DEMOGRAPHIC RESEARCH

A peer-reviewed, open-access journal of population sciences

DEMOGRAPHIC RESEARCH

VOLUME 51, ARTICLE 5, PAGES 107–154
PUBLISHED 30 JULY 2024
https://www.demographic-research.org/Volumes/Vol51/5
DOI: 10.4054/DemRes.2024.51.5

Research Article

Impact of family policies and economic situation on low fertility in Tehran, Iran: A multi-agent-based modeling

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Contents

Demographic Research: Volume 51, Article 5
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Abstract

OBJECTIVE
This paper investigates and predicts the impact of family policies and the economic situation on women's reproductive behavior in Tehran Province, Iran.

METHODS
The low fertility behavior of women in terms of simultaneous interaction among such agents as household, women, and government is modeled using a multi-agent-based modeling. The probability, heterogeneity, uncertainty, and interactions of agents are the top features of the model. The model is developed based on the micro level and utilized at the macro level for the prediction of a range of such reproductive outcomes as the total fertility rate (TFR), the cumulative frequency of children ever born, unwanted and wanted pregnancies, miscarriage, and induced abortions of women in Tehran Province during 2019 and 2029.

RESULTS
The results derived by the model projects show that the TFR in Tehran Province will decline with a steep downward trend over 10 years from 1.4 children in 2019 to 1.06 children in 2029 while the peak of childbearing is observed for the age group 25 to 29. With the implementation of the optimistic economic scenario and the provision of family support policies by the government, the TFR would reach 1.1 children in 2029, and the peak of childbearing will shift to the 20 to 24 age group.

CONTRIBUTION
This paper provides a multi-agent-based model for low fertility as a complex system. This model facilitates computer-based simulations, enhances demographic methods, and is a useful tool for evaluating the impacts of long-term population policies. The results

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help policymakers to predict the outcomes that may be obtained in the future based on the current population policies and programs.

1. Introduction

Iran's fertility has declined to a below-replacement level since the early 2000s (Abbasi-Shavazi, McDonald, and Hosseini-Chavoshi 2009; McDonald, Hosseini-Chavoshi, and Abbasi-Shavazi 2015). The country's population growth rate has decreased from a peak of 3.9% during 1976–1986 to around 0.7 per annum in recent years (Fathi 2021). A large number of the post-revolutionary baby-boom generation are in their middle ages. The low level of fertility, increased life expectancy, and the special feature of the population age structure in Iran will lead to rapid aging and has considerable social, economic, and health consequences. In response, the government has shifted its antinatalist policies to a pronatalist policy aimed at increasing fertility and preventing further decline in the population growth rate. To this end, on 15 November 2021 the Parliament ratified the Rejuvenating Population and Family Protection Law (Iran Islamic Council Research Center 2021), based on which the government has implemented policies to support marriage and increase fertility. However, the provision of various incentives for women's childbearing has been made without a comprehensive evaluation of the impacts of such incentives on women's fertility intentions and behaviors. This paper takes a step in this direction.

The role of population-oriented programs should be examined in the light and structure of fertility theories. The institutional framework plays a crucial role in understanding the decline in fertility rates across countries and regions. The institutional explanation considers the existing structures in the society related to the demographic change components. McNicoll's (1980; 2001) institutional framework explains women's reproductive behavior from macro and micro perspectives. The effect of population policies, the provision of government facilities, and societal institutions on fertility are considered from a macro view (top-down perspective), while the impacts of women's characteristics on their fertility attitudes, intentions, and behaviors are seen at the family, individual, or micro level (i.e., a bottom-up perspective). McNicoll (1980; 2001) believes that the government has an important role in fertility changes. Governments and policymakers can play an influential role through better implementation of policies, programs, and service quality.

Based on this framework, establishing the linkages between micro- and macro-level factors that shape fertility behavior is essential. Multi-agent-based modeling is useful to examine and simulate the interwoven process of decision-making that is affected by micro and macro factors. Extensive studies (Gauthier 2007; Bjorklund 2006; Rindfuss and Choe 2015) point to the role of the governments in increasing fertility or slowing down the steep decline in fertility. A group of these studies has addressed the role of governments in providing family support policies to increase fertility. Fent, Aparicio Diaz, and Prskawetz (2013) investigate the effectiveness of family policies in changing women's reproductive behavior using the agent-based modeling approach. Their simulation results show that family policies have a positive and significant effect on increasing fertility. Gauthier (2007), in a review study, investigates the impact of family policies on women's reproductive behavior and shows that studies using micro-level data confirm the result that the provision of facilities for childbearing, parental leave, and childbirth have positive effects on completed cohort fertility, while the results of studies based on macro-level data consider the effect of family policies to be effective at the timing of births. Baroni et al. (2009) use agent-based models to examine the reforms in family policy and its effect on fertility. Their simulation results show that only highly educated and employed women benefited from the reforms due to their higher labor force participation and income. In the conclusion of their study, Rindfuss and Choe (2015) suggest that policies as a control lever can stop or even increase fertility in the short and long term. Bjorklund (2006) looks into the question of whether family policies can affect fertility or not. The results of his research show that the economic incentives created by the government will affect the level and pattern of fertility.

The government's role in improving the economic situation has a direct and indirect effect on women's reproductive behavior. As Vignoli et al. (2021) argue that under uncertain conditions, narratives of the future play a potent role in directing individuals' decision-making about childbearing. Thus, structural economic change is required to increase and maintain fertility above or close to the replacement level. Unfavorable economic situations in Iran along with the high demand for employment arising from the post-revolutionary baby-boom generation have led to unemployment and economic insecurity among the young generation (Salehi-Isfahani 2023). The young generation is affected by economic hardship in reality, and as a consequence, they have a negative narrative about the future, and in turn, their attitudes toward fertility and childbearing are affected. The negative impact of economic insecurity on fertility in Iran has been shown by previous studies (Abbasi-Shavazi, McDonald, and Hosseini-Chavoshi 2009; Moeeni et al. 2014; and Abbasi-Shavazi and Khani 2017). Moeeni et al. (2014), in a two-level study, show that the economic determinants are among the most important factors affecting Iranian households both at the micro and macro levels. Abbasi-Shavazi and Khani (2017) also find that economic insecurity had a significant impact on fertility in Kurdistan, Iran. Sobotka, Skirbekk, and Philipov (2011) reveal that women with high education will delay childbearing in case of economic uncertainty. The authors show that women's uncertainty about household income will have an effect on childlessness and delay in having children. In times of economic inflation, women delay childbearing to gain work experience and further education. Long-term and widespread youth unemployment, together with economic recession, has a great negative impact on household income, resulting in reduced fertility.

The impacts of family policies adopted by governments at the macro level on women's reproductive behavior vary by their characteristics (e.g., age, income, education, employment, number of children, social interaction, social pressure) at the micro level (Baroni et al. 2009; Fent, Aparicio Diaz, and Prskawetz 2013). The agent-based modeling (ABM) is the best method to consider the heterogeneity of women at the micro level concerning family policies. It can also be used in similar economic situations for all members of society at the macro level to establish a link between the micro and macro levels (Billari et al. 2006; Grow and Van Bavel 2016). ABM is a suitable method that can help policymakers in realizing their goals by adopting effective and targeted policies. In ABM, fictitious communities can be modeled in software form, and these models can be used as a computational laboratory to analyze theories and policies. ABM, with the creation of a connection between micro and macro levels, enables the accuracy, purposefulness, and satisfaction of policies by involving the perspective of the micro level in policies (Billari 2015; Bijak et al. 2021).

In this style of modeling, based on the interactions between the agents at the micro level, a set of responses under the title of outputs and behavior is created, which is formed from the aggregation of these outputs at the macro level. Because this modeling pattern starts from the micro level and leads to the macro level, it is called 'micro-to-macro modeling' or 'bottom-up modeling.' The creation of a connection between the micro level and macro level as a considerable property of the ABM approach has been addressed by other scholars (Fent, Aparicio Diaz, and Prskawetz 2013; Baroni et al. 2009). These studies evaluate the effectiveness of family policies implemented by the government at the macro level by considering the characteristics of women at the micro level, social interaction, and the heterogeneity between agents. However, in the studies conducted about the role of governments, a limited task has been considered for the government, while the government, as one of the effective agents in the decision-making process of women for having children, can have several tasks. Given the complex nature of fertility behavior, the simulation of a fertility system is not possible by using single-agent models only. Multiple ABMs allow us to simulate the complex low fertility system containing different agents that play critical roles in the emergence and formation of the system's output. The multi-agent system is used to predict the complexities of the low fertility system and its behavior outcomes. This technique involves two or more agents working together to achieve local goals. In the modeling of complex systems, people with different and possibly contradictory goals interact and communicate with each other, which can be modeled using a multi-agent modeling approach (Balaji and Srinivasan 2010).

To explain the complex system of low fertility in Tehran Province,[3] a multi-agent modeling approach is used, in which the three agents of household, women, and government are in an interactive relationship with each other simultaneously. Considering the possibility of making long-term predictions by multi-agent-based modeling and the importance of the behavior of the modeled process under different conditions, a scenario following the desired goals is designed, and the model for each scenario can be implemented to predict the behavior of low fertility in Tehran Province under different conditions. Based on the level of effectiveness of each scenario, the best solution to increase fertility without spending money and time with the help of virtual simulations is obtained. In this paper, eight government facilities[4] are selected and tested through different scenarios in an agent-based virtual environment to determine which scenarios will have the most impact on women's reproductive behavior. Next, the economic situation of the government agent will be tested on the two pessimistic and optimistic economic scenarios based on which changing women's reproductive behavior is predicted.

The following questions are addressed in the paper:

1) Considering the impact and interactions of agents at the micro and macro levels, what trend and pattern of reproductive behavior of women will be observed in Tehran Province?
2) How do the economic scenarios (favorable and unfavorable economic situations), as well as family-oriented policies provided by the government agent, affect women's reproductive behavior in Tehran Province?

2. The model

In this section, the multi-agent-based modeling approach utilized for model development is reported step by step. This model is used for the investigation of the impact of family policies and economic situations on women's reproductive behavior. To this end, the simultaneous interaction of the three agents of the household, women, and the government with different attributes in terms of the heterogeneity and uncertainty of the

[3] Tehran Province is the capital of Iran, and the total fertility rate of this province is lower than that of the country and is considered one of the provinces with very low fertility.

[4] These facilities were extracted from the 2017 Iran Fertility Transition Survey dataset. Women respondents have been asked which of the following items and facilities can have an impact on their childbearing: providing facilities for the child's education in the future, creating a job with a suitable income for parents, allowance for the treatment of infertility, providing the cost and access to kindergarten, financial aid for childbirth expenses, financial assistance to families, feeding children during childhood, creating facilities for working women and housewives.

model, the interaction of the agents with each other at the micro level, and the model verification through the implementation of different scenarios in the modeling process are reviewed. Based on the model made at the micro level, the reproductive behaviors at the macro level – including such measures as total fertility rate (TFR), the cumulative frequency of children ever born, total pregnancies, unwanted and wanted pregnancies, miscarriage, and induced abortions of women in Tehran Province from 2019 to 2029 – are being predicted. In modeling, the female agent is located within the household agent. The household agent in the simulation environment has two attributes: (a) the economic situation of the household (which improves with the better economic situation of the government at the macro level, i.e., the decrease in the inflation rate and the increase in wage[5] and worsens when vice versa), and (b) the number of household members (with the increase of each child, it is assumed that the family's expenses will increase and the family's economic situation will worsen and the desire for childbearing will decrease). In the simulation environment, 11 attributes have been considered for the female agent: age, duration of marriage, income, contraceptive use, the effectiveness of government facilities, number of children, education, autonomy in decision-making, degree of adherence to religion, the experience of intentional abortion, and miscarriage. The main components of our model operate in an environment in which the government agent acts as an exogenous stimulus, and the attributes of the household agent and the female agent play a role in women's pregnancy decisions as an endogenous stimulus.

