop between population and urban attractiveness presented as feedback loop B1. This loop is considered as balancing, because all components have increasing effects, except the emissions and waste, on urban attractiveness.

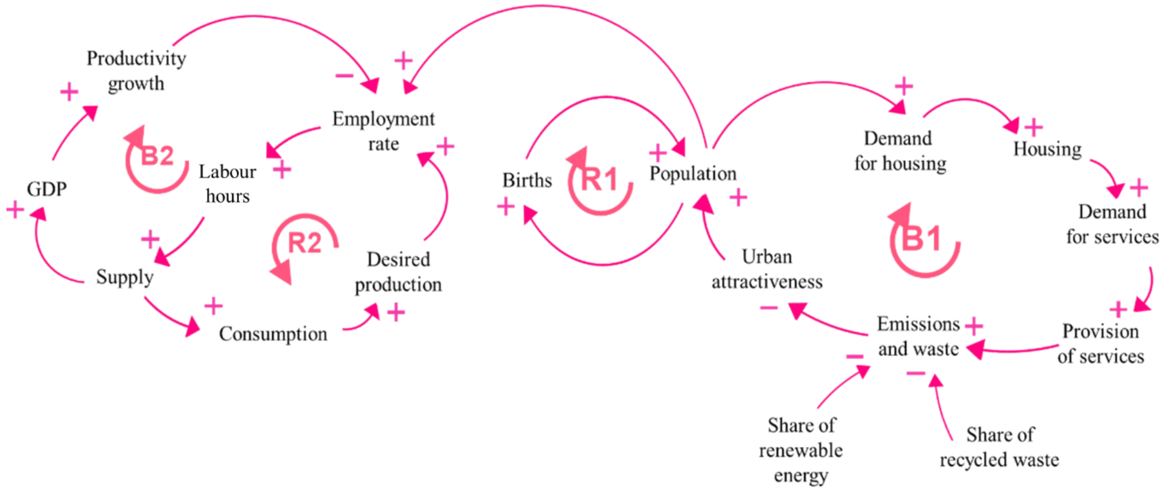

Fig. 2.3. Summary of CLDs of urban resilience SD model.

For economic dimension, reinforcing loop R2 in the economic sector of SD model includes the feedback between consumption and employment rate. Loop R2 foresees that the increase in consumption component value will increase the desired production and, consequently, the employment rate component value. The employment rate is also dependent on the working age of population in the urban area.

The feedback between social dimension and economic dimension is created with a link between population and employment. The increase in population will increases the number of working age people that can be employed. This link can increase the production in the urban area and thus the value of GDP component. Balancing feedback loop B2 in the economic sector of SD model includes feedback between the employment rate and GDP.

Definition of Baseline Scenario for Urban Resilience Assessment

A local urban area is selected for a case study to validate and test the developed urban resilience SD model in terms of application of different urban resilience scenarios. Full study is reported in Article 6. As a first step towards validation and testing of the model a baseline scenario without a hazard is defined based on data from the Central Statistical Bureau for Jelgava city. The gathered data has granularity of 1 year, and therefore the simulation time step is selected as 1 year. However, dt of the simulation is defined as 1/12, which makes the output presented by the model appears as a smooth trend line.

The gathered data from the Central Statistical Bureau is 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 endogenous structure of SD model defined by CLD. 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 during further development of the model.

Baseline scenario without hazard simulation output for social dimension and economic dimension components, population and GDP are shown in Fig. 2.4 A and B. The population component shows gradual decrease in number of people living in the urban area and gradual GDP increase.

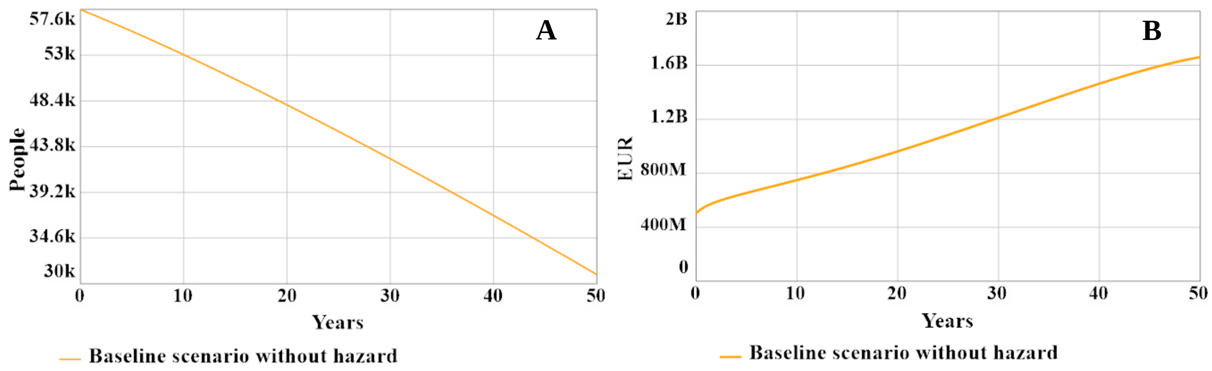

Fig. 2.4. A and B. Simulation output for population and GDP in baseline scenario without hazard.

Baseline scenario without hazard simulation output for infrastructure dimension component occupied dwellings in Fig. 2.5 A shows how the number of occupied dwellings decreases depending on the total population. Consequently, the values of electricity supply, heating, water supply and wastewater treatment components of infrastructure dimension decrease. An example for heating component is shown in Fig. 2.5 B.

