System Dynamics Framework for Sustainable Development Analysis of Local Governments

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Abstract
This article presents a concept and theoretical specification for a system dynamics based framework for sustainable development analysis of local governments. Although many countries in the world aspire to the principles of sustainable development, there exists a relatively small number of theoretical studies and practical results in the area of simulation modelling of sustainable development. The proposed modelling framework is based on the concept of sustainable regional development as an unending process defined neither by fixed goals nor by specific means of achieving them. A sustainable region demands a mutual balance among economic, social, political and naturally environmental development. The system dynamics framework is considered as a useful tool in assisting decion-makers in development planning allowing to evaluate alternative scenarios and planning options.

Keywords: System Dynamics, Sustainable Development, Regional Development.

Introduction

The notion of sustainable development is originated from the term Limits to Growth (Owens and Cowell, 1994), which is derived from a report called Club of Rome published in 1972 according to Forrester's system dynamics modelling on urban and globe problems in his books Urban Dynamics (Forrester, 1969) and World Dynamics (Forrester, 1971). The concept of sustainable development has recently been discussed in different studies, and many attempts have been made to define sustainable development as a practical approach (Huser et al., 2009; Mayerthaler et al., 2009).

The European Council in its Sustainable Development Strategy (European Council, 2006) has defined that the overall aim of sustainable development strategy is to identify and develop actions to enable to achieve continuous improvement of quality of life both for current and for future generations, through the creation of sustainable communities

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able to manage and use resources efficiently and to tap the ecological and social innovation potential of the economy, ensuring prosperity, environmental protection and social cohesion. A sustainable region demands a mutual balance among economic, social, cultural, political and naturally environmental development. Joining together the four dimensions of environment, economy, politics and society, sustainable development refers to a process in which the economy, environment, politics and ecosystem of a region change in harmony, and in a way that will improve over time. Sustainable development must be seen as an unending process defined neither by fixed goals nor the specific means of achieving them (Hjorth and Bagheri, 2006).

Although many countries in the world aspire to the principles of sustainable development, there exists a relatively small number of theoretical studies and practical results in the area of simulation modelling of sustainable development at national, regional and local levels. Sustainable spatial planning at regional level is very important due to increasing globalization effects including the disparities between territories and settlements.

This paper describes a conceptual framework for system dynamics modelling of sustainable development to assist local governments. This is a multi-disciplinary collaborative approach with an overall objective to strengthen cooperation between education establishments, R&D institutions and municipalities at local and international level for promotion of spatial development and regional innovation activities, resulting in increased jobs, revenues and enhanced capacity of municipalities in supporting innovation and sustainable development.

The paper is organized as follows: Section 2 provides a description of the methodology used in model development. The conceptual model and a detailed description of the framework structure and implementation are presented in Section 3. The preliminary simulation results and concluding comments are presented in Sections 4 and 5.

Methodology

The use of systems-thinking approach by involving the creation of a system dynamics model has been given increasing attention in recent years. This paper applies system dynamics techniques to formulate, simulate, calibrate and validate the sustainable development of Kuldiga municipality. This study uses the concepts and procedures of system

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analysis to develop and explore dynamics of sustainable development. To simplify complex real-world phenomena and the inter-relations among the various components in the development planning process, a model, as a real-world abstraction, is used. The model development process includes several iterative steps:

1. Identification of systems and components:
    (a) Identification of indicators and orientors.
2. Identification of relationships and interactions.
3. Development of conceptual model.
4. Model implementation.
5. Model verification, calibration, validation and approbation for Kuldiga municipality.

Sustainable development can be mathematically characterized by two main constituents: security of population (I_{sec}) and quality of their life (I_{ql}) (Zgurovsky, 2009). A generalized sustainable development measure (sustainability) I_{sd} may be presented as a modulus of a complex number:

$$I_{sd} = \left| jI_{\text{sec}} + I_{ql} \right| = \sqrt{I_{\text{sec}}^2 + I_{ql}^2}, \quad (1)$$

The quality of life component of sustainable development can be defined as follows:

$$I_{ql} = \sqrt{I_{\text{ec}}^2 + I_e^2 + I_s^2} \cdot \cos\alpha, \quad (2)$$

where: I_{ec} is economic dimension (economical cohesion);
I_e is ecological dimension (environmental balance);
I_s is social / institutional dimension (social cohesion);
$\cos\alpha = \dfrac{I_{ec} + I_e + I_s}{\sqrt{3\left(I_{ec}^2 + I_e^2 + I_s^2\right)}}$ is degree of harmonization.

Identification of Systems and Components

All of the components in the system, which are related to sustainable development, should be considered. A key challenge to developing a sustainable development model is deciding on the scope of the system to study and prioritizing the issues or questions to address.

