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Assessing resilience against floods with a system dynamics approach: a comparative study of two models

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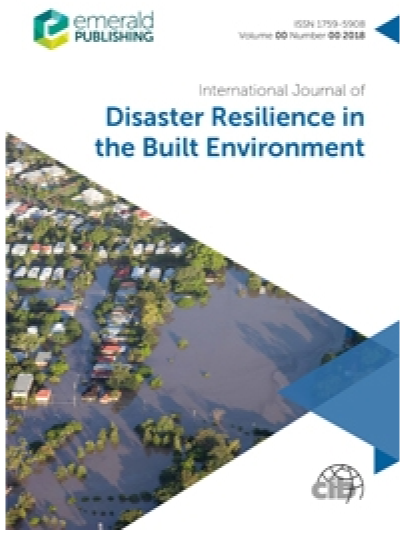

Assessing Resilience Against Floods With A System Dynamics Approach: A Comparative Study Of Two Models

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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 vulnerability of the system. Within the approach, the purpose is to properly and efficiently evaluate the effect of different Flood Risk Management strategies, i.e., prevention, defence, mitigation, preparation, and recovery for consistent and resilient flood governance plans with different type of resilience scenarios.

Two system dynamics model structures are presented in form of Casual Loop Diagrams. The main differences among the tow approach are the time horizon and the approach that regulates the assessment of the resilience trough a dynamic composite indicator: the first model refers to baseline at initial simulation time; the second model is 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.

1 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.

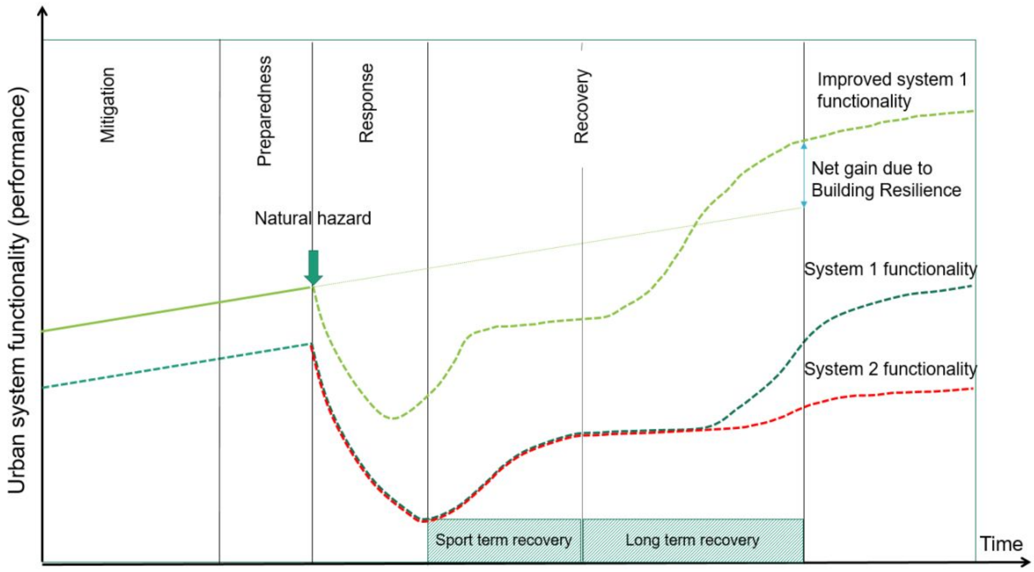

Fig. 1. Dynamic hypothesis for model 1- the dotted blue line represents the performance of an urban system without measures aimed to build resilience (system 1); the dotted light green line represents the performance of a system with measures aimed to build resilience (improved system 1); the dotted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

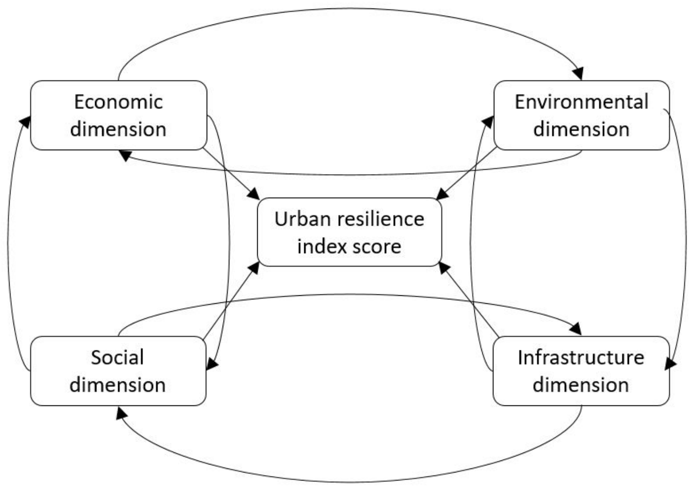

Fig.2. Concept of system dynamics model 1.

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 $\Delta URI\text{-}I$ 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.

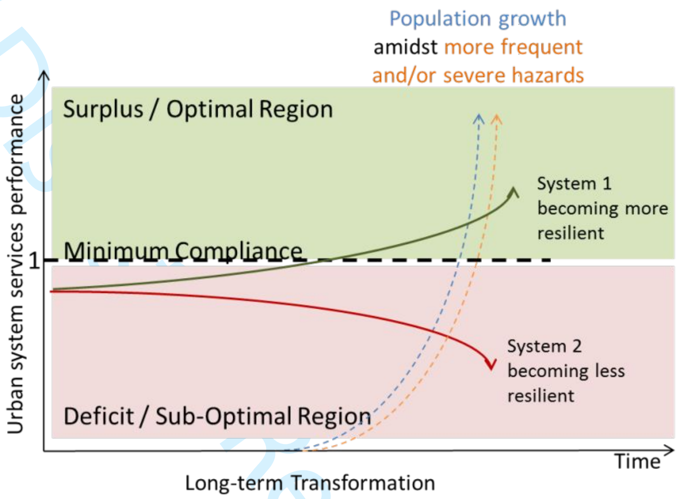

Fig.3. Dynamic hypothesis for the system dynamics model 2.