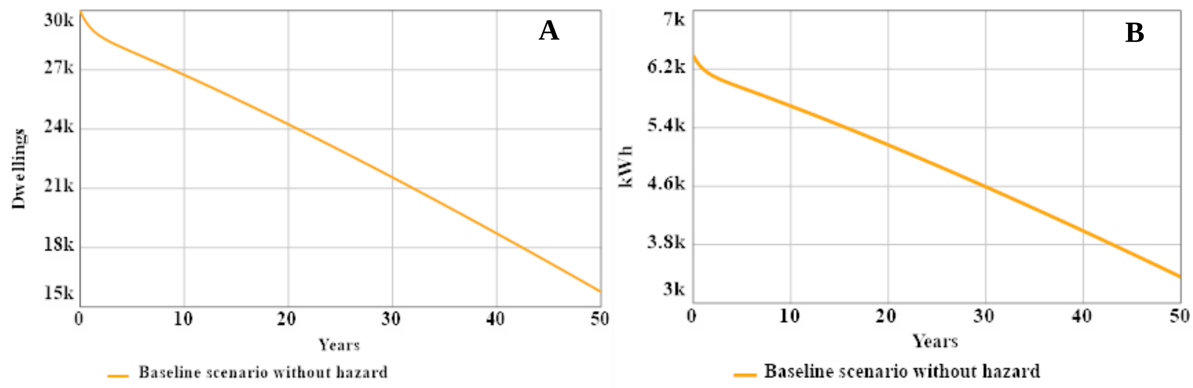

Fig. 2.5. A and B. Simulation output for occupied dwellings and heating in baseline scenario without hazard.

The output for environmental dimension component CO_2 emissions in Fig. 2.6 A shows how the CO_2 emissions decreases because of the decreasing trend in electricity consumption and heating.

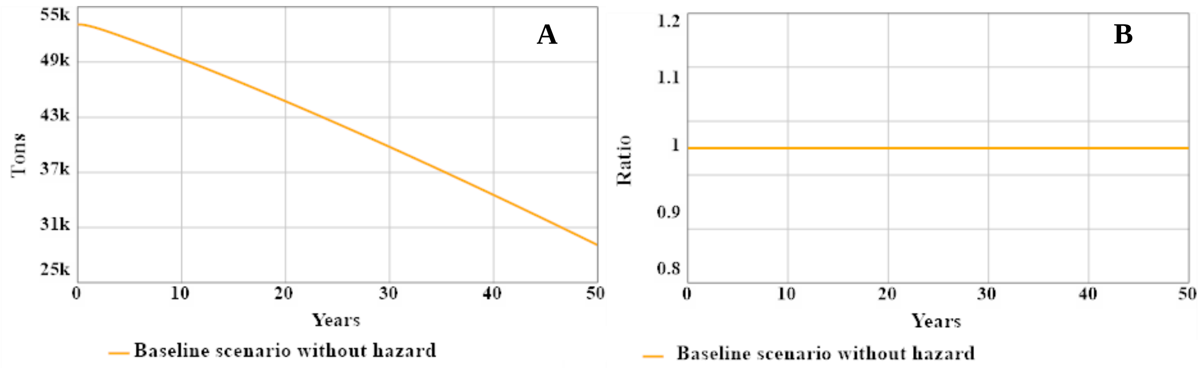

Fig. 2.6. A and B. Simulation output for CO_2 emissions and waste produced vs waste treated in baseline scenario without hazard.

The output for environmental dimension component waste produced vs waste treated in Fig. 2.6 B. shows change in the ratio of waste production and waste treatment. Such output of the model is explained by 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 the selected urban area of case study for population and GDP components and is presented in in Article 7. From the Central Statistical Bureau a data set for Jelgava population is used for years 2011–2018. The model output for population component (Fig. 2.7) fits historical data of population with coefficient of determination R^2 equal to 0.92669. This is considered as a very high relationship, and the model is valid to provide a consistent output for population component in urban resilience assessment.

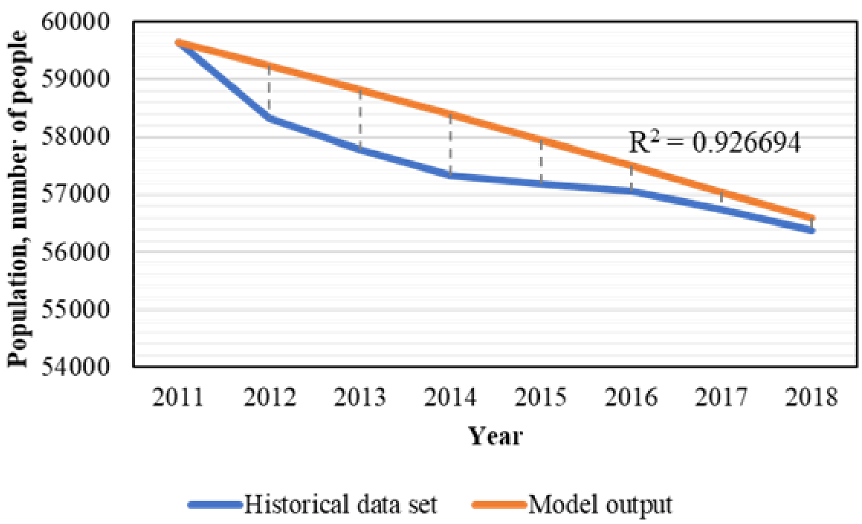

Fig. 2.7. Results of population component validation.