One of the most important features of the model is the consideration of the uncertainty in the modeling process. Factors that are identifiable, extractable, and quantifiable in the model are probabilistically taken into account in decision-making related to the agents. The rest of the factors and quantities whose exact and certain values are not extractable are introduced into the model through the calibration process. In Appendix C, details related to the implementation of uncertainties in the model and how to construct the model are presented in ODD+D form. To bring the model closer to a real process, social pressure and social interaction between agents were also considered. As mentioned, there is a female agent in every household agent. Therefore, the first step in building the model is to divide households into eight groups. The primary division scale is based on the age of women in the household. A five-year division interval is considered, and the agents of the first group can be between 15 and 19 years old at the zero time of the simulation.[6] The primary division in modeling is based on age only, and

[5] The wage is the payment provided by an employer to an employee for work done within a specific period (OECD 1992). The wage information cited in this paper is obtained from the Supreme Labor Council. Further information on this can be located in Sections 4 and 3 of this paper.

[6] The second to eighth five-year age groups follow consecutively (i.e., 20 to 24, 25 to 29, 30 to 34, 34 to 39, 40 to 44, 45 to 49, and 50 to 54. The selection of the 15-to-49-year-old periods is considered due to women's ability to have children, and the 50-to-54-year-old period is considered in the process of social interaction. The age of women is determined randomly using EasyFit software.

within each age group based on the grouping, the attributes of other agents are formed. In each age group, the attributes of other agents are determined based on the decision tree and Chi-square automatic interaction detection (CHIAD) algorithm and rule extraction. The rule and data sources are presented in Appendix A.1 and A.2.

In modeling for the government agent, two attributes were considered, providing government facilities and setting the economic situation, taking into account the determination of the inflation rate and wages. The government agent has been included in the modeling process in each of these scenarios related to the provision of facilities based on scoring (1 = weak impact; 3 = neutral; 5 = strong impact). In this way, by performing a sensitivity analysis, it is determined which of the government facilities will lead to a change in women's reproductive behavior. The next characteristic is inflation and wages, which are included in the codes related to the model. Considering the inflation index makes it possible for the model to predict the pattern of changes in household income and expenses. The smaller the gap between inflation and wages, the better the economic situation of families and the desire to have children, and the greater this gap, the more unfavorable the economic situation of families and the less desire to have children. In the form of an optimistic economic scenario, it can be assumed that economic inflation will decrease but wages will increase. On the other hand, in a pessimistic scenario, the inflation rate can be increased and the wage can be decreased, and the results can be seen in the output of women's reproductive behavior.

All in all, agents are the main components in the presented model. The generated agents include attributes that play a fundamental role in determining the behavior of agents. We have implemented the behavior of the agents using these attributes within the software AnyLogic. The attributes of the agents are fed to the model as the inputs in the form of variables and parameters. Table 1 displays the inputs and outputs of the simulation model.

Table 1: Inputs and outputs of the simulation model

Simulation model inputs	Simulation model outputs
Attributes of the government agent:	
1) providing facilities for the child's education in the future	1) total fertility rate (TFR)
2) creating a job with a suitable income for parents	2) the cumulative frequency of children ever born
3) allowance for the treatment of infertility	3) the cumulative frequency of total pregnancies
4) providing the cost and access to kindergarten	4) the cumulative frequency of wanted pregnancies
5) financial aid for childbirth expenses	5) the cumulative frequency of unwanted pregnancies
6) financial assistance to families	6) the cumulative frequency of miscarriage
7) feeding children during childhood	7) the cumulative frequency of induced abortions
8) creating facilities for working women and housewives	
9) inflation rate	
10) wage	
Attributes of the household agent:	
11) economic situation of the household	
12) number of household members	
Attributes of the female agent:	
13) woman's age	
14) duration of marriage	
15) woman's income	
16) contraceptive use	
17) the effectiveness of government facilities	
18) number of children	
19) woman's education	
20) autonomy in decision-making	
21) degree of adherence to religion	
22) the experience of intentional abortion	
23) miscarriage	
24) ideal income	
25) social interaction	
26) social pressure	

2.1 Data preprocessing for implementing the agent-based model

In utilizing the available data to develop the simulation model and define agent attributes, a comprehensive range of statistical and probabilistic analyses were conducted. The data were scrutinized using decision trees, probability distribution functions, and a roulette wheel mechanism to inform the simulation model. Specifically, probability distribution functions were customized to the collected data, facilitating the extraction of variable values. The initial attribute addressed was the age of women, quantified by inputting data from different age groups into EasyFit software. The software output enabled the quantification of women's ages using a discrete uniform distribution function. Similarly, the number of children and household members were quantified using discrete and Poisson uniform distribution functions. The duration of women's marriages was determined through the CHIAD algorithm and decision tree, quantified via a normal distribution function. Women's income was calculated using a triangular distribution function.

Variables such as the influence of government facilities, education, religiosity, and women's experiences with intentional abortion were integrated into the model using a continuous uniform distribution function and the roulette wheel logic. The level of autonomy in women's decision-making and their use of contraception were quantified through the CHIAD algorithm and decision tree. The probability of adopting a specific contraceptive method and the extent of decision-making autonomy were computed based on event space, with cumulative probabilities implemented using the roulette wheel logic in the software. Notably, all agent attribute values were derived probabilistically.

2.2 Modeling logic: belief–desire–intention[7]

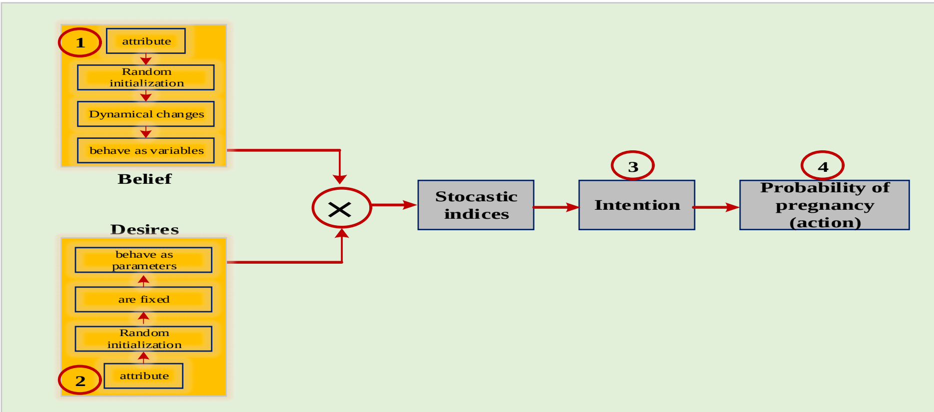
This article utilizes belief–desire–intention (BDI) modeling logic and architecture to construct an agent-based simulation model. The modeling process is developed using the BDI theory, which is divided into three components that have been implemented in developing the agents. In the BDI theory, the first component, known as 'beliefs,' embodies a set of attributes of individuals, particularly women, whose values evolve dynamically within the model. These attributes, initially set randomly at the simulation's onset, dynamically change based on interactions with the government agent, household agent, and the women throughout the simulation process. The dynamic attributes in the beliefs set encompass the woman's age, income, number of children, the length of marriage, household's economic situation, and the number of household members. Namely, beliefs serve as input variables given their deliberate changes. These attributes are labeled as beliefs in our simulation model. The second component in the BDI model, known as 'desires,' comprises various attributes of women that are assigned random values at the start of the simulation. In contrast to other attributes, the values of these attributes remain constant throughout the simulation process. This component of the BDI model is regarded as the parameter. Desires, which are randomly initialized and subsequently remain constant, acting as parameters in our model, encompass attributes such as the effectiveness of government facilities, women's education, autonomy in decision-making, degree of adherence to religion, and experience of intentional abortion. The process for the derivation of stochastic variables was discussed in Section 2.1.

The third component in the BDI logic, known as 'intentions,' is derived from the total product of beliefs multiplied by desires as desired. Put simply, beliefs and desires are utilized to create indices for quantifying a pregnancy probability score, which is

[7] For further information regarding this modeling algorithm, see Rao and Georgeff (1995).

determined by the sum of these influential indices in the intention pregnancy score. Following this, the score is translated into action with a certain probability. In Figure 1, the schematic of the BDI model is shown.

Figure 1: Schematic representation of BDI logic



In the following section, the procedure for the derivation of pregnancy intention indicators is discussed.

2.3 Procedure used for derivation of intention indices in BDI logic

In this section, we discuss the process of calculating and scoping each female agent during the decision-making phase regarding wanted pregnancy. These indices, referred to as intentions in BDI logic, play a crucial role in guiding the agent's actions and choices. The output of BDI modeling logic derives decision-making variables used for developing the model.

The indicators used and defined are economic situation, the effectiveness of government facilities, social pressure, and social interaction. In the modeling process, the output indicators are normalized in the range of 0 to 5. The constructed indicators perform a function. The input to the function can be any number, but the output will be a number between 0 and 5. For this purpose, the normalization operation must be performed so that different indicators are checked; in other words, normalization is a method that, when the data are not in the same range, puts the corresponding values in a similar range (Garcia, Luengo, and Herrera 2015).

In the subsequent step, the total score of each indicator is multiplied by its corresponding weight, determined using the analytical hierarchy process (AHP) method and insights obtained from interviews with scientific experts,[8] particularly faculty members specializing in fertility and family studies. This ensures that each indicator's impact and effectiveness in the simulation model are considered. To this end, each indicator is assigned a value and weight, with the value ranging from 0 to 5 and the weight ranging from 0 to 1 (Abbasi-Shavazi and Esmaeili 2021).