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Indicators and Orientors

In order to select key components to represent system behavior, this study examines analytical indicators, which are used in the previous studies dealing with sustainable development (Meadows, 1998; Bossel, 1999; Ministry of Environment and Energy, National Environmental Research Institute, 2001). Indicators are quantitative or qualitative measurements of the state of something that is important to us, like our body temperature, heart beat or blood pressure (Bossel, 1999). The choice of indicators is a critical determinant of the behavior of a sustainable system, poorly chosen indicators can cause serious malfunctions (Meadows, 1998). Orientors are labels for certain categories of concerns or interests (Bossel, 1999). Different systems may have the same orientors, but would have different corresponding indicators.

In this study, 33 key indicators based on expert discussions and workshops are chosen grouped into three subsystems (human system, support system, natural system) and categorized by 7 composite indicators or basic orientors proposed by Bossel (Bossel, 1998). The seven basic orientors are aggregated into three dimensions (Zgurovsky, 2009): social cohesion, economical cohesion, environmental balance. From the basic orientors and dimensions the main indicators - the quality of life and sustainability are calculated.

System Components

The top-down model should cover a broad range of issues that a region faces on the path to sustainable development, for example, demographic shifts, environmental degradation, education, healthcare, economic growth. Summarizing these key issues the model framework distinguishes four main systems containing six aggregated sub-components or sectors. The proposed model structure is based on well accepted works in the field (Bossel, 1998, 1999):

1. Human system: the human system represents the social dimension of sustainable development. The sustainable development concept requires a strong human basis, such as people capability of acting effectively, accordingly, efforts must focus on promoting education, abilities, and opportunities for each individual as well as for the community. The human system has three components:
    (a) The Individual development sector.

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(b) The Social system sector.
(c) The Government sector.

2. Support system: the support system implements the economic aspect of sustainable development. The growth of economy is the most important precondition of human needs and for any lasting improvements in the living conditions. The support system has two components:
   (a) The Infrastructure sector.
   (b) The Economic system sector.

To be necessary to note, regional models can include different elements of infrastructure and economic system sectors, such as transport or energy infrastructure. If we analyse Kuldiga municipality, it is part Baltic energy infrastructure (Tuvikene et al., 2015), so this part is not shown in the research.

3. Natural system: the natural system represents the environmental aspect of sustainable development. The natural-environmental constraint to human development is the main reason for any concern about sustainability:
   (a) The Resources and environment sector.
4. Indicator system: the indicator system consolidates information from the other components for the purpose of calculating indicators of the system state.

Identification of Relationships and Interactions
The long-term goal of the research project is to develop a multi-scale, spatially explicit, dynamic systems model linking components at five spatial scales (Figure 1): global (world and Europe Union), country, regional, municipality and local. The given concept of a multi- scale model is borrowed from an integrated spatial decision support system developed for local government in New Zealand (Huser et al., 2009).

The world, Europe Union and country scales represent external drivers and scenarios such as climate, economy and legislation change that will influence the region and the municipality to be modeled. The regional scale represents a system dynamics model of economy-environment interaction model of the region. The municipality scale contains an economy- environment interaction model of a local municipality, The model should balance and integrate the social, economic and environmental components of the region community.