The validation of model output for GDP of Jelgava is performed for years 2013–2017. For the purpose of GDP validation, the change in population component is considered for the respective years of historical GDP data set. The model output for GDP component fits historical data of GDP with coefficient of determination R^2 equal to 0.95564 (Fig. 2.8). 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.

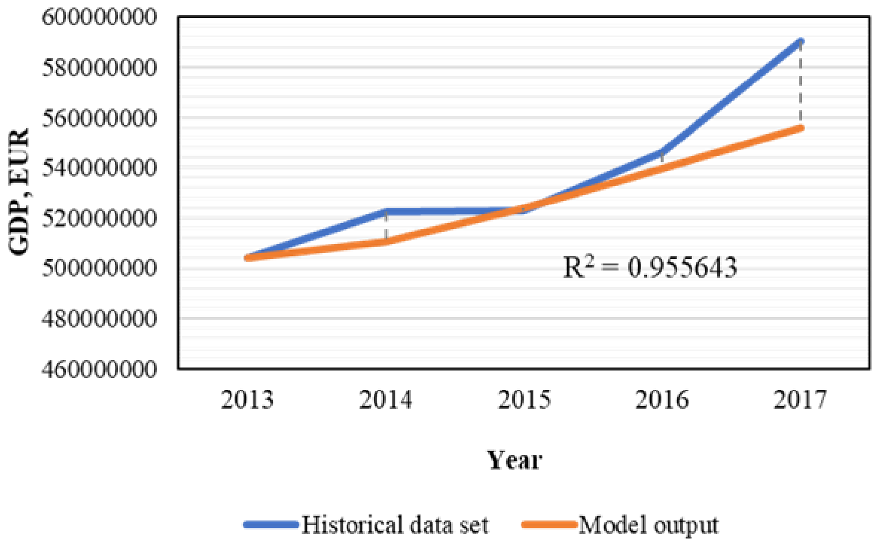

Fig. 2.8. Results of GDP component validation.

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.

Integration of Probabilistic Simulation into Urban Resilience Model

Natural hazard in SD model is defined as an event with a certain impact on population and provision of services. The impact for a specific component is described by Equation (2.1):

$$Hazard\ impact_i = Hazard_j \cdot Exposure_i \cdot Vulnerability_i, \tag{2.1}$$

where $Hazard\ impact_i$ – the effect of hazard on component i;

$Hazard_j$ – the hazard magnitute for hazard probability j;

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

$Vulnerability_i$ – the vulnerability of component i.

Natural hazard definition for the selected case study used in this study is based on information prepared by "Latvian Environment, Geology and Meteorology Centre" for national flood risk assessment. The hazard probability and magnitude in terms of flooded area for spring floods in Jelgava city in Fig. 9 is based on the historical data of hazard events. $Hazard_j$ is generated by a built-in function in software with probabilities of occurrence once in 200 years (0.5 % probability), once in 100 years (1 % probability), and every 10 years (10 % probability).

To determine the hazard impact on other components, proxy data is used due to lack of historical records for defining $Exposure_i$ and $Vulnerability_i$ in this study. The exposure is determined as exposed population according to the flooded area in Jelgava city during spring floods.

From the exposed population, the *Exposure*$_i$ of specific components is determined as components value per capita. The higher the number of exposed population, the higher is the *Exposure*$_i$.

The *Vulnerability*$_i$ of components 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 impact assigned by *Exposure*$_i$ per capita. The defined specific components i of urban resilience SD model for hazard impact are reported in Table 2.1.

Table 2.1

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, h
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, m^3
Environmental dimension	
Wastewater treatment	Decrease in wastewater treatment, m^3
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 of available number of dwellings in Fig. 2.9. However, there is no available historical data for the selected case study area that describes the recovery process from the hazard event, thus only s-shaped recovery function is used for the case study of Jelgava city.

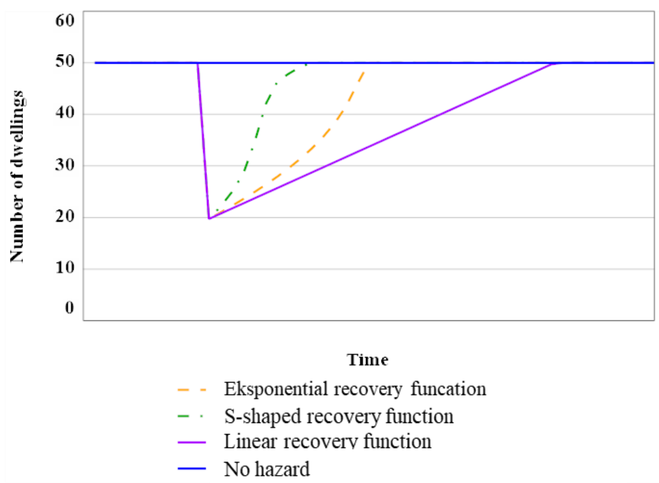

Fig. 2.9. Different recovery functions for available number of dwellings.

Probabilistic simulation of integration within urban resilience SD model allows to generate stochastic hazard events according to Equation (2.1). This means that every simulation of baseline scenario with natural hazard will have a number of hazards and their magnitude. The effects of such probabilistic – stochastic simulation is hard to quantify; thus, Monte Carlo simulation are used.