It should be pointed out that the score obtained in this stage should be in the range of 0 to 1 according to the probability description of the process. To achieve this goal, the total wanted pregnancy score, which is between 0 and 5, is multiplied by 0.2, resulting in a number in the range of 0 to 1. As it is clear, the occurrence of events such as fertility and the probability of pregnancy is highly dependent on the age of the woman. Therefore, the probability of pregnancy age of women was chosen from the age groups of 15 to 50 years. Therefore, the product of wanted pregnancy scores, which are in the range of 0 to 1, is multiplied by the probability of a woman's pregnancy age at different ages, between 0 and 1, and the result for each woman's wanted pregnancy decision will have a value between 0 and 1. It is clear that the higher the number of wanted pregnancy scores and the younger the woman, the higher the chance of wanted pregnancy, and the event space of wanted pregnancy enlarges. In the following, the method of calculating the wanted pregnancy score is shown in the form of equations:

$$Wanted\ Pregnancy = \sum Standardization\ of\ indicators(0-5) \times Weight(0-1) = (0-5) \tag{1}$$

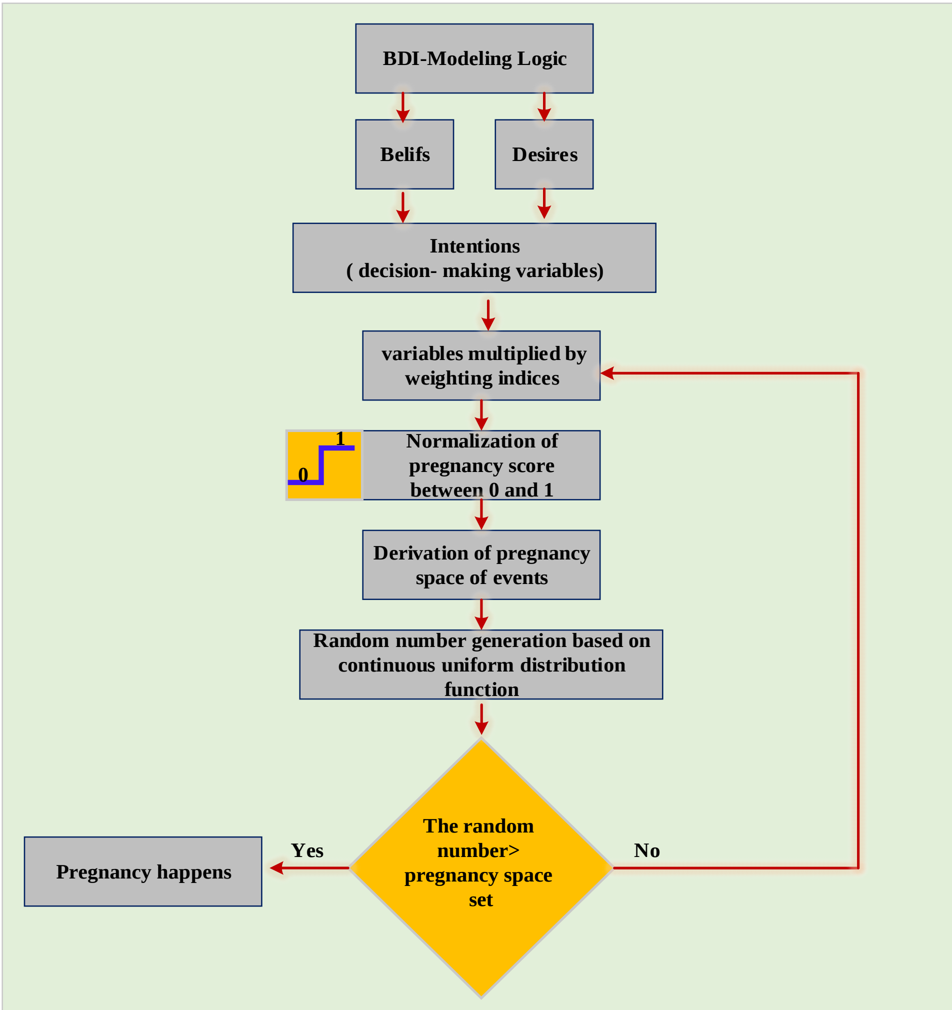
$$Temp1 =: Wanted\ Pregnancy\ Score \times 0.2 = (0-1) \tag{2}$$

$$Child\ born = Temp1 \times Pregnancy\ Chance(15-19 \ldots 50-54) = (0-1) \tag{3}$$

Figure 2, which has been drawn based on the intention algorithm, describes the process of pregnancy decision-making procedure followed by the agents schematically.

[8] The opinions of scientific experts were utilized in two separate issues in this paper. First, interviews were conducted with 10 scientific experts who had conducted research in the fields of family and fertility. Subsequently, the hierarchical analysis process and the results obtained by Expert Choice software were employed to weigh the indicators for pregnancy decision-making. Second, the research team discussed and decided how to create effective indicators for decision-making, which was done in consultation with scientific experts. See Abbasi-Shavazi and Esmaeili (2021) for further details.

Figure 2: Schematic chart representing the pregnancy decision-making procedure followed by agents that has been developed based on the intention algorithm



2.4 Making effective indicators in a wanted pregnancy[9]

This section examines how to make effective indicators in a wanted pregnancy, which include the economic situation of the family, influence of government facilities, pressure, and social interactions. Additionally, the way in which the effective indicators in wanted pregnancy are normalized is discussed. The process used for the derivation of indicators has been developed based on the opinions of experts issued through the paper (Abbasi-Shavazi and Esmaeili 2021).

2.4.1 Normalizing the household economic situation indicator

As discussed earlier, economic situation is one of the important and influential indicators of fertility behavior (Becker 1960; Sobotka, Skirbekk, and Philipov 2010; Leridon 2015; Lee 1990; Abbasi Shavazi, and Khani 2017; Western et al. 2012; Santarelli 2011; Adsera 2006; Vignoli et al. 2021). Based on economic theory, people consider calculations taking into account the framework of maximum utility when deciding to have a child. If the benefit of an additional child is greater than the cost, childbearing occurs (Leridon 2015; Lee 1990). Based on the demand theory (Becker 1960), if we want to have a positive effect on the decision to have children, we should reduce the economic costs of children, and by increasing parents' income, the beneficial function should be changed toward childbearing. Orsal and Goldstein (2010) state that economic issues play a more prominent role in determining fertility behaviors compared to the past. Accordingly, the indicator of the economic situation of the household was considered one of the influencing indicators on the decision-making of the female agent for pregnancy in the simulation model. As explained in the discussion of model construction, the female agent has a characteristic called income, which was valued using the triangular distribution function. The ideal income according to the number of household members is entered as an input in the model according to Equation (4) based on the opinion of scientific experts.

$$\text{Percentage of deviation} = \frac{Ideal\ Income - Actual\ Income}{\text{Actual Income}} \tag{4}$$

For the result to be between 0 and 5, a linear relationship between the deviation from the real income and the ideal income is assumed. In this way, the agent that deviates between 0% and 20% from the ideal income will get a score of 5. An agent that deviates

[9] In the Section 2 of this paper, the method of building the indicator model of providing government facilities was explained.

between 20% and 40% scores 4, if it deviates between 40% and 60%, it scores 3, if it deviates between 60% and 80%, it scores 2, and if it deviates between 80% and 100%, it scores 1, and if it has 100% deviation, it gets a score of 0.

2.4.2 Normalizing the social pressure indicator

Social pressure is one of the factors that affect women's reproductive behavior. Bernardi (2003) emphasizes the factor of social pressure in having children. From her point of view, when a person receives normative pressure from the social environment, this pressure can be the result of anticipated rewards for conforming to social expectations (for example, giving birth at a certain age) and possible sanctions in case of noncompliance. Social pressure leads to the requirement of matching one's expectations with the expectations of others in the field of fertility. According to experts, it is assumed that social pressure is affected by women's age and the duration of the marriage. Also, with the increase in age and the duration of the marriage, the social pressure on women to decide to have a wanted pregnancy increases. To create this indicator in the model, first, a relationship is defined as follows:

$$Temp1 = The\ maximum\ age\ of\ pregnancy - \text{Women's age}. \qquad (5)$$

Next, in order for the index to be between 0 and 5, the obtained number must be divided by 7 because in the worst case, when the age of the woman is 50 years, by putting the age of the female agent in the output equations, number 5 is obtained. It means that the most pressure from people around to encourage fertility is applied to the woman. If the age of the female agent is 15 years, the index output will be zero, which means no pressure is applied to the female agent. Since the probability of pregnancy of women depends on their age, finally the total scores obtained from the indicators are multiplied by the probability of pregnancy at different ages and Equation (6) results will be obtained.

$$\text{Temp2} = \frac{(\text{The maximum age of pregnancy} - 15) - (\text{Temp1})}{7}. \qquad (6)$$

Another issue that is considered in the discussion of social pressure is the women's marriage duration. According to the opinion of experts, this relationship was considered as Equations (7) and (8):

$$\text{Temp2} = 5 < \text{Duration of Marriage} < 10, \quad (7)$$

$$\text{Temp2} = 0.20. \quad (8)$$

If the women's duration of marriage is between 5 and 10 years, the social pressure will increase by 20%:

$$\text{Temp2} = \text{Duration of Marriage} > 10, \quad (9)$$

$$\text{Temp2} = 0.50. \quad (10)$$

If the women's duration of marriage is more than 10 years, the social pressure increases by 50%.

Finally, for the output of the indicator not to exceed the number 5, a condition is set based on which the maximum social pressure should not exceed the number 5.

2.4.3 Normalizing the social interaction indicator

The most important part of the simulation model is how to build and normalize the social interaction indicator. Several studies investigate the role of social interaction in fertility. For example, Gonzalez-Bailon and Murphy (2013), by using agent-based models, address the impact of social interactions on fertility decline in France in the 19th century. They look at how different decision-making rules, with and without decision-making dependent on social interactions, caused changes in population growth and fertility levels. The results show that considering social influence in the model allows the observed behavior to be imitated experimentally. In another study, Berndt, Rodermund, and Timm (2018) investigate the effect of social contagion on fertility using agent-based modeling. The results of their study show that as a result of social interactions, people get to know ideal fertility ideas and are influenced by these ideas. Aparicio Diaz et al. (2011), investigate the role of social interactions and internal networks in reducing fertility in Austria using agent-based models. Their empirical studies show that the transition to parenthood is influenced by a person's peer group. Based on the studies having been done in connection with the effect of social interaction on fertility, the indicator of social interaction was considered in the simulation model. The first input parameter in the discussion of social interaction is the interaction policy as the first step, which is given to the model as input and with the opinion of experts.

Two types of interactive policies can be considered: (1) random and (2) isomorphism. In the modeling structure used in this paper and in consultation with experts and literature review, the interactive policy was chosen in the form of isomorphism. This assumption is closer to reality, and people in the same age group with similar characteristics are more likely to interact with each other and thus be more influential. When this interactive policy is selected, its concentration percentage should be entered into the simulation model. According to experts, the concentration percentage of the number was considered 50%. This means that each agent in any age group has a 50% chance to randomly interact with agents in her group and 50% with agents in other groups.

In the first step, the interactive policy has been chosen, and in the second step of making the indicator, it should be determined which agent affects the others. Based on the literature review, experts' opinions, and available data, it is assumed that the two variables of autonomy in decision-making and education are more important in discussing the influence of two agents on each other regarding fertility. Education is the main agent that affects fertility attitudes and behaviors. In recent decades, Iran has witnessed an unprecedented decline in fertility rates, which has been closely linked to a substantial rise in female education levels (Lutz, Cuaresma, and Abbasi-Shavazi 2010; Abbasi-Shavazi, McDonald, and Hosseini-Chavoshi 2009). The relationship between education and fertility is not always negative. For instance, a study conducted by Hwang (2023) in South Korea shows that the relationship between education and fertility in the 1970 cohort follows an inverted U-shaped pattern. Women with less than a high school education had the lowest fertility rates, while those with a graduate school degree had the highest fertility rates. Those with a high school or college education fell in between with an average fertility level. Doepke et al. (2023) conclude that the relationship between education and fertility varies across European countries. For example, in France and Germany, the highest fertility rates are observed among individuals with higher levels of education, whereas in Italy and Spain, there was no increase in fertility among the educated population. This suggests that there is not always a negative relationship between education and fertility in certain high-income countries.