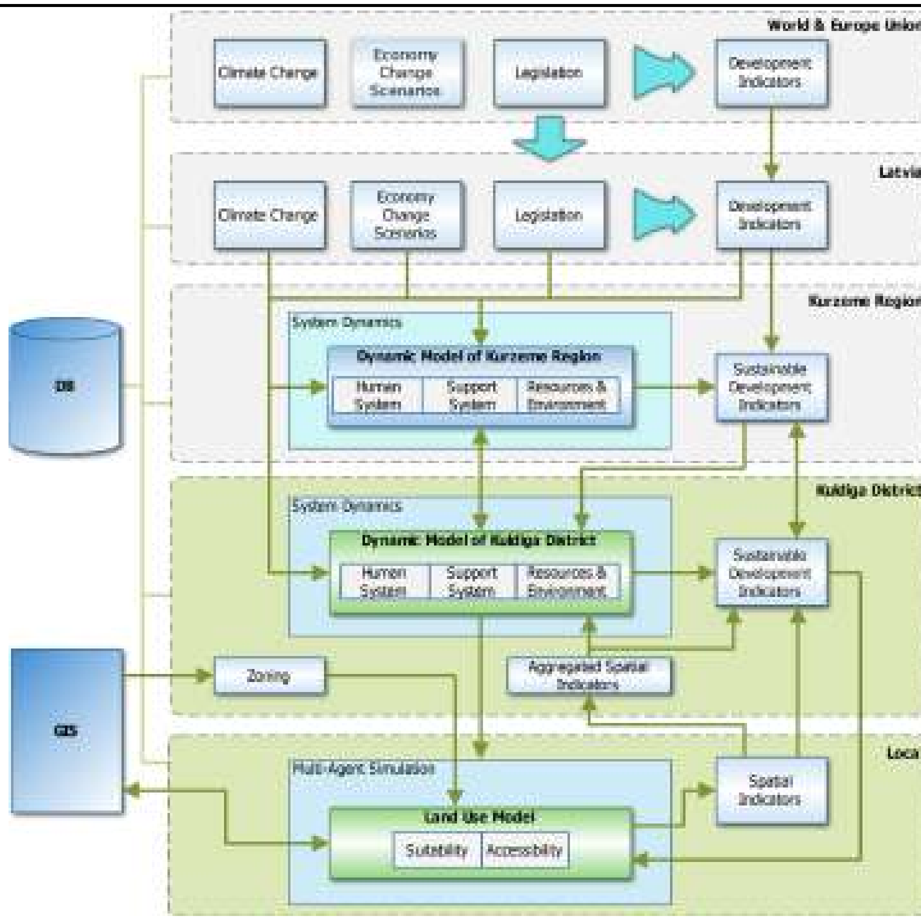

Figure 1: Conceptual system design of a multi-scale model for a local government

Model implementation

Based on the conceptual model, this study develops a sustainable development system dynamics model using the Vensim software tool. The model implementation is based on the existing experience presented by such well known system dynamics models as WORLD2 (Forrester, 1971), Miniworld (Bossel, 1994), WORLD3 (Meadows et al., 2004), T21 (Threshold 21 (T21)).

Sustainable development requires a long-term perspective, and uncertainty in long-term prediction is high. The time horizon of the

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model is 30 years, from 2010 to 2040. This time horizon is sufficiently long meaning that the future of the system is relatively independent from its initial conditions. The time step of the calculations is one year.

Conceptual system dynamics model

In Figure 2 a conceptual structure of the system dynamics model is shown. The model consists of four main components including human system component, support system component, natural system component and indicator system component.

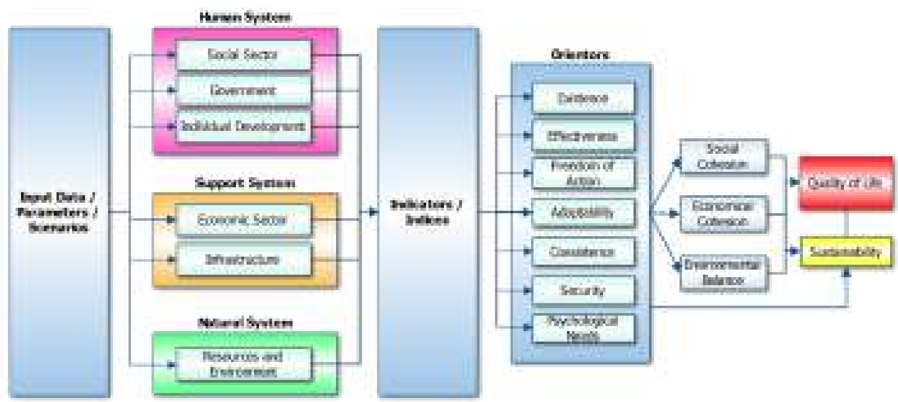

Figure 2: Conceptual structure of system dynamics model

On the basis of the conceptual model, the flowcharts of the sustainable development system are defined below, with consideration of system characteristics. The variables are identified and relevant equations are established based on the feedbacks and cause-and-effect loops. The details of the contents and structures of the four sub-models and their components are described as follows and their according stock-flow diagrams are presented in each section, respectively.

Human system component

The human system component contains individual development, social system and government sectors.

The individual development sector contains elements of social integration and participation, material standard of living, adult education, leisure and recreation.

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The social system sector implements behavioral aspects of population development (Figure 3), income composition, social groups and organizations, social security, medical care and old age provision.