Selected Set of Indicators

The selected indicators that fit the model structure and have reference data in EUROSTAT database are reported in Table 3. Positive effect '+' means that the increase in indicator value shows increase in urban resilience. Negative effect '–' means that the increase in indicator value shows decrease in urban resilience. The indicators presented here are used for the creation of composite indicator-based index, which is able to present the dynamic change of urban resilience in short term and long term.

Table 2.2

Characteristics of Final Set of Indicators Regarding URI and SD Model

Selected indicator per urban dimension	**Effect on urban resilience**
Social dimension	
Share of unemployed population	–
Youth dependency	–
Elderly dependency	–
Share of migrant population	–
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	+

URI Definition

From the selected set of indicators, a dimensionless index for urban resilience measurement is defined – urban resilience index (URI). The definition of index is presented in Article 6. The index allows to capture the dynamics of urban resilience to natural hazard as estimation based on normalized indicators and presents the dynamic change as a single value measurement.

The definition of URI score in the model is presented in Equation (2.2) and is estimated as mean average of weighted indicators:

$$URI\ score = \frac{\sum_{i=1}^{n}(\omega_i x_{i\ \mathrm{norm}})}{n}, \quad (2.2)$$

where $x_{i\ \mathrm{norm}}$ – normalized indicator;

ω_i – weight of indicator;

i – indicator number,

n – number of indicators.

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

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.

For indicator normalization MinMax method is selected, which transforms values of indicators to a common scale of 0 to 1.

Integration of URI into Urban Resilience Model

To include URI into urban resilience SD model, a converter component is created for estimating URI score from indicator values during every time step of the simulation according to Equation (2.2). This allows to present urban resilience measurement with a dynamic metric changing over time due to changes in long-term resilience and short-term resilience. The integration of URI into urban resilience model is presented in Article 7.

To inspect the behaviour of URI score, natural hazard event was predefined in years 10, 20 and 30 shown in Fig. 2.10 without probabilistic simulation enabled. The long-term change in URI score occurs according to changes in indicator value of social dimension and economic dimension. The disruptive impact of hazard event on urban area is presented as a short-term decrease in URI values. This short- term change in URI values occurs due to change in the value of infrastructure dimension and environmental dimension indicators.

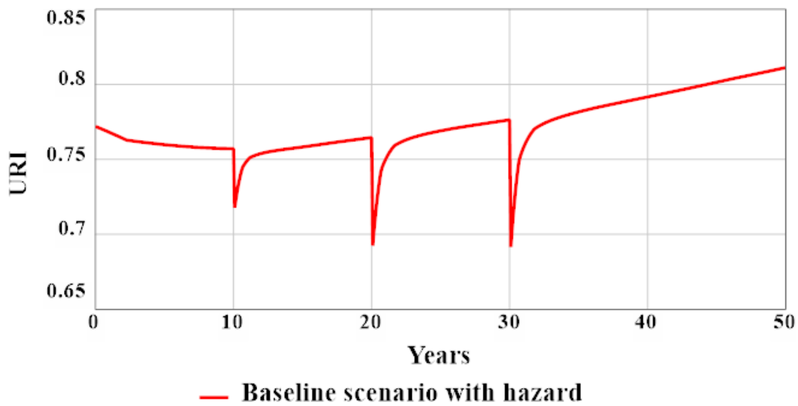

Fig. 2.10. Changes in URI score over simulation period for baseline scenario with hazard.

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. URI is converted to a single value for simulation with help of stock component in the SD model.

The score of URI computed in converter component during the simulation is used as an inflow into the URI score stock. At the end of simulation, the value of stock for URI score is a cumulative value of URI scores in converter component over simulation time. This cumulative value of URI score is presented as an area below the URI trend line over the period of all simulation time as shown in Fig. 2.11 with a coloured background.

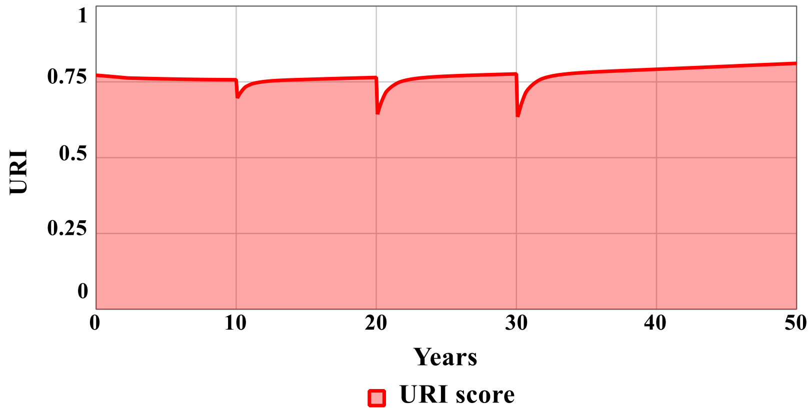

Fig. 2.11. Cumulative value of URI over simulation time presented as area.

The cumulative value URI over the simulation time can be used for the comparison of different urban resilience scenarios, however, it is not in line with previously defined URI scale of measures from 0 to 1. For this purpose, the cumulative value of URI, which is an output, is divided by simulation time. This allows to keep the value of cumulative URI score from 0 to 1 for a simple display of results.