Also, the role of women in society and the ability and autonomy to make decisions in family matters are affecting women's fertility behavior. Women who have more autonomy in family decisions have more power in fertility decision-making (Alvarez 2011; Forty, Navaneetham, and Letamo 2021; Abbasi-Shavazi and Alimandegarie 2010). The two variables of autonomy in decision-making and education were considered in the discussion of the effectiveness of the agent in social interaction in the simulation model, but since the nature of their influence in the model is not the same, they must be normalized. For normalization, the AHP method and interviews with experts were used. Therefore, according to Equations (11) and (12), both agents get a score as a result of interacting with each other. For example, suppose agent A interacts with agent B:

$$\text{Agent ScoreA} = (\text{Education} \times \text{E Weight}) + (\text{Autonomy in decision} \times \text{A Weight}) \quad (11)$$

$$\text{Agent ScoreB} = (\text{Education} \times \text{E Weight}) + (\text{Autonomy in decision} \times \text{A Weight}). \quad (12)$$

The probability that A affects B is

$$\text{PA} = \frac{\text{Score a}}{\text{Score a} + \text{Score b}}. \quad (13)$$

The probability that B affects A is

$$\text{PB} = \frac{\text{Score b}}{\text{Score a} + \text{Score b}}. \quad (14)$$

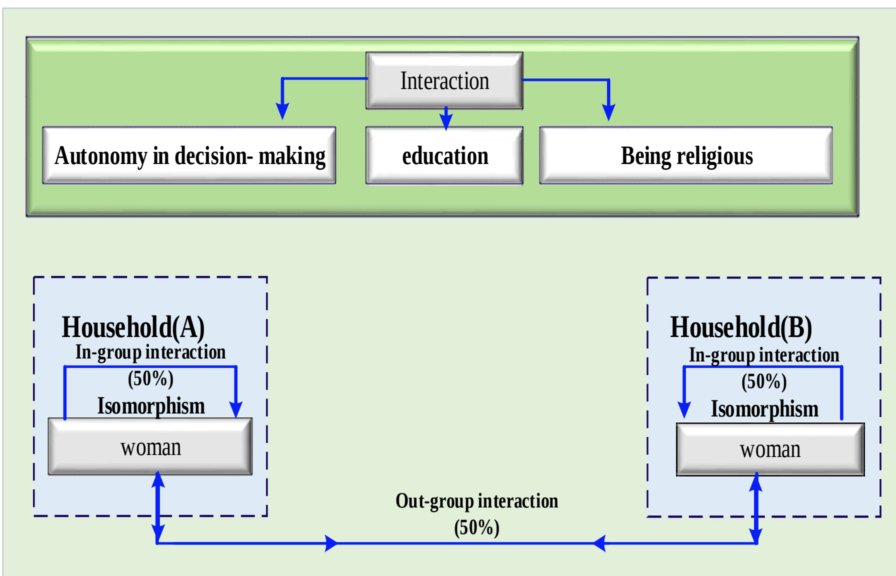
Which agent affects the other agent is determined based on the randomly generated number not based on the score of the agents. Next, in the third step of making the indicator, the question arises as to how much these two agents (A, B) affect each other. In response, the degree of influence is determined based on how much these two agents are in the same stratum or not. The percentage of being religious is determined according to the importance of religion in Iran and other studies about the importance of religiosity and its effect on women's reproductive behavior worldwide (Bisin and Verdier 2001; McQuillan 2004; Heyford and Morgan 2008; Baudin 2015). Hubert (2014) considers religiosity and religion as signs of a culture that leads to the formation of values. Based on the importance of religiosity on women's fertility behavior, two agents were considered. The level of influence in the model when two agents are from the same stratum or not is considered as input to the model, according to the opinion of experts. Suppose that in the second step agent A affects B, and A's score does not change but B's score changes. The question that arises is whether the score of agent B decreases or increases. As in the second step, it is randomly determined which agent affects the other, an agent may have a lower score, but that agent is chosen randomly. Therefore, in this step, a condition is set: If the score of agent A is higher than the score of agent B, then

If (ScoreA >ScoreB)
ScoreB = ScoreB*(1+Impact Rate)

Else if (ScoreB >ScoreA)
ScoreB = ScoreB*(1-Impact Rate).

This indicator, like other indicators, must be between 0 and 5 to be normal. By writing a conditional command $0 \leq$ Social Interaction ≤ 5, this limitation is created. Since it is not clear how many times each agent has social interaction, normalization cannot be done with a function. Therefore, this restriction was established with a condition. According to the opinion of experts, the level of influence will be entered into the model as an input, so that if two agents are of the same stratum, they will influence each other between 5% and 10%, and if they are not of the same stratum, they will be influenced between 2% and 5%. In the following, the continuous uniform distribution function is called and a random number is generated and the effectiveness percentage of the agent is determined. Entering random processes and actions into the model is the most attractive feature in building the simulation model for the study. In other words, all the actions in the modeling process are random, so the results of the simulation are very close to the real world. Inside the simulation model, all four indicators are updated monthly through an event, and all calculations are repeated. Figure 3 shows schematically how household and female agents interact with each other.

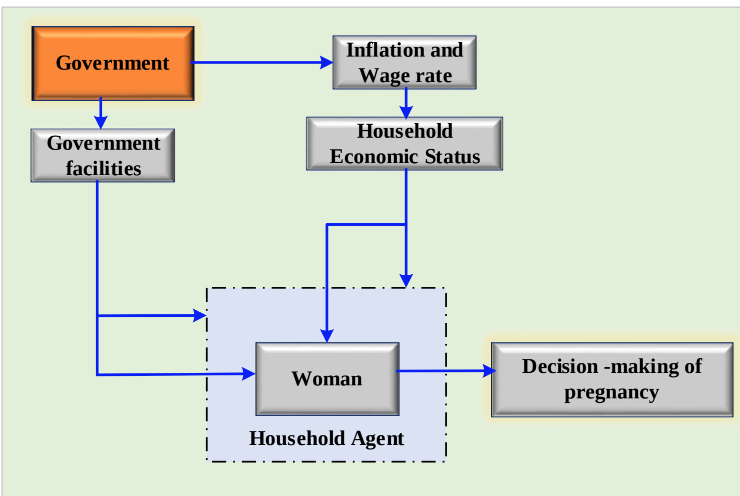
Figure 3: Interactions between household agents and females inside the household agent



2.5 The sensitivity of the household and female agents from the government as an external variable

This section examines the impact of the government as an external stimulus on the household and female agents in decision-making regarding pregnancy. The government, as an external variable, influences household income and female income through the determination of inflation rates and wage. It is worth mentioning that the government agent affects the reduction in household income; in other words, it answers the question of how much the household expenses will increase at the time of childbirth. Additionally, the government impacts households and women by providing government facilities. All the effects of the government on households and women are modeled as a single unit factor, influencing the decision-making of the female agent regarding pregnancy. In Figure 4, the sensitivity of the household and female agents to the government as an external variable is depicted.

Figure 4: The sensitivity of the household and female agent from the government agent



2.6 Interaction of female agent in the simulation environment

In this section, the interaction and behavior of the female agent in the simulation environment will be discussed and investigated. Figure 5 clarifies the different states used for modeling the female agent in the simulation environment. Initially assumed to be in normal conditions, not pregnant yet, the female agent transits to a menopause state if they are 50 years or older and potentially infertile. This transition occurs at time zero, leading to their exclusion from subsequent calculations.

In the modeling process, the question will arise of how the woman gets pregnant in the simulation model. To answer this question, a woman becomes pregnant when a person receives the message of becoming pregnant. This message is sent from both sides to the female agent and finally received by the agent, which is

- An unwanted pregnancy event (based on the error of any contraceptive method).
- A wanted pregnancy event (based on the total scores of the female agent in the indicators of the economic situation, social pressure, social interaction, and influence of government facilities). Calculating the indicators is given in Section 2.2 of the paper.

In this way, the female agent changes from the normal state to the state of pregnancy, either wanted or unwanted. A woman can experience several different situations after pregnancy. These situations include the following:

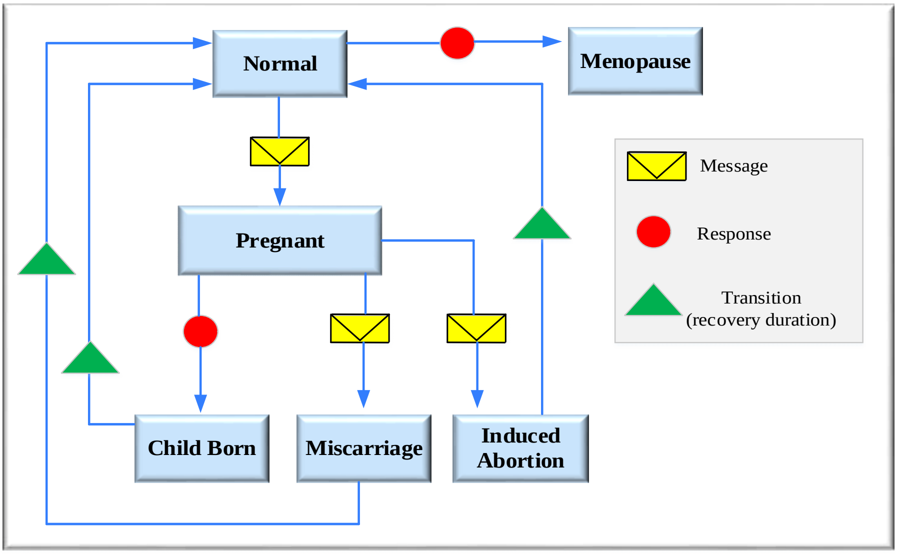
- The fetus is aborted inducibly (based on the agent's experience of induced abortion).
- The fetus is miscarried (calculated based on the agent's experience of miscarriage).
- After 9 months of pregnancy, a baby is born.
- After 9 to 12 months, the female agent in each of the situations of miscarriage, induced abortion, and the child's birth is again included in the pregnancy calculations and considered.

In our model's statechart diagram, there is a recovery duration[10] that is considered a transition taking between 9 to 12 months with a probabilistic variable for women to change their state to normal. It is worth mentioning that children born in the model do not reenter the simulation, as the model's scope is limited to 10 years, and the starting age for childbearing is set at 15 based on women's fertility capability.

The schematic in Figure 5 shows the interaction and behavior of the female agent at the micro level. The directions of the arrows in Figure 5 show that the female agent can get pregnant when she is in a normal state. In other states, the female agent cannot get pregnant.

[10] Transitions to the normal state equals the recovery duration are obtained by multiplying the recovery duration by the recovery calibration.

Figure 5: How the female agent interacts and behaves within the household agent in an agent-based simulation environment



3. Calibration and validation

In order to calibrate the simulation model, the TFR is entered into the simulation model, and the method of its calculation is written in AnyLogic software. The event that calculates the TFR is updated annually by parameters. To check and validate the simulation model, the TFR for three consecutive years was extracted as a reference behavior in the real world by referring to the figures published by the Statistical Center of Iran (2017). Further, considering that the calibration of the three parameters of unwanted pregnancy, wanted pregnancy, and recovery duration is directly effective on women's fertility, these parameters were selected to calibrate the simulation model. In AnyLogic software, model parameters were set by programming commands. In this regard, the software executes the proposed model several times and, in each execution, changes the values of the mentioned parameters according to the written instructions. This process continues until the behavior of the simulated model matches the behavior of the real world. The process of setting the parameters of the model is carried out by commands with the ability to change the range and steps of the model in the software. The following is the structure and form of the commands:

(0 and 1]	Determine the value range for the specified parameters	(a)
Step=0.001		(b)
Unwanted P ‹ wanted P		(c)

Finally, the values of the three parameters mentioned in the simulation model are adjusted by the software, and the outputs of the simulation model are extracted. The results shown in Table 2 confirm that the TFR based on the Statistical Center of Iran and the simulated figures are almost identical.

