Comparing Transition Procedures in Modified Simulated-Annealing-Based Synthetic Reconstruction Method without Samples

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Abstract: In this paper, we modify a synthetic reconstruction (SR) method without samples. The synthetic reconstruction method is a method to generate attributes of population such as age, sex and kinship within a family according to available statistics. Although the original SR method employs some individual samples that are collected to make a statistics, it is criticized that generated attributes are only within the samples used in the reconstruction process. In this paper, we employ a simulated annealing-based SR method without samples. We compare two types of generation methods of a candidate solution in a search of simulated annealing: changing age of an agent (age-change) or swapping ages of two agents (age-swap). Results of synthetic reconstruction show that age-change is better when we limit the number of search. On the other hand, age-swap is better when we have enough number of search for reconstructing a population.

Key Words: agent-based simulation, synthetic reconstruction method using statistics, simulated annealing method.

1. Introduction

Computational science has been regarded as the third leg of science and accepted as a complement of traditional legs or pillars of theory and experimentation [1]. It is a growing multi- and inter-disciplinary field including science (biological, physical, and social), engineering, medicine, and humanities. Among them, social simulation has attracted attentions as one of the promising research fields. However, some social simulations are regarded as toy programs since they treat only a small number of agents (an agent is something that makes decisions based on its rules and what it senses from its environment) in an artificial environment. In this paper, we try to increase the number of agents toward the same size of the real world. Social simulations with the same number of agents as the real world can be called real-scale social simulations. When we develop a real-scale social simulation tool [2],[3], it becomes a challenge to prepare a population with agents in its real-scale environment. Each agent should have age, sex, and its family at the least. In order to support developing real-scale social simulation tools, synthetic reconstruction (SR) methods are proposed.

First method to generate a synthetic population from statistical data was proposed in 1976 by Wilson and Pownall [4]. They proposed a method called synthetic reconstruction method that tries to reconstruct individual and household data from statistics and some real sample data using an iterative proportional fitting procedure (IPFP) [5]. Several succeeding algorithms are proposed based on the SR method. Barthelemy and Toint [6] indicated that the SR method has a difficulty to reconstruct populations fitting to both the statistics of individuals and that of households simultaneously. In order to cope with this difficulty, Gargiulo et al. [7] and Barthelemy [6] proposed reconstruction methods not using sample data. Lenormand and Deffuant [8] compare the reconstruction method without sample data and the SR method, and show that the former can reconstruct a better population.

Essentially, the correctness or the accuracy of generated households cannot be confirmed since the real compositions of population in an area are not available for security reasons. Besides, the number of available statistics is very few to generate a number of households. There must be multiple compositions that satisfy the available statistics. However, needs of real household compositions are growing as a technique of social simulations for the real world with households. For example, Ichikawa et al. [9] tried to implement a real-scale social simulation on influenza spreads in Izu-Oshima Island, Tokyo, Japan. They employ an SR method without samples [10] to reconstruct a population with about 8,000 people and 5,000 houses. They apply their infection model on the reconstructed population to compare two cases to see how long infections continues in each case. In their model, they prepare a virtual city model for Izu-Oshima Island. Their virtual city model has four layers: the first layer corresponds to a city or Izu-Oshima Island itself, the second layer includes 6 main areas in the island, the third layer has 100 small areas in 6 main areas, and the fourth layer corresponds to 6,000 elements such as homes, schools, working places, and hospitals where each citizen has its own activity. They conduct their simulation using the synthesized population and the virtual structures of the island. Although they find interesting simulation results using their model, the number of agents reconstructed using [10] had a large difference from 8,000 of the original population from Izu-Oshima Island. They need to have a better synthesized population that has the same statistical characteristic from the real statistics.

In this paper, we employ a reconstruction method without sample data proposed by Ikeda et al. [10]. They employ a simulated annealing (SA) method [11] to generate a synthesized population. In the search of the SA method, deterioration
of the solution is accepted according to a probability function with a parameter of temperature. When the temperature is high, the acceptance probability is high even if the score of a candidate solution is much worse than the current solution. When the temperature becomes low, the acceptance probability becomes low, that is, only a better solution or slightly worse solution is accepted. As a cooling schedule of temperature, we employ an exponential function.

