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Agent-based modelling for ecological economics: A case study of the Republic of Armenia

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ABSTRACT

The ecological modernisation of enterprises has led to significant levels of total emissions in the atmosphere. This is a very important and complex issue for the Republic of Armenia (RA). An agent-based model was developed to determine the best trade-offs for the ecological modernisation of enterprises. The aim is to solve the bi-objective optimisation problem, the objectives of which are the 'Integrated Volume of Total Emissions' and the 'Integrated Index of Industrial Production'. The results indicate that it is possible to reduce the total emissions in the atmosphere by more than 20% for a ten-year period. This may be done by keeping up the positive dynamics of industrial production through choosing trade-offs in the frame of the 'Pareto-optimal ecological modernisation' scenario. The scenario was obtained with the help of the suggested genetic algorithm, modified for the problem of the binary control of transitions from initial non-ecological states of each enterprise, towards the target state of ecologically pure manufacturing.

1. Introduction

Both ecology and economics are concerned with interactions between the government regulation system and enterprises, which are the main stationary sources of emissions. The Republic of Armenia has significant opportunities to develop ecological economics in the high-tech, green agriculture, tourism, solar energy, and others low-emission economic sectors.

This work is devoted to the developed agent-based model, which is intended for decision-makers of the government regulation system of the Republic of Armenia (RA), who decide on the ecological modernisation of enterprises in order to transform them from the initial non-ecological state towards ecologically pure manufacturing. To support this process, the government regulator should set optimal annual values of emission fee rates, levels of penalties and subsidies, air pollution limits and other parameters for agent-enterprises having stationary sources of emissions. In addition, the government regulator forms the investment fund for supporting ecological modernisation through subsidies for agent-enterprises. Finally, the government regulator allows or blocks the modernisation processes of enterprises and distributes subsidies between them.

One of the biggest problems of the government regulation system involves finding the best scenario for the ecological modernisation of large agent-enterprises characterised by significant levels of air pollution. Such a scenario can be referred to as '*The Pareto optimal ecological modernisation*' and assumes a reduction in the total emissions in the atmosphere while keeping up the positive dynamics of industrial production. The best scenario can be achieved without closing any enterprises. This is especially important for the Republic of Armenia because of its social and economic problems, in particular, its high level of unemployment and the low profit of its households.

Another important issue for the government regulator is related to the appropriate assessment of the consequences of boundary scenarios of slow and fast ecological modernisation. On the one hand, the slow ecological modernisation implemented currently does not require significant investments for enterprises and subsidies from the government. On the other hand, the observed

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emissions in the atmosphere produced by enterprises have grown during the last ten years in the RA. The possible effects on fast ecological modernisation are not obvious because its implementation can require closing some enterprises and significant subsidies from the government.

Finally, the government has a series of regulation tools, which are not used to full effect in the RA. For example, emissions fee rates are seldom changed. At the same time, many enterprises in the RA increase their output through extensive increases in the use of resources (for example, they increase the production capacity for ore deposits instead of the capacity efficiency). Increasing the outputs without a transition to new technologies increases air pollution. At the same time, the government can influence the production policy of enterprises through increasing emissions fee rates and penalties. However, there is also a feedback effect caused by a possible decrease in profit and tax revenues in the budget of the Republic of Armenia. Therefore, the quantitative assessment of coupled ecological and economic effects is very important.

The developed simulation model can be useful also for an agent-enterprise as a tool for determining the optimal ecological modernisation strategy in case of the government regulation. Estimating the possible consequences of avoiding ecological modernisation or the time shift of appropriate investments is important for the agent-enterprise in case of the financial deficit. If most enterprises choose the same strategy of avoiding ecological modernisation, it will cause some consequences in the government ecological regulation, for example, increasing emissions fee rates and penalties. Therefore, an assessment of the benefits of transformation from the initial non-ecological state towards the state of ecologically pure manufacturing is important for all enterprises. Besides, any non-ecological enterprise will be less attractive for investors compared to environmentally friendly and partially ecological enterprises. Therefore, ecological modernisation is important for the reputation of enterprises.