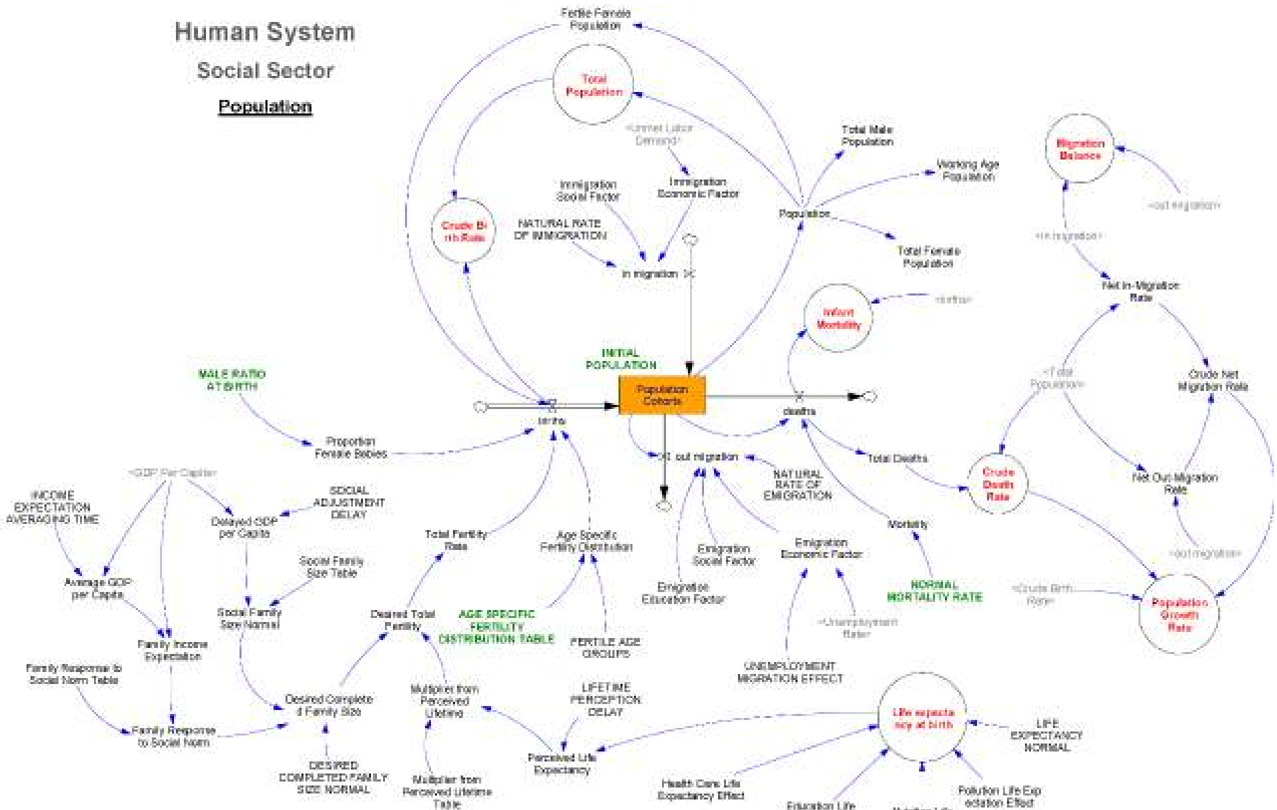

Figure 3: Population sub-model

The all population is divided into population cohorts of 5 years each. Each cohort has the births and in migration input flows, as well as deaths and out migration output flows. Both out-migration *OM* and in-migration *IM* are modelled based on a *logit* function of the form (Mayerthaler et al., 2009):

$$OM = e^{\alpha_0 + \alpha_1 POP + \alpha_2 LR + \alpha_2 GL + \alpha_3 ACC},$$
$$IM = e^{\alpha_0 + \alpha_1 POP + \alpha_2 LR + \alpha_2 GL + \alpha_3 ACC}, \quad (3)$$

where: $\alpha_0 \ldots \alpha_3$ are parameters;

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POP is number of residents in a region;
LR is land rent;
GL is area of green land in a region;
ACC is access attractiveness in modelled region.

The government sub-model (Figure 4) represents a regional government and administration, public finances and taxes.