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 city two urban resilience scenarios were selected representing different policy strategies for comparison with the baseline scenario with hazard. The changes in input parameters used for urban resilience SD model to present the effects of policy planning strategies considered are reported in Table 2.3.

The output for Urban resilience scenarios 1 and 2 shows how the selected s-type-function changes the CO_2 emissions over simulation time in Fig. 2.12 A and increases recycled waste in Fig. 2.13 A. The Urban resilience scenario 2 in Figs. 2.12 B and 2.13 B, additionally to the 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 decrease in disruption amount in all the infrastructural services.

Table 2.3

Parameters for Selected Urban Resilience Scenarios

Scenario	**Parameters**		
	CO_2 emissions	Waste recycling	Hazard effect component
Baseline scenario with hazard	18 g/kWh for heat and 400 g/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/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 $Vulnerability_i$

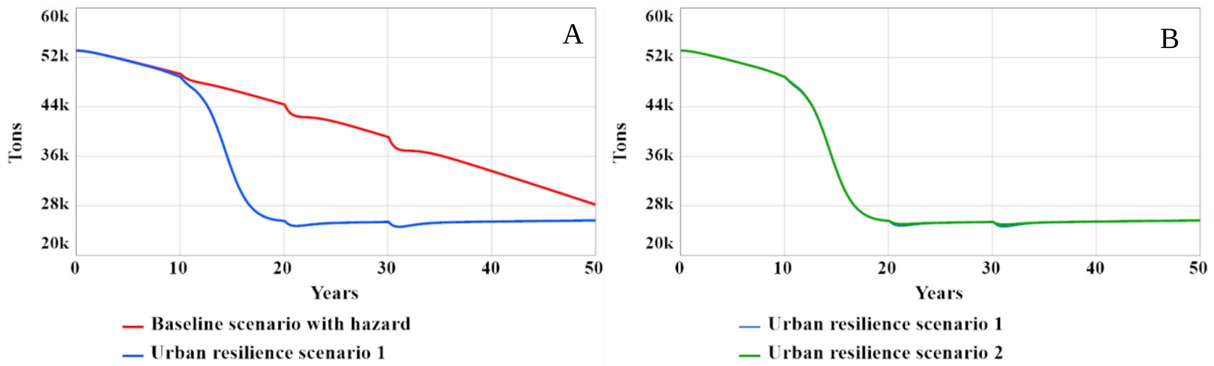

Fig. 2.12. A and B. Simulation outputs from the CO_2 emission component for urban resilience scenarios.

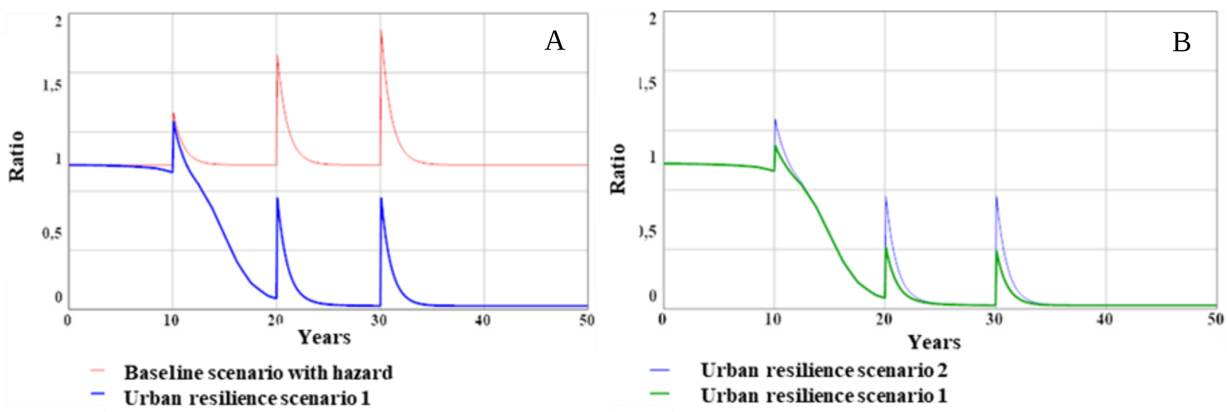

Fig. 2.13. A and B. Simulation outputs from waste production vs waste treatment component for urban resilience scenarios.

According to the presented CLD there is a feedback on urban attractiveness component from implementing the policy strategy aiming at CO_2 emissions reduction and waste recycling increase. Thus urban attractiveness has an s-shaped type increase, consequently having a positive impact on migration into urban area. This results in population increase in Fig. 2.14. For urban resilience scenario 2 the output for population component is the same as for urban resilience scenarios 1.

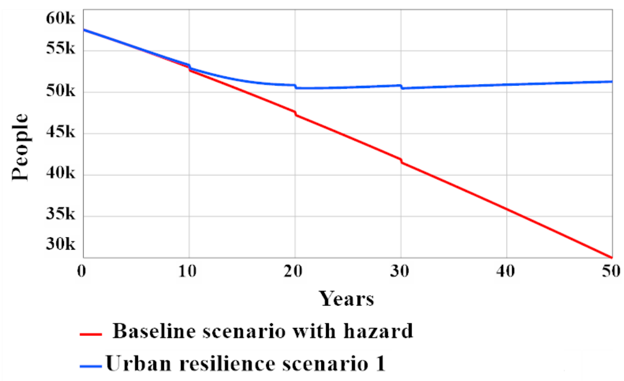

Fig. 2.14. Simulation outputs from population component for urban resilience scenario 1.

