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Combining Microsimulation and Agent-Based Model for Micro-Level Population Dynamics

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Abstract

Population dynamics illustrates the changes of the size and age composition of populations. Modeling and simulation techniques have been used to model the population dynamics, and the developed models are utilized to design and analyze public polices. One classic modeling method is microsimulation. The microsimulation describes the population dynamics at the individual level, and actions conducted by the individuals are generated by stochastic process. An emerging method is agent-based model, which rather focuses on the interactions among individuals and expects to see unexpected situations created from the interactions. Their similar but different approaches can make them to complement weak points of the opponent in population dynamics analysis. From this perspective, This paper proposes a hybrid model structure combining microsimulation and agent-based model for modeling population dynamics. In the proposed model, the microsimulation model takes a role to depict how an individual chooses its behavior based on stochastic process parameterized by real data; the agent-based model incorporates interactions among individuals considering their own states and rules. The case study introduces Korean population dynamics model developed by the proposed approach, and its simulation results show the population changes triggered by a variance of behavior and interaction factors.

Keywords: population dynamics model, agent-based model, microsimulation model, hybrid population dynamics model

1 Introduction

Population dynamics is used to understand the changes that occur in the population over the course of time, so it helps us to estimate the future population composition and establish political strategies for the future. For limiting the scope of this paper, we limit the meaning

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of the population changes as the variation of size, or age distribution of individuals comprising the population, or movement of the individuals from one place to the other. Such population changes are difficult to measure because they are closely associated with the collective behavior of individuals. Even if we define the individual behaviors relating with the population dynamics, they are intricately relevant to individual personality and social factors.

Understanding the population dynamics recently has received great attention from governments as well as researchers. For example, many countries have the low-fertility problem [14]; while Niger have very high fertility rates (6.89 children per woman), the average fertility rates in OECD countries is 1.74, which indicates the overall populations are decreasing [2]. The low-fertility problem could be the clue of other economical, industrial, social problems [22]. Many countries built birth encouragement policies to alleviate these problems, but most of them have not led meaningful results [22]. Such failures may indicate that there needs the analyses on population dynamics from multiple perspectives.

To analyze the population dynamics, various analysis techniques have been applied. Microsimulation model (MSM) is one classical method to model the population dynamics at a micro-level. Specifically, MSM describes individuals in population with micro population data (e.g, census data) and simulates their behaviors with transition probabilities developed from the population statistics (e.g., fertility rate). When the simulation ends, MSM provides the projection of future population by aggregating the simulated individuals' data. Agent-based model (ABM) is considered as an emerging method to analyze population dynamics. Similar as MSM, ABM is based on individuals (or agents), but it has more focuses on the interactions among individuals (e.g., deciding a marriage partner). Hence, the objective of ABM is to see a unexpected situation (or emergence) created by encouraging the interactions and to provide insights to analyze that situation.

Two approaches have similar concepts on individual-level modeling. In other words, they both take the bottom-up approach to replicate the population dynamics, and each individual holds heterogeneous properties. Having said that, they also have different characteristics in the individual descriptions: In MSM, rich detailed data are utilized for individual behaviors, yet the interaction and feedback among individuals are often missing; in ABM, however, individual behaviors are translated into the process of interaction and feedback, which influences on other behaviors. Moreover, this could lead to an emergence of population dynamics that could provide invaluable insights.

Keeping their modeling characteristics in mind, there arises a need for a mechanism which incorporates positive points of both techniques. In this sense, this paper proposes a hybrid model structure consisting of both ABM and MSM. This composition is enabled by the bridge between them (i.e., individual-level modeling). Moreover, by the virtue of this bridge, their weak points would be compensated by the opponent's strong points. Specifically, the hybrid model for population dynamics describes an individual in the population, and the behavior and interactions are separately handled by MSM and ABM methods, respectively. Using the hybrid model, we expect to provide additional but precious information about the population dynamics as well as to estimate the future population structure.

This paper introduces the development of Korean population dynamics model as a case study of the proposed method. We designed an individual with separating its behaviors as MSM components and interactions as ABM components. Also, Korean population statistics and micro population data are utilized for the better replication. The simulation results from the developed model illustrate how the future population structure of Korea would change when the fertility rate (i.e., behavior factor) and the marriage rules (i.e., interaction factor) are varied.

