Combination of analytical and agent-based modeling in studying migration processes in the Arctic regions of Eurasia

V Bystrov¹, S Malygina¹,², M Shishaev¹,³ and D Maevsky⁴

¹ Institute for Informatics and Mathematical Modeling — Subdivision of the Federal Research Centre «Kola Science Centre of the Russian Academy of Sciences, Apatity, Russia
² Apatity branch of Murmansk Arctic State University, Apatity, Russia
³ Murmansk Arctic State University, Murmansk, Russia
⁴ Omsk State Technical University, Omsk, Russia

shishaev@iimm.ru

Abstract. The article is devoted to the development of forecasting methods for the research on migratory processes. The authors pay attention to specific problems of migration in the Arctic regions of Eurasia. It is proposed to use a combination of analytical and simulation modeling to enhance the quality of prognoses for migration flows. Two parts of the ongoing research are described: technology of entropy-robust identification of the parameters of simulation models and a set of simulation models. The technology of entropy-robust assessment is based on the idea of re-use of formalized knowledge in the analysis of statistical characteristics of the parameters of simulation models. The technology allows to shorten the time and reduce the complexity of development of appropriate simulation models of migration. The complex of simulation models is developed on the basis of a combination of system dynamics, discrete-event and agent-based modeling. The integration of agent-based and analytical modeling to create simulation models of migration processes allows, on the one hand, to ensure the accuracy of the simulation according to the quality of the source data, and on the other, to analyze socioeconomic systems at the required level of abstraction. The results of computational experiments to identify trends in migratory processes in the Arctic regions are presented.

1. Introduction
A characteristic feature of the modern world is the realization of a variety of migratory processes, involving a significant number of people worldwide. Migratory processes can dramatically alter demographic indicators (the population, its age structure, death and birth rates) and the labour force participation rate, which is causing the economic indicators dynamics and which will determine the living conditions of future generations. The labour market highly depends on migration. Moreover, the transformation of socio-spatial relations comes about through the migratory process. The rates of changes listed above are different and are not always consistent with the adaptability skills of migrants and indigenous communities, which can lead to the increase of social tension.

In comparison with the tasks of forecasting the dynamics of the population of some region, the study of migration is considerably more difficult. The reason for the risen complexity of forecasting migration is the paucity of complete information on the components of migratory processes. This leads
to the impossibility for the prognosis to be as accurate as when modeling the natural dynamics of the population within a considered area.

The macroregion of Arctic countries of the Eurasian continent, including Russia, Canada, USA, Norway, Denmark, Finland, Iceland and Sweden [1], is of particular interest for the study of migratory processes. In spite of cultural differences and political contradictions, the common economic interest and similar geographical and climatic conditions make a comprehensive study of Arctic countries as a unified system topical. Currently, an explosive growth of interest of the international community in the development of the Arctic, the sustainable use of its rich resource base and the transport options [2] is noticed. Together with the strengthening of economic motives for cooperation in the Arctic regions, the political and legal base of this cooperation strengthens: international agreements and declarations regulating various aspects of activities are formed, for instance, the Declaration on the Protection of the Arctic Environment (“Rovaniemi Declaration”) adopted in 1991. At the same time, the successful realization of national and international projects for the development of the Arctic is impossible without the development of human capital, which nowadays significantly depends on migratory processes.

According to the website of the University of the Arctic “UArctic” (https://research.uarctic.org/), more than 50 international centers and institutes are engaged in the research on the Arctic, in particular in the study of migratory processes. This underlines the fact that migration issues in Arctic regions are in the focus of scientific and practical interest. It is worthy to mention that the problems of migration are specific for each of the Arctic countries. A good illustration of this is Scandinavia, where the issue of the rise of migration flows from the countries of the Middle East, North Africa and Asia has become topical. The key problems connected with migration in the Nordic countries are the assimilation of the newcomers in the context of objective cultural differences, the integration of immigrants into local communities, the establishment of a balanced regional labour market. The issue of migration in Arctic regions of the Russian Federation has a different focus: the outflow of the young people from the northern territories, the possible ways of staff shortage abolition, personnel logistics of major infrastructure projects etc.