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. 2.15 A and B.

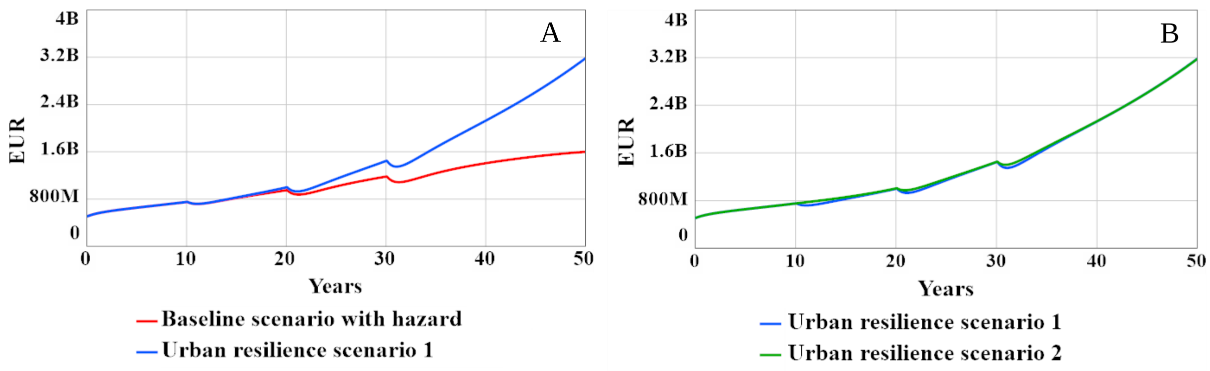

Fig. 2.15. A and B. Simulation outputs from GDP component for urban resilience scenarios.

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, electricity, water and heat supply, and wastewater treatment service increases. The example for infrastructural service increase shown for housing services in terms of number of dwellings occupied is shown in Fig. 2.16 A and B, and for heating in Fig. 2.17 A and B.

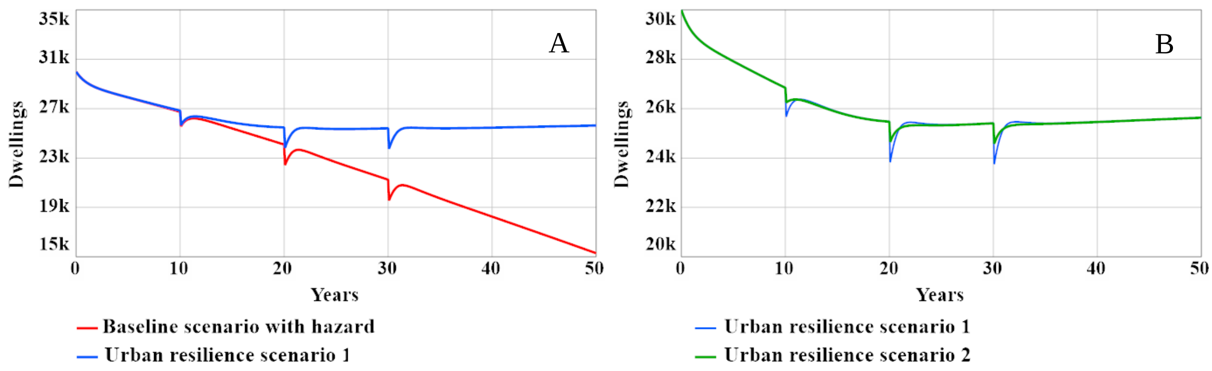

Fig. 2.16 A and B. Simulation outputs from occupied dwellings component for urban resilience scenarios.

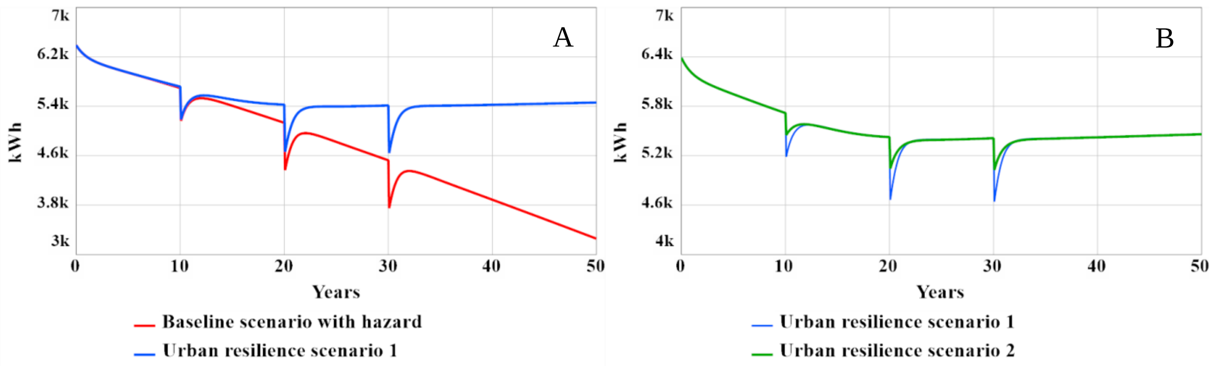

Fig. 2.17. A and B. Simulation outputs from heating component for urban resilience scenarios.

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. 2.12 A and B.