Murata and Masui extended the method by modifying an objective function in the method and including a heuristic to improve directly some objective functions [12],[13]. They proposed their methods to minimize errors of statistics of a generated population. However, they reconstructed a small-case population with the same statistical tendency. That is, they consider only 500 or 1,000 households. We have proposed a method [14] to reconstruct a real-scale population that includes 350 thousand households and about a million individuals. As an example, we reconstruct a synthetic population of Yamagata Prefecture, Japan.

In [14], we improve the SA-based reconstruction method by employing additional statistics to reduce errors of statistics of the generated population. We modify three procedures in an optimization method using the SA method. First, we modify the generation procedure of an initial population. Second, we modify the transition procedure of a solution in the SA method. Third, we evaluate a generated solution using additional statistics. In [12]–[14], the transition procedure of a solution in the SA method is defined by changing age of an agent based on a demographic pyramid for each sex. In this paper, we propose a transition procedure that generates a candidate solution in SA by swapping ages of two agents in a solution. We compare these two transition procedures and show their advantages using the case of Yamagata Prefecture, Japan.

Section 2 explains a simulated-annealing based synthetic reconstruction method without samples. Section 3 describes a modified generation method of an initial population. In order to introduce the proposed transition procedure, a generation method of an initial population is important. Some modifications are proposed for this method. Section 4 explains procedures of the previous transition procedure, and the proposed one. Results of reconstruction of populations using two transition procedures are shown in Section 5. We compare two transition procedures in SA. Finally Section 6 concludes this paper.

2. Synthetic Reconstruction Method Using Simulated Annealing

Ikeda et al. [10] proposed a reconstruction method using the simulated annealing (SA) method [11] that reconstructs a population based on statistics. They designed a function that calculates errors of statistics of the generated population toward the real statistics. The reconstructed population consists of households and their members. The number of households $H$ defines the number of population in the reconstructed society. Figure 1 depicts a model of a reconstructed population. Ikeda et al. [10] employed nine family types specified in the real statistics issued by National Institute of Population and Social Security Research [15] and Ministry of Internal Affairs and Communications [16]. Figure 2 shows the nine family types they employed. These nine family types cover 95% of whole households in Japan. Each household has its members. Each member has five properties such as age, sex, family type, role in a household, and kinship. As for the role in a household, there are three roles in a household of a couple and their children. That is, husband, wife and child. The kinship indicates a relation between parent-child or husband-wife. When the age difference between a couple is calculated, this kinship is used to detect who is the spouse of the agent.

A reconstructed population is initially generated according to the statistics on the number of households. Table 1 shows the rate of each family type in Japan. Ikeda et al. generated initial households according to the statistics in Table 1.

The number of children in households with children is also considered according to other statistics released by National Institute of Population and Social Security Research [17] and the Ministry of Health, Labour and Welfare, the Government of Japan [18]. Table 2 shows the number of children in households with children. Among nine family types in Fig. 2, “couple and children”, “couple, children and parents”, and “couple, children and a parent” are categorized into “couple” in Table 2. As for the category “4 or more” in Table 2, we assign four children to that household since we have no information about the correct number of children in those households. Therefore, we have households with one, or two or three or four children in our

Table 1 Rate of nine family types.

| Family type | Rate (%) |
|-------------|----------|
| Single      | 33.98    |
| Couple      | 20.74    |
| Couple and children | 29.24 |
| Father and children | 1.34 |
| Mother and children | 7.81 |
| Couple and parents | 0.47 |
| Couple and a parent | 1.48 |
| Couple, children and parents | 1.86 |
| Couple, children and a parent | 3.07 |
| Total       | 100.00   |

Table 2 The number of children in households.

| Type           | The number of children |
|----------------|------------------------|
|                | 1        | 2        | 3        | 4 and more |
| Couple         | 16.97    | 59.98    | 20.70    | 2.35       |
| Father         | 54.70    | 36.00    | 8.20     | 1.10       |
| Mother         | 54.70    | 34.50    | 8.90     | 1.90       |
reconstructed population.