Table 2: Comparison between real data and the results obtained from simulations

Years	TFR based on simulation model	TFR from the Statistical Center of Iran
2017	1.66	1.60
2018	1.50	1.49
2019	1.45	1.44

It should be noted that due to the stochastic nature of the model, the TFR results in Table 2 have been obtained after 100 instances of simulation runs and averaging the results. After the model calibration, the outputs will be derived based on the proposed scenarios.

4. Simulation results

The output results of the simulation model include the 10-year prediction of the fertility behavior of women in Tehran Province from 2020 to 2029. The first three years of simulation (2017, 2018, 2019) are considered as the validity of the simulation model, and the next 10 years are considered as the prediction of the simulation model based on the current situation of fertility. It should be noted that the output time unit is the TFR of the year (14 years) and other outputs of the month simulation model (168 months). All simulation outputs are obtained based on the Monte Carlo method after 100 executions using different random number kernels and averaging the results. To determine the number of random agents at the zero moment of the simulation, the ratio of women in each age group in Tehran Province was derived from data issued by the Statistical Center of Iran in 2016 (Iran Statistics Center 2017), and due to the growth rate of the female population in Iran in each age group, the number of agents in the simulation model has increased annually. More detailed expressions reporting the process followed for the generation of random agents have been presented in Appendix B. The outputs of the simulation model can be viewed as the outcome of interactions among the agents within the model. These interactions involve diverse dynamics and relationships among the agents, which ultimately impact the overall output of the simulation model. It is crucial to acknowledge that the results of the simulation model stem from these interactions, reflecting the intricacy and interdependence of the modeled system.

4.1 Current fertility simulation results

In this section, the results obtained from the prediction based on the multi-agent-based model on the current conditions of fertility in Tehran Province are examined. Figure 6 shows the results related to the prediction of the cumulative frequency of children ever born, women by seven age groups, the cumulative frequency of pregnancies, the cumulative frequency of wanted and unwanted pregnancies, the cumulative frequency of induced abortions, cumulative frequency of miscarriage in the next 120 months (from 48 to 168 months of simulation), and the TFR during 10 years according to the current conditions of fertility. The outputs are extracted from the interaction of the female agent in the simulation environment, which was explained in Sections 1 and 2. Based on the outputs of the model as shown in Figure 6, TFR in Tehran Province during 10 years will follow a steep downward trend concerning the current conditions of fertility, and the peak of childbearing is in the age group of 25 to 29 years old.

In our explanation of the concentration of childbearing in this age pattern, it is clear that the average age of marriage of women in Tehran Province, based on the data of the Statistical Center of Iran, is 28 years with a standard deviation of 5 years (National Organization for Civil Registration of Iran 2019), which, in the model with normal distribution function, is randomly assigned. Therefore, the majority of married model inputs are in this age group. In the discussion of the social pressure indicator, the assumption of the simulation model was that with the increasing age and duration of marriage of women, the social pressure for women to decide to get pregnant increases. Considering that the average age of marriage is 28 years and the standard deviation is 5 years, women get married between the ages of 23 and 33. Therefore, at the age of 28, 5 years have passed since the marriage, and based on the assumption considered in the model, the social pressure of women to decide to get pregnant increases by 20%. On the other hand, in the construction of the social interaction indicator, it was assumed that if two agents are of the same stratum (being religious was considered as being of the same stratum), female agents will influence each other between 5% and 10%. According to the extracted rule, the percentage of religiosity in the age group of 25 to 29 years old is higher than that in the age groups before and after it, and thus, this age group will be more influenced by social interactions.

Finally, the wanted pregnancy score of agents in the age group of 25 to 29 years in deciding to get pregnant is higher than that in other age groups. Figure 6 shows that the age group between 45 and 49 years has the lowest fertility rate. The reason for this is related to the fertility rate in this age group, which is lower than in other age groups, resulting in fewer children being born in this group. This result is entirely consistent with the natural principle that fertility decreases in older age groups. In this article, when referring to cumulative outputs, we mean the number of children born only to women in the same age group. For example, the cumulative output in the group of women aged 45 to 49 years refers to the number of pregnancy events that occurred in this group during the simulation period, which in this article is 168 months. As observed in Figure 6, the age group between 45 to 49 years has the lowest fertility rate. The reason for this is related to the fertility probability space in this age group, which has been lower compared to other groups, resulting in a lower probability of childbearing in this group. In this paper, the cumulative outputs refer to the number of children born by the women only from the beginning and the end year of the group, not from the age of the beginning of fertility, which is 15 years. For example, the cumulative output of women aged from 45 to 49 years expresses the probability of occurrence of pregnancy events in this group during the simulation period, which is adjusted to 168 months in the simulated model in this paper.

Figure 6 also indicates that the age group of 30 to 34 had the most unwanted pregnancies. Unwanted pregnancy of women in the model is calculated based on the error of each of the contraceptive methods. Based on the rule extracted from the decision tree with the CHIAD criterion, there is a significant relationship between women's contraceptive methods and the number of children and women's age. Thus, it can be said that women of this age group have used more contraceptives, and as a result of which a higher error can be seen in this group. On the other hand, based on how many times each female agent has a sexual relationship per month, the number of contraceptive method errors per month is different for each female agent. According to the results of the simulation diagram, the cumulative frequency of miscarriage and induced abortions of women in Tehran Province will increase by 2.7 and 2.9 times, respectively, within 10 years. Miscarriage and induced abortions based on the personal experience of women are available in the results extracted from the questionnaire, and their trends do not change in the proposed model during the simulation period. As stated, to consider the uncertainty in the simulation model, all the outputs of the simulation model were obtained based on the Monte Carlo method and based on 100 times of execution and averaging of the results. Next, in Table 3, the results of Figure 6 are shown in the prediction of TFR by showing the mean and standard deviation from 2017 to 2029.

Table 3: Mean and standard deviation of TFR during the years 2017–2029

Years	Mean	Standard deviation
2017	1.66	0.038
2018	1.50	0.023
2019	1.45	0.037
2020	1.41	0.036
2021	1.40	0.024
2022	1.35	0.023
2023	1.32	0.032
2024	1.28	0.044
2025	1.23	0.028
2026	1.16	0.034
2027	1.13	0.025
2028	1.08	0.039
2029	1.06	0.027

4.2 Simulation results of the effect of government facilities on fertility behavior

In this section, the simulation of scenarios based on the tasks of the government agent in the model is considered. In this scenario, the question arises whether the increase of government facilities will be effective in increasing the fertility of women in Tehran Province or not. Finally, the results of the condition of women's reproductive behavior by implementing the scenario of the impact of government facilities are compared with the condition of fertility forecasting without the implementation of the scenarios that were predicted in Figure 6 of the simulation results. Based on the mentioned scenario, the sensitivity analysis of the model was done on eight government facilities that were extracted from the available questionnaire. In this way, all eight government facilities in the first stage in the current conditions of fertility have an initial value of three (neutral) in the model.

To do the sensitivity analysis, a score of five was given to each of these government facilities, which is the best number in modeling. Also, a score of three (neutral) was given to the rest of the features, and finally, a sensitivity analysis was taken from the model. This analysis states which one of these features has changed and improved the TFR more than the others. Therefore, the simultaneous effect of the government's financial aid to families and childbirth allowance on the TFR was measured. The prediction results obtained from the simulation model in Figure 7 clearly show that the effect of government financial aid and childbirth allowance have had a significant impact on increasing TFR so that in 2020 TFR for the baseline scenario will increase from 1.40 to 1.49 and after simulating the scenario will increase from 1.06 to 1.10 in 2029. In other words, it can be acknowledged that the provision of government facilities (government financial aid and childbirth allowance) lowers the steep decline in fertility, which in turn is a pioneering achievement to strengthen the solutions proposed to the government to realize targeted and effective policies. The point to consider is that financial and economic facilities would have a higher impact than other government facilities in changing the reproductive behavior of women in Tehran.

Figure 7 clearly shows that the age pattern of fertility has shifted from the age group of 25 to 29 years old in the current situation of fertility to the lower age group of 20 to 24 years old. In other words, the provision of financial government facilities would affect the timing of births. Also, the simulation results in Figure 7 show that from the 48th month to the 168th month of the simulation, the cumulative frequency of children ever born, the cumulative frequency of total pregnancies, and the cumulative frequency of wanted pregnancies increased 3.9, 3.4, and 3.2 times, respectively, while in the current situation of fertility, these indicators increased by 3.7, 1.3, and 3.0 times, respectively.

It can be seen that the provision of government facilities has led to an increase in these indicators compared to the current situation of fertility. Concerning the indicators of the cumulative frequency of unwanted fertility and the cumulative frequency of miscarriage and intended abortions, according to Figure 7, there is no change in their pattern and trend compared to the current situation of fertility because the scenarios considered in the simulation model based on the BDI algorithm are effective in changing only the decision to pregnancy.

Figure 6: Predicting cumulative frequency of children ever born, total pregnancies, wanted pregnancies, unwanted pregnancies, miscarriage, induced abortions, and TFR by age group from 2020 to 2029, Tehran Province, Iran

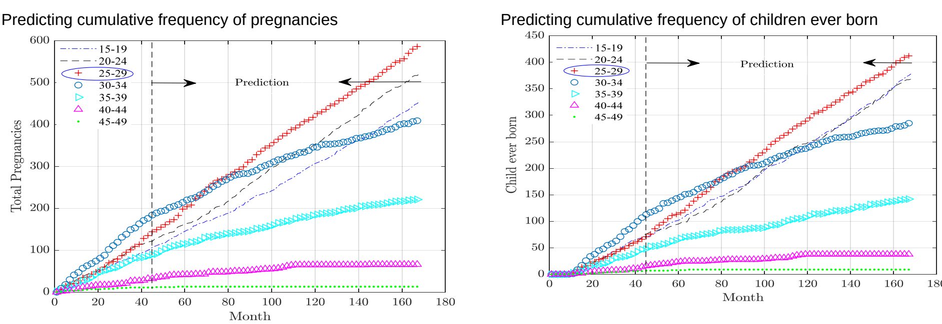
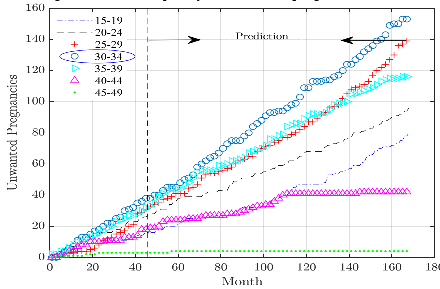
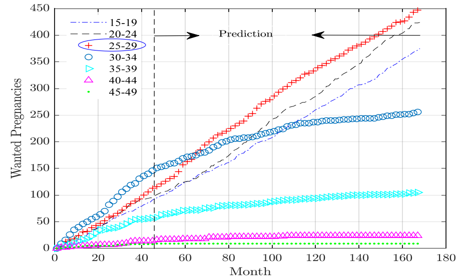


Figure 6: (Continued)

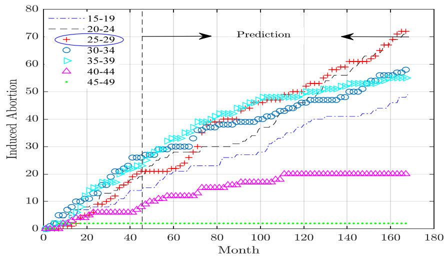
Predicting cumulative frequency of unwanted pregnancies



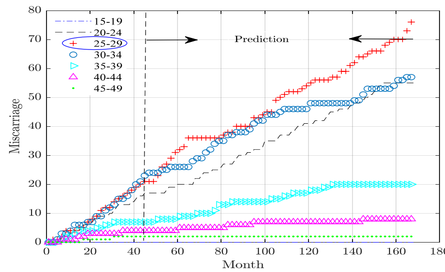
Predicting cumulative frequency of wanted pregnancies