The presented trends for different parts of urban resilience SD model are consistent in terms of feedbacks also when changes are introduced in predefined parameters, as reported in Table 2.4, and thus the model is considered to be appropriate for further urban resilience assessment with URI for different urban resilience scenarios.

Monte Carlo Simulation for Urban Resilience Scenarios

The results of Monte Carlo simulation are used to compare different urban resilience scenario outputs from probabilistic simulations made with urban resilience SD model. The comparison of urban resilience scenarios is presented in Article 7.

The results in this sub-chapter are presented in Histogram type graphs showing the probability of getting a certain cumulative URI score result. High probability of getting high URI score in scenario means that the scenario of specific urban resilience strategy 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 is equal to 286 samples according to Equation 2.4. 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. 2.18. The results of statistics analysis of Monte Carlo simulations show that the mean average of cumulative URI score for the baseline scenario with hazard occurrence is 0.769 and the median is 0.767. The results show that most frequent cumulative URI score in the baseline scenario is from 0.761 to 0.786. The scores in period from 0.736 to 0.761 and period from 0.786 to 0.811 also occur frequently.

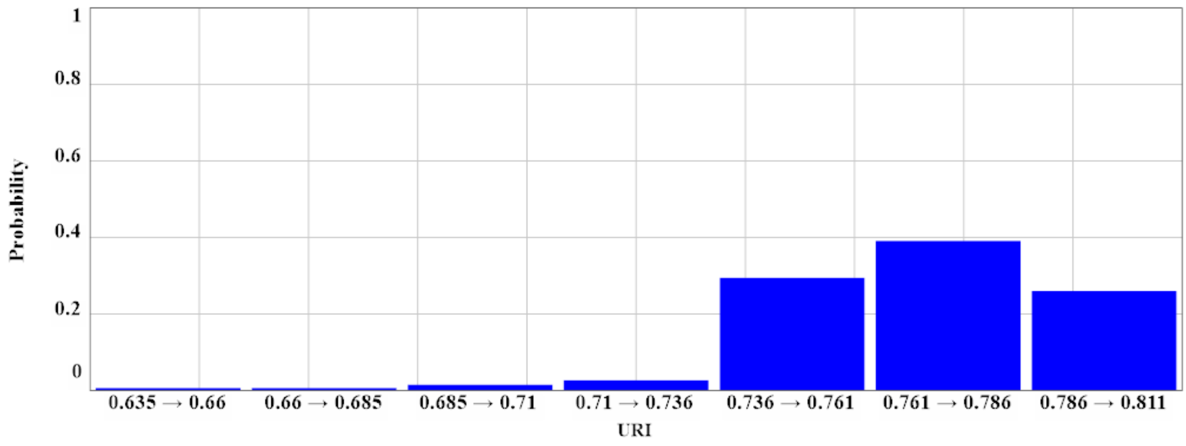

Fig. 2.18. Probability of cumulative URI scores in baseline scenario with hazard.

The results show that the mean average of cumulative URI score in Monte Carlo simulations for Urban resilience scenario 1 is 0.802 and the median is 0.809 and most frequent cumulative URI score is in the period from 0.761 to 0.786 (Fig. 2.19). Thus, according to the 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.

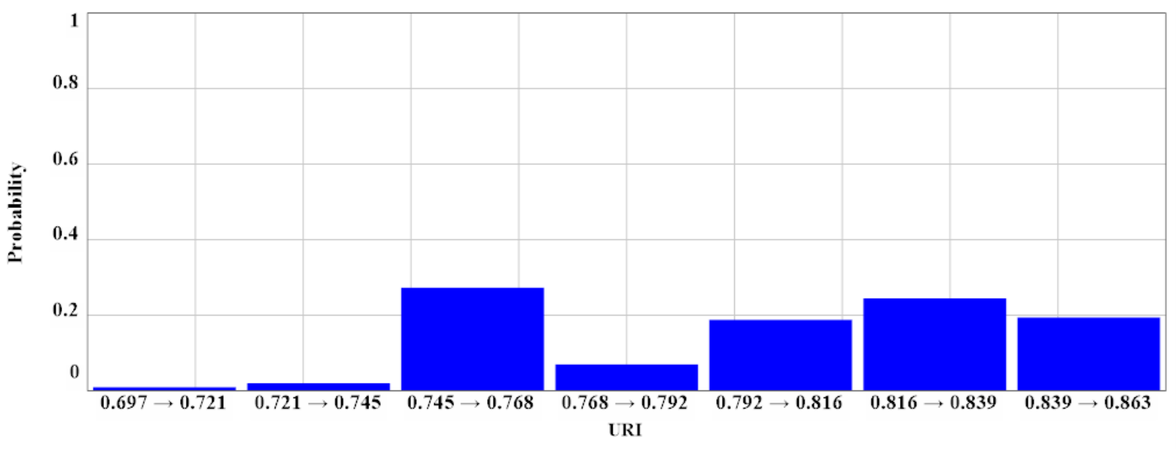

Fig. 2.19. Probability of cumulative URI scores in Urban resilience scenario 1.

The statistics of probability of getting a certain URI score in Urban resilience scenario 2 is computed according to the results shown in Fig. 2.20. The 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 most frequent cumulative Urban resilience scenario 2 is from 0.754 to 0.772, which is lower than the most frequent score for Urban resilience scenario 1.