The importance of staffing for the development of the Arctic territories makes the problem of the migratory process modeling in the macroregion in question highly relevant. Its solution requires the elaboration of an effective methodological apparatus to obtain adequate predictions about the movement of a considerable amount of people from one region to another. Currently, the most developed analytical models of migration [3-6] based on differential equations and other mathematical apparatus. Analytical models, as a rule, rely on observational data in the form of time series of significant parameters [7, 8] and provide sufficiently high accuracy, however, with the complexity of the structure of the simulated system, the complexity of their development increases dramatically. Another problem is the availability of basic data: in the case of socio-economic systems, only macro-level observational data are most often available. This forces to increase the scale of the model, which inevitably leads to a decrease in the accuracy of modeling and limits the possibility of using the corresponding models at the lower levels of management (tactical, operational, ...). An alternative approach is agent-based modeling, where the structure of the system as a whole is initially described, and then model parameters are identified using statistical, expert, and other methods. In comparison with analytical approaches, agent-based models make it possible to reproduce the structure of the system with the required detail without a significant increase in costs. In this paper, we consider the technology of combined use of agent-based and analytical modeling within migration simulation models, which allows, on the one hand, to ensure the accuracy of modeling according to the quality of the source data, and on the other, to analyze the system under study at the required level of abstraction.

2. Methods and technologies

2.1. Entropy-robust identification technology for simulation models

One of the crucial and complex issues in the creation of simulation migratory models is the identification of their parameters, which are mostly characterized by uncertainty. Uncertainty
manifests itself both at the level of quantitative evaluations of parameters and at the structural level. The parameters of complicated systems generally have an internal complex structure, which is also not determined. The problem is complicated by the fact that in real situations the identification of parameters has to be performed on the basis of a limited number of measurements. At the same time, taking into account the internal structure of a complex measurement (factors affecting the value of a parameter) makes it possible to expand the scope of a priori observations, available for use as part of the identification problem. Traditional statistical methods are poorly applicable in this case. The use of the entropy-robust identification method will allow us to obtain an acceptable solution to the problem in the form of evaluations of the statistical characteristics of the model parameters.

As a part of the research project “The development of methods for identifying dynamic models with random parameters and their use for predicting migration in Eurasia”, a technology for using entropy-robust identification for simulation models of forecasting migratory processes based on formalized expert knowledge is proposed. The traditional entropy-robust estimation methodology involves the participation of mathematicians and system engineers at different stages of the model development. As the practice shows, interaction with experts is a non-trivial problem that requires a sufficient amount of time and resources. The proposed technology involves the accumulation and reuse of experience in the use of entropy-robust estimation in the modeling of various systems. According to the authors, this will help to reduce the time frame and the complexity of developing appropriate simulation migratory models.

The general scheme of the technology is presented in Figure 1.

![Figure 1. Information technology of using entropy-robust identification for simulation models for predicting migration processes.](image-url)

The technology being developed can be divided into two relatively independent parts:

1) Determination of the values of the parameters of simulation models based on entropy-robust identification.
2) Formation of recommendations for the formulation of the problem of entropy-robust identification in terms of determining the type of entropy function and a set of constraints.

The first part of the technology being developed is the sequential implementation of the following stages:

1) Formation of the structure of complex measurement.
2) Determination of the characteristics of a random measurement.
3) Entropy-robust estimation.
4) Determination of the statistical characteristics of the parameters of simulation models.
The result of the entropy-robust identification of forecasting models of migratory processes is formation of statistical evaluations of model parameters. In this case, the entropy-robust identification method is based on the idea of maximizing the entropy function, which includes both random independent parameters and random measurement noise. For the formulation of the task of maximizing the entropy function, various boundary conditions are determined, either due to the limitations of the subject area of the problem being solved, or to statistical limitations arising because of the probabilistic nature of the parameters studied. According to the analysis of scientific works related to the development of the entropy-robust estimation approach, it was assumed that when solving a particular problem, the choice of the type of entropy function and the type of boundary conditions for the formulation of the entropy maximization problem is based on the experience gained and the researcher's intuition. In this regard, an idea emerged about the development of information technology, which simplifies the process of analytical formulation of the problem of maximizing the entropy function. It is proposed to base this technology on the accumulation of information on the precedents of various versions of the formulation of the entropy-robust estimation problem and their subsequent use in solving similar problems.

The technology of using entropy-robust identification to model simulation migratory processes is based on the idea of reusing formalized knowledge. Ontological descriptions are used as a repository of knowledge, the main source of which is the results of interaction with “subject” experts. In particular, the study develops two types of ontologies: a top-level ontology and an applied ontology. Each of the generated ontologies has its own purpose. The upper level ontology contains structured information about the concepts, terms and relations between them, which are used in the methods of developing simulation models. This ontology also includes formalized procedures for the automatized synthesis of simulation models based on logical inference. The applied ontology contains formalized knowledge of the entities and relations between them, which characterize migratory processes. When forming the applied ontology, the main aspect was shifted towards the practical application of the concept of mathematical demoeconomics, which was invented by academician Yu.S. Popkov [9].

