

Combined Multi-Scale System Dynamics and Agent-Based Framework for Sustainable Community Modelling

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Abstract. In this paper, a community-modelling (COMMOD) framework for integrating of system dynamics models with agent-based systems and geographic information systems in the context of modelling and simulation of sustainable community development is proposed. The proposed framework has been developed for local government of Kuldiga District in Kurzeme Region, Latvia. The combined modelling framework is considered as an invaluable tool in assisting decision-makers in development planning allowing evaluation of alternative scenarios and planning options.

Keywords: Sustainable Community, System Dynamics, Multi-Agent Modelling.

INTRODUCTION

Sustainable development has become a widely used term. It originated from the term *Limits to Growth* [1], which was first used in 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* [2] and *World Dynamics* [3]. 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 [4, 5].

The term *sustainable community* is closely related to sustainable development; however the definition of sustainable community varies according to the interest, needs, and culture of different communities [6]. Sustainable community is a community planned, built or modified to promote sustainable living. A sustainable community demands a mutual balance among economic, social, political and natural environmental development.

This article presents a concept and theoretical specification for a combined system dynamics and agent-based model of sustainable community development for local government of Kuldiga District in Kurzeme Region, Latvia. The paper presents an initial stage of development of the model, so no results are currently available regarding calibration, validation or main findings about sustainable community development in the study site.

Latvia aspires to the principles of sustainable development, which have been included in the Law of Regional Development (01.01.2009) and in the Latvia's Sustainable Development Strategy 2030 [7]. Although Latvia aspires to the principles of sustainable development, there exist a relatively small number of theoretical studies and practical

results in the area of simulation modelling of sustainable development. Therefore the proposed framework presents a novel approach in the context of spatial and regional planning in Latvia.

The goal of the proposed COMMOD modelling framework is to provide a technical decision support tool for stakeholders and decision-makers in territorial management planning allowing them to evaluate alternative development scenarios and planning options. The hypothesis of the research is that the quality of life and sustainability are the primary goals and criteria of sustainable community development. The modelling framework is based on an overall concept of sustainable community and regional development as an continuous process defined neither by fixed goals nor by specific means of achieving them.

METHODOLOGY

In recent years, new forms of simulation have come into popular use in urban, environmental and economic research, supported by an array of interdisciplinary advances in many scientific areas, especially in the computer and geographical sciences. Generally all simulation models can be roughly divided into two categories: macroscopic (top-down) and microscopic (bottom-up) models. The microscopic models are most commonly based on Cellular Automata (CA) or Multi-Agent Systems (MAS) formalism and are often applied to the simulation of spatial systems in dynamic and high-resolution contexts. Modelling systems behaviour with explicit dependency on the geographic space requires a geographic information support that is usually accomplished within Geographic Information Systems (GIS). Agent-based models give importance to the definition of each agent's internal structure and are focused on the definition of rules modifying the state of the agents and relations between them.

The use of top-down systems-thinking approach by involving the creation of a system dynamics models has been given increasing attention in the recent years [8, 9], because system dynamics is particularly suited to the investigation of complex systems containing many interconnected elements with complicated interactions. System dynamics ascribes a great importance to definition of the model structure, and establishes relations between variables of stock, flow and auxiliaries [2]. However, the system dynamics has disadvantages in revealing the spatial pattern change of

regional growth, and in incorporating those spatial variables into modelling.

An integration of the system dynamics and agent-based concepts can be fruitful allowing combining the best properties of each single concept. In the recent years, several ideas and practical implementations for integrating system dynamics and agent-based concepts have been proposed [10, 11].

A. 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.

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 [12, 13, 14]. 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 [13]. The choice of indicators is a critical determinant of the behavior of a sustainable system, poorly chosen indicators can cause serious malfunctions [12]. Orientors are labels for certain categories of concerns or interests [13]. Different systems may have the same orientors, but would have different corresponding indicators.