Predicting cumulative frequency of induced abortions



Predicting cumulative frequency of miscarriage



Prediction of TFR

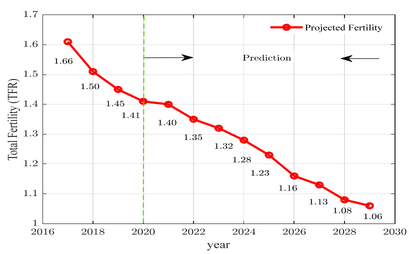


Figure 7: Predicting cumulative frequency of children ever born, total pregnancies, wanted pregnancies, unwanted pregnancies, miscarriage, induced abortions, and TFR by age group from 2020 to 2029, Tehran Province after the implementation of the government facilities scenario

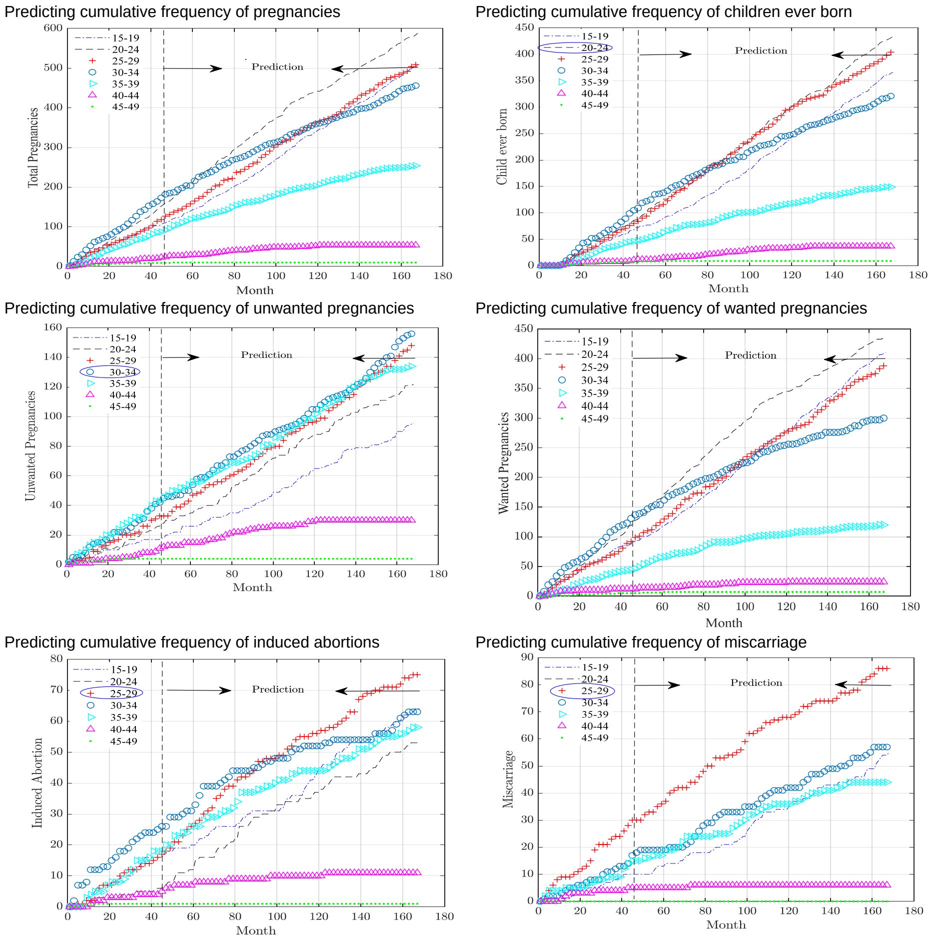
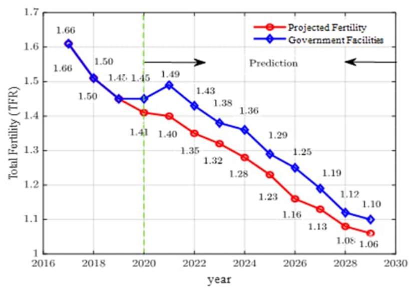


Figure 7: (Continued)

Prediction of TFR after the implementation of the government facilities scenario



4.3 Simulation results of the effect of favorable and unfavorable economic situations on fertility behavior

In the rest of the paper, the other task of the government agent (setting the economic situation) is discussed in the simulation environment, and two pessimistic and optimistic economic scenarios are presented. First, the pessimistic economic scenario is examined. In the following scenario, the question will be answered, What effect can it have on the reproductive behavior of women in Tehran Province if the economic situation in Iran becomes more unfavorable in 10 years (i.e., the inflation rate increases and wages decrease)?

The results of women's reproductive behavior are compared by implementing the pessimistic economic scenario with the current situation of fertility without implementing the scenarios that were predicted in the results of Figure 6. In this scenario, it is assumed that the gap between the wage and the inflation rate will be doubled. In other words, the household income is halved every year, and then the impact of the unfavorable economic situation on the fertility behavior of women in Tehran Province should be predicted and evaluated in 10 years. Next, the optimistic economic scenario will be implemented. Based on this, the economic situation of people improves and people face the benefit of having children in their economic and logical calculations. In other words, if the government tries to improve the economic situation of the household and reduce the inflation rate compared to the current situation and increase the wage, will we see a decline in fertility in ten years? Based on this scenario, it is assumed that the inflation rate will not be less than 0.15 and not more than 0.20, and the wage will not be less than 0.20 and not more than 0.35. As the simulation results in Figure 8 show, it is predicted that the improvement of the economic situation of households will lead to an increase in TFR and will improve the steep decline in fertility. Based on this assumption, as seen in Table 4, the statistics related to the inflation rate and wage during the years 2017–2019 from the Statistical Center of Iran, the Central Bank of Iran, and the Supreme Labor Council were extracted in order to determine the past behavior of the model. From 2020 onward the rate of inflation and wage were chosen as a hypothetical range, and it was assumed that the inflation rate was not less than 0.4 and not more than 0.6, and the wage was not less than 0.2 and not more than 0.3. In the following, based on the continuous uniform distribution function, the income of the households will be randomly quantified during these ten years. It should be noted that in the pessimistic scenario, the worst possible economic situation is simulated. Based on the stochastic nature of agent-based modeling in this paper, the economic status of the household is updated annually and randomly.

Table 4: Inflation rate and wage during 2017–2020

Years	Inflation rate	Wage
2017	0.1	0.12
2018	0.27	0.19
2019	0.30	0.18
2020	0.36	0.25
From 2020 with the consideration of the pessimistic economic scenario	0.4–0.6	0.2–0.3
From 2020 with the consideration of the optimistic economic scenario	0.15–0.20	0.2–0.35

Sources: Statistical Centre of Iran (2018, 2019, 2020), Central Bank Iran (2017), and Supreme Labor Council, (2017, 2018, 2019, 2020).

As observed in Figure 8, after the implementation of the pessimistic economic scenario in the multi-agent-based simulation model, the decreasing trend of TFR would experience a slightly steeper downward slope, from 1.42 in 2020 to 1.41, and from 1.06 to 1.04 in 2029. The results of agent-based simulation confirm the studies based on the importance of the role of the economic situation on women's reproductive behavior. In this way, the unfavorable economic situation and its effect on the reduction of parents' benefits as well as the increase of household costs are effective on the reproductive behavior of women and will lead to a decrease in fertility in Tehran Province. Other figures related to the pessimistic economic scenario are not shown due to little change in the current fertility situation. With the implementation of the pessimistic economic scenario, fertility behavior patterns have not changed significantly. The point that can be mentioned in explaining these results is that, due to the inappropriateness of the country's economic situation in the current situation of fertility, the deterioration of the economic situation has not had much effect on women's decision to get pregnant. Thus, by improving the economic situation of the household, according to Gary Becker (1960), who argues based on the demand theory, if we want to have a positive effect on the decision to have children, we should reduce the economic costs of children. And by increasing the income of parents, the utility function should change toward to have children.

The simulation results following the optimistic economic scenario is a confirmation of studies based on economic theories. As a result, it is predicted that the TFR will increase from 1.42 to 1.43 in 2020 and from 1.06 to 1.1 in 2029. According to the results, with the improvement of the economic situation, the reproductive behavior of women has changed more than the worsening of the economic situation, so the improvement of the economic situation of the family has had a significant impact on the timing of birth, and the age pattern of having children has changed from the age group of 25 to 29 years old to 20 to 24 years old. On the other hand, the cumulative frequency of wanted pregnancies, which is calculated based on the total scores of each female agent from the indicators affecting fertility, has moved from the age pattern of 25 to 29 years old to the lower age group – that is, the age group of 20 to 24 years old. This shows the importance of the economic situation indicator. In other words, the scores of the female agent in the economic indicator in the model, calculated based on the difference between the actual income and the ideal income in terms of the number of family members, decreased. As a result, the score obtained from the economic indicator of agents in the age group of 20 to 24 years is higher than are other age groups.

Since according to the statistics of the civil registration organization in the simulation model, the average age of marriage is 28 years with a standard deviation of 5 years (National Organization for Civil Registration of Iran, 2019). Women get married at the age of 23 and due to the favorable economic situation, they do not delay childbearing and quickly give birth. Also, the results of the simulation in Figure 8 show that from the 48th month to the 168th month of simulation, the cumulative frequency of children ever born, the cumulative frequency of total pregnancies, and the cumulative frequency of wanted pregnancies have increased 3.9, 3.4, and 3.2 times, respectively, while in the current situation of fertility, these indicators have increased by 3.7, 1.3, and 3.0 times, respectively. It can be seen that the improvement of the economic situation has led to an increase in these indicators compared to the current situation of fertility. About the indicators of the cumulative frequency of unwanted fertility and that of miscarriage and induced abortions, as can be seen, there is no change in their pattern compared to the current situation of fertility because the scenarios considered in the simulation model based on the BDI algorithm are effective in changing only the decision to pregnancy.

The predicted indicators of reproductive behavior after the implementation of the scenarios of providing government facilities and improving the economic situation have led to a change in the same reproductive behavior in women in the simulation environment. It is worth mentioning that among the government facilities, financial aid for childbirth expenses and financial assistance to families with an economic nature have the greatest effect on fertility behavior, which is in line with the results of the optimistic economic scenario. In other words, the simulation results clearly show that the government agent can have a high impact on the reproductive behavior of women in Tehran by improving the economic situation and providing cash and financial facilities to the households and as a result improving the economic situation of the household.