After determining the number of households and the number of children in those households, we assign an age to each member of households according to demographic statistics [15]. The statistics has the number of population in each age for male and female. In this paper, we modify this generation method of an initial population. We show the modified procedure in the next section.

The reconstruction method using SA by Ikeda et al. [10] adjusts ages of members in the generated population according to the real statistics. They employ the following nine statistics shown in [15],[16] to see the difference from the statistics of the generated population by their reconstruction method.

A) Age difference between father and his child,  
B) Age difference between mother and her child,  
C) Age difference between a couple,  
D) Male demographic pyramid,  
E) Female demographic pyramid,  
F) Male demographic pyramid in single households,  
G) Female demographic pyramid in single households,  
H) Male demographic pyramid in couple households,  
I) Female demographic pyramid in couple households.

Table 3 shows an example of Statistics A) and B). It is the statistics of age difference by five-year age groups. Table 4 shows a part of Statistics C) that is the statistics of age difference by one-year age groups. Table 5 shows an example of Statistics D) and E). It is the statistics of population of each age for male and female. Table 6 shows an example of Statistics F) to I). In Tables 3 to 6, “Rate” means the rate of people that satisfies Condition Y among members that meet Condition X.

To minimize the errors in statistics employed for synthesizing a population:

\[
f(A) = \sum_{j=1}^{9} \sum_{s=1}^{G_{s}} \left| e_{sj}(A) - \text{Round} \left( r_{sj} \cdot m_{sj}(A) \right) \right|,
\]

where \( A \) is a reconstructed population, \( s \) is an ID of statistics among the above nine statistics, \( G_{s} \) is the number of terms in Statistics \( s, e_{sj}(A) \) is the number of members for the \( j \)-th term of Statistics \( s \) in the reconstructed population \( A, r_{sj} \) is the rate of the \( j \)-th term of Statistics \( s, m_{sj}(A) \) is the number of members in the reconstructed population \( A \). The procedure of the SA method in [10],[12]–[14] to minimize the total error for nine statistics using \( 1 \) is shown as follows:

Step 1: Initialize reconstructed population.  
Step 2: Terminate the procedure at the presupposed terminate condition.  
Step 3: Change probabilistically an age of a randomly selected agent according to the rate of people in demographic pyramids by age.  
Step 4: Evaluate the generated solution using the nine statistics and decide the transition.  
Step 5: Update parameters.  
Step 6: Go to Step 2.

### 3. Modification in Generating Initial Population

In [14], we modify a generation procedure of an initial population in Step 1. As described in the last section, our previous approach generates an initial population according to the number of households for each of nine family types (Table 1), and the number of children in a household (Table 2). Although the List 11 of the census [19] shows the relation between the family types and the number of family members, the maximum value of the number of family members is 7 or more. If we treat this category as 7 members in a household, the number of population can not meet the real value of the statistics. Therefore, we should create households with 8 members from the category of “7 or more”. Table 7 shows the number of households and population in the category of “7 or more” by the family type in Yamagata Prefecture, Japan. Table 8 shows the number of households by the number of family members.

We utilize another SA method to estimate the number of households that meet Tables 7 and 8. In the SA method, we employ the following objective function:

\[
\hat{g} = \sum_{j=1}^{s} \sum_{s=1}^{G_{s}} | d_{sj} - R_{sj} |,
\]
where \( d_{ij} \) is a control variable that shows the number of households or population that corresponds to the \( j \)-th term in Statistics \( s \) in Tables 7 or 8, and \( R_{sj} \) is the real values of the term \( j \) of Statistics \( s \).

We apply the following SA method to find \( d_{ij} \) where \( j = 7,8,\ldots,M_{\text{max}} \) that meets the real values.

Step 1: Employ values of \( d_{ij} \) in Table 7 as initial values.

Step 2: Terminate the procedure at the prespecified terminate condition or \( g = 0 \).

Step 3: Select two \( d_{ij} (j = 7,8,\ldots,M_{\text{max}}) \) of the number of household randomly as \( d_{ij}^p \) and \( d_{ij}^q \), then decrement \( d_{ij}^p \) by 1 and increment \( d_{ij}^q \) by 1.

Step 4: Evaluate the objective function (2) and decide the transition.

Step 5: Update parameters.