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:

$$URI - S = \frac{\sum_{i=1}^{n} r_i}{n} \tag{3}$$

where $r_{1...n}$ 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.

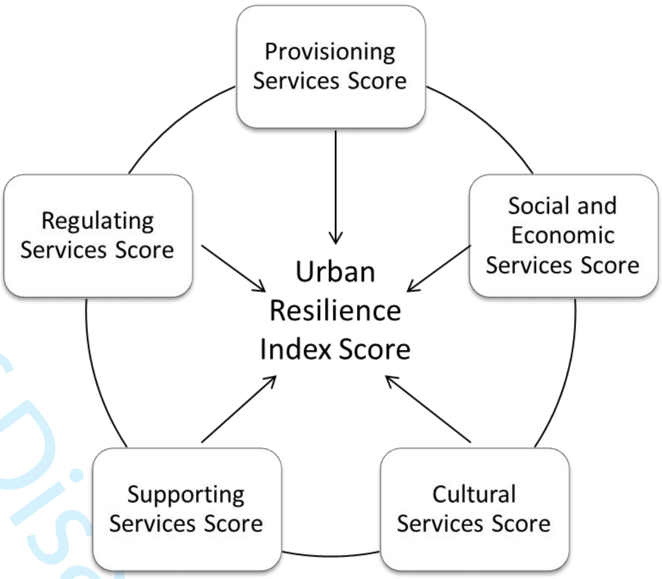

Fig.4. Concept of system dynamic model 2.

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.

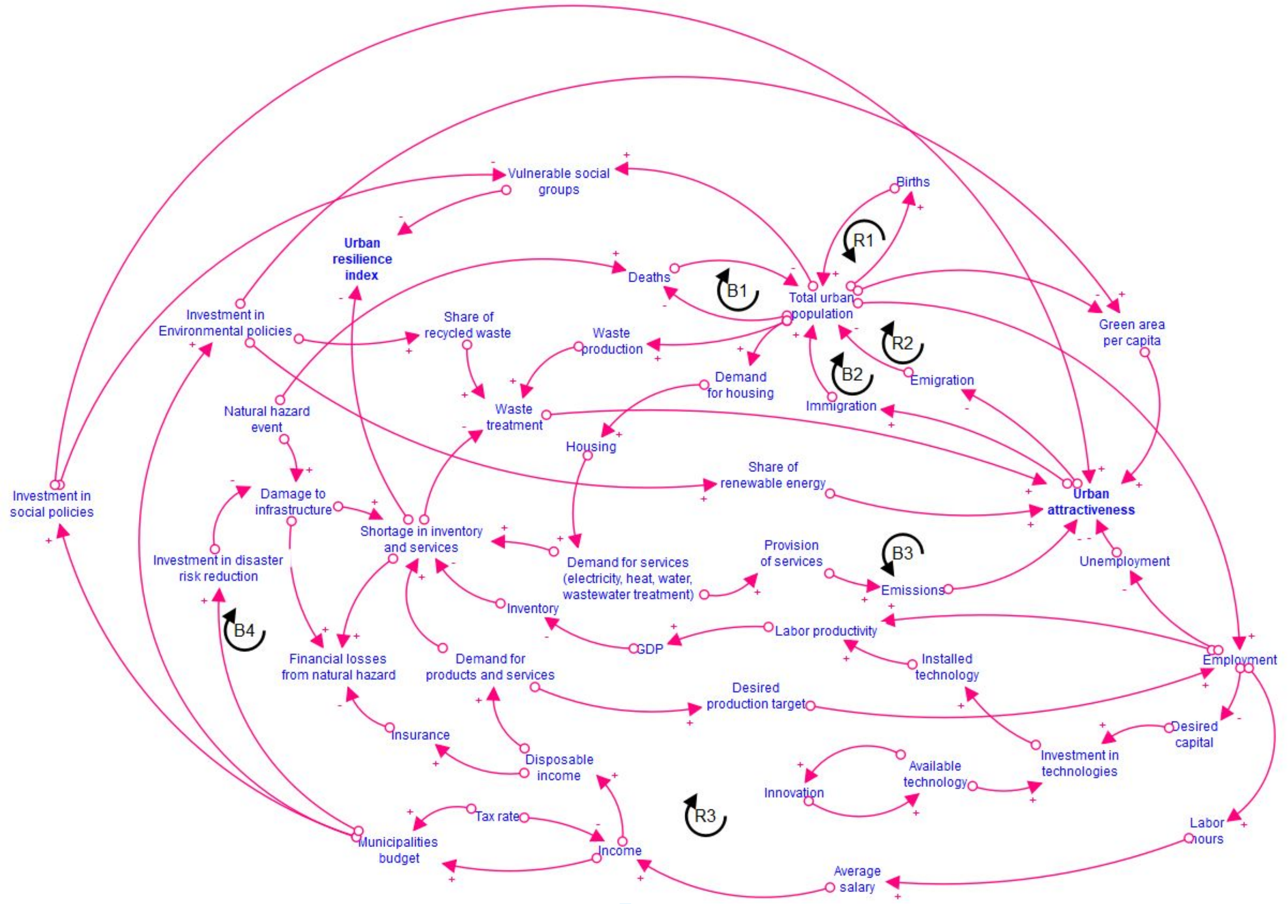

Fig.5. Generalized causal loop diagram of system dynamic model 1.