Figure 8: Predicting cumulative frequency of children ever born, total pregnancies, wanted and unwanted pregnancies, miscarriage, induced abortions, and TFR by age group from 2020 to 2029, Tehran Province, after the implementation of the optimistic economic scenario and predicting TFR after the implementation of the pessimistic economic scenario

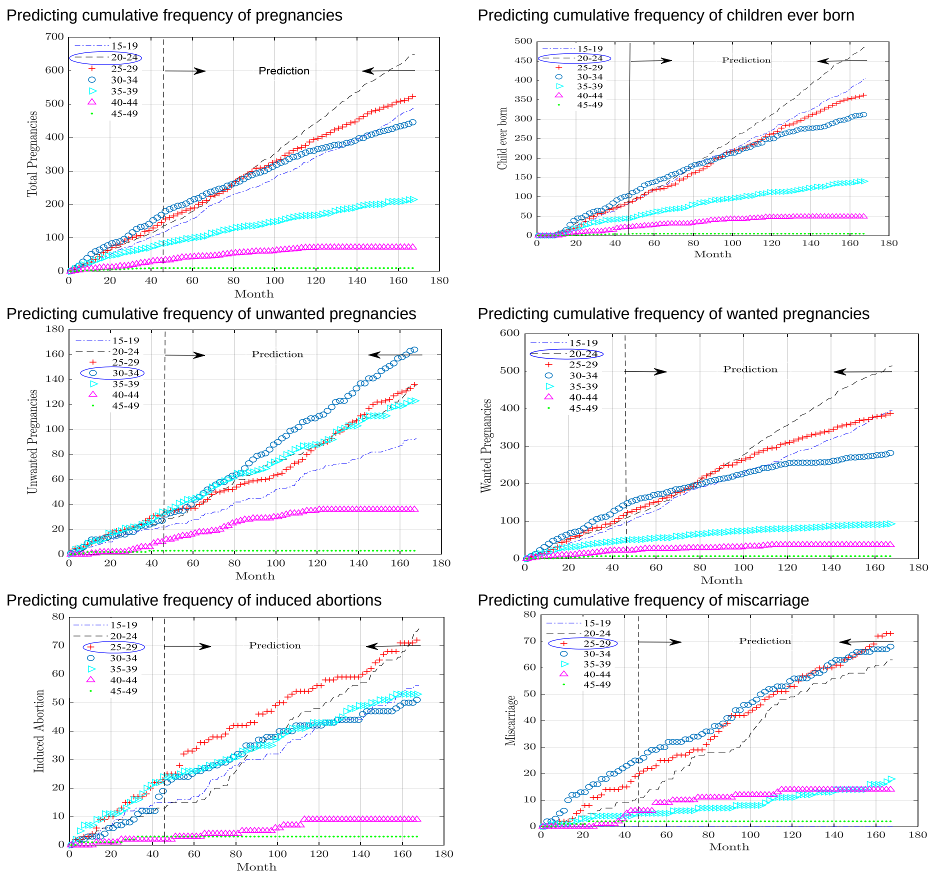
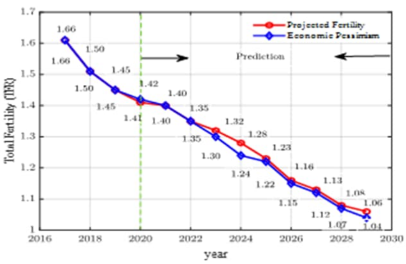
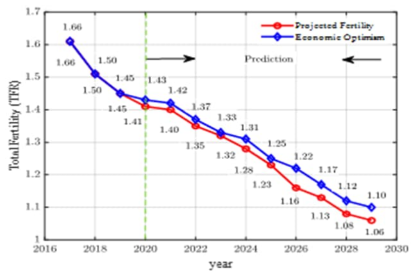


Figure 8: (Continued)

Predicting TFR after the implementation of the pessimistic economic scenario



Prediction of TFR after the implementation of the Optimistic economic scenario



5. Discussion

One of the important issues in demography is helping to adopt appropriate and effective policies in dealing with low fertility. This topic has special importance in Iran due to the attainment of below-replacement fertility. Nowadays, the reduction of below-replacement fertility in Iran has become a challenge, and planners are looking for solutions and facilities for having children and increasing fertility. Achieving the goals of the programs requires understanding the determinants of reproductive behavior so that various government support can be prioritized based on the impacts of these incentives. As one of the effective factors in the decision-making process of women for having children, the government can perform several tasks. Due to the government's role in regulating the economic situation and providing government facilities, this paper predicts and compares the influence of each of these factors on women's reproductive behavior. Forecasting and comparing the influence of each of these factors on fertility behavior will provide a reliable platform for policymakers to plan. In order to achieve the above objectives, agent-based modeling has been used as a method with the ability to communicate between micro and macro levels and consider the heterogeneity of agents at the micro level. By using this method, the accuracy, purposefulness, and satisfaction of policies can be realized by involving the perspective of the micro level in the policies (Billari et al. 2007; Billari et al. 2006; Yang 2016; Grow and Van Bavel 2016; Abbasi Shavazi and Esmaeili 2022). In this paper, the low fertility modeling process is carried out for Tehran Province, the capital of Iran having a lower fertility rate (1.5 children per woman) than the national average (Statistical Center of Iran 2016).

In order to achieve the desired goals in the paper, a multi-agent system was used in the process of modeling the low fertility behavior, in which the interactive relationship between the three agents of the household, women, and the government has been considered at the same time. Based on the uncertainty of the model, heterogeneity and attention to the interactions of agents with each other at the micro level are considered through the design, selection, and implementation of scenarios in the model development process.

The results of the multi-agent-based modeling showed that the fertility trend in Tehran Province will be declining within the next 10 years and reach from 1.41 in 2020 to 1.06 in 2029. On the other hand, other simulation model output prediction results showed that during the years 2020–2029 in Tehran Province, the highest cumulative frequency of children ever born, total pregnancies, and wanted pregnancies will belong to the age group of 25 to 29 years old. The results showed that the highest cumulative frequency of unwanted pregnancies belongs to the age group of 30 to 34 years old and the cumulative frequency of miscarriage and induced abortions of women in Tehran Province will increase by 2.7 and 2.9 times, respectively, in 10 years.

According to the agent-based modeling capability, three scenarios were designed according to the tasks of the government agent and then entered into the model, the behavior of the simulated model was checked and the best solution with the ability to increase fertility as policy suggestions for planners and policymakers were determined. Based on this, the first task of the government agent in the simulation environment was to regulate the economic situation of the country by regulating the inflation rate and wage. Accordingly, two pessimistic and optimistic economic scenarios were tested and evaluated after the design and implementation of the model. In the pessimistic scenario, the question was how women's decision to get pregnant would be different if the government agent is unable to adjust the inflation rate following the wage, and the gap between these two economic indicators becomes greater in ten years. As a result, the economic situation of households becomes more unfavorable. The simulation results showed that after the implementation of the pessimistic economic scenario, the decreasing trend of the TFR accelerated a little more steeply than the current situation of fertility, and the results confirmed the studies carried out based on economic theory.

On the other hand, in the optimistic economic scenario, the ability of the government agent to reduce the gap between the inflation rate and wages and consequently improve the economic situation of households was considered. Also, its effect on women's decision to get pregnant was investigated. The simulation results indicated the effect of the optimistic economic scenario on women's reproductive behavior. The results showed that the improvement of the economic situation of the household has led to an increase in the TFR compared to the current situation of fertility and the increase in the cumulative frequency of children ever born, total pregnancies, and wanted pregnancies. The greatest impact of the optimistic economic scenario will be on the fertility behavior of the 20- to 24-year-old age group. In other words, with the improvement of the economic situation, the age pattern of fertility has shifted from 25 to 29 years old in the current situation of fertility to the lower age group of 20 to 24 years old, and accordingly, it will have a great impact on the timing of births. It can be seen that based on the economic theory, the improvement of the economic situation of the household will lead to a change in the fertility behavior of women and eventually to an increase in the fertility of women in Tehran Province.

On the other hand, with the deterioration of the economic situation, the number of births and pregnancies of women in Tehran Province will decrease slightly in 10 years. The findings of the economic simulation of the present study are in line with much research that has been done in this field. The results of various studies show that the economic situation and conditions of society and families have always been one of the important determinants of fertility, which is consistent with the results of muti-agent-based modeling implemented in this paper (Lutz, Cuaresma, and Abbasi-Shavazi 2010; Sobotka, Skirbekk, and Philipov 2010; Santarelli 2011; Adsera 2006; Bjorklund 2006; Lee 1990; Abbasi-Shavazi and Khani 2017; Abbasi-Shavazi, McDonald, and Hosseini-Chavoshi 2009, Ammar 2015; Fiori et al. 2013; Moeeni et al. 2014). Based on the second task of the government agent in the simulation environment, which was to provide facilities for women to have children, eight facilities were considered, which were extracted based on the available questionnaire. According to the results of the sensitivity analysis on the model, two cases of facilities (i.e., financial aid for childbirth expenses and financial assistance to families) led to further change and improvement in the TFR. In this regard, we can refer to McNicoll's (2001) argument that the government plays an important role in fertility changes. He points out that governments and policymakers can have an impactful role through better implementation of policies, programs, and service quality. The simulation results showed that by providing government facilities, the slope of fertility decline becomes slower and will prevent very low fertility in Tehran Province.

Of course, due to the unfavorable economic situation of the country, there can be observed a slight change in the reproductive behavior of women with the deterioration of economic conditions, but with the improvement of the economic situation and the provision of government facilities that have financial and cash nature, there will appear noticeable changes in the behavior and fertility pattern of women in the province of Tehran. It seems that the economic obstacles are placed as obstacles in the way of realizing the fertility of women in Tehran Province. As the results of studies have shown, in times of uncertainty, future narratives play an important role in shaping people's decisions about having children. Therefore, structural economic changes are necessary to increase and maintain fertility rates at or near replacement levels. The unfavorable economic conditions, along with the high demand for jobs caused by the baby-boom generation after the revolution, have contributed to youth unemployment and economic insecurity in Iran. The younger generation is indeed affected by economic challenges that lead to a pessimistic view of the future, which in turn affects their views on fertility and childbearing (Vignoli et al. 2020; Vignoli et al. 2021; Salehi-Isfahani 2023). Considering the current unfavorable economic conditions in Iran, with unemployment and inflation, it is understandable that people may feel worried about their financial stability and the future of their children. These concerns can certainly influence people’s decisions about starting or expanding a family. To address this issue and the possible increase in the fertility rate in Tehran Province, it is very important for the government to prioritize financial support for families. In addition, efforts to reduce overall economic costs, reduce unemployment, and manage inflation are necessary to create a more stable and conducive environment for people to feel more secure about their financial situation and future prospects. Reassuring families about their children’s well-being and opportunities can also play an important role in encouraging people to consider expanding their family. As a result, the improvement of economic conditions through interventions and targeted support of the government is the key to potentially increasing the fertility rate in Tehran Province. By addressing these economic challenges, the government can help alleviate concerns and create a more conducive environment for individuals to pursue their fertility goals (Abbasi-Shavazi, Razeghi-Nasrabad, and Hosseini-Chavoshi 2020).

Based on the results of the simulation, it is possible to provide key suggestions to the planners and policymakers to help reduce and stop the steep decline in fertility in Tehran Province. Since the improvement of the economic conditions of the country with the provision of financial facilities by the government has had the same effect on changing the fertility behavior of women, it is possible to suggest to the policymakers and planners to provide financial and cash assistance to the households and also to provide maternity facilities for the families on the condition of continuity over time.

From a research point of view, the use of artificial intelligence and neural networks in the construction of agent-based models is proposed as a new field of study. This consideration provides agents with memory, which leads to the possibility of intelligent decision-making based on both the present and previous knowledge of the agents. In addition to the use of new artificial intelligence–based methods, the use of hybrid models is also suggested.

6. Acknowledgments

The authors wish to acknowledge the generous support from Dr. Meimanat Hosseini-Chavoshi and Dr. Hajieh Bibi Razeghi-Nasrabad for providing the data necessary for this paper, and to appreciate valuable comments from the reviewers.

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Appendix

The appendix has three subsections. Section A.1 lists the data sources used in the paper. In Section A.2, the method of agent formation and constructing rules are discussed, and in Section B, the method of generating the number of random agents is explained. Finally, in Section C, the method of building the model with technical details in ODD+D protocol is presented.