Step 6: Go to Step 2.

In this paper, we specify the maximum number of family members as \( M_{\text{max}} = 16 \). After deciding the number of households with 7 or more family members, we obtain a cross table of types of households and the number of members in a household shown in Table 9 [19]. The number of households with 6 and less family members in Table 9 are the real number of households in Yamagata prefecture in Japan. The number of households with 7 and more family members are estimated values by the above SA method.

We assign a sex for each agent according to the number of male and female in each demographic pyramid for each family type. That statistics is like Table 5. In our real-scale synthetic reconstruction, we employ real values of statistics that are not a rate. We generate an initial population using these statistics.

In Step 4, we employ the following 21 statistics in evaluating a solution generated in Step 3. We do not employ the statistics D) and E) in our previous method but employ finer demographic pyramids by sex and family type that are summarized by one-year-age group (not by five-year-age group). Since we synthesize a population with the same size of the real population, we do not have to use values of the rates in Tables 1 to 6 but real values in the statistics. We calculate the sum of errors of the following 21 statistics as follows:

\[
 f'(A) = \sum_{j=1}^{21} \sum_{s=1}^{G_i} |c_{sj}(A) - R_{sj}|, \tag{3}
\]

where \( R_{sj} \) is a real value of the term \( j \) in Statistics \( s \). The following 21 statistics are employed:

A) Age difference between father and his child¹,
B) Age difference between mother and her child²,
C) Age difference between a couple³,
F) Male demographic pyramid in single households⁴,
G) Female demographic pyramid in single households⁴,
H) Male demographic pyramid in couple households⁴,
I) Female demographic pyramid in couple households⁴,
J) Male demographic pyramid in households of couple and children⁴,
K) Female demographic pyramid in households of couple and children⁴,
L) Male demographic pyramid in households of father and children⁴,
M) Female demographic pyramid in households of father and children⁴,
N) Male demographic pyramid in households of mother and children⁴,
O) Female demographic pyramid in households of mother and children⁴,
P) Male demographic pyramid in households of couple and parents⁴,
Q) Female demographic pyramid in households of couple and parents⁴,
R) Male demographic pyramid in households of couple and a parent⁴,
S) Female demographic pyramid in households of couple and a parent⁴,
T) Male demographic pyramid in households of couple, children and parents⁴,
U) Female demographic pyramid in households of couple, children and parents⁴,
V) Male demographic pyramid in households of couple, children and a parent⁴,
W) Female demographic pyramid in households of couple, children and a parent⁴.

Using the proposed generation method of an initial population with the above statistics, we can synthesize a population with no errors from the statistics F) to W). The errors in the statistics A) to C) about relations among family members should be minimized by an SA method. It should be noted that the above 21 statistics is available for all of 47 prefectures in Japan. Therefore, we can reconstruct populations for all 47 prefectures in Japan using the SR method shown in this paper.

4. Two Solution Transitions in SA Method

In [14], we also modify the transition procedure in Step 3. We employ the demographic pyramids of single male, married male, divorced or bereaved male, and unknown materiel status male. Each demographic pyramid is given by age and by family type. According to these demographic pyramids, we interpret single male in a household of couple and children as a son of that household. In the same manner, we interpret divorced or bereaved male in a household of couple and children as a parent in that household. Using such interpretation, we

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¹ List 1 in [20].
² List 2 in [20].
³ List 17 in [19].
⁴ List 16-1 in [19].
Table 9 The number of households and their members.

| Family Type          | The number of members in a household |
|----------------------|--------------------------------------|
|                      | 1 | 2   | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| Single               | 86654 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Couple               | 0 | 66170 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Couple & children    | 0 | 0 | 48859 | 31138 | 6774 | 662 | 86 | 31 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Father & children    | 0 | 3909 | 773 | 111 | 11 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Mother & children    | 0 | 21592 | 5963 | 983 | 105 | 22 | 3 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Couple & parents     | 0 | 0 | 0 | 6438 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Couple & a parent    | 0 | 0 | 13360 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Couple, children & parents | 0 | 0 | 0 | 9644 | 13587 | 4391 | 364 | 19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Couple, children & a parent | 0 | 0 | 0 | 14927 | 10861 | 2958 | 218 | 38 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Fig. 3 Probability distributions of male in households of couple and children.