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.

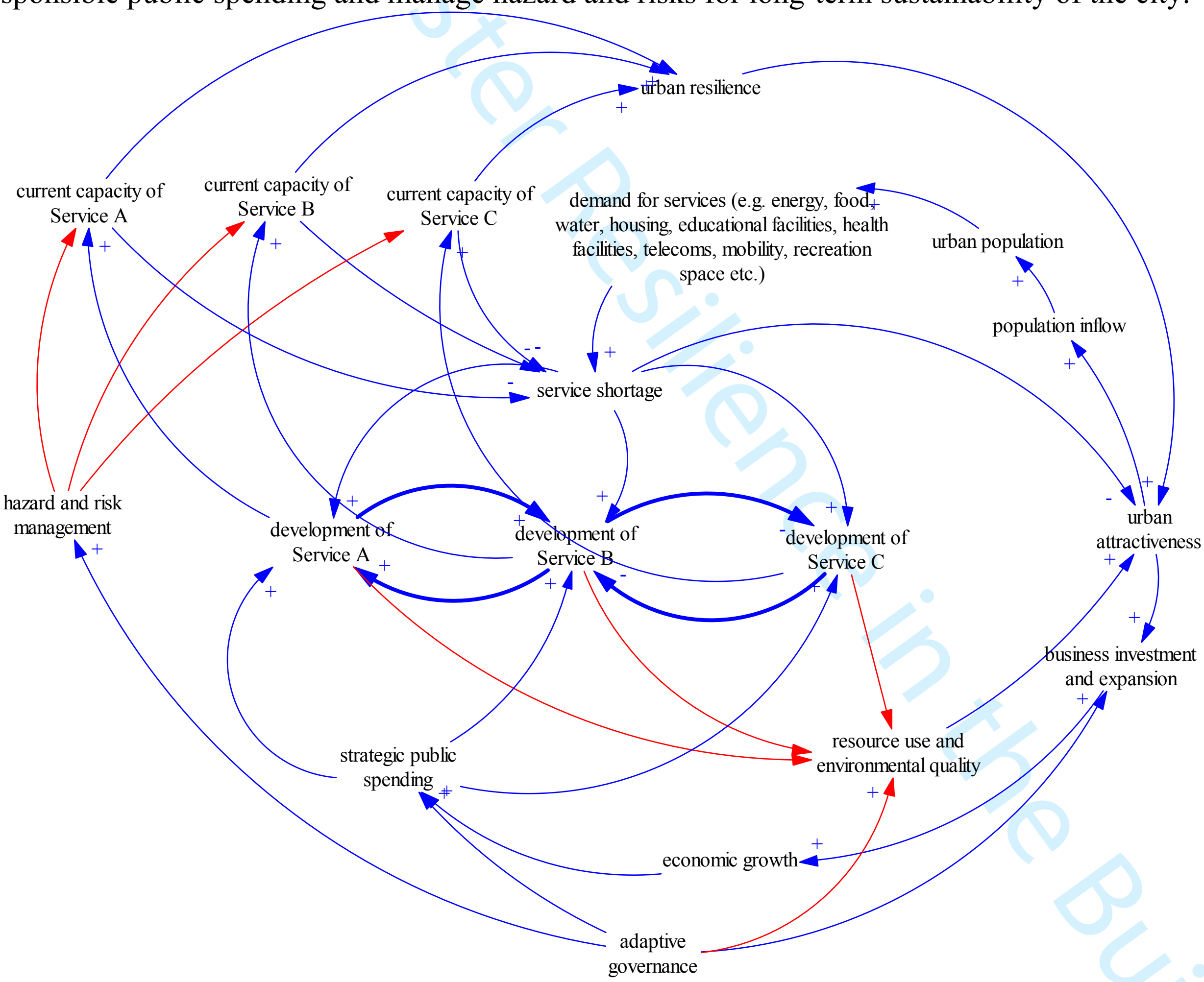

Fig. 6. Causal Loop Diagram representing a General Template of the Services Approach to Urban Resilience Index Development (Arrows in red are those whose polarities are not indicated as they would depend on the specific services and decisions being considered. Arrows in bold represent where synergies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