The rest of this paper is organized as follows: Chapter 2 introduces related works about the population dynamics model; Chapter 3 explains how the proposed model is structured and its future usages, and chapter 4 presents a case study about the development of Korean population dynamics model with the proposed method and its simulation results and analyses; then, the paper is concluded in Chapter 5.

2 Backgrounds

This chapter provides the background about microsimulation and agent-based modeling, and introduces previous population dynamics models developed by both techniques.

2.1 Microsimulation Model for Population Dynamics

Microsimulation model (MSM) pioneered by Orcutt was applied to analyze socio-economic policies [16]. He identified and represented individual entities in the socio economic system with changing their behaviors as time evolved. MSM describes a target system at the individual-level, so the system dynamics are represented as the aggregation of individuals (i.e., bottom-up approach)[11]. With the bottom-up approach, population dynamics models developed by MSM were utilized as the evaluation tool of public polices [15].

MSM for the population dynamics generally requires a large sample of data from population census or survey, such as age at first childbirth, household income, etc. and uses this data to impart properties (or states) to individuals. The idea is simply to represent the constituent units with individual characteristics, which comes from real data rather than the average values. MSM is initialized by deploying this synthetic population where individual characteristics are associated with a particular unit or individual so that the distributions of the virtual world population are in conformance with the real one. With this initialization, an individual in MSM is simulated by its behavior executed by transition probabilities parameterized with population statistics. When the simulation ends, the simulation results are provided as the aggregation of individual properties.

Many population dynamics models have been developed in many countries for estimating of the future population and public policies: DYNASIM3 (USA), DYNACAN (Canada), MOSART (Norway), SESIM (Sweden), SAGE (UK), DYNAMOD (Australia), and DESTINIE (France). These models held similar structure —individuals are initialized with micro population data, and they decide their actions based on the transition probabilities.

2.2 Agent-Based Model for Population Dynamics

Agent-based model (ABM) consists of autonomous agents (or individuals) that decide their action with their own conditions, environment where the agents are situated, and their interactions. The interaction is considered as a key factor since it enables to analyze complex population dynamics [7]. The origin of ABM can be tracked back to Von Neumann machine [21]. Famous starting examples of ABMs are the segregation model by Schelling [18] and John Conways Game of Life [8]. Particularly during the lasts two decades, ABM has been improved from the theoretical perspectives, such as hierarchical and dynamic structure [5], and its application range has been widely spread, such as social science [9], biology [3], disaster response [4] and economics [13].

ABM is focused on the interactions of individuals to see unexpected situations (i.e., emergence) of a system. The main assumption under ABM is that interactions can produce the system behavior which is more than the aggregated sum of the individualistic activities. The emergence generated from ABM is expected to suggest the distinguished angles to a target system. There have been a variety of ABMs about understanding population dynamics. The agent based social simulation for population dynamics was initiated by Billari and Prskawetz [7]. Most of the previous works have been proposed in demographic contexts from the interaction perspectives, such as family formation [7], migration [12], residential mobility [6], household dynamics [10].

3 Combining MSM and ABM for Population Dynamics

MSM and ABM hold a common ground that they focus on the micro-level description to represent the real phenomena. Meanwhile, they also differ in the methods for modeling individual behaviors. This chapter explain the their similarities and differences, and these characteristics would become the possibility and necessity of their hybrid model for population dynamics.

3.1 Micro-Level Population Dynamics

Population dynamics shows us how population evolves and changes over a course of time. Demography has studied about the population dynamics, and its researchers see that the population changes are originated from behaviors and interactions of people in the population, such as fertility, migration, matrimony, mortality, etc. [17]. Micro-level population dynamics models follow demographic approaches: the proposed model describes an individual in population, and it behaves with their own states.