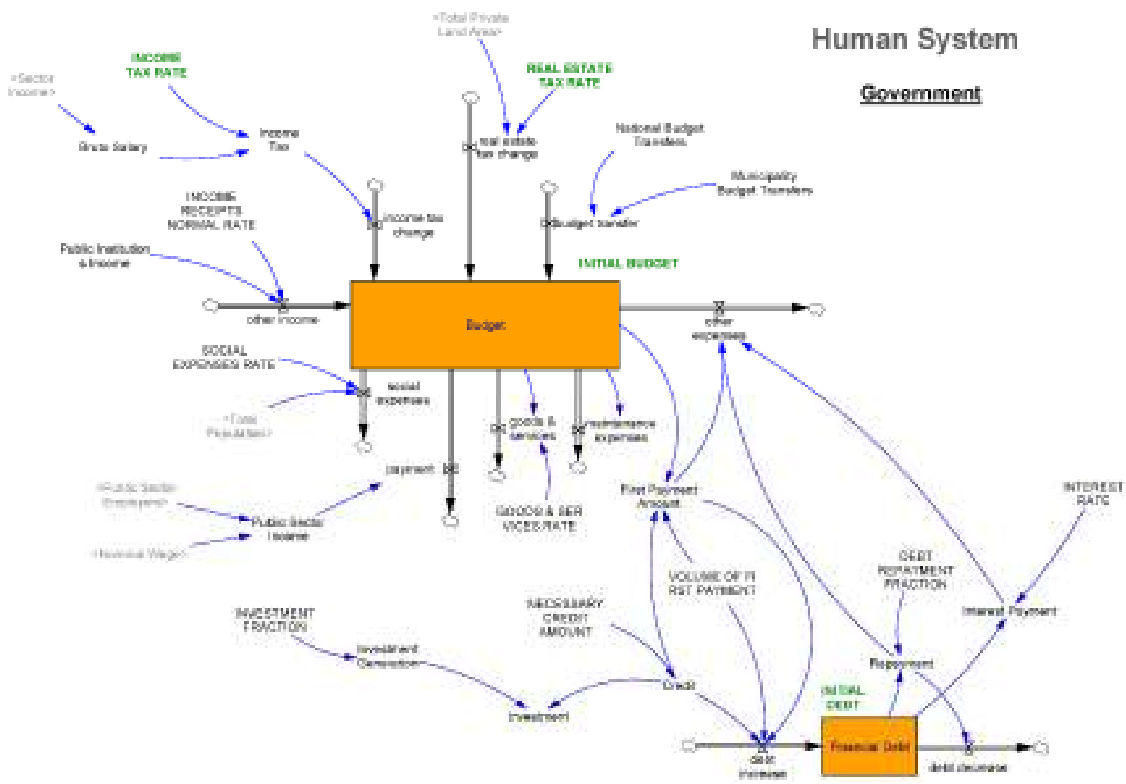

Figure 4: Government sub-model

Support system component

The support system component consists of two sectors - infrastructure sector and economic system sector.

The infrastructure sector implements elements of supply system (energy, water, food, goods, services), waste disposal, health services, tourism objects, facilities for education and training, research and

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development. Increasing population results in increasing demand for infrastructure capacities.

The economic system sector simulates industrial production (Figure 5), agricultural production, consumption, commerce and trade processes, labor and employment.

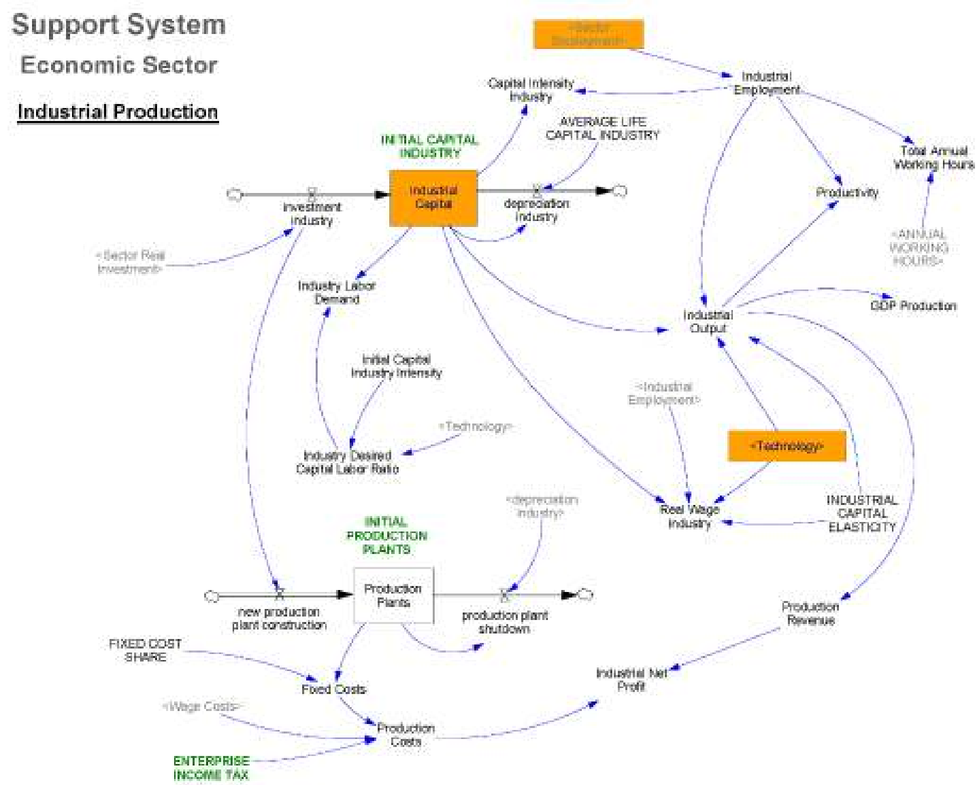

Figure 5: Industrial production sub-model

The industrial production sub-model is based on the classical Cobb-Douglas production function:

$$Y = A \cdot K^{\alpha} \cdot L^{1-\alpha}, \tag{4}$$

where: Y is industrial output;
- A is total factor productivity or Solow residual;
- K is industrial capital input;
- L is employment in industrial production;
- α is capital elasticity.

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Currently the parameters of industrial capital and employment elasticity are constants, whose values are obtained from a regression analysis performed by a Bank of Latvia. In the future, the industrial capital and employment elasticity should be made as variables, to more precisely model a long term economical development.