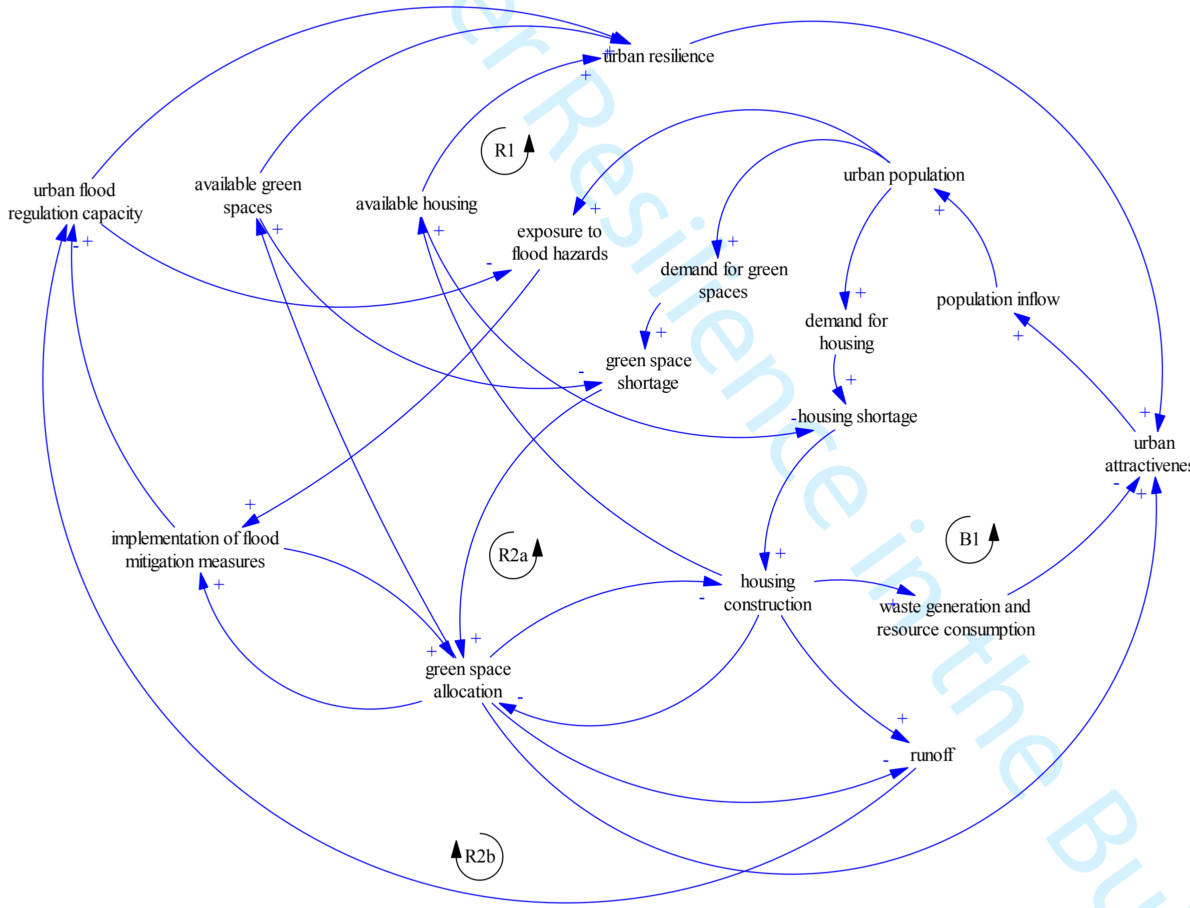

Fig. 7. Causal Loop Diagram illustrating the application of the general template for specific services: flood regulation, green space allocation, housing. (Variables pertaining the economic and governance aspects were omitted from the diagram only to simplify the figure and highlight the synergies and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