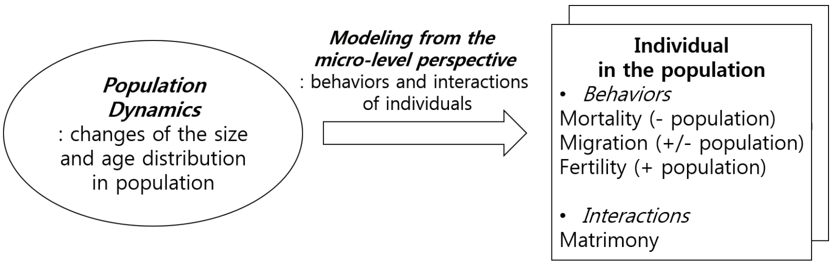

Figure 1: Modeling population dynamics from the micro-level perspective: behaviors and interaction of individuals

Figure 1 shows how we model an individual in population from the micro-level perspective. Among the individual behaviors and interactions considered in the Demographic view, we selected those that are strongly relevant to variations of the population size: mortality (behavior decreasing population size (- population)), fertility (behavior increasing population size (+ population)), migration (behavior increasing or decreasing population size (+/- population)), and matrimony (interaction strongly related with the fertility behavior). Therefore, the future population can be estimated by aggregating individuals who hold those behaviors and interactions.

3.2 Hybrid Model Structure for Population Dynamics

MSM and ABM have been widely used in modeling the population dynamics at the micro-level, but their interests are different: individual behaviors for MSM and interactions for ABM.

However, population dynamics does not depend on one side only, but both. For example, the population size is varied by fertility, mortality, and migration behavior, but those behaviors are strongly related with the interactions with others, such as the relationship between fertility and matrimony. We considered that when the population dynamics are depicted by not only direct factors but also indirect ones, that model could generate an emergence for more understanding and insights for the future population.

	Micro-Simulation Model	Agent-Based Model
Modeling Approach	Bottom-up	
Modeling Level	Individual level	
Individuals	Heterogeneous	
Interaction	Rarely considered	Readily considered
Behavior Modeling	Stochastic process	Rule-based or inference
Objectives	Projections	Emergence
Data Dependency	Highly dependent	Less dependent
Complexity	Lower	Higher

Table 1: Common and different features from micro-simulation model (MSM) and agent-based model (ABM)

To discover the way to integrate MSM and ABM, we unfolded their characteristics, which is summarized in Table 1. We found there are common grounds between them: the bottom-up approach. The bottom-up approach is understood as the integration of simple building blocks to give rise to bigger ones. In both MSM and ABM, the individuals act as the building blocks for the population dynamics. Moreover, each individual is initialized using the individual information obtained from micro population data, which enables the individuals to be heterogeneous.

They have distinguished features as well. While the interactions are less highlighted in MSM, they are significant parts in ABM. These different interests are followed from their objectives; the goal of MSM is to see the future projection if the present tendency of individuals continues, so it often uses transition probabilities for their behavior decisions. However, the efforts of ABM are to discover an emergence for understanding and ultimately managing the system, so it often concentrates on how to develop the interactions. Most interactions of ABMs are started from assumptions, social norms, previous research results, and they are getting calibrated with respect to the simulation results.

Their objective also lead the differences of their behavior modeling, data dependency, and complexity. MSM describes an individual behavior using stochastic process with the transition probabilities, which also means that it is highly dependent on the real data. Its modeling complexity are relatively lower due to its simple operations of individuals. On the other hand, individuals in ABM usually act based on their own rules or inferences, which indicates that it is less dependent on the real data. About the complexity, ABM requires more resources and time, since it would deal with the interactions of individuals.

Based on the common parts of MSM and ABM, we designed the hybrid model structure consisting of them for population dynamics. There was an early work about the hybrid method of MSM and ABM [19], and we improved it from the perspective of 1) the combining method with their general model structure and 2) the benefits created from their objectives. In the proposed method, we separate the behaviors and interactions of individuals related with the population size, such as fertility, mortality, and migration as behaviors and finding a marriage partner as an interaction. To model these behaviors and interactions, the states, transition probabilities, and rules of individuals should be developed. Governments in these days gather and provide micro information and statistics of their population for analyzing plenty of political and social issues, so we can utilize that information to build the individual components.