Fig. 4 Probability distributions of male in households of couple, children and a parent.

generate demographic pyramids like Figs. 3 and 4. We modify the transition procedure as follows:

[Procedure of Changing Age in Step 3]

Step 3-1: Select a family type randomly.
Step 3-2: Select a member in the selected family type randomly.
Step 3-3: Change the age of the selected member according to the probability distribution of its role in the selected household.

In this paper, we propose a swap procedure in generating a candidate solution in Step 3 of SA. The original procedure and the modified procedure in [14] generate a candidate solution by changing the age of a selected agent. The considered demographic pyramid by sex and family type may help to change the age of an agent properly, however, still this age changing procedure sometimes increases errors in the statistics. Since our modified synthetic reconstruction method in generating the initial population has no errors in the statistics F) to W), a procedure that can keep the consistency in the statistics is preferable. To keep the consistency, we propose a swapping procedure of age of two agents. We modify the transition procedure of Step 3 as follows:

[Procedure of Swapping Ages in Step 3]

Step 3-1: Select a family type and sex randomly.
Step 3-2: Select two members of the selected sex from the selected family type randomly.
Step 3-3: Swap ages of the selected members.

Using this procedure, there happens no change in the statistics of F) to W) but we should adjust errors in the statistics A) to C).

5. Experimental Results for Reconstructing Households

In this paper, we try to reconstruct a population using the statistical data of Yamagata Prefecture in Japan. We chose this prefecture since the average number of family members is the highest in Japan (3.01 members in a household in Yamagata, and 2.46 in Japan). That means a reconstruction becomes more difficult since the prefecture has more unique composition of households even in nine family types. Table 10 shows the basic statistics of Yamagata Prefecture.

Table 10 The basic statistics of Yamagata Prefecture, Japan.

| Statistics                  | Value       |
|-----------------------------|-------------|
| The number of households    | 350,662     |
| The number of population    | 968,213     |
| The number of males         | 471,650     |
| The number of females       | 496,563     |

Table 11 Average and standard deviation of errors and computation time (1,000 evaluations/agent).

| 1,000 Evaluations | Age-change | Age-swap |
|-------------------|------------|----------|
|                   | Error      | Time (s) | Error   | Time (s) |
| Av.               | 491.0      | 611.1    | 4,954.0 | 699.3    |
| Standard deviation| 30.2       | 12.4     | 118.7   | 7.4      |
should be noted that the vertical axis is depicted using a logarithmic scale. Therefore, the swapping procedure is ten times worth than the changing procedure when the number of evaluations for each agent is small. However, the swapping procedure becomes better when the number of evaluations is enough. As shown in Tables 11 and 12, the computation time of changing age with 1,000 evaluations per agent is 18 times faster than that of swapping age with 16,000 evaluations. Since there are a trade-off between performance and computation time, a better procedure depends on user’s preference.

6. Conclusion

In this paper, we propose a procedure of swapping ages of two agents in a solution transition of an SA method. By comparing the proposed procedure with our previous procedure that changes an age according to the statistics, we find that the previous procedure is better when the number of evaluations per agent is small. If users need a synthesized population as soon as possible, they can employ the procedure of changing age. If users need a population with a small error, they should employ the procedure of swapping age.

In order to introduce the proposed swapping procedure in the simulated-annealing-based SR method, we modified the generation method of an initial population using the available statistics in Japan. Since the statistics we employed in this paper are enough for synthesizing whole households in Japan. Since the statistics we employed in this paper are enough for synthesizing whole households in Japan.

As for the scalability of the proposed algorithm, the memory usage of each agent is one byte. That is, a bit for sex, seven bits for age. The family type is defined by a memory area where agents are defined in the corresponding family type. A role in a family and kinship are represented by an element number of an array. Therefore each household has 16 bytes for 16 members.

In order to see the relation between the number of evaluations and the errors, we employ five settings for the number of evaluations per agent: 1,000, 2,000, 4,000, 8,000 and 16,000. Figure 5 shows total errors obtained by those five settings. It should be noted that the vertical axis is depicted using a logarithmic scale.
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