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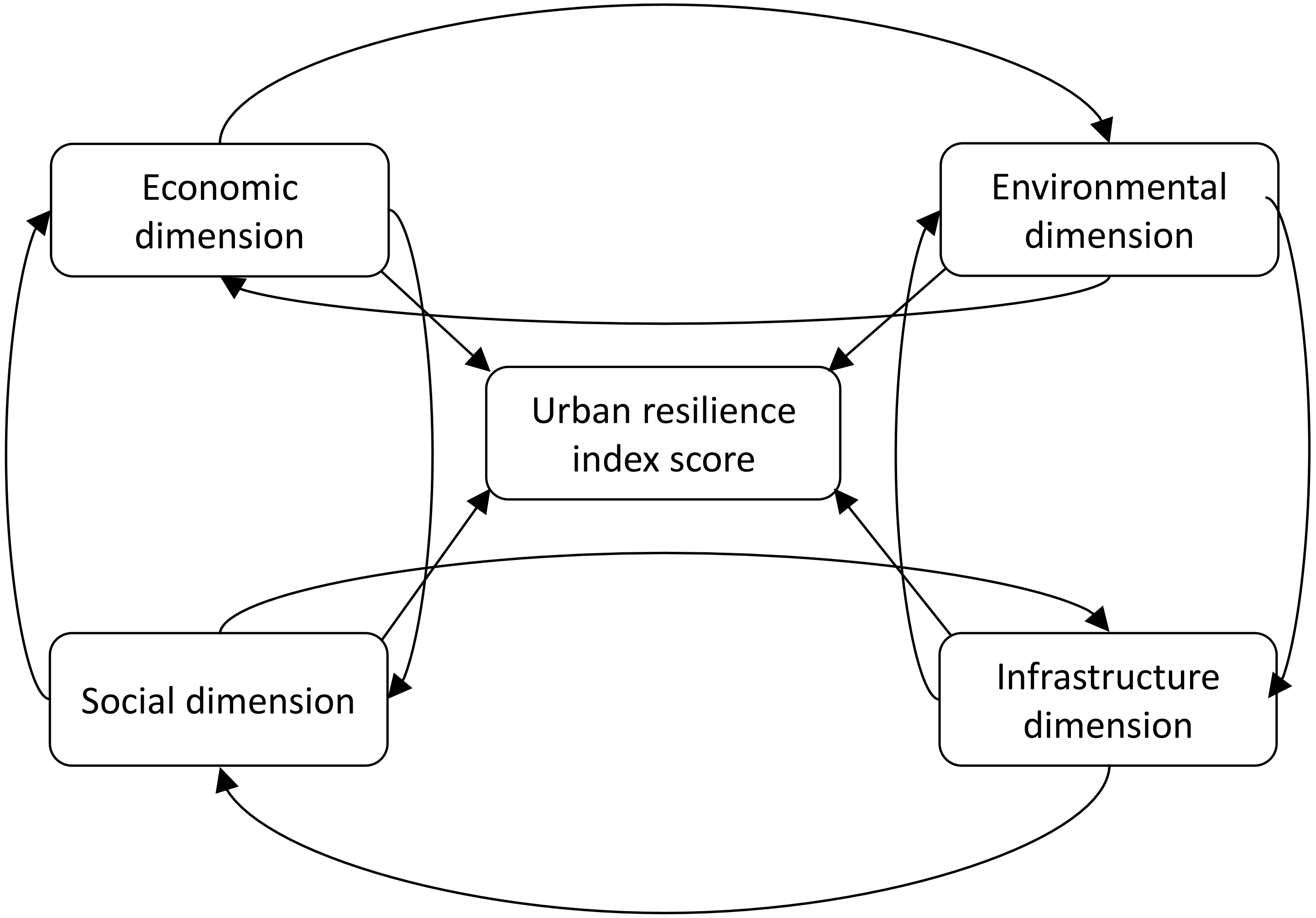