To implement the interactions, assumptions based on the research interests, social norms in a target society, and the results of the previous research could be utilized. By relating those behaviors and interactions, a set of individual would form a population, and population dynamics from this model enables us to see and examine the future population and the following changes with varying social factors. Figure 2 illustrates the conceptual design of individual model, the procedure to develop a population dynamics model using the proposed method, and the usage of micro-level population dynamics models, e.g., policy evaluation.

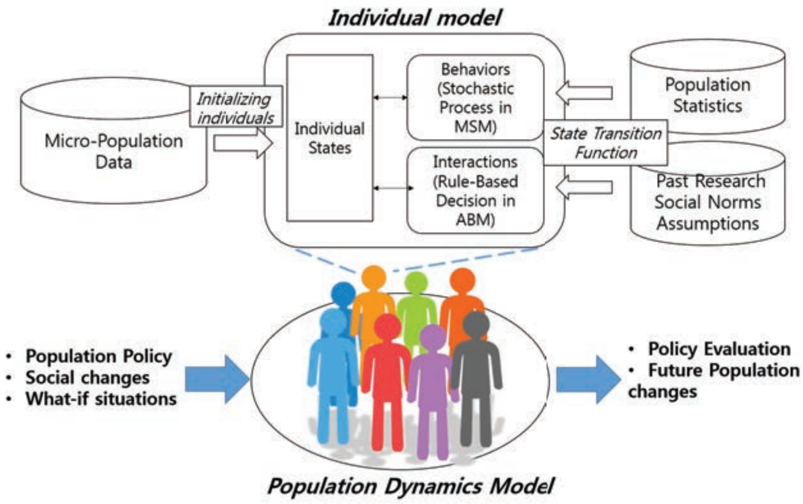

Figure 2: Structure of the proposed hybrid model with real-data and its future usage

4 Case Study: Korean Population Dynamics Model

Applying the proposed modeling method, we developed a Korean population dynamics model (KPDM). In the following subsections, we explain how the KPDM was developed using various real data and present an estimation of the future population structure with varying model parameters.

4.1 Development of Korean Population Dynamics Model using Hybrid Model

The Korean population dynamics model (KPDM) consists of individuals mirroring the real-data for the initial population of individuals and individual behaviors.

4.1.1 Stochastic process for individual behavior

The hybrid model describes population dynamics with individuals in the population, so how the individuals are deployed and characterized in Korea is critical to estimate the future population.

Moreover, each individual should be originated from Korean population information. Korean government opened various type of statistics through Korean Statistical Information Service (KOSIS) [1]. One service provided by KOSIS is Korean micro-population data that illustrate the individual information of about 890,000 individuals (2% of Korean population) including biological, social, family, environmental properties. Among the individual properties, KPDM utilized those that are relevant to individual fertility, mortality, migration, and matrimony (see Figure 3 (a)).

To distinguish the relevant features, we referred to the population statistics provided by KOSIS. The population statistics provides not only general population statistics (e.g., such as the size of population group) but the number of the demographic events with several conditions (e.g., the number of dead people conditioned by age, sex, employment, and marriage status). With these provided statistics, we built up the probability of individual behaviors with the associated conditions, and those conditions are defined as individual states. Hence, we can describe the next behavior of an individual with its transition probabilities and states through the Monte-Carlo method (i.e., generating random number and checking if the number is below the probability or not).

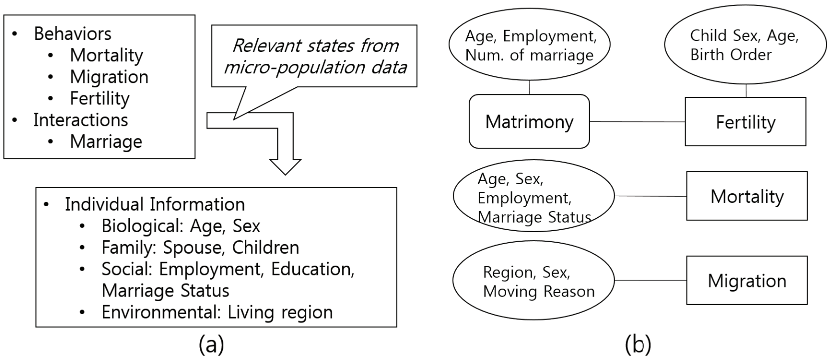

Figure 3: (a) Individual states relevant to individual behaviors and interaction; (b) relationships between individual states, and behaviors and interaction