The services sub-model has a similar structure to the sub-model of industrial production. For modelling of agricultural production (Figure 6), a modified Cobb-Douglas function is used, where as an additional factor the area of agricultural land is used (Barro, 1998):

$$Y = A \cdot L^{\alpha} \cdot K^{\beta} \cdot Z^{1-\alpha-\beta},$$

where: Y is agricultural output;
A is agricultural technology;
K is agricultural capital input;
Z is land input;
L is employment in agriculture;
α is employment elasticity;
β is capital elasticity .

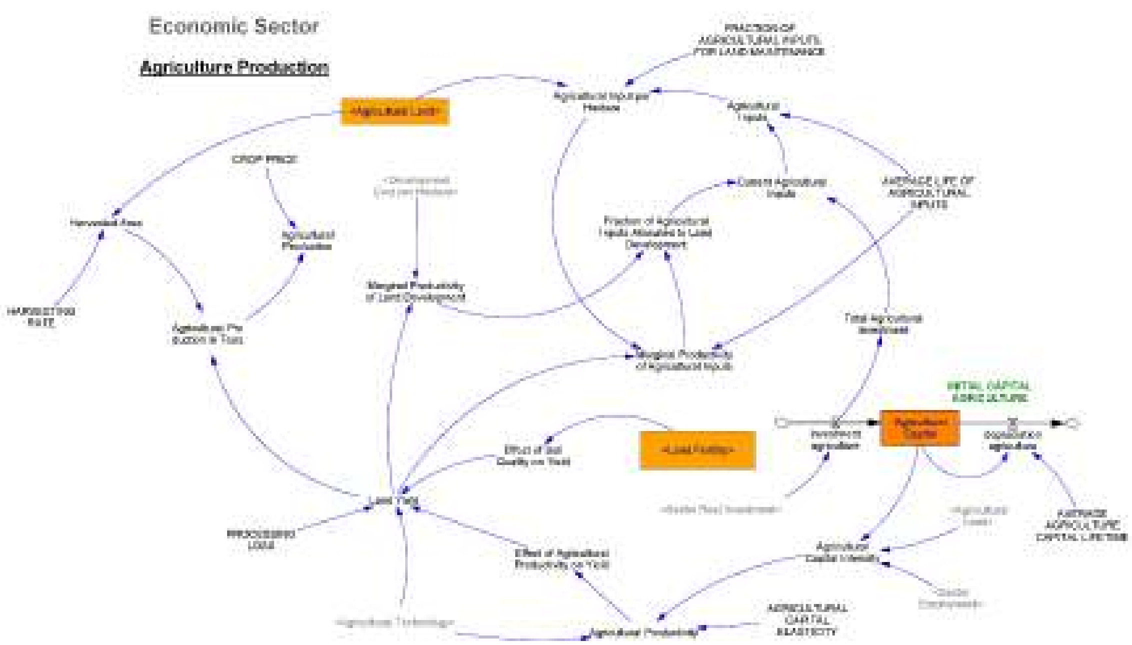

Figure 6: Agricultural production sub-model

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Natural system component

The natural system component by implementing the resources and environment sector represents a natural environment, atmosphere and hydrosphere, natural resources, ecosystems, depletion of nenrenewable resources, regeneration of renewable resources, waste absorption, material recycling and pollution. It also examines the effect of soil erosion and other forms of environmental degradation and their impact on other sectors, such as agricultural productivity and nutrition.