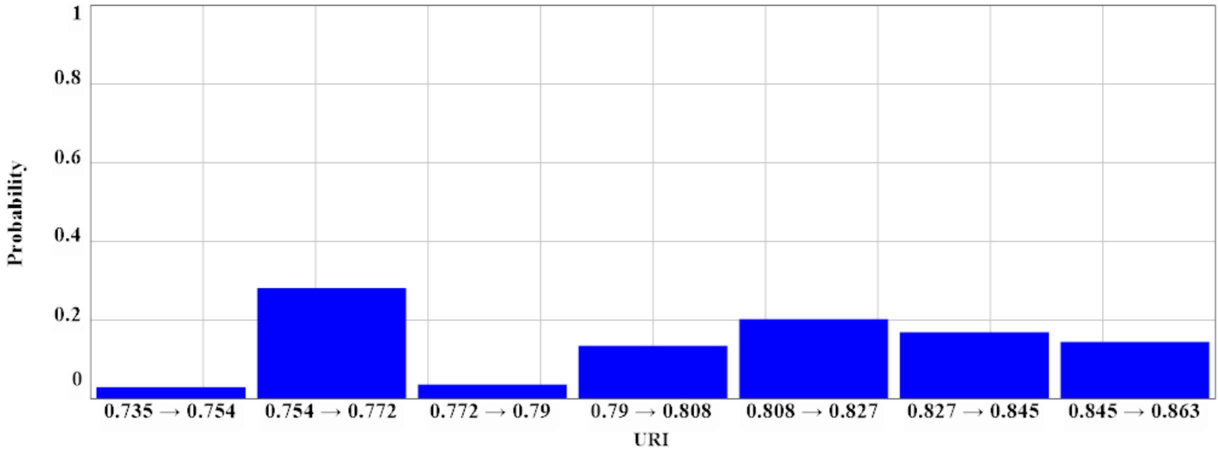

Fig. 2.20. Probability of cumulative URI scores in Urban resilience scenario 2.

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. 2.21. 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 the baseline scenario with hazard.

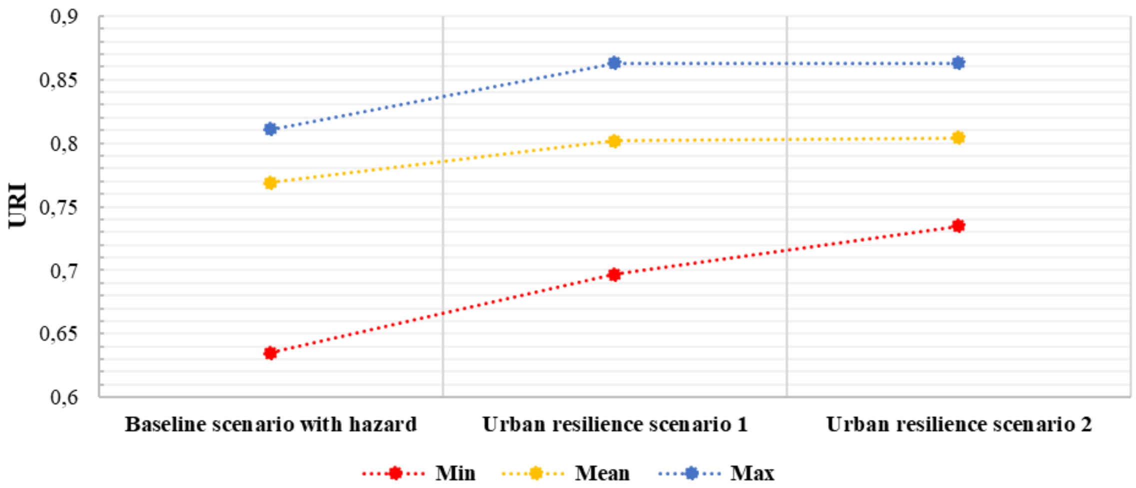

Fig. 2.21. Summary of Monte Carlo simulation results for different scenarios.

There is a notable increase in the min value of cumulative URI score for Urban resilience scenario 2 compared with Urban resilience scenario 1, but only a small increase in mean average value and no increase in max value. In this case, 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.

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 in resilience assessment. The content and structure of the tool is validated, and different urban resilience scenarios are tested in a local case study on Jelgava city with the defined natural hazard of spring floods.

The main conclusions of the Thesis

- The integration of three methods – composite indicator, probabilistic simulation and system dynamics within the developed tool allows to overcome the limitations of methods, which are reported in literature. Specifically, the implementation of probabilistic simulation in system dynamics model with output inform of index allows to capture all the possible outcomes of different urban resilience scenarios with consideration of the dynamic change in urban system and perform comparison of these different urban resilience scenarios in a holistic way.
- The results of model validation and simulation show that the tool is suitable for different urban resilience scenario evaluation in case studies. The multi-dimensionality of the tool and feedbacks between the defined dimensions allows to capture the tradeoffs occurring 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 strengthening 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 long term when the selected urban resilience strategy is aiming at the increase of urban attractiveness. Consequently, such strategy has a positive 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 surpass the benefit of decreasing social vulnerability increase in the long term, but are rather an added 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 the 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. Such sub-models can include additional infrastructure, like roads and telecommunications, 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 attractiveness 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 occurrence, which does not change in urban resilience scenario. 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 on 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 availability on disaster response and recovery for different dimensions of urban areas should be improved as well as the availability of indicators for normalization of URI scores to enable wider application the tool in policy planning.

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