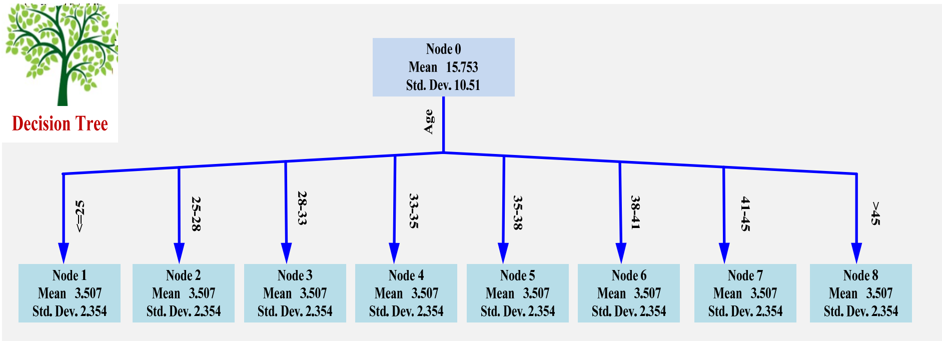
A.1 Data

In order to achieve the goals of this paper, various data are used at micro and macro levels. However, the main analysis is based on the subsample of data from the 2017 Iran Fertility Transition Survey conducted in five selected provinces of Iran (Abbasi Shavazi, Razeghi-Nasrabad, and Hosseini-Chavoshi 2019). The data were collected from 1,500 households in Tehran Province, including 798 women who have been or are still married. The questionnaires were developed in the form of a general household questionnaire and a special questionnaire for previously or currently married women aged between 15 to 54. At the macro level, the data from the Statistics Center of Iran, the National Organization for Civil Registration, the Supreme Labor Council, and the Iran Central Bank were used.

A.2 Agent generation and role extraction

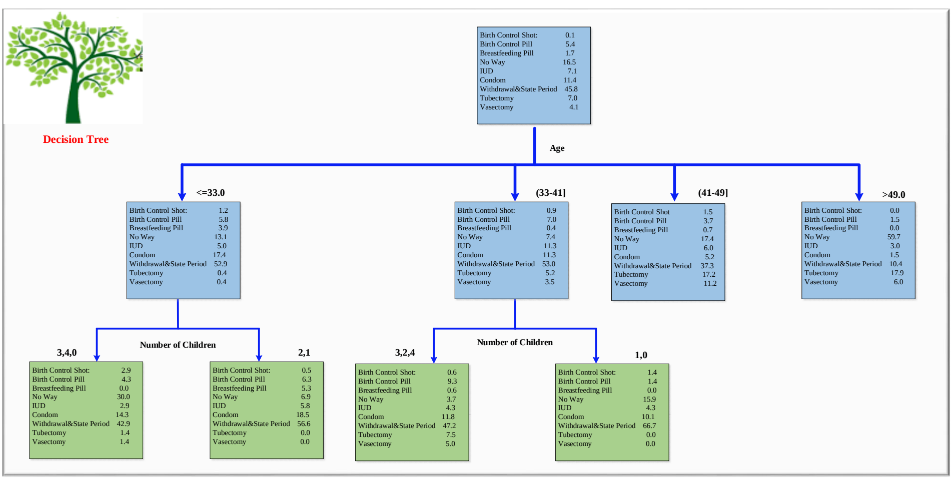
In this paper, the decision tree concept was used to define the agent and the agent's behavior. In addition to using the decision tree, in order to randomly value the agents and choose the appropriate probability distribution functions, EasyFit software was used. In this section, the construction of the duration of the agent's marriage and the contraceptive method are discussed as two examples of the rules extracted using the decision tree. In Figure A-1, the random quantification of the duration of the agent's marriage is shown.

Figure A-1: Randomizing of the marriage duration of the agents



As Figure 6 shows, based on the CHIAD criterion, there is a significant relationship between the age of women and the duration of the marriage. For this reason, a new branch has been created in different age groups in the decision tree. In Figure A-2, the random value assignment of the contraceptive method is shown. As the figure shows, there is a significant relationship between a woman's contraceptive method, the number of children, and the age of women.

Figure A-2: Randomizing of the agents based on the contraceptive method



Appendix B. The way in which random agent generation is developed

Table A-1: The weight percentage for women in Tehran Province

Age groups	The number of women in Tehran Province	Weight percent
15–19	401,141	**0.093**
20–24	402,908	**0.093**
25–29	485,620	**0.11**
30–34	679,824	**0.15**
35–39	778,351	**0.18**
40–44	633,394	**0.14**
45–49	475,615	**0.11**
50–54	439,231	**0.10**
total sum	4,296,084	**100**

In the third step, due to the ratio of 53% for married women with respect to the total female population, the total number of women aged 15 to 55 is multiplied by 53%:

$$\text{Total married women} = 4296084 \times 0.53 = 2316757 \qquad (15)$$

In the fourth step, due to the limitations in performing calculations for a large number of agents due to the extent of the model, a scale of 500 to 1 was considered for generating random agents. Equation (16) shows how to calculate the number of agents.

$$\text{Number of agents} = 2316757/500 = 4633 \qquad (16)$$

Table A-2: The number of random agents in each age group

Age groups of women	Weight percent	The number of random agents in each age group
15–19	0.093	**432**
20–24	0.093	**433**
25–29	0.11	**523**
30–34	0.15	**733**
35–39	0.18	**839**
40–44	0.14	**683**
45–49	0.11	**512**
50–54	0.10	**473**
Total sum	100	**4,633**

Appendix C. Building the simulation model

In this section, the introduction of the agent, how the agents interact, the algorithm, and how to build the simulation model according to the ODD+D protocol are presented.[11]

[11] The ODD+D protocol utilized in this paper is developed based on Muller et al. (2013) and Grimm et al. (2010).

Table A-3: The ODD + D protocol including the guiding questions

Structural elements	Answers
1) Overview	
a) Purpose	a) This paper predicts and investigates the impact of family policies and the economic situation on women's reproductive behavior in Tehran Province, Iran.
b) Entities, state variables, and scales	b) The main components of our model are defined as agents. In our simulation model, three agents – government, household, and woman – are defined and interact with each other. Therefore, the agents serve as the main building blocks in the presented model. The agents are built up based on attributes that play a fundamental role in determining the behavior of agents. We have implemented the behavior of the agents using these attributes within the software AnyLogic. The attributes of the agents are inputted into the model as variables and parameters. In the second part of the article, Table 1 presents the main variables and parameters of the model, which represent the attributes of the agents entered into the simulation model.
c) What are the exogenous factors/drivers of the model? If applicable, how is space included in the model?	c) The agent of the government in the model acts as an exogenous stimulus affecting both household and female agents, while the household and female agents influence only each other. Overall, the government, as an exogenous stimulus agent, in conjunction with the household and female agents, influences women's pregnancy decisions.
2) Design concepts	
d) Theoretical and empirical background	d) The model is developed based on the belief–desire–intention (BDI) theory, which is fully discussed in Section 2.2 of the article.
e) Individual decision-making	e) The decision-making process of agents in the simulation model is developed based on the BDI theory, where decisions related to pregnancy are made probabilistically. The second part of the article describes the decision-making algorithm followed by the agents, which is demonstrated schematically in Figure 2. It is important to highlight that the ultimate decision regarding pregnancy is influenced by both the government agent and the attributes of the household and women.
f) Learning	f) Learning is not integrated into the simulation model in the paper. Although the values of probabilistic variables that impact decision-making change throughout the simulation, their weights in the decision-making process remain unchanged.
g) Individual sensing	g) In the simulation environment, the government serves as an external stimulus affecting both the household and female agents, while the attributes of the household and female agents act as internal agents that influence women's decisions toward pregnancy.
h) Individual prediction	h) Not applicable.
i) Interaction	i) In the simulation environment, household and female agents interact with each other, and they are influenced by the government as an external stimulus, which is shown schematically in the second part of the article in Figures 3 and 4.
j) Collectives	j) In the simulation model, we divided our households into 8 groups ranging from 15 to 55 years old based on the age group of the women in the household. Women are organized into household groups 1 to 8 according to their age group. These household groups interact and influence each other within the simulation environment. It is important to highlight that in the model, each female agent interacts within the household agent with a 50% probability of interacting with women from her own group and a 50% chance of interacting with women from other groups.

Table A-3: (Continued)

k) Heterogeneity	k) Considering the heterogeneity of agents is one of the important features of the presented simulation model, women in the simulation environment have different attributes that set them apart from each other. In other words, women take varying value in each attribute, resulting in different value for the agent. In Table 1 of the article, the attributes of the agents are given.
l) Stochasticity	l) In a general classification, there are five main areas of Stochasticity in our simulation model. (1) Concerning the concept of decision-making for pregnancy, both wanted and unwanted pregnancy as well as the recovery duration for another pregnancy are taken into account as stochastic quantities in the generated model. (2) In the modeling, abortions, including miscarriage and induced abortions, are treated as stochastic variables. The event space of abortion in this paper is obtained using roulette wheel algorithm in the simulation environment. (3) All the values related to the attributes of the agents are formed in a probabilistic way. It is given in Section 2.1 of the paper. (4) Social interactions have been seen in the model as a stochastic quantity. (5) Other possibilities and uncertainties: The scope of the problem was big and many factors may influence the behavior of the model, which cannot be directly taken into account due to the lack of knowledge or the difficulty of quantification. It is worth mentioning that in the presented paper the authors have entered the unknown quantities using the calibration process. In the simulation model, we consider the possibilities of wanted pregnancy, unwanted pregnancy, and abortion. The recovery duration, uncertainties, and unknown effects that are affecting the probabilities have been addressed through the calibration process in this manuscript. As a result, our simulation environment is not a closed system, and the probabilities of pregnancy and abortion are derived directly. The influence of other unknown factors is taken into account with the calibration coefficients.
m) Observation	(1) total fertility rate (TFR) (2) cumulative frequency of children ever born (3) cumulative frequency of total pregnancies (4) cumulative frequency of wanted pregnancies (5) cumulative frequency of unwanted pregnancies (6) cumulative frequency of miscarriage (7) cumulative frequency of induced abortions
3) Implementation details	
n) Initializations	n) The simulated model has been initialized stochastically. It is worth mentioning that the details of this process are provided and explained in Section 2.1. This model is processed using a set of data extracted from a questionnaire, on which a series of probabilistic and statistical analyses have been performed, and based on that, the model is constructed and initialized. The implementation and simulation of the model have been carried out in the AnyLogic software environment; the software link is included in the references. The number of agents at the starting point in the simulation is derived based on the number of women in Tehran Province in the year 2016, then the agents are generated randomly. The method utilized for extracting the random agents at the starting moment of the simulation is reported in Appendix B. Subsequently, the number of agents in the software is updated annually based on the population growth rate in Iran. After generating the agents, household agents are divided into 8 groups based on a 5-year age difference. It is worth mentioning that the initial division criterion of household agents is based on the age of the woman inside the household agent. It is worth mentioning that based on the explanations the developed model is not accessible.

Table A-3: (Continued)

o) Input data	o) Our input data were derived based on a survey, where data have been gathered and then analyzed statistically and probabilistically. Then rules were extracted and entered into the simulation model. Required information regarding data is reported in Appendix A.1. In addition, no external sources were used during the execution of the model.
p) Submodels	p) The model dose not include any submodels at all.