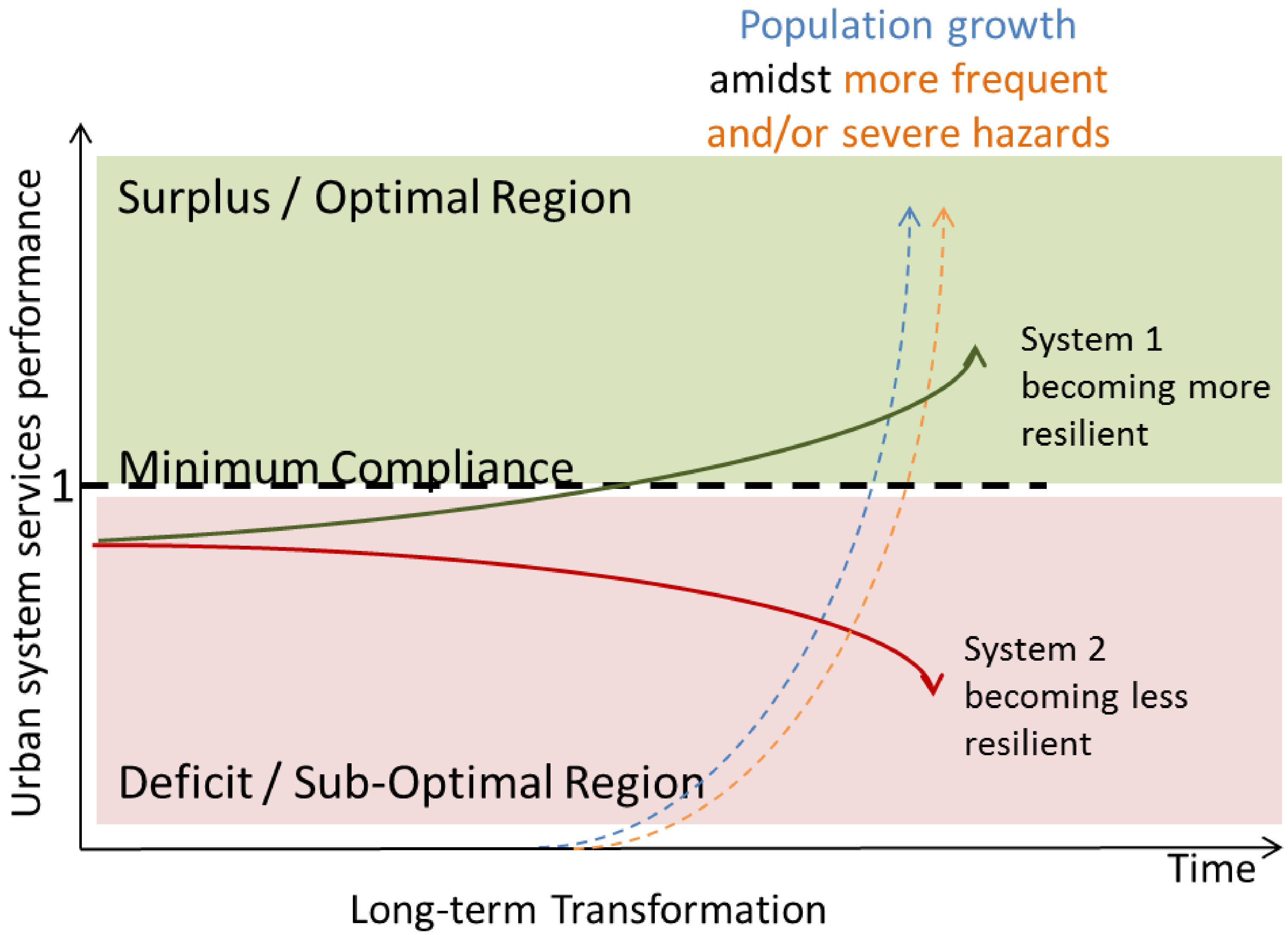
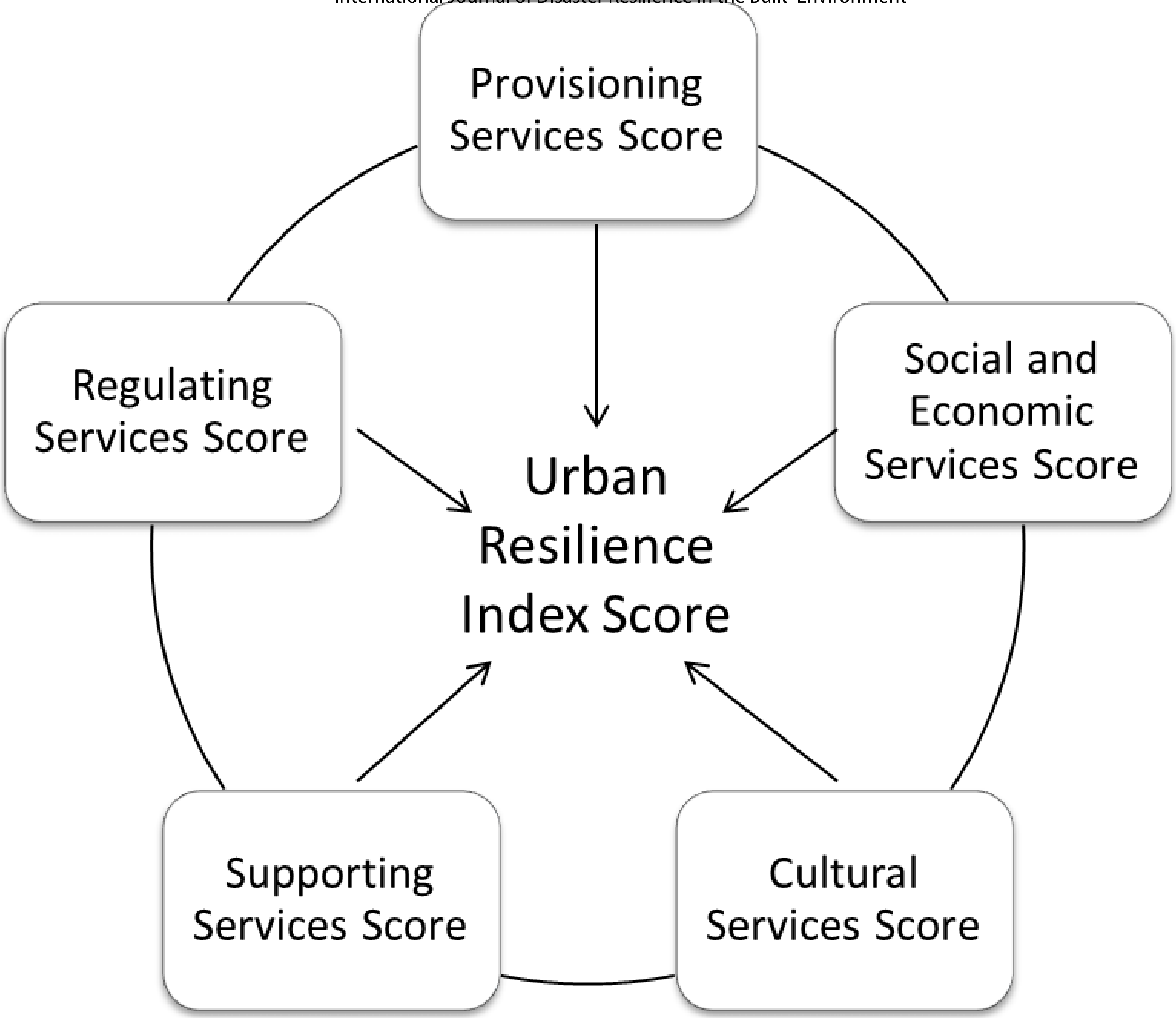