4.1.2 Rule-based individual interactions

Contrary to the other behaviors, matrimony requires the interplay with other individuals; in other words, to make a marriage, there need lots of communications between the marrying couple. Moreover, their rules (or social norms) for the matrimony would take important roles in the future population dynamics. It is because the fertility rate is largely associated with the marriage (especially in Korea) and the properties of the bride (e.g., biological and social status). However, most of the previous works covers the marriage with less interactions [20].

KPDM is designed to describe individual interactions using ABM component in the hybrid model structure. Figure 4 illustrates how KPDM handle the marriage interactions: 1) According to the population statistics about the marriage, each individual would decide to find its spouse candidates; 2) when others heard about the searching for a marriage, they respond to the request if their marriage conditions would be met to the sender); 3) When the sender receive a response, it also check its conditions. if there are many candidates, it selects one to marry; 4) Then, the two individuals are married, and their marital states are also changed.

Rules applied to the matrimony of KPDM are important to decide a marriage partner, so how to develop the rules would affect the population estimation. Also, these rules are important to structure the associated interactions. In KPDM, we incorporate social norms and trends into the matrimony rules. For example, in Korea, there is a tendency that the average age at first marriage is rising because of complicated problems. We can develop interaction rules for marriage by reflecting such situations (e.g., marriage requires certain amount of money). The hybrid model structure enables application of those rules, so it help us to see the future changes with various respects.

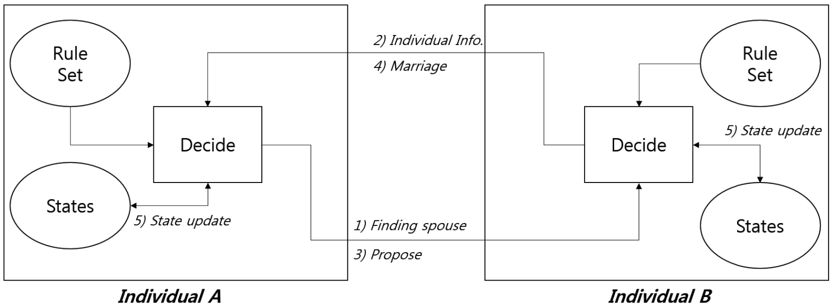

Figure 4: Marriage Interactions between two individuals; they communicate with their personal information and decide to marry or not based on both the received information and their own conditions

4.2 Experiments and Result Analysis

We performed experiments using the developed KPDM. As simulation results, KPDM can provide the future population structure. In the experiment, we varied model parameters about individual behavior and interaction factors and see how the future population structure would changed with respect to the varied parameters.

Korean population statistics were utilized as parameters of stochastic processes for deciding individual behaviors. Among those parameters, we varied fertility rate from no changes (*NC*) to 10% up (*10%*). As the interaction variable, we changed the rule for finding a marriage partner: we designed a random selection rule (*Random*) and "Man should be elder than woman" rule (*ElderMan*) as the parameter variance. For the model initialization, we utilized population statistics and 2% micro-population data (about 890,000 individuals) in 2010 provided by KOSIS. Figure 5 illustrates the future population changes in 2049 as the two parameters are varied (cf., Random rule and no change to the fertility rate case is used as the baseline for the comparisons)

Before the result analysis, we note that In Korea, a childbirth generally is provided by married couples and the fertility rate is highly correlated with the mother age. Therefore, Figure 5 illustrates that population changes occur from 0 to 40 ages. For quantitative analysis, we present the number of births through the simulation executions from 2010 to 2050 (see Table 2). Even if the experiments requires statistical procedures, this table offers interesting results: 1) *ElderMan* rule has a negative effect to increasing the fertility, 2) but the combination of *ElderMan 10%* case encourages more fertility than *Random 10%* in some cases.