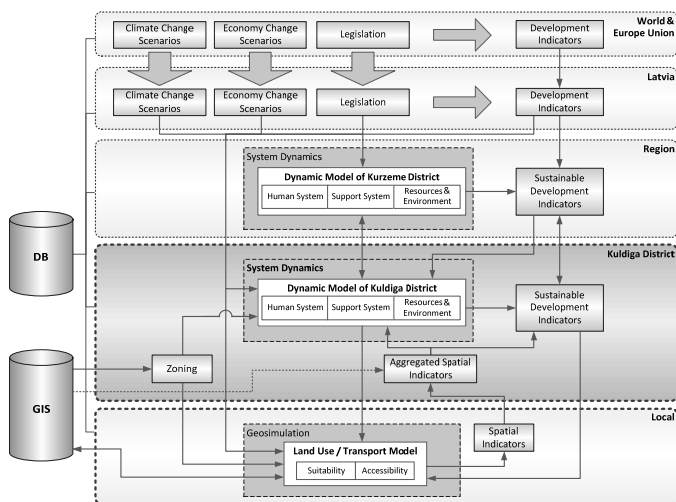


Fig. 1. Conceptual design of the COMMOD framework to study sustainable community development (adapted from [4]).

In this study, 42 key indicators based on expert discussions and workshops are chosen, they are grouped into three subsystems (human system, support system, natural system) and categorized by 7 composite indicators or basic orientors proposed by H. Bossel [13]. The seven basic orientors are aggregated into three dimensions [15]: social cohesion, economical cohesion, environmental balance. The main indicator - the quality of life – is calculated from the basic orientors and dimensions.

B. 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 the European 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 [4].

The world, the European Union and Latvia scales represent external drivers and scenarios such as climate, economy and legislation change that will influence Kurzeme Region and Kuldiga District. The regional scale represents a system dynamics model of economy-environment interaction model of Kurzeme Region. The district scale contains an economy-environment interaction model of Kuldiga District.

Sustainable development should be compliant with legislation of the Republic of Latvia and the European Union. The model should balance and integrate the social, economic and environmental components of the community of the region.

C. Concept of System Dynamics Sub-Model

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 system dynamics modelling part distinguishes four main systems containing six aggregated sub-components or sectors. In Figure 2 a conceptual structure of the system dynamics model is shown.

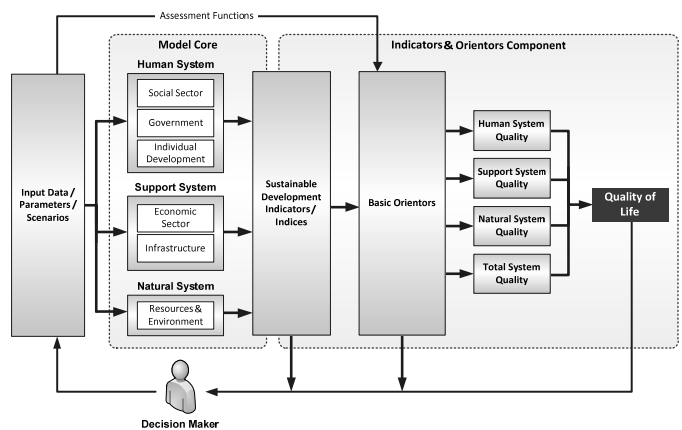


Fig. 2. The conceptual system dynamics sub-model [23].

The proposed model structure is based on prominent works in the field [13, 16]:

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.

- (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 for meeting 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.

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. This system has one component:

- (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.

D. Concept of Agent-Based Sub-Model

The multi-agent sub-model of the COMMOD framework consists of three inter-related levels (Figure 3) representing the dynamics of the human community at detailed level: population, landscape environment and industrial environment.