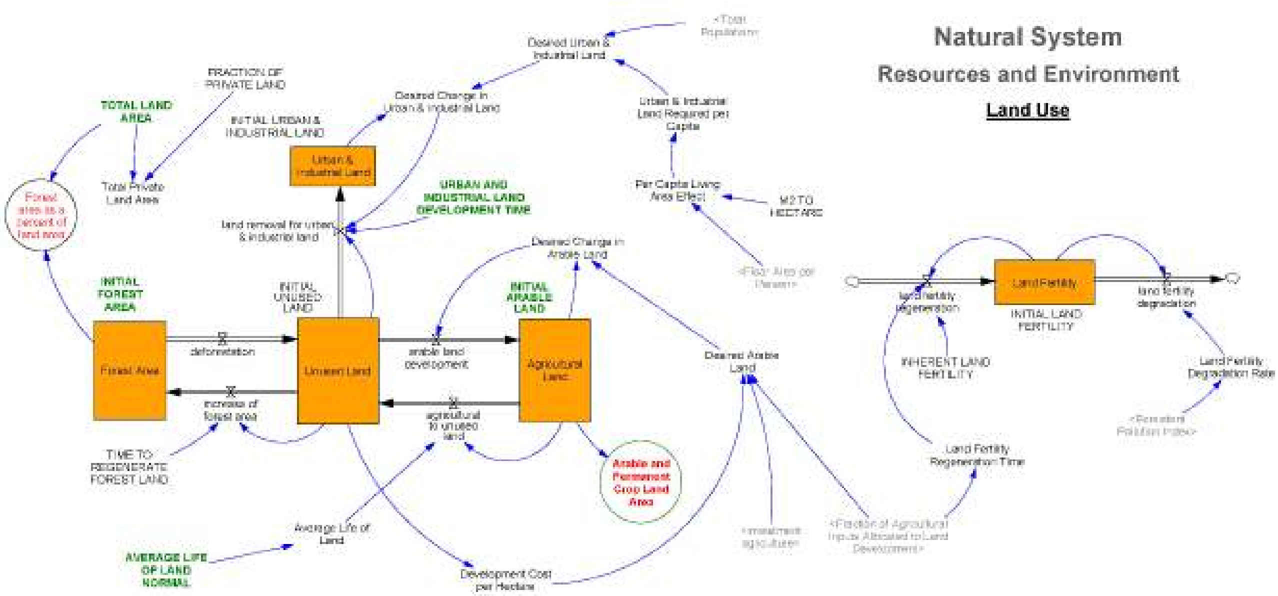

Figure 7: Land use sub-model

In Figure 7 a land sub-model of the natural system's resources and environment sector is shown. The total land area consists of different land types such as forest, agricultural land, unused land un land used for urban & industrial settlements. A transition between different land types is driven by economical and environmental factors. The expansion/increment of the agricultural and urban areas is a process of transformation/conversion of the undeveloped land to the developed land.

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Indicators component

The indicators component (Figure 8) performs the housekeeping tasks of consolidating information from the other components for the purpose of calculating indicators of the state of the system. This component implements 33 indicators aggregated into seven basic orientors and three dimensions, as previously discussed in Subsection 2.1.1.

The quality of life is calculated by Equation 2 described in Section 2. The sustainability is calculated by Equation 1.

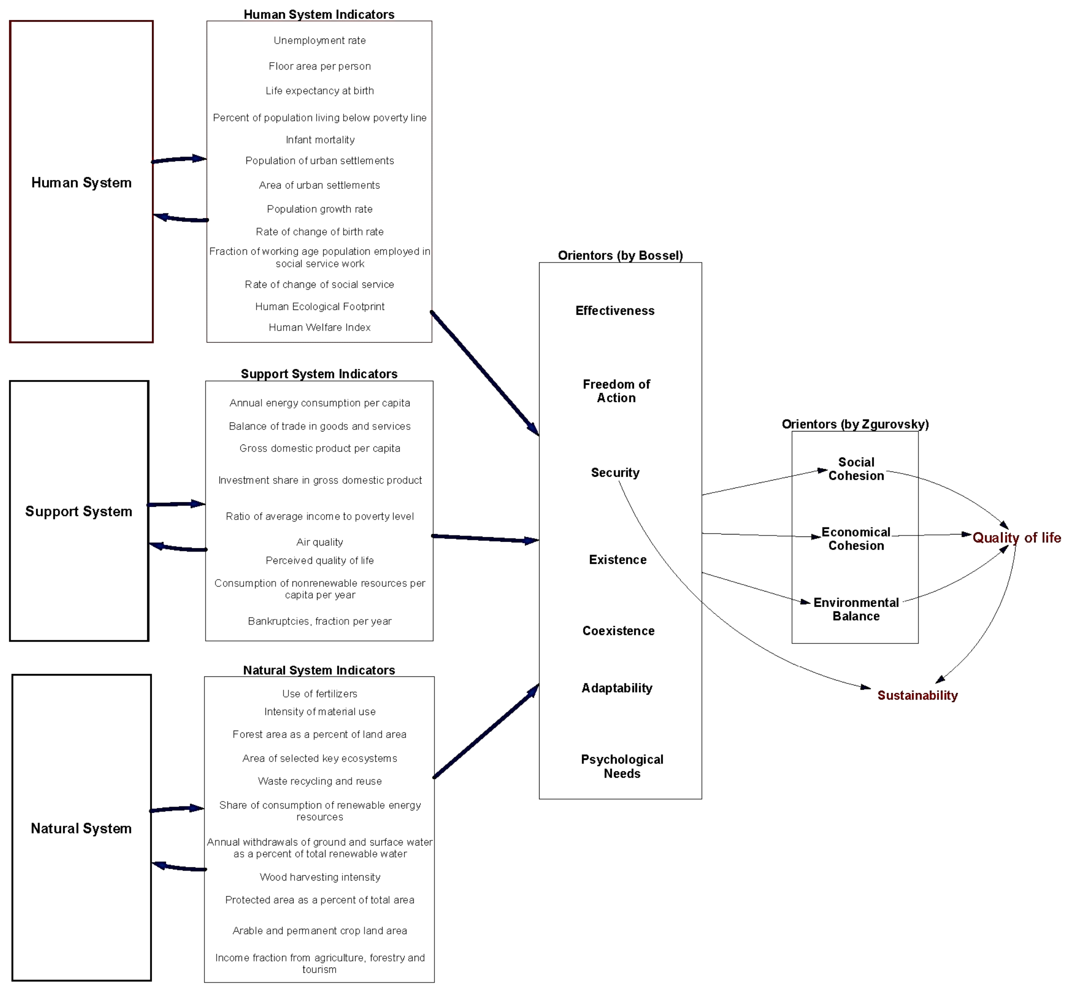
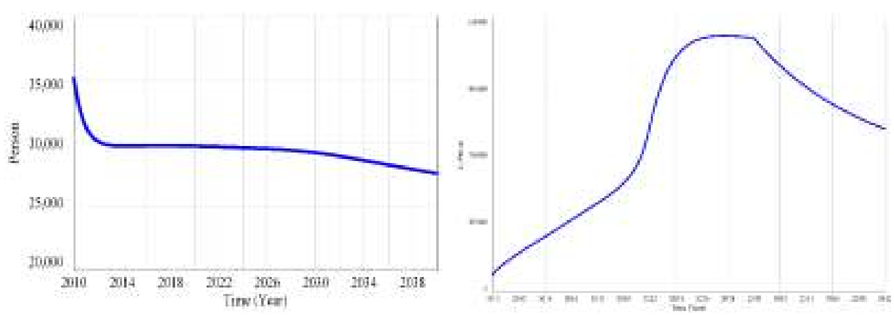