Thus, the second part of the technology of using entropy-robust identification for building simulation models consists in the implementation of the following stages:

1) Analysis of observed precedents.
2) Making of recommendations on the choice of the type of entropy function for solving a specific problem of the entropy-robust estimation.
3) Recommending on the set of boundaries for the problem of maximizing the entropy function.
4) Providing recommendations to the researcher.

If the technology being developed is considered from the point of view of the control theory, two feedback loops are clearly distinguished. The first loop is connected with the processes of accumulating precedents about variants of the formulation of the entropy maximization problem when performing entropy-robust identification and their subsequent use in the development of recommendations on choosing the entropy function and parameters of the entropy maximization problem. The second loop defines the procedure for obtaining statistical evaluations of the parameters of simulation models based on the entropy-robust approach.

2.2. Simulation Models of Migration

Based on the analytical model of migration and the technology of using entropy-robust identification, a complex of simulation models was developed. Structurally, the complex, being a set of model agents, reproduces the basic principles of mathematical demoeconomics. To implement the simulation models, the Anylogic instrumental environment was used, providing the opportunity to combine system dynamics, discrete-event and agent-based modeling. In the process of developing a set of models, all three methods of simulation modeling were used:

- Agent-based modeling. It was used to encapsulate the characteristic properties of the entities of the subject area in separate software agents. As agents were identified: a man, a zone, a sector of economics.
- System dynamics. It was used to describe the dynamic processes occurring within certain agents. For example, the process of formation of the flow of goods between the zones for the agent "sector of economics."

- Discrete-event modeling. It was used in the form of state diagrams to describe the behavior of some agents. For instance, a person’s decision-making algorithm for migration to another zone.

According to the principle of mathematical demoeconomics, the model in its general form consists of two subsystems: “Population”, “Economy”, which are interconnected by direct and reverse connections. "Population" models the natural change in population size (fertility and mortality) and migration (internal and external). "Economy" reflects the economic state of each zone and the distribution of economic sectors in it.

Countries belonging to the Arctic and located on the Eurasian continent (Iceland, Sweden, Finland, Norway, Denmark, Russia) are considered as zones. As it was noticed above, each zone is represented by a model agent. The agent structure includes subsystems "Population" and "Economy". The main parameters, characterizing the agent "Zone", are: the name of the zone; zone size; the number of sectors of the economy; the percentage distribution of men and women. Filling the zone with people occurs in accordance with the percentage distribution of women and men, as well as the probability distribution of types of women. The type of women was determined on the basis of their fertile ability. For the western type of women, the birth is on average up to 2 children, and for the eastern type - from 3 to 6 children.

The main entity, which serves as the basic participant in the migratory process, is implemented as a separate model agent “Individual”. The essential characteristics of this type of agents are: age, the type of migration: satisfaction with the area of residence, probability of death, gender, the number of children, etc. The “Type of Migration” property of a person is determined by two main factors influencing the decision to change their place of residence: for economic reasons or family reasons.

The "Sector of Economics" agent is intended to reproduce the activities of enterprises and organizations engaged in a particular type of economic activity. The agent does not make a detailed division into specific goods and services, but uses some generalized indicators, for example, goods and services of the food industry. This approach is borrowed from statistical data on the types of economic activity adopted in the European Union (Eurostat - http://ec.europa.eu/eurostat/).

\[
M^k(n,t+1) = M^k(n,t) + h a_p M^k(n,t) \sigma^k(n) \phi^k(n,p) \phi^k(\lambda^k(n,t), n,t) M^k(n,t) - \left( h a_p M^k(n,t) (\phi^k(n) + \mu^k(n) M^k(n,t)) \right)
\]

Figure 2. Implementation of a system-dynamic model of changes in the production capacity of the economy sector.

To demonstrate the applicability of analytical migratory models in the composition of the developed simulation models, an example can be given. Consider a system dynamics model of changes in the production capacities of the economy sector of one of the zones. In this example, one of
the equations of the analytical migratory model is used to determine the input and output flow of the model. To solve this analytical equation, separate program functions were implemented that numerically solve the entropy-robust optimization problem. Figure 2 provides an illustration explaining this process, where the output parameters are M - production capacity; Rent_level - profitability threshold \((\lambda^k(n,t))\), Issue - sector’s output; Req_manpower - labor resources required. The input parameters of the model are Profit_Per_Inv – the share of profits allocated to investments \((q^k(n))\); Coef_ef_inv - investment efficiency ratio \((\sigma^k(n))\); Q, Q1 – are the coefficients of the depreciation functions \((\theta^k(n)),\mu^k(n))\); p is the equilibrium price \((p^k(n,t))\); b is a parameter of the technological structure \((b^k(n,t))\); S - salary; Profit_rate - rate of gain. The difference equations used in this system dynamics model are described in detail in [10].