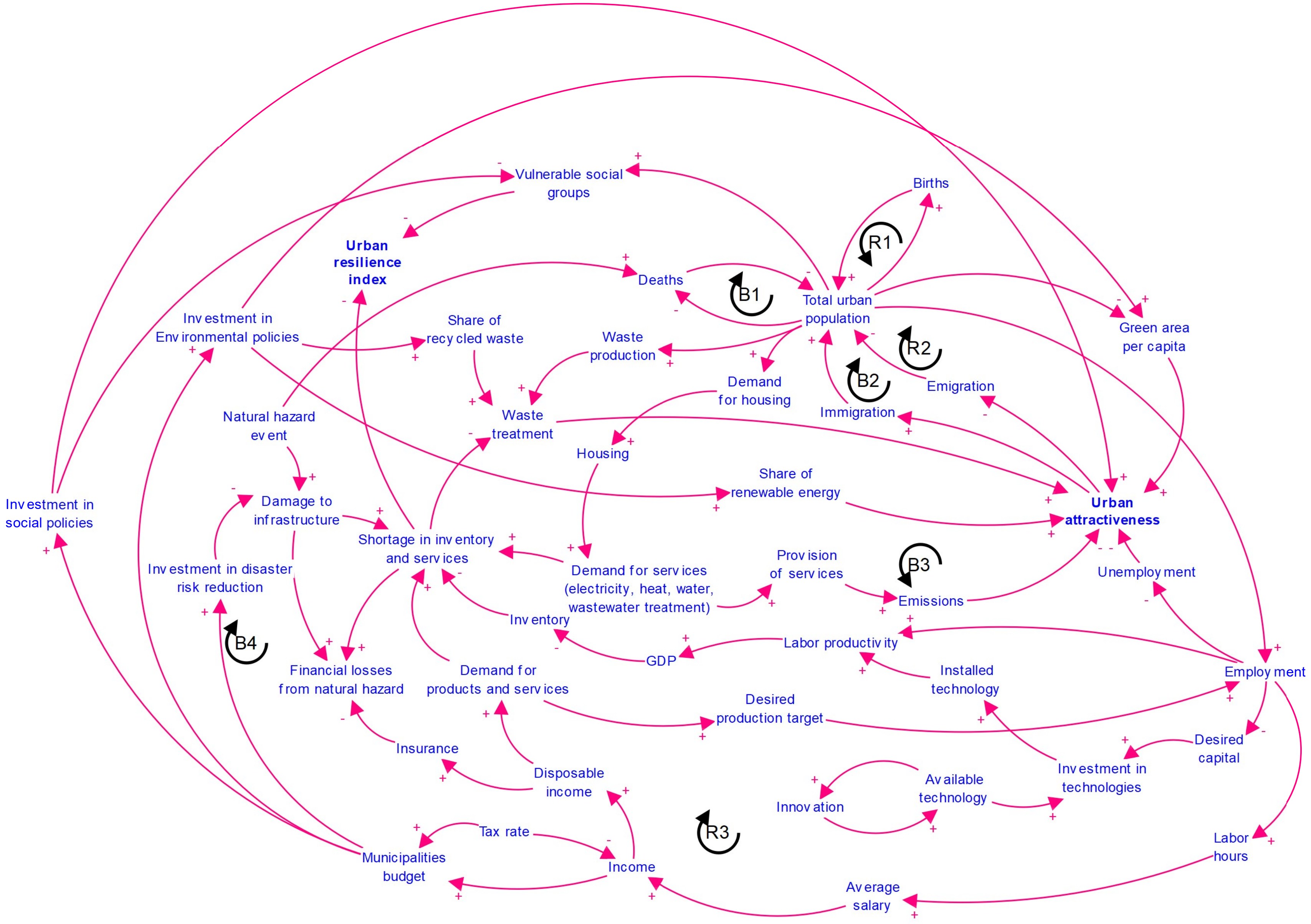
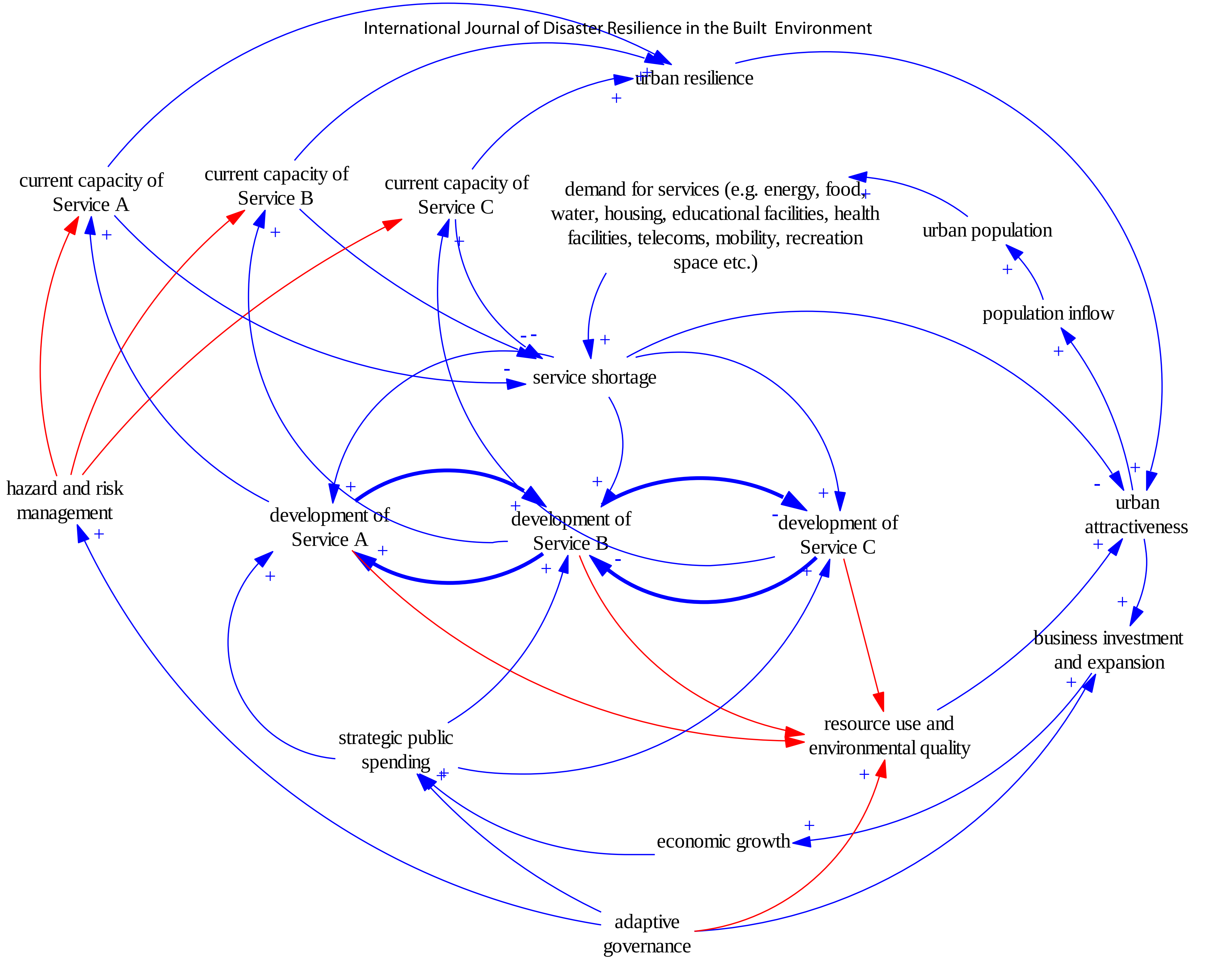

