AN INTEGRATED ECONOMY-DEMOGRAPHY MODEL REFRAMED IN A SYSTEM DYNAMICS SETTING

Gozdem Dural-Selcuk
Department of Industrial Engineering, Atilim University, Ankara, Turkey

Huseyin Tunc
Department of Business Administration, Social Sciences University of Ankara, Ankara, Turkey

S. Armagan Tarim
Cork University Business School, University College Cork, Cork, Ireland

ABSTRACT

In recent history, there has been an increasing concern about population aging and the associated increased economic burden in terms of high health care expenses and pension payments. The need for decision support tools that can explore population dynamics has become a prominent issue. This study presents a comprehensive framework, where one can scrutinize the key demographic drives of fertility (Total Fertility Rate/Age-Specific Fertility Rate) over macroeconomic indicators (technology, education, human capital) under exogenous mortality. The integrated model in this paper is developed based on a reformulation of the unified growth theory. In the reformulated model, namely the "economy-demography model", the population age/sex structure is preserved, age-specific mortality is included and fertility is measured in conventional demographic terms. The model is then presented in system dynamics framework and its practical use is showcased with data obtained from Turkish Statistical Institute.

Keywords: system dynamics, ageing chain, economic theory of fertility, unified growth model, cohort component modelling

INTRODUCTION

It is challenging to divide the history of humanity into mutually exclusive time slots in terms of demographic and economic changes. Rather, it is a continuous process starting from Neolithic Age through agricultural societies, industrial revolution and eventually the age of technology. Nevertheless, the process has not been completed yet. The inevitable final stage of global demographic transition is the so-called population ageing arising as a fundamental demographic problem in the developed countries (Lee, 2003). The United Nations also highlight the significance of global population ageing in its recent reports by noting population ageing as the most significant social transformation of the twenty-first century (World Population Ageing 2015).

Governmental agencies worldwide aim to understand the dynamics of population ageing and they try to find ways to cope with its spillover effects on the economy. In this study, the objective is to provide a framework for public policy makers focusing on family-size decision making. The current study is built on an economic growth theory, which presents a unified theory explaining the historical development of the economy and demography starting from the Malthusian era until the times of sustained economic growth (Galor and Weil, 2000). The Malthusian era represents the time frame where fertility levels were proportional to income per capita levels and the technological development rate was quite low, whereas the times of sustained economic growth refer to the period of fast growing economies with high level of technological development accompanied by lower fertility rates. Galor and Weil (2000)'s unified growth theory presents an approach that explains the population dynamics over macroeconomic factors of education, human capital, and technology in a continuum. However, their study remains a theoretical work with a high level of abstraction restricting its use in practice.

We, hereby, revisit the unified growth theory and reformulate the model in a way that it is integrated with cohort component modeling (CCM) adopted from the field of conventional demography. The objective of the integrated economy-demography model is to aid decision makers to analyze generic fertility measures (i.e. Total Fertility Rate - TFR/Age-specific Fertility Rate - ASFR) over macroeconomic indicators (i.e. technology, education, human capital) under exogenous mortality without losing the track of population age/sex structure through the years. We implement the proposed model in a system dynamics context, which is found to be a suitable platform to test economic theories and 'attach economy to real life' by the touch of 'a system profession' (Forrester, 2013). We conduct simulation experiments to showcase the model's practical use for economists and demographers by a comparative display of the model results with Turkish historical data (2008-2019) along with the projections published by TURKSTAT (Turkish Statistical Institute).

The paper is organized as follows. In the next section, we present background information, the methodology, and the contribution of our study. Then, we introduce our economy-demography model. Following that, we display preliminary model results before commenting on model validity. We finalize the paper with sensitivity simulations and concluding remarks.

BACKGROUND INFORMATION AND CONTRIBUTION

There is a causal relationship between economic and demographic dynamics (Liao ,2011) and an extensive literature investigates the demographic transition, namely the decline in fertility rates, through economic growth models. In particular, fertility decline in growing economies is a common and well-documented phenomenon. This can be represented for Turkey, as an example, over the years 1960-2017 (World Bank

Data) in Figure 1. Figure 1 displays the total fertility rate over many years where the size of each point is proportional to GDP per capita in respective year.

Some of the studies associate the fertility decline with income per capita levels (e.g. Becker, 1960, 1974; Barro, 1974; Becker & Barro, 1988), while others claim that it originates from declining mortality rates (e.g. Eckstein et al., 1999; Jones, 2001; Boldrin & Jones, 2002; Fernandez & Villaverde, 2001; Mateos-Planas, 2002; Kalemli-Ozcan, 2002, 2003, 2008; Lagerlöf, 2003; Weisdorf, 2004; Doepke, 2005; Tamura, 2006). A third group propose that the quality of child and the technological development are the main factors, such that the fertility decline stems from the rise in the demand for higher human capital formation (e.g. Becker et al., 1990; Tamura, 1996; Galor & Weil, 2000; Jones, 2001; Hansen & Prescott, 2002; Tamura, 2002; Galor & Moav, 2002; Doepke, 2004; Liao, 2011).

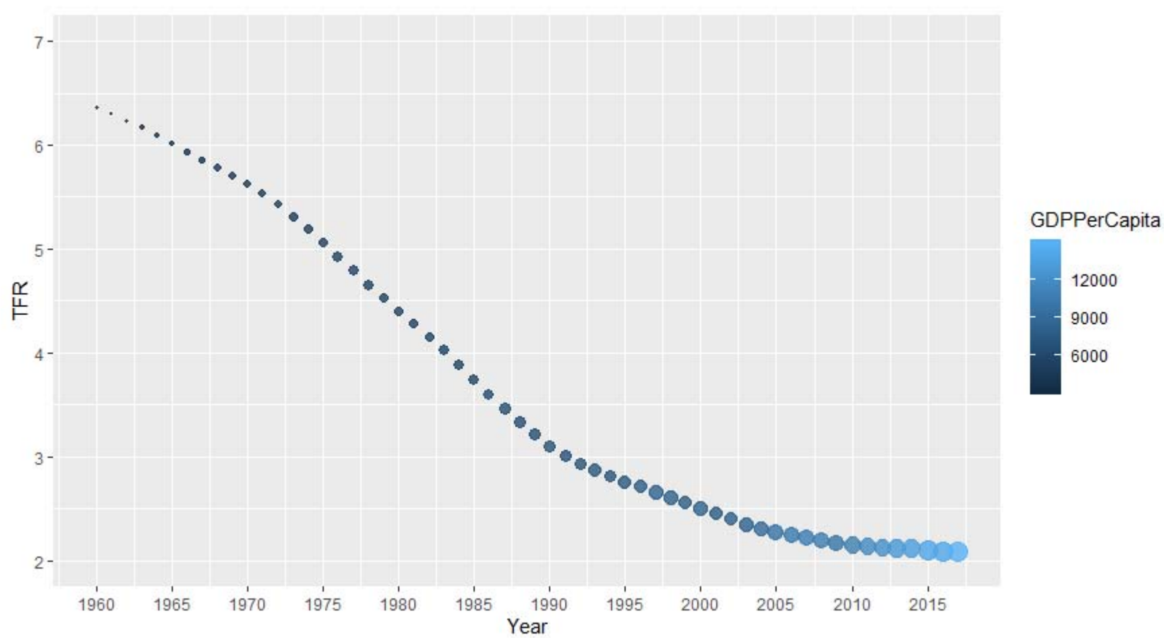

Figure 1 TFR-GDP Per Capita relationship for Turkey over the years 1960-2017

Unified growth theory extends the economic theory of fertility. In the following section, we address the key concepts that unified growth theory is built on rather than providing a complete review of the economic theory of fertility.

Economic Theory of Fertility

Becker is the first who forms the economic theory of fertility (Becker, 1960). In his seminal paper (Becker, 1960), Becker introduced the concept of "quality of child" and mentioned the "quantity-quality trade off" for the first time. In a nutshell, Becker views children as akin to consumer durable goods. The parents decide on the quantity (i.e. number of children) and the associated quality level of children (i.e. time/money investment made by parents for their children's education) so as to maximize the total utility gathered from child bearing and their own consumption subject to a budget constraint. Becker (1974) and Barro (1974) introduced another key concept: "Altruism", and afterwards published a joint paper (Becker and Barro, 1988) where altruism is taken into account within the economic theory of fertility. Altruistic parents care about the future welfare of their offspring. In a later study (Barro & Becker, 1989), the authors remarked that the technological progress can also affect the levels of fertility either positively or negatively via increasing income levels.

Caldwell introduced the "wealth flows theory" (Caldwell, 1976) claiming that parents are rational decision makers and they consider intergenerational transfer of wealth. In the early times, when brute labor force (i.e. physical man power) was the key driver of productivity, children were regarded as an asset for their parents. As a result of the industrial revolution, however, urbanization rates increased and new job opportunities arose, thereby decreasing the need for extended families. In the meantime, compulsory mass schooling forced people to invest in their children. These fundamental changes invited the reversal of the direction of wealth flow as from 'the offspring to parents' to 'parents to the offspring'. In this regard, the reversal of the wealth flow theory shared a common ground with the altruistic parents described by Becker. Easterlin later extended this theory by introducing the "intergeneration taste effect" as well as the "subsistence level of consumption" (Easterlin, 1978). The former refers to a presupposition that a luxury product in one generation becomes a necessity in the next, whereas the latter represents a constraint that stands for the level of income that an individual reserves for minimum consumption requirements, which is mainly determined by the consumption habits of the ancestors of that individual.

Finally, the "human capital" concept is introduced in the economic theory of fertility literature. As technology took place of the brute force labor in the contemporary world, the skills and experiences of workers gained importance. That is, the hereditary transfer of knowledge became obsolete and people needed to possess a lifetime knowledge accumulation to be able to compete in the market. The lifetime knowledge accumulation argument created the term "human capital". Studies that takes the human capital as the main reason for the demographic transition has significantly increased in number mostly after 1990s (e.g. Becker et al., 1990; Tamura, 1996; Galor & Weil, 2000; Jones, 2001; Hansen & Prescott, 2002; Tamura, 2002; Galor & Moav, 2002; Doepke, 2004; Liao, 2011).

In the new millennia, Galor and Weil (2000) presented break-through study of the unified growth theory, which is shown to be valid for the entire evolution process from Malthusian era through the industrial revolution, demographic transition and the period of sustained economic growth (Galor & Weil, 2000). Unified growth theory differentiates from other economic growth theories since it is the most comprehensive theory and evaluates the entire process in a continuum. In the next section, we elaborate further on the unified growth theory.

The Unified Growth Theory

The unified growth theory is constructed on four main assumptions:

- Individuals decide on the quality of their children as a response to technological progress.
- The rate of technological progress is proportional to the level of education of the children.
- Larger populations are assumed to provide a productive environment to spread new ideas, so that technological progress is positively linked to the population size.
- The economy is characterized by a fixed factor of production, land and a subsistence level of consumption below which individuals cannot survive.

The unified growth theory (UGT) is conceptualized as an overlapping generations model, where individuals live for two periods: childhood and adulthood. Adults decide on quantity and quality of children in order to maximize their utility over their own consumption and child rearing subject to a budget constraint, human capital production function and a subsistence level of consumption constraint.

The income level of an adult in period t is denoted as z_t and expressed as follows:

$$z_t = h_t^a \left(\frac{A_t X}{L_t}\right)^{1-a} \tag{1}$$

The first term, h_t, represents the human capital level of the adult and the second term shows the effective resources per adult where A_t is technology level, X is fixed amount of land and L_t is the population size of adults. The labor share in the production function is denoted by a, where a is in the range (0,1).

The technological progress rate, g_{t+1}, is the relative change in the technology level between two consecutive years:

$$g_{t+1} = \frac{A_{t+1} - A_t}{A_t} \tag{2}$$

The human capital of an offspring, h_{t+1}, is a function of the education level attributed to a child (e_{t+1}) and the technological progress rate. Note that the education and human capital levels of an offspring are denoted by e_{t+1} and h_{t+1}, where it is e_t and h_t for adults respectively.

$$h_{t+1} = h(e_{t+1}, g_{t+1}) \quad (3)$$

Here, it is assumed that human capital increases with education, but at a declining marginal rate. Technological progress rate, on the other hand, renders the knowledge obsolete and has a negative effect on human capital formation. However, it is stated that this erosion effect could be weakened by higher education investments. Although the education level of an offspring is an increasing function of technological progress rate, it is implied that there should be a threshold value of technological progress rate ($g_{t+1} < \hat{g}$), where adults do not need to invest in the education of their children.

The dynamics between education and technological development is also defined to be reciprocal given that the technological progress rate is a function of the level of education and the size of the adult population:

$$g_{t+1} = g(e_t, L_t) \quad (4)$$

The larger the population the faster to spread the new ideas. Thus, the population size has a positive effect on the technological progress rate which is the so-called scale effect with a finite upper bound, i.e. $\lim_{L\to\infty} g(e, L) \neq \infty$.

The utility function of an adult, u_t, is expressed by:

$$u_t = (n_t h_{t+1})^{\gamma}(c_t)^{1-\gamma} \quad (5)$$

This equation represents the utility an adult gets from child rearing ($n_t h_{t+1}$, where n_t is the number of children per an adult) and own consumption, c_t, with a fertility weight factor of γ where $\gamma \leq 1$.

The cost of child rearing is calculated in terms of time units. A fixed amount of time is allocated just to raise a child regardless of the quality and it is denoted by, τ, whereas a variable time allocation determined upon the adult's decision of education endowment for the offspring is represented by e_{t+1}.

Accordingly, the level of consumption of an adult is the income level proportional to the unit time left after child rearing:

$$c_t = z_t[1 - (\tau + e_{t+1})n_t] \quad (6)$$

In the light of the equations above, the optimization model that the unified growth theory is built on can be expressed as follows:

$$\max u_t \quad (7)$$

$$subject\ to$$

$$c_t \geq \tilde{c}\ and\ n_t, e_{t+1} \geq 0 \quad (8), (9)$$

where constraint (8) states that the consumption of an adult should be above a subsistence level of consumption, $\tilde{c}$.

Galor and Weil (2000) show that there exists a steady-state equilibrium for the above optimization model and the decision variables, say the number of children per an adult, n_t and e_{t+1}, at steady-state is given as:

$$n_t[\tau + e_{t+1}] = \left\{ \begin{array}{c|c} \gamma & if\ \ z_t \geq \tilde{z} \\ 1 - \tilde{c}/z_t & if\ \ z_t \in (\tilde{c}, \tilde{z}) \\ 0 & if\ z_t \leq \tilde{c} \end{array} \right\} \quad (10)$$

where $\tilde{z}$ denotes the level of income at which the subsistence level of consumption constraint is binding. The steady-state equilibrium condition implies that an adult's fertility decision depends on whether the subsistence level of consumption is binding. If the income level is high enough (i.e. $z_t \geq \tilde{z}$ where $\tilde{z} \equiv \tilde{c}/(1-\gamma)$), γ amount of time is allocated to childcare. If the income level is not even enough to afford the subsistence level of consumption (i.e. $z_t \leq \tilde{c}$), adults cannot have a child. Otherwise, (i.e. $z_t \in (\tilde{c}, \tilde{z})$), the subsistence level is afforded and the rest of the income is allocated to child rearing.

Galor and Weil (2000) further demonstrate the steady-state equilibrium conditions via phase diagrams in a pairwise fashion. For further details, we refer the interested reader to the original paper (Galor and Weil, 2000). Lagerlöf (2006), on the other hand, develops the parametric forms of originally implicit functions of the unified growth theory, so as to simulate the model and to present results in terms of time paths instead of bilateral relationships. The simulation results show that the time paths of the parameterized model appear as perfect replicas of the historical process yet after significant smoothing is done (Lagerlöf, 2006).

The Methodology

With the aim of applying a theoretical model into a practical setting, we have chosen system dynamics (SD) as the methodological approach. The first well-known SD model addressing population dynamics is "World Dynamics" proposed by Jay Forrester (Forrester, 1971). The main concern was scarce resources and the exponential growth of the population and thus "World Dynamics" explores the interactions between economy, population and ecology. It is immediately followed by “Limits to Growth” (Meadows et al., 1972) and “Dynamics of Growth in a Finite World” (Meadows et al., 1974). The extensions of these studies are published in 1992 and in 2004 (Meadows et al., 1992, 2004).

Some recent SD studies, on the other hand, relate demographic changes with economical and societal aspects and they are more policy oriented (Pedercini and Barney, 2010; Auping et al.,2015). Pedercini and Barney (2010) provide a decision support tool to evaluate the possible outcomes of the interventions related to the United Nations Millennium Development Goals (MDG). They particularly discuss the effects of interventions on economic and demographic development of countries and their interaction with education and health systems. Auping et al. (2015) similarly focus on population ageing and its effects on social security, health care, and economy. Those studies illustrate how the SD methodology is used in economy-demography-related interdisciplinary areas.

Our Contribution

In this paper, we propose, in a system dynamics context, an integrated economy-demography model as a reformulation of the unified growth theory (UGT). We aim to extend the limitations of the unified growth theory and make the following contributions:

- We break down the population by age and sex and keep track of population age/sex structure throughout the years.
- We include age-specific mortality instead of two-period life cycle.
- We periodically calculate the conventional measures of fertility (i.e. TFR/ASFR) over macroeconomic indicators.
- We conduct a series of simulation experiments so as to illustrate the practical use of the model.

As a result, we extend the UGT model, grounded on solid economic theory, so as to reveal practical insights on conventional demographic indicators for reasonably short time scales. This paper is of interest due to its potential relevance for demographers, economists, and system dynamics community, and it demonstrates the value of an inter-disciplinary systems approach to economics.

THE MODEL

Before we introduce our economy-demography model we present the unified growth theory (UGT) in a stock-flow diagram in Figure 2. For consistency, the notations in the diagram are the same as the model formulation.

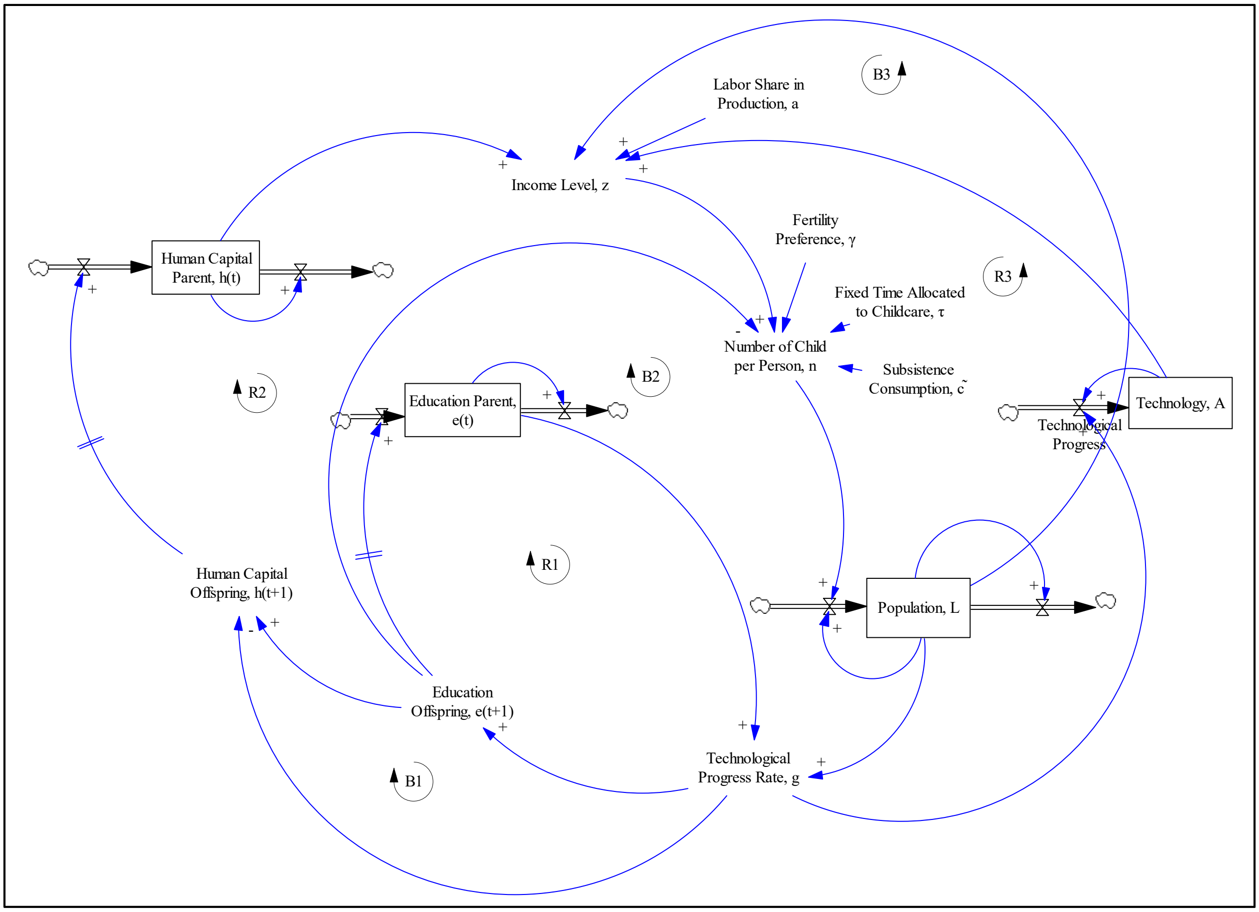

Figure 2 Stock-flow diagram-UGT

The model is composed of four stock variables (i.e. education and human capital level of parents, technology, and population) and six major feedback loops, namely R1, R2, R3, B1, B2, and B3.

The major feedback loops capture the main structure and assumptions that underlie the UGT. R1 illustrates that educated parents raise an educated generation. That is, the education accumulation of parents causes the technological progress rate to increase, resulting in a need for higher levels of educational investment for the offspring. R2 shows that parents with higher levels of human capital have higher levels of income and they can afford having larger families implying that higher quality generations may yield a larger population. In particular, population is increased by the number of children born and it is assumed that any inflow to population leaves the system after a particular time lag, i.e. one generation. Thus, it is treated as a first order material delay. Continuing with R2, the size of the population has a positive effect on technological development as a larger population provides a productive environment to spread new technologies. Consequently, this stimulates the need for higher education and human capital level of the offspring. The education and human capital levels of the offspring are treated as auxiliaries which positively contribute to the education and human capital stocks of parents with a time lag. R3 implies that higher levels of technology results in higher level of incomes and, in a similar fashion with R2, this leads to a larger population.

The education of offspring, on the other hand, contributes to the human capital accumulation of parents, but it is partly eroded by the technological progress rate. This implies that educational investment loses marginal value as the level of technology increases. This fact characterizes the negative relationship between technological progress rate and the human capital levels (B1). As stated earlier, technological development increases the need for higher level of educational investment. This leads parents to have less children to be able to allocate required resources for educational endowment under a limited budget (B2). In the model, it is assumed that the size of the population and income per capita are inversely proportional. This creates a balancing loop between population, income level, and number of children per person (B3). The detailed list of the feedback loops of UGT is provided in the supplementary material.

Fallah-Fini et al. (2013) propose disaggregating population stock according to some common attributes and aim to estimate macro-dynamics of the population via micro-dynamics of a representative individual who is a member of the sub-group in the population. In such a model, a representative individual of a sub-group can move among the groups, but the characteristics of each group stay the same. Following a similar principle, we disaggregate the total population and assume that each group is homogenous and consists of individuals with the same characteristics.

The reformulation decomposes the main optimization problem of UGT as follows:

$$\text{maximize } u_{ti} = (1-\gamma)\ln c_{ti} + \gamma \ln(n_{ti} hn_{ti}) \tag{11}$$

$$\textit{subject to}$$

$$c_{ti} = z_{ti}[1-(\tau_i + en_{ti})n_{ti}] \tag{12}$$

$$c_{ti} \geq \tilde{c}_i \tag{13}$$

$$en_{ti}, n_{ti} \geq 0 \tag{14}$$

$where$

$\underline{objective\ function}$:

$u_{ti} = utility\ of\ an\ individual\ of\ age\ group\ i\ in\ time\ t$

$\underline{decision\ variables}$:

$c_{ti} = consumption\ level\ of\ an\ individual\ of\ age\ group\ i\ in\ time\ t$

$en_{ti} = education\ level\ invested\ in\ the\ child\ parented\ by\ age\ group\ i\ in\ time\ t$

$n_{ti} = number\ of\ children\ \ born\ per\ person\ in\ age\ group\ i\ in\ time\ t$

$hn_{ti} = human\ capital\ level\ of\ adults\ in\ time\ t + 15\ who\ were\ born\ in\ time\ t\ by\ age\ group\ i$

$z_{ti} = income\ level\ of\ an\ individual\ of\ age\ group\ i\ in\ time\ t$

$\underline{parameters:}$

$\gamma = weight\ on\ fertility\ in\ utility\ function\ (i.e. fertility\ preference)$

$\tau_i = fixed\ time\ cost\ of\ children\ parented\ by\ age\ group\ i$

$\tilde{c}_i = subsistence\ level\ of\ consumption\ of\ age\ group\ i$

The reformulation mainly decomposes the population into mutually exclusive age groups with equal time units, and each age group in the reproductive period is assumed to have its own optimization model with corresponding age-specific parameters. That is, the reformulation decomposes a single optimization problem into smaller identical sub problems with different parameter settings, so that the equilibrium conditions of UGT remain for the reformulated economy-demography model.

The decomposition of the population makes it possible to combine the UGT model with the cohort component modelling technique (CCM), which is one of the most frequently used conventional demographic tools for population projection (Rowland, 2003). The CCM disaggregates population by age and sex to project population change parameters such as birth, death, and migration for each cohort. By doing so, we make use of the explanatory power of the unified growth model, and gather the population age/sex structure with reasonably short time brackets by the means of CCM. Additionally, we include exogenous mortality by the age-specific survival rates with endogenous education, human capital and technology levels.

The economy-demography model is shown as a stock and flow diagram (Figure 3), and then explained in detail using difference equations. Galor and Weil (2000) presented the model variables in general form, which prohibits the user to conduct a quantitative exercise. Lagerlöf (2006), on the other hand, has developed UGT in a parametric form so that they could be directly used in an experimental study. In this study, we use the parameterization developed in Lagerlöf (2006) with an adjustment for age-specific setting. We refer interested reader to Lagerlöf (2006) for the details on how the preliminary parameterization is established for UGT.

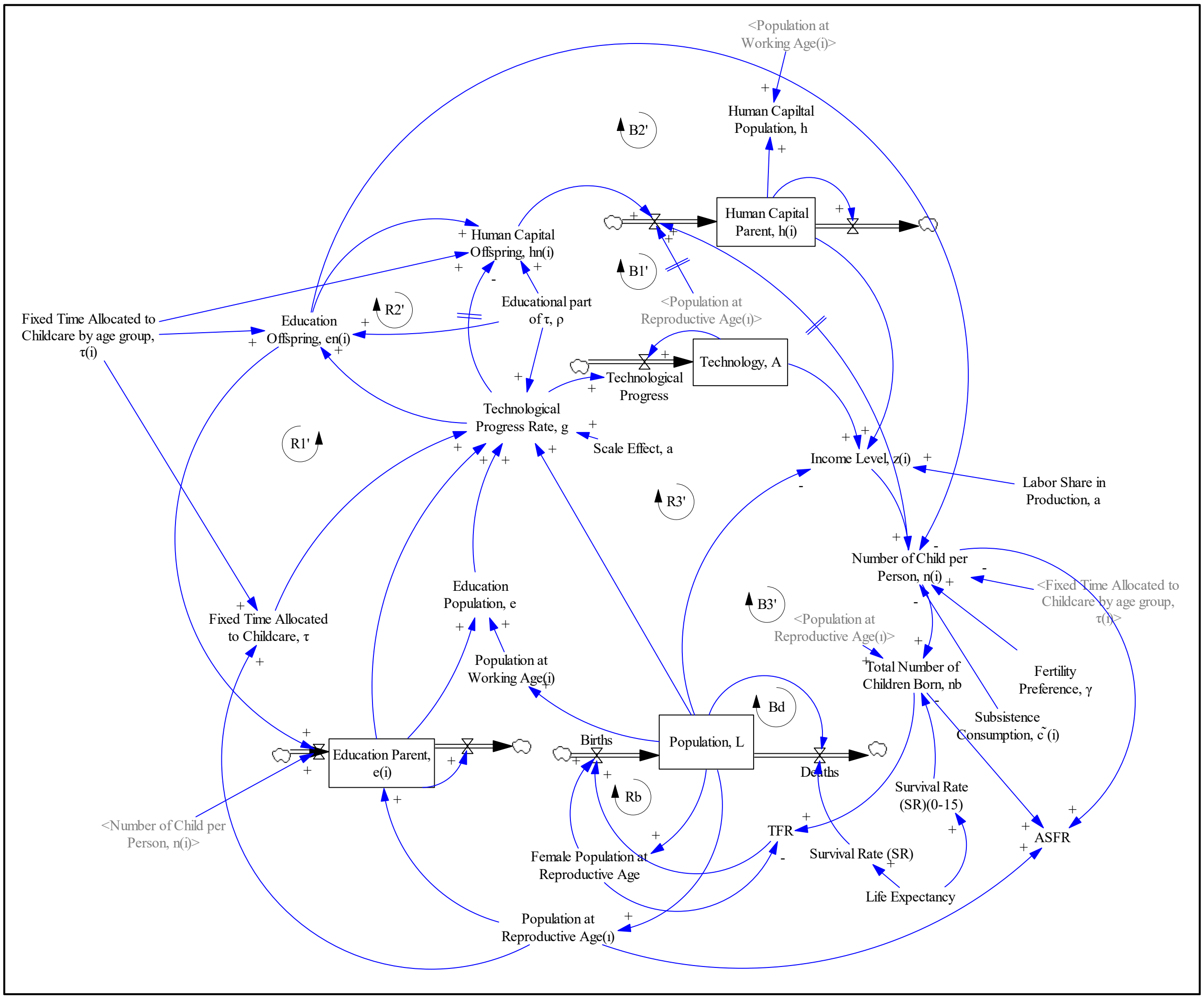

Figure 3 Stock-flow diagram of the economy-demography model

As it is displayed in Figure 3, the main structure of UGT remains almost same with its six major feedback loops. Nevertheless, to be able to distinguish the feedback loops of the economy-demography model, here we refer them as R1', R2', R3', B1', B2', and B3'. The reformulation and the parameterization of the equations, on the other hand, introduce a higher level of detail along with many intermediate calculations within the loops. As a result, the economy-demography model introduces two new feedback loops and slightly extends some of the feedback loops inherited from UGT. The details of the components in each loop is given in the supplementary material and the use of the auxiliaries are explained in the remaining part of this section via difference equations. In the following, we first focus on the new feedback loops and then discuss how UGT loops are extended.

There are two new feedback loops in our economy-demography model: Rb and Bd. Rb is the reinforcing loop arising from births, whereas Bd is the balancing loop established by deaths. For simplicity, migration is not taken into account. Note that fertility, technology, education, and human capital are endogenous as it is in UGT, whereas mortality rate is assumed to be exogenous which is not taken into account in UGT. With the reformulation and decomposition, we can now keep track of the population age/sex structure and use it through our intermediate calculations. Therefore, we can calculate fertility rates in terms of TFR. Accordingly, we assume that the reproductive period, where the women are able to give birth, starts at age 15 and ends at age 49. Moreover, labor force participation is assumed to be between ages 15-64.

Another important highlight of Figure 3 stems from the parameterization as well as the decomposition we used to reformulate the main model structure. That is the causal relationship between Population, L and Technological Progress Rate, g. The main feedback loops R2', R3', B1' and B2' shown in Figure 3 assume a direct relationship between L and g. Nevertheless, the interplay between population, education, and technology results in three other paths between L and g. These are given as follows;

a) Population, L - Population at Working Age (i) - Education Population, e - Technological Progress Rate, g;

b) Population, L - Population at Reproductive Age (i) - Education Parent, e(i) - Education Population, e - Technological Progress Rate, g;

c) Population, L - Population at Reproductive Age (i) - Fixed Time Allocated to Childcare, τ - Technological Progress Rate, g.

This immediately suggests that the economy-demography model has three additional loops for each feedback loop of R2', R3', B1' and B2'. However, these feedback loops are not shown explicitly in Figure 3 for better readability, but listed in the supplementary material. The details of the intermediate calculations are given below. The equations provided in the following are adopted from Lagerlöf (2006) and extended to capture age-specific variables and parameters.

Education / Human Capital

Each age group, that is each decision maker, has different levels of income and subsistence level of consumption. Accordingly, each age group in reproductive age attributes different levels of education to their offspring (en_{ti}). In UGT, education of offspring is assumed to be the function of technological progress rate and the time spent for child rearing. Also, as the technology develops at a faster rate, parents tend to provide higher levels of education to their children, so as to keep up with the diminishing rate of return. Parents, on the other hand, may opt not to invest in their children's education if the technological progress is very low. A constant portion of the fixed time allocated to child rearing contributes to human capital formation. This constant portion is presumed to negatively contribute to educational investment of the offspring. Following these, Lagerlöf (2006) develops the parameterized equality which we have slightly extended to capture age-specific attributes.

$$en_{ti} = max\{0, \sqrt{g_t \tau_i (1-\rho)} - \rho\tau_i\} \qquad (15)$$

where

$g_t = technological\ progress\ rate\ between\ years\ t\ and\ t+1$

$\rho = portion\ of\ fixed\ time\ cost\ of\ children\ that\ contributes\ to\ human\ capital\ formation, \rho \in (0,1)$

The human capital level of an offspring directly depends on the education level attributed at birth (en_{ti}) and the technological progress rate in the next 15 years after birth, when the offspring is assumed to participate in the labor force. The total educational endowment of an individual is a function of the parental investment on education (en_{ti}) and a portion of the fixed time ($\rho\tau_i$) that a child ought to spend in the family. This is the part that is independent of formal schooling and represents the hereditary knowledge an individual gains within the family. As it is mentioned earlier, the human capital and the technological progress rate are inversely related such that the technological development makes the knowledge obsolete and weakens the education's marginal effect on human capital accumulation. Since it is assumed that an individual commence participation in labor force at the age of 15, the depreciation of education is calculated over the technological development rate over the preceding 15 years. Accordingly, the equation for the human capital of an adult whose parents are in age group i at time t is :

$$hn_{ti} = \frac{en_{ti} + \rho\tau_i}{en_{ti} + \rho\tau_i + g_{t+15}} \qquad (16)$$

$where$

$g_{t+15} = \frac{A_{t+15} - A_t}{A_t}$

$g_{t+15} = technological\ progress\ rate\ between\ years\ t\ and\ t+15$

$A_t = technology\ level\ at\ time\ t$

Each cohort parented by different age groups at a particular time is assigned a different education level at birth (en_{ti}). However, those together constitute a single new-born cohort who is supposed to have a common value for its age-specific education level. We calculate the pooled value for the education level of that new born cohort (e_{t0-4}) by taking the weighted average of the education levels of the offspring parented by different age groups (en_{ti}).

$$e_{t0-4} = \sum_{i \in I} P_{ti} n_{ti} en_{ti} \Big/ \sum_{i \in I} P_{ti} n_{ti} \tag{17}$$

$where$

$P_{ti} = population\ size\ of\ age\ group\ i\ in\ time\ t$

$n_{ti} = number\ of\ child\ born\ per\ person\ in\ age\ group\ i\ in\ time\ t$

$\mathrm{I} = \{(15-19), (20-24), \dots, (45-49)\}$

At time period t+1, this value becomes the education level of the older age-group ($e_{t+1,4-9}$) and the education level of the first age-groups is re-calculated with the newcomer's educational investment. The flow of age-specific education levels to an older age-group continues till the last age group. Thus, age-specific education level (e_{ti}) is treated as a material delay where the consecutive age-groups are the intermediate stages that the education levels go through without any external in/out flow to/from the stocks (see Figure 4).

The human capital by age (h_{ti}) is also calculated and treated in a similar fashion, but with 15-year time lag, when the individuals commence participation in the labor force.

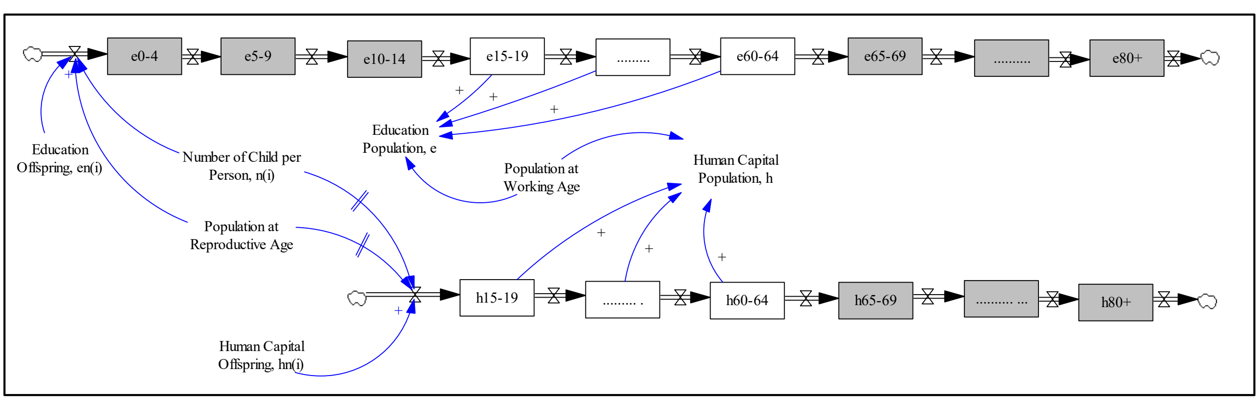

Figure 4 Stock-flow diagram of education/human capital sector

In the following parts, we also need an aggregate value of education and human capital that is representative for the whole population, i.e. e_t and h_t. These are calculated again with the weighted average method with the weight factor of population by age. Though, education/human capital level of age groups who are not in the labor force are used for representative purposes but not included in the calculations of the aggregate levels. As depicted in the Figure 4, we illustrate the inactive age groups with shaded grey to emphasize.

Technology

The level of technology accumulates with a technological progress rate, g_t:

$$A_{t+1} = A_t(1 + g_t) \tag{18}$$

Technological progress rate is a function of the total education level of the population and the total population size, as the penetration of technological development is assumed to be faster in a larger population. Effect of population size on technological progress is assumed to be limited by a scale parameter, a.

$$g_t = (e_t + \rho\tau)a(L_t) \tag{19}$$

$where$
$e_t = total\ education\ level\ of\ population\ at\ time\ t$
$\tau = average\ fixed\ time\ cost\ of\ children$
$a(L_t) = scale\ effect\ component\ and\ a(L_t) = \min(\theta L_t, a^*)$
$L_t = normalized\ population\ at\ time\ t$
$L_t = P_t/P_0\ (P_0\ is\ the\ initial\ population\ size)$

Note that average fixed time cost of children, τ is calculated over the weighted average of age-specific values (τ_i) in the reproductive age period, i.e.15-49 with the weight factors of the relevant population size, i.e. the number of people in the age groups between 15-49.

This level of technology directly affects the income levels, whose formulation is based upon a conventional production function that calculates average output per individual:

$$z_{ti} = [h_{ti}]^{\alpha} \left[\frac{A_t X}{L_t}\right]^{1-\alpha} \tag{20}$$

Population

Basically, the main contribution of the proposed reformulated model stems from the decomposition of the population into smaller age brackets where the exogenous mortality is also considered. By this means, we create an approximation of the original population over which we can calculate and comment on conventional demographic indicators over macroeconomic conditions. This approximation scheme is widely used to explore the behavior of large number of individuals (Geard et al., 2013, Gargiulo et al., 2010). The details of the decomposition and how the conventional demographic measures are integrated within the model are described in the following.

Following the equilibrium conditions of Galor and Weil (2000) and the parameterization of Lagerlöf (2006), the optimization with respect to n_{ti} yields the optimal decision rule for number of surviving child as:

$$n_{ti}[\tau_i + en_{ti}] = \left\{\begin{array}{c|c} \gamma & if\ \ z_{ti} \geq \tilde{z}_i \\ 1 - \tilde{c}_i/z_{ti} & if\ \ z_{ti} \in (\tilde{c}_i, \tilde{z}_i) \\ 0 & if\ z_{ti} \leq \tilde{c}_i \end{array}\right\} \tag{21}$$

$where\ \tilde{z}_i \equiv \tilde{c}_i/(1-\gamma).$

Note that the population that is subject to the optimization problem is the so-called approximate population, whose members are assumed to live until the end of their reproductive age. Thus, the number of children per adult calculated by the optimization problem is a life time decision. By definition, if we know the reproductive population size by age, we can calculate the total number of newborn:

$$nb_t = \sum_{i \in I} {}^{P_{ti} n_{ti}}\!/_{SR_{0-15}} \tag{22}$$

$where$

$nb_t = total\ number\ of\ births\ in\ time\ t$

$P_{ti} = population\ size\ of\ age\ group\ i\ in\ time\ t$

$n_{ti} = number\ of\ child\ born\ per\ person\ in\ age\ group\ i\ in\ time\ t$

$SR_{0-15} = survival\ probability\ of\ a\ new\ born\ till\ the\ age\ of\ 15$

$I = \{(15-19), (20-24), \dots, (45-49)\}$

In the optimization problem, the number of children corresponds to the ones that survives until adolescence. Thus, we divide the number of children ($\sum_{i\epsilon I} P_{ti} n_{ti}$) by survival rate ($SR_{0-15}$) to the age of 15 in order to get the exact number of newborns.

The demographic literature defines TFR as the number of births per woman in reproductive age and ASFR as the distribution of births among the age groups in reproductive period. Accordingly, equations for TFR and ASFR are as follows:

$$TFR_t = {}^{nb_t}\!\Big/_{\sum_{i\in I} P_{fti}} \tag{23}$$

$$ASFR_{ti} = {}^{P_{ti} n_{ti}}\!\Big/_{nb_t} \tag{24}$$

$where$

$P_{fti} = female\ population\ of\ age\ i\ in\ time\ t$

TFR determines the birth rate together with the female population size at reproductive age. As mentioned before, the population is modeled as a cohort component model and disaggregated into 5-year age groups. It is designed as an aging chain (Figure 5), where each age group either survives to the next one or leaves the system according to age-specific survival rates that are read from life tables according to the value of the life expectancy at birth and the age.

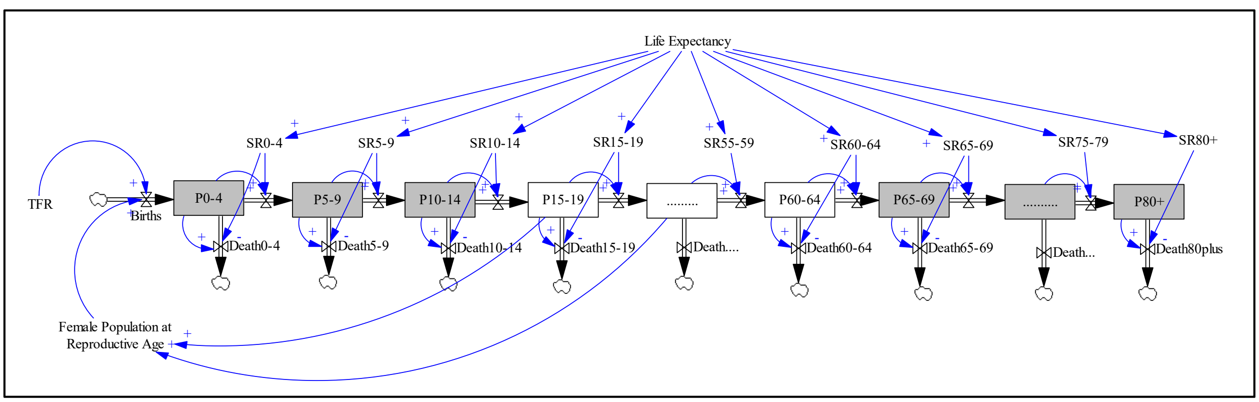

Figure 5 Stock-flow diagram of Population Sector

Births are inflows to the first age group, while deaths and aging population are outflows of each age group except the last one having only deaths as an outflow. CCM actually consists of two aging-chains for both sexes; but one representative aging chain with five-year age brackets is depicted in Figure 5.

The use of an aging chain structure in population projection has been criticized because it causes cohort blending, and lacks precision, which results in inaccuracy over the long run (Eberlein and Thompson, 2013). Demographers overcome the problem of cohort blending by defining the computational interval equal to the time that cohorts spend in each age-group. By this way, members of one age-group entirely move to an older age group in the succeeding time step. In this study, we follow a similar approximation by disaggregating the population into 5-year age brackets and setting the computational time as 5 years.

In this paper, model calibration is mostly performed using normalized values. This enables us to exploit different data sources with different units on a common ground. Thus, for the sake of completeness, we take the population size in normalized form (L), when we need to calculate a normalized variable (i.e. equations 19 and 20). Otherwise, we use the nominal values (P) (i.e. equations 22, 23, 24 and the ageing chain). Normalization of the population is performed with respect to the initial population size. That is, the normalized population size is obtained simply by dividing nominal population size to the initial size. We also want to remark that equations between (15) and (21) are the extended versions of the parametrized equations of Lagerlöf (2006), whereas equations (22), (23), and (24) are introduced solely for our economy-demography model.

MODEL BEHAVIOR

The SD representation of the models (Figure 2-5) is generated in Vensim PLE, however, we conducted the entire experimental study in an open source programming language Python 2.7 with discrete time steps. As such, Vensim is used to represent the stock and flow model, whereas the implementations including model calibration and simulation experiments are performed in Python. This is due to the fact that the model has many repetitive age-specific variables which makes the modelling in any conventional software is a tedious task that is also prone to errors. Python, on the other hand, provides us with a flexible and efficient platform to work with the model where we can automate recurrent tasks easily at a desired level of granularity.

Model calibration is mostly done with Turkish data sources, i.e. TURKSTAT, ABPRS (Address Based Population Registry System) and public data sources of UN. For the cases that we could not find a reliable data source, we either made parameter calibration upon the steady-state conditions or we conducted parameter optimization with a random search algorithm. Consequently, the parameter set is a combination of different data sources covering different time frames, which makes it challenging for us to apply a historical fit. Even so, such models with approximate population are still used for explanatory purposes in demography (Geard et al., 2013; Silverman et al., 2013). In our case, the model results display a strong resemblance with Turkish past real data (years 2008-2019) as well as the projections published by TURKSTAT.

We examine the behavior of the economy-demography model over a base case scenario. The parameter set and the initial state conditions for the base case are provided in the appendix material with the relevant data sources and years (if applicable) included. Note that the time horizon of base case run is taken as 20 time steps each of which consists of 5 years, i.e. the total time horizon elapsed is 100 years. As we take the initial population of Turkey at year 2008, we assume that the simulation run is initiated at that particular year, 2008. For the ease of exposition, we focus our analysis on key demographic and macroeconomic indicators. We present the demographic indicators in a comparative way with Turkish past real data and/or TURKSTAT projections where it is possible. We present R^2 values to quantify the correlation between the simulated and the observed and/or projected statistics. Note that TURKSTAT projections might have been presented over different time horizons and we strictly follow the official statistics that are publicly available. Additionally, we want to remark that the results are presented without any smoothing and/or adjustment as is the case in Lagerlöf (2006).

From the simulation runs, TFR starts with a value of 2.13, follows a non-increasing trend in the first 30 years, then starts to oscillate and reaches a steady-state with smaller oscillations around 2.03 and 2.04 after 50 years. The steady-state TFR is slightly below the replacement level, i.e. 2.1 (Figure 6). The behavioral trend of TFR resembles the dynamics in real life where TFR levels decline overall, then oscillates around the steady-state. Here, TURKSTAT data is presented yearly, whereas the model output is given in 5 year brackets. As such, R^2 is calculated for 5-year-intervals of TURKSTAT and model output data. We note that this might lead to a smoothing effect on TURKSTAT-TFR plot, resulting in a relatively high value of R^2.

ASFR rates, on the other hand, reveal a bell-shaped distribution as is the case in reality, indicating that the first motherhood age is mostly around 25-29 and the women have fewer children at younger and older ages (Figure 7). Note that the ASFR graph presents the average value over the simulation time horizon, i.e. 100 years.

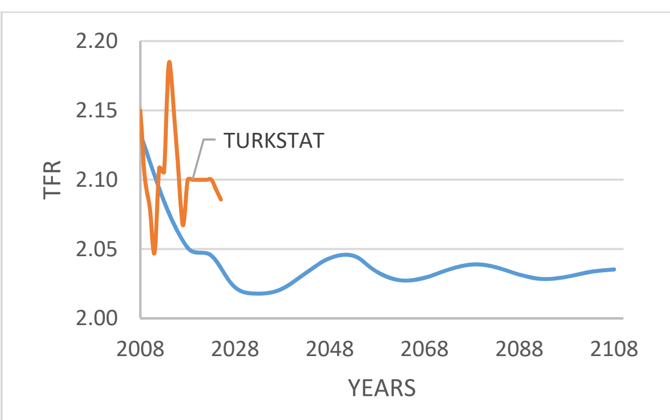

Figure 6 Total fertility rate (TFR) (R^2 = 0.8907)

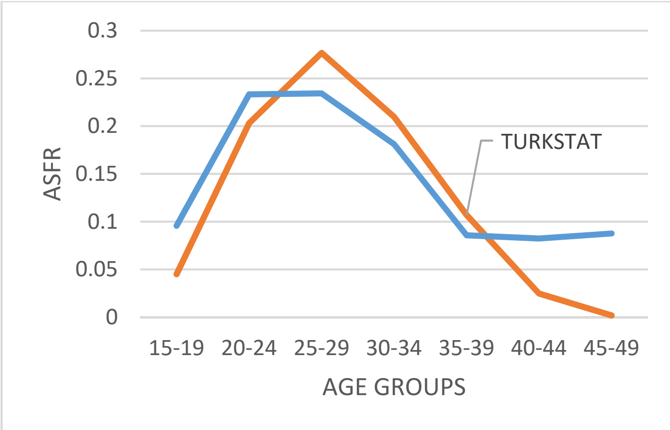

Figure 7 Age-specific fertility rate (ASFR) (R^2=0.9292)

The dynamics of fertility rates have an obvious impact on population growth. The annual growth rate has a non-increasing trend with positive values in the first half of the simulation run, while it turns negative afterwards. Figure 8 displays the annual growth rates for each consecutive 5-year time period. It starts with 11.2‰ and decreases monotonically to -0.9‰ at the end of the simulation run. As a result, the population size in our illustrative example starts around 72 million and reaches its maximum value at 99.5 million, then shrinks back to 96.6 million after 100 years (Figure 9). Overall, the model appears to underestimate fertility and population growth, though demonstrating a very similar trend in time, when compared to the real data and the projections. This difference could be explained by the fact that the proposed model does not include migration. According to the reports by Turkish governmental agencies, the number of Syrian refugees has been reported to increase from around 14,000 to over 3.6 million people in last 7 years (i.e. 2012-2019) (Republic of Turkey Ministry of Interior Directorate General of Migration Management).

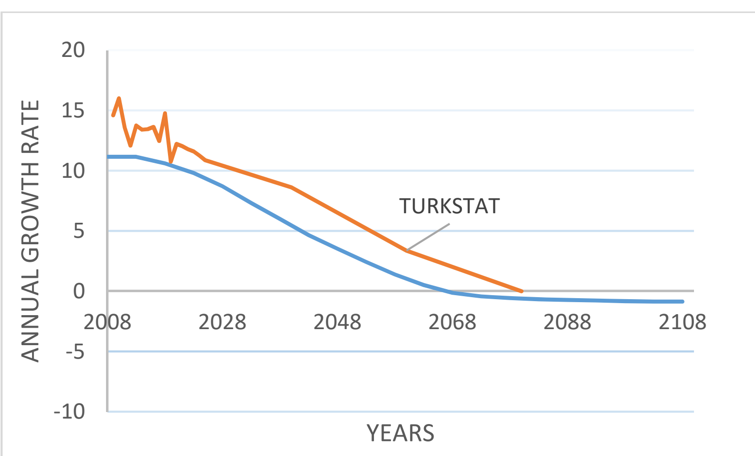

Figure 8 Annual population growth rate (R^2 = 0.9812)

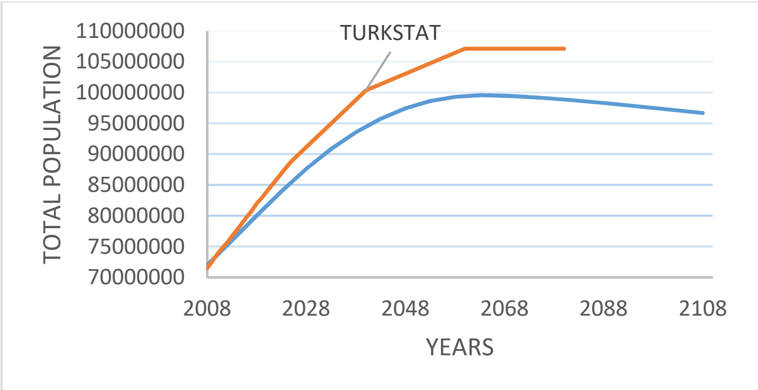

Figure 9 Total Population (R^2 = 0.9978)

The economy –demography model also yields population age structure, which we analyze with three indicators: proportion of population over the age of 65, proportion of population below the age of 15 and total dependency ratio (DR), i.e. the ratio of population below 15 and above 65 over the working age population between 15-64. Figure 10 shows that the population goes into an ageing process resulting in a higher proportion of 65 plus and higher dependency ratios over the years. As it is shown in the graph, age structure indicators are also following a very similar trend with TURKSTAT data and projections Yet, we can once again observe that the proposed model underestimates the original data obtained from TURKSTAT. Especially after considering the fact that Turkey has been experiencing an intense immigration from her neighbors, we strongly believe that this observation is due to neglecting migration in the proposed model. One would expect that migration might impact the population age structure depending on the age distribution of the immigrants.