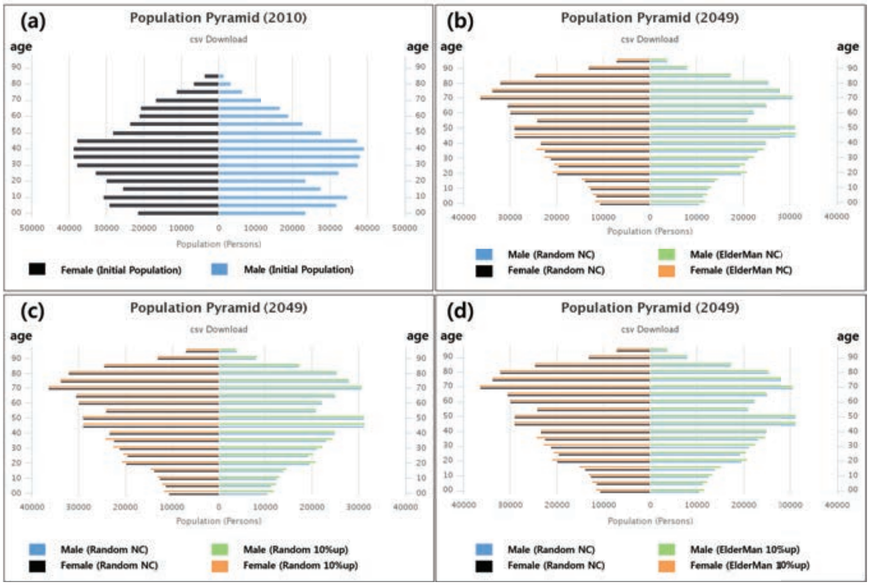

Figure 5: Population pyramids generated from the simulation results: (a) population structure in 2010 (i.e., starting year of the simulation) and comparison population structures in 2049 from the simulation results – (b) Random selection rule for marriage partners (*Random*) with no changes in the fertility rate (*NC*) vs. "Man should be elder than woman" rule (*ElderMan*) with NC; (c) *Random* with *NC* vs. *Random* with 10% fertility rate up (*10%*); (d) *Random* with *NC* vs. *ElderMan* with 10%

Years	Random NC	ElderMan NC	Random 10%	ElderMan 10%
2010	23,557	23,557 (-)	23,557 (-)	23,557 (-)
2015	23,630	23,454 (−1%)	25,272 (+6%)	25,389 (+7%)
2020	20,832	20,653 (−1%)	22,022 (+5%)	22,273 (+6%)
2025	19,159	18,936 (−2%)	20,402 (+6%)	20,556 (+7%)
2030	18,797	18,989 (+1%)	20,035 (+6%)	20,104 (+6%)
2035	13,608	13,375 (−2%)	14,052 (+3%)	14,656 (+7%)
2040	12,344	12,051 (−3%)	13,229 (+7%)	13,118 (+6%)
2045	11,048	11,394 (+3%)	12,352 (+11%)	12,097 (+9%)
2050	10,604	10,542 (−1%)	11,643 (+9%)	11,578 (+6%)

Table 2: Number of births per 5 years generated from the experiments with varying the fertility rate (i.e., no change (*NC*) and 10% up (*10%*)) and the rule for marriage partner (i.e., Randomly selection (*Random*) and Man should be elder than woman (*ElderMan*) rules):% values in the parenthesis indicate the increasing or decreasing rate compared to *Random* and *NC* case.

5 Conclusion and Further Works

Population dynamics has been modeled using microsimulation (MSM) and agent-based model (ABM) techniques. These two methods hold both strong and weak points in modeling the population dynamics, so we proposed a hybrid model structure that can demonstrate the advantages of both. By discovering their common and different features, we confirmed that they can be integrated into a hybrid model and the hybrid model could deliver insights that are not seen in each sole method. Korean population dynamics model illustrates how the proposed method is applied, and the experiment results represent a clue of its contribution.

This paper stands in the middle of our research. To complete this research, we consider 1) formulating modeling components in the hybrid model structure for general usages and 2) executing more simulations and analyzing the simulation results with statistical methods as our further works.

5.1 Acknowledgements

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