Figure 8: A simplified structure of indicators component

Results

The simulation test results are obtained based on statistical data for Kuldiga district of the Kurzeme region, Latvia. Kurzeme Region is one of five planning regions in Latvia, situated in the western part of Latvia, at the shores of the Baltic Sea and Gulf of Riga. The Kuldiga municipality was formed in 2009 by merging 13 parishes and Kuldiga town the administrative centre being Kuldiga. The municipality has a total land area of 1756,7 km2, a population of 25 615 people in 2015.

The simulated population dynamics (Figure 9a) shows a pattern corresponding population change trends to currently observable in Kuldiga municipality, respectively, a rapid population decrease due to high emigration rate and a predomination of deaths over births. Latvia and also its regions has recovered from economical crisis, and by economical growth the emigration rate is decreasing. However, if birth rate stays low then a trend of population dynamics still will be decreasing.



(a) Total Population (b) GDP per capita

Figure 9: Simulation results

The simulated GDP per capita (Figure 9b) shows an increasing trend, however in 2030 begins a decline. That can be explained by constrained demographical resources needed for a sustainable economical development.

In Figure 10 two possible population change scenarios are shown. In the first scenario (Figure 10a), the birth rate is increased by a factor 1.6. In this case the total population after an initial decline period will return to level close by the initial value. In the second scenario (Figure 10b, the initial birth rate is increased by a factor 2. In this case the total population

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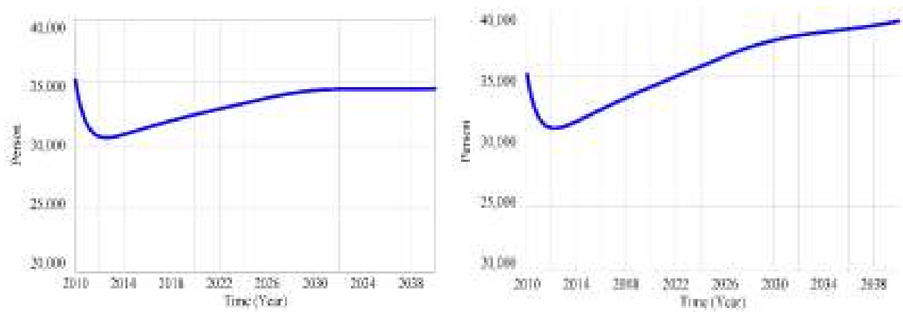
after an initial period of decline will start to grow. The initial decrease of population in these scenarios can be explained by the relatively high out-migration rate.



(a) Birth rate increased by factor 1.6 (b) Birth rate increased by factor 2
Figure 10: Simulated population change scenarios

Conclusion

The goal of the proposed model is to explore alternative scenarios to improve the quality of life and sustainability within a regional and national context. A dynamic model within a systems-thinking framework is considered beneficial both as useful tool for existing decision- makers in development planning and as a educational mean in understanding how various regional sub-systems function.

The calibration was based on data for the Kuldiga municipality, including population, land use and energy production. The calibration might be described as impressionistic in the sense that the overall magnitudes are in the right ballpark, but it must be emphasized that a great deal more effort would be required to understand and exploit additional data.

The long-term goal of the research is to develop a spatially explicit systems model operating at five scales: global, country, regional, municipality and local.

The research work and development continues and the system dynamics framework is currently being enhanced to correctly represent regional and municipal processes along with interaction with policies coming down from national levels. The proposed framework could be an invaluable tool in assisting decision-makers in sustainable development planning, as well as an educational mean in understanding how various regional sub-systems function.

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