Economic dimension
Environmental dimension
Urban resilience index score
Social dimension
Infrastructure dimension

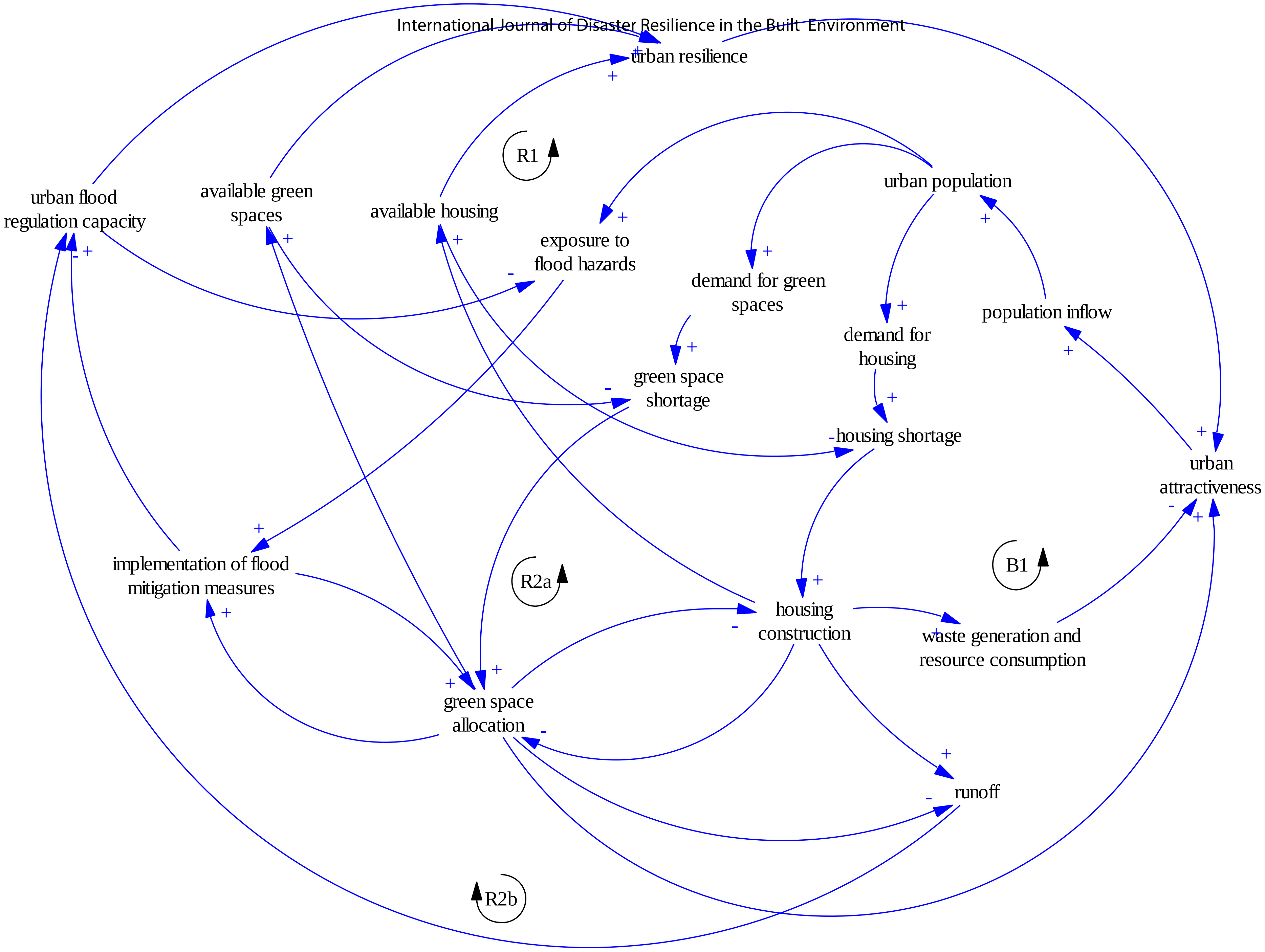

Population growth
amidst more frequent
and/or severe hazards
Surplus / Optimal Region
Minimum Compliance
1
System 1
becoming more
resilient
System 2
becoming less
resilient
Deficit / Sub-Optimal Region
Urban system services performance
Time
Long-term Transformation


Provisioning Services Score
Regulating Services Score
Social and Economic Services Score
Urban Resilience Index Score
Supporting Services Score
Cultural Services Score



Vulnerable social groups
Births
R1
Urban resilience index
Deaths
B1
Total urban population
Investment in Environmental policies
Share of recycled waste
Waste production
R2
Demand for housing
B2
Emigration
Immigration
Green area per capita
Natural hazard event
Waste treatment
Housing
Share of renewable energy
Urban attractiveness
Investment in social policies
Damage to infrastructure
Shortage in inventory and services
Demand for services (electricity, heat, water, wastewater treatment)
Provision of services
B3
Emissions
Unemployment
Investment in disaster risk reduction
Inventory
GDP
Labor productivity
B4
Financial losses from natural hazard
Demand for products and services
Installed technology
Employment
Desired production target
Insurance
Desired capital
Disposable income
Investment in technologies
Available technology
Innovation
Tax rate
R3
Labor hours
Municipalities budget
Income
Average salary


urban resilience
current capacity of Service A
current capacity of Service B
current capacity of Service C
demand for services (e.g. energy, food, water, housing, educational facilities, health facilities, telecoms, mobility, recreation space etc.)
urban population
population inflow
service shortage
hazard and risk management
development of Service A
development of Service B
development of Service C
urban attractiveness
business investment and expansion
resource use and environmental quality
strategic public spending
economic growth
adaptive governance


urban resilience
R1
urban population
urban flood
regulation capacity
available green
spaces
available housing
exposure to
flood hazards
demand for green
spaces
demand for
housing
population inflow
green space
shortage
housing shortage
urban
attractiveness
implementation of flood
mitigation measures
R2a
B1
housing
construction
waste generation and
resource consumption
green space
allocation
runoff
R2b