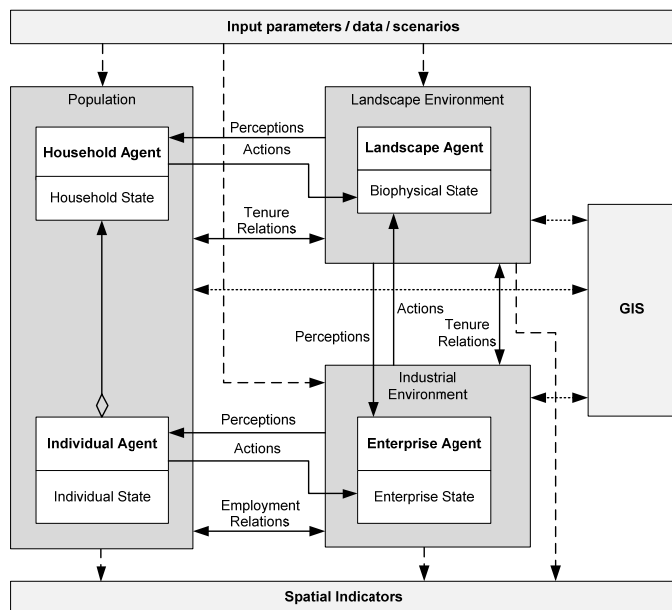


Fig. 3. The conceptual COMMOD multi-agent sub-model [23].

A household agent represents an individual household, the members of which have spatial knowledge about the landscape environment. The household agent model contains a collection of person agents representing individuals of a household. The dynamics of household and person agents includes natural changes, which occur regularly without any actions of the agents (e.g. person's age), and externally-driven changes, which occur due to interventions from outside of the system (e.g. education status, wage level), as well as impacts

due to the effects of agent activities during simulation. Each agent contains a predefined rule set determining the agent's behaviour and reaction to external stimuli.

The landscape environment is a system consisting of spatially structured landscape agents. Each landscape agent represents a fixed land cell corresponding to the geographical data from a GIS-raster layer. The landscape environment contains two sub-models for simulation of agricultural yield dynamics and forest yield dynamics.

The industrial environment contains spatially organized enterprise agents representing industrial production and service companies in a given region. Households provide the labour force.

IMPLEMENTATION OF SYSTEM DYNAMICS SUB-MODEL

Based on the conceptual model, this study develops a sustainable development system dynamics model using the software Vensim 5.10. The model implementation is based on the existing experience presented by such well known system dynamics models as WORLD2 [3], Miniworld [8], WORLD3 [9], T21 [17].

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

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 corresponding stock-flow diagrams are presented in each section, respectively.

A. 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.

The social system sector implements behavioural aspects of population development (Figure 4), income composition, social groups and organizations, social security, medical care and old age provision.

The entire population is divided into four population cohorts. Each cohort has 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 [5]:

$$\begin{aligned}
 OM &= e^{\alpha_0 + \alpha_1 POP + \alpha_2 LR + \alpha_3 GL + \alpha_4 ACC}, \\
 IM &= e^{\alpha_0 + \alpha_1 POP + \alpha_2 LR + \alpha_3 GL + \alpha_4 ACC},
 \end{aligned}
 \tag{1}$$

where $\alpha_0 \dots \alpha_3$ are parameters;
 POP is the number of residents in a region;
 LR is land rent;
 GL is the area of green land in a region;
 ACC is access attractiveness in the modelled region.

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.

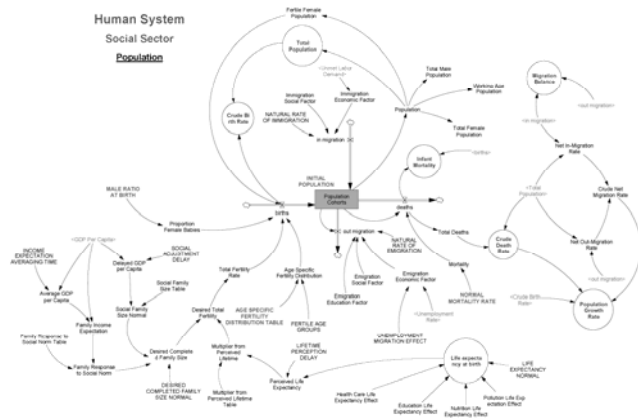


Fig. 4. Population sub-model [23].

The government sub-model (Figure 5) represents a regional government and administration, public finances and taxes.

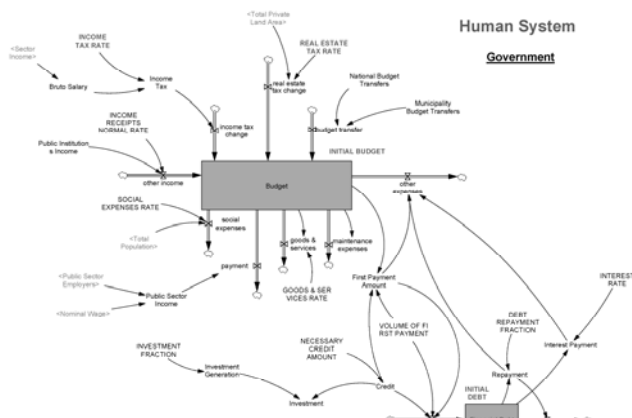


Fig. 5. Government sub-model [23].

B. 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 development. An increasing population results in increasing demand for infrastructure capacities.

The economic system sector simulates industrial production (Figure 6), agricultural production, consumption, commerce and trade processes, labour and employment.

The industrial production sub-model is based on the classical Cobb-Douglas production function with parameters adapted to Latvia [18, 19]:

$$Y = A \cdot K^\alpha \cdot L^{1-\alpha} \quad (2)$$

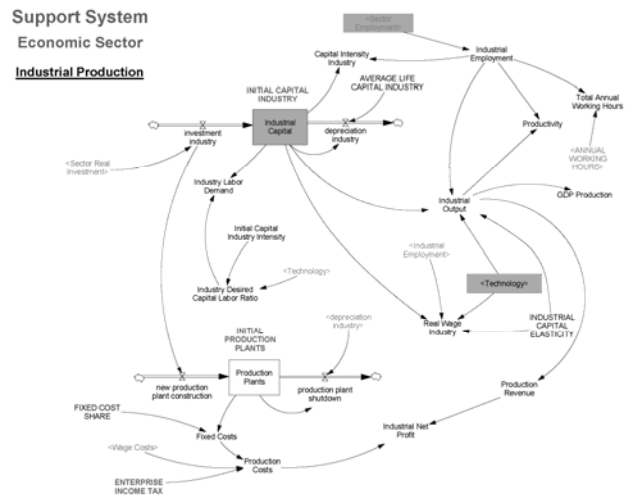


Fig. 6. Industrial production sub-model [23].

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

The services sub-model has a similar structure to the sub-model of industrial production.

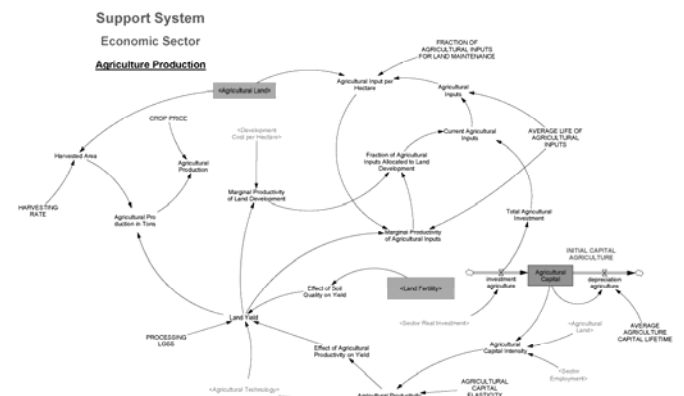


Fig. 7. Agricultural production sub-model [23].

For modelling of agricultural production (Figure 7), a modified Cobb-Douglas function is used, where the area of agricultural land is used as an additional factor [20]:

$$Y = A \cdot L^\alpha \cdot K^\beta \cdot Z^{1-\alpha-\beta} \quad (3)$$

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.

Similar function has been previously used [21, 22] to describe and model agricultural output for certain time period in Latvia.

C. 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 non-renewable 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.

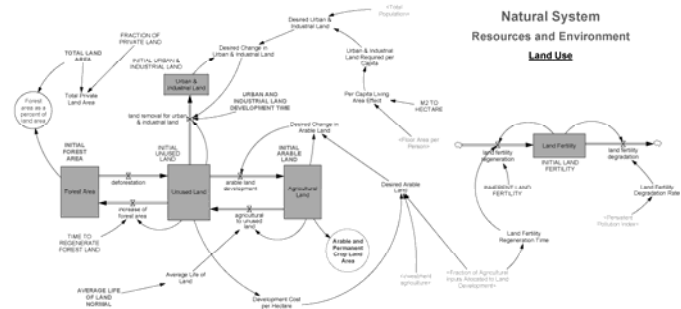


Fig. 8. Land use sub-model [23].

In Figure 8 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 and land used for urban & industrial settlements referring to Kuldiga municipality. A transition between different land types is driven by economic and environmental factors. The expansion/increment of the agricultural and urban areas is a process of transformation/conversion of the undeveloped land into the developed land.

D. Indicators Component

The indicators component (Figure 9) 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 42 indicators aggregated into seven basic orientors and three dimensions, as previously discussed in Subsection II. A.

RESULTS

Currently the model has not been fully completed and a model calibration has not been performed. However, the first preliminary simulation results have been obtained based on statistical data for Kuldiga District in 2009. The main

statistical data source for model development is the database of Central Statistical Bureau of Latvia.

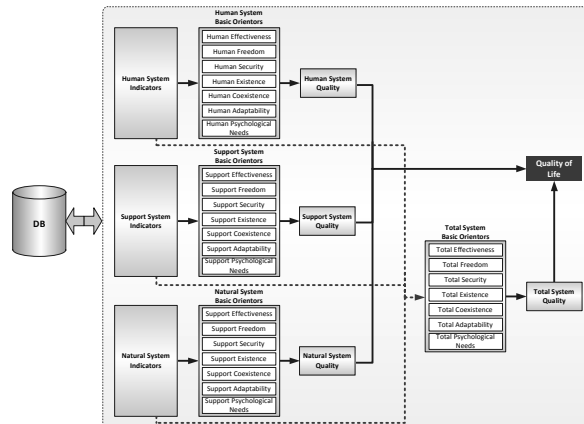


Fig. 9. A simplified structure of indicators component [23].

Preliminary

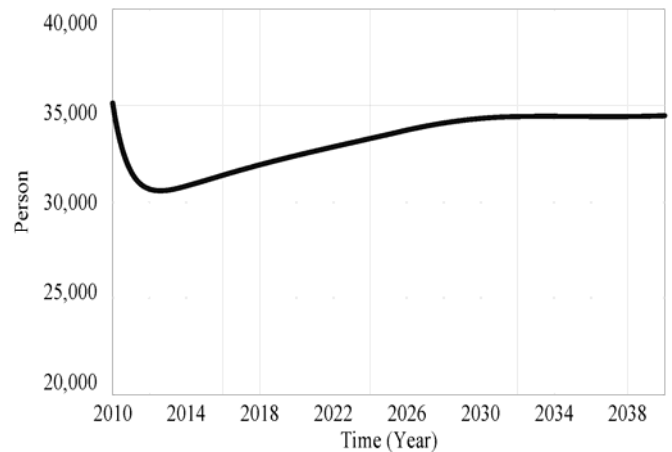


Fig. 10. Preliminary simulation results: total population [23].

The simulated population dynamics (Figure 10) 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 show the first signs of a recovery from the economic crisis, and along with the economic growth the emigration rate will decrease. However, if birth rate stays low then a trend of population dynamics still will be decreasing. The simulated GDP per capita (Figure 11) shows an increasing trend, however in 2030 a decline will begin. That can be explained by constrained demographical resources needed for a sustainable economic development.

In Figures 12, 13 two possible population change scenarios are shown. In the first scenario (Figure 12), the birth rate is increased by factor 1.6. In this case the total population after an initial decline period will return to the level close to the initial value.

In the second scenario (Figure 13), the initial birth rate is increased by factor 2. In this case the total population after an

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

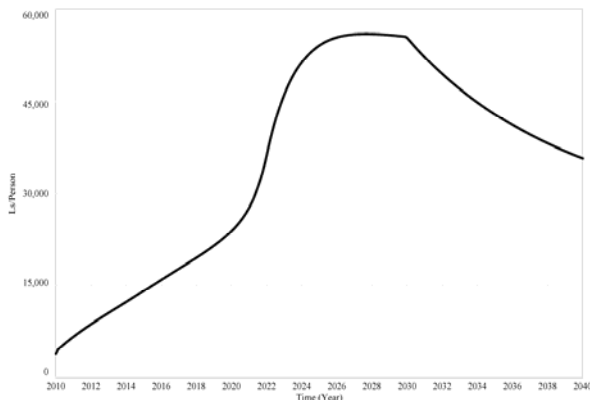


Fig. 11. Preliminary simulation results: GDP per capita [23].

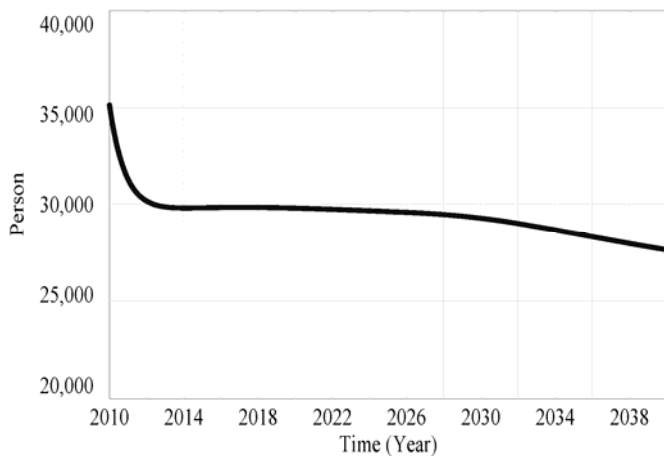


Fig. 12. Simulated population change scenarios: Birth rate increased by factor 1.6 [23].

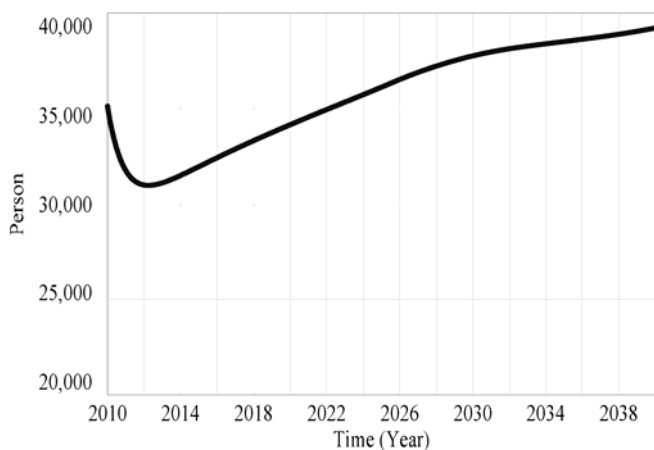


Fig. 13. Simulated population change scenarios: Birth rate increased by factor 2 [23].

CONCLUSIONS AND FUTURE WORK

In order to understand, analyse and forecast the temporal and spatial factors influencing and determining the sustainable community development, accurate evaluation of regional

growth has become increasingly important. In this context, an integrated system dynamics and agent-based model for sustainable development assessment is presented. The key to implementing a sustainable community development model is the ability to successfully apply integrated cross-disciplinary knowledge in social, cultural, economic and environmental domains.

Research work and development continues and the COMMOD framework model is currently being enhanced to correctly represent regional and municipal processes along with interaction with policies coming down from national and the EU levels. Once fully developed, calibrated and tested, the proposed framework will be an invaluable tool in assisting decision-makers in sustainable development planning, as well as an educational means in understanding how various regional sub-systems function.

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Arnis Lektāuers, Jēkabs Trušiņš, Inese Trušiņa. Kombinēts daudzņēmēju sistēmdinamikas un aģentu bāzēts ietvars ilgspējīgas kopienas modelēšanai
Pēdējos gados virkne zinātnisko mēģinājumu ir vērsti uz risinājumu iegūšanu ilgspējīgas attīstības procesu modelēšanai un imitācijai, izmantojot automātu bāzētus modeļus, kas ļauj pāriet no vispārēja mēroga, apvienota statistiskā līdzsvarā esoša telpiskā attēlojuma uz daudz detalizētāka mēroga formām, kur imitācijas modelēšanas centrā atrodas dinamiskie procesi. Šajā rakstā ir piedāvāts ilgspējīgas kopienas modelēšanas ietvars (COMMOD) sistēmdinamikas modeļu integrācijai ar aģentu bāzētām sistēmām un ģeogrāfiskajām informācijas sistēmām ilgspējīgas kopienas attīstības imitācijas modelēšanas kontekstā. Piedāvātais ietvars ir izstrādāts Kurzemes reģiona Kuldīgas pašvaldībai Latvijā. Dotā pētījuma projekta ilgtermiņa mērķis ir izstrādāt daudzņēmēju telpiski precīzu dinamisku modeli, kas apvieno komponentus piecos telpiskos līmeņos: globālajā (pasaule un Eiropas Savienība (ES)), nacionālajā, reģionālajā, novada un lokālajā līmenī. Reģionālo līmeni atspoguļo Kurzemes reģiona ekonomikas un vides mijiedarbības sistēmdinamikas modelis. Novada mērogs satur Kuldīgas novada ekonomikas un vides mijiedarbības modeli.
Pētniecības darbs un izstrāde joprojām turpinās, un COMMOD ietvars pašlaik tiek paplašināts, lai korekti attēlotu reģionālos un pašvaldības procesus līdztekus mijiedarbībai ar nacionālā un ES līmeņa ietekmes procesiem. Kad piedāvātais ietvars tiks pilnībā izstrādāts, nokalibrēts un notestēts, tas būs vērtīgs palīginstrumentis lēmuma pieņemējiem ilgspējīgas attīstības plānošanā, kā arī mācību līdzeklis izpratnes gūšanai par to, kā funkcionē dažādas reģionālās apakšsistēmas.

Арнис Лектауэрс, Екабс Трушиньш, Инесе Трушина. Комбинированная многомасштабная система на базе системной динамики и агентов для моделирования устойчивой общины

Последние годы ряд научных попыток ориентированы на получение решений для имитационного моделирования процессов устойчивого развития, используя автоматные модели, что позволяет переходить от укрупнённого, находящегося в статическом равновесии пространственного представления всеобщего масштаба, к формам на много более детализированного масштаба, где в центре имитационного моделирования находятся динамические процессы. В данной статье предложена система моделирования устойчивой общины (COMMOD) для интегрирования системно-динамических моделей с агентно-базированными системами и геoinформационными системами в контексте имитационного моделирования устойчивого развития общины.

Предложенная система разработана для самоуправления Кулдиги в Курземском регионе Латвии. Долгосрочной целью данного научного проекта является разработка многомасштабной пространственно-четкой динамической модели, которая объединяет компоненты в пяти пространственных масштабах: в глобальном (мир, Европейский Союз (ЕС)), национальном, региональном, областном и локальном масштабе. Региональный уровень представляет системно-динамическая модель взаимодействия экономики и среды Курземского региона. Областной масштаб содержит модель взаимодействия экономики и среды Кулдигской области.

Исследовательская работа и разработка продолжается, и система COMMOD расширяется, чтобы корректно представлять региональные и областные процессы параллельно с взаимодействием с процессами влияния национального уровня и уровня ЕС. Когда предложенная система будет полностью разработана, калибрована и протестирована, она будет ценным вспомогательным инструментом планировщикам устойчивого развития, и также пособием для обучения с целью понимания образа функционирования разных региональных подсистем.

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