The interaction between agents is implemented by transferring information about the values of certain parameters of each agent. In this case, the result of the imitation of the “Population” subsystem is the calculation of the spatial age and gender distribution of people by zones. A labour force supply based on the result obtained is formed in each of the zones important for the production of goods and services. These data are transmitted to the “Economy” subsystem, at the output of which the calculation of the spatial age and gender distribution of people by zones is made from this source.

According to the concept of entropy-robust optimization, the result of a series of computational experiments is an ensemble of all admissible trajectories of model output parameters under given conditions. In order to visualize the results of the simulation, the procedure of averaging and allocating the median of all possible values of the parameter at a certain point of time was performed. The step of presenting the simulation results is 1 year.

Tables with simulation results were formed for each of the six Arctic countries located on the continent of Eurasia. As an example, table 1 presents data on the total number of immigrants and emigrants in Norway. The table shows migration flows both between the Arctic countries and other regions of the world.

### Table 1. Total number of immigrants and emigrants in Norway.

| Immigration (people) | 2013  | 2014  | 2015  | 2016  | 2017  | 2018  | 2019  | 2020  | 2021  | 2022  | 2023  |
|---------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Denmark             | 4222  | 3653  | 3111  | 2973  | 3059  | 3449  | 3480  | 3257  | 3300  | 3578  | 3778  |
| Finland             | 574   | 631   | 566   | 544   | 466   | 463   | 446   | 431   | 416   | 402   | 388   |
| Iceland             | 1082  | 1112  | 1015  | 604   | 401   | 423   | 404   | 424   | 375   | 378   | 353   |
| Sweden              | 7138  | 6452  | 5204  | 4009  | 3672  | 3159  | 2919  | 2584  | 2806  | 2688  | 2707  |
| Russia              | 918   | 679   | 647   | 684   | 682   | 645   | 683   | 655   | 684   | 602   | 577   |
| Other               | 61855 | 57503 | 56733 | 57986 | 49912 | 51884 | 51702 | 51916 | 51336 | 50935 | 50460 |
| **Total**           | 75789 | 70030 | 67276 | 66800 | 58192 | 60023 | 59635 | 59267 | 58917 | 58583 | 58264 |

| Emigration (people) | 2013  | 2014  | 2015  | 2016  | 2017  | 2018  | 2019  | 2020  | 2021  | 2022  | 2023  |
|---------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Denmark             | 3117  | 1081  | 3737  | 3560  | 3262  | 3112  | 3121  | 3129  | 3698  | 3146  | 3154  |
| Finland             | 405   | 456   | 479   | 494   | 447   | 802   | 748   | 759   | 664   | 703   | 599   |

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Figures 3-6 show the dynamics of the total number of migrants for other Arctic countries without representation of the sex and age structure of migration.

In comparison with other Arctic countries, Russia has its own specificity in the structure of migration flows. As the retrospective data and forecasts show, the number of people leaving the Russian Federation to Iceland varies from 0 to 2 people a year. The same quantitative indicators are characteristic for people immigrating to Russia from the countries of Iceland and Denmark.

![Figure 3. Dynamics of the total number of migration in Sweden (unit of measurement - man).](image)

![Figure 4. Dynamics of the total number of migration in Finland (unit of measurement - man).](image)

![Figure 5. Dynamics of the total number of migration in Denmark (unit of measurement - man).](image)
4. Discussion
The research is aimed at developing forecasting modeling tools for migratory processes. The integration of demo-economic entropic and simulation models is one of the ways to improve the quality of methodological support for forecasting. Such a combination allows the flexibility to change the scale of consideration of the system under study while maintaining the level of accuracy of the prediction results determined by the modeling methodology used and the quality of the source data. The article describes the testing of such an approach on the example of a study of the migration of Arctic regions of the Eurasian continent. Further development of the work is the improvement of the integration mechanisms of analytical and simulation models in the direction of automating the processing of collective expert knowledge and their application to customize models.

Acknowledgments
The research is being carried out with the financial support of the Russian Foundation for Basic Research (projects # 16-29-12878 ofi_m "Development of methods for identifying dynamic models with random parameters and their application for predicting migration in Eurasia" and # 19-07-01193 A "Methods and means of information support for personnel management security of the regional mining and chemical cluster").

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