The suggested model allows forecasting to be carried out and the optimization of some parameters of the ecological-economics system, which will be interesting for both the government and agent-enterprises by taking into account their inter-relationship. The model is the intellectual core of a decision support system for determining optimal strategies for the ecological modernisation of the Ministry of Nature Protection of the Republic of Armenia and the largest industrial enterprises contributing to stationary sources of emissions in the atmosphere.

The developed model uses methods of agent-based modelling. Agent-based models have been widely used in ecological economics and allow exploration of the individual behaviour of interacting agents that have an impact on the environment (Heckbert et al., 2010).

Agent-based models for ecological economics can be classified into three major groups. The first group deals with homogeneous economic agents. For example, research has been conducted involving modelling the dynamics of different organism populations depending on ecological conditions. In a study by Stillman et al. (2015), individual-based models of birds, including their prey and habitats, are used to provide the evidence-base for coastal bird conservation and shellfishery management. In the work by Reidsma et al. (2015), an agent-based land-use change model is used to simulate rural development under two plausible global change scenarios at both the farm and landscape level. A multi-level agent-based model is presented in a study by Koleva and Hellweger (2015). The model explicitly combines mechanisms at multiple levels of organisation, both at the intracellular and population level, which is a common challenge in the biological sciences. Agent-based modelling is often applied in the investigation of epidemiological dynamics, depending on ecological and other conditions (Siettos et al., 2015; Belsare and Gompper, 2015; Crooks and Hailegiorgis, 2014).

The second group of studies concerns heterogeneous interacting economic agents. For example, in the work by Pérez and Janssen (2015), an agent-based model is used to analyse the effects of spatial heterogeneity and agent mobility on social-ecological outcomes. In the work by Bert et al. (2015), an agent-based model of Argentinean agricultural systems involving many heterogeneous and interacting agents is employed. It is necessary to highlight the study by Murray-Rust et al. (2014), in which an agent-based model is designed to investigate the multifunctional ecosystem service production and heterogeneous behaviour of land managers. Another work by Rebaudo and Dangles (2013) involved the development of an agent-based simulation of heterogeneous human populations in interaction with the environment.

The third group of studies investigates the trade-offs for ecological economics between opposite interests of economic agents. This research involves the development of models and multi-objective systems to determine the trade-offs in sustainability assessments (Zhang et al., 2016; Hadka and Reed, 2015; Pollesch and Dale, 2015; Efroymson et al., 2012; Kurek and Ostfeld, 2013).

The simulation built in this study was based both on a population of homogeneous economic agents, such as agent-enterprises interacting with each other; and also heterogeneous agents, such as government regulators with their own economic objectives. A special evolutionary algorithm is used for the control of transitions between the states of each agent in order to shift agent-enterprises towards ecologically pure manufacturing.

The developed simulation was implemented in the *AnyLogic* tool. *AnyLogic* brings together different simulation modelling methods, including both system dynamics and agent-based modelling (Borshchev, 2013). We combine these methods in order to forecast activity indicators of agent-enterprises, taking into account feedback and forward links. We also consider time delays between such important characteristics as the emission of harmful substances into the atmosphere and the dynamics of diagnosed diseases caused by emissions. Many variables can be described by a flow process with such elements as reservoirs, flows with rates, and fixed parameters. The system dynamics approach has been applied successfully in the existing literature on ecological modelling (Walters et al., 2016; Dace et al., 2015; Zhang et al., 2014; Crookes et al., 2013; Marimon et al., 2013; Li et al., 2012; Shi and Gill, 2005). Hence, system dynamics methods are effective for modelling individual characteristics of agent-enterprises. On the other hand, there are different finite states for each agent-enterprise, which have a significant impact on its indicators. Taking into account such agent states allows us to control the dynamics of ecological modernisation.

The major objectives of this study are: (1) to build the first simulation of an ecological-economics system for the Republic of Armenia (RA); (2) to compute the best trade-offs for the ecological modernisation of Armenian enterprises through solving a complex bi-objective optimisation problem; (3) to investigate the performance and potential applications of the developed system (http://smartersim.com/ecmodel) for other regional ecological-economics systems.

2. Simulation for ecological economics

2.1. Model concept

The main aim is to seek the best trade-offs and optimise the ecological-economics system through optimal control of the agent-enterprises transformation. This process occurs from their initial non-ecological state towards the target state of ecologically pure manufacturing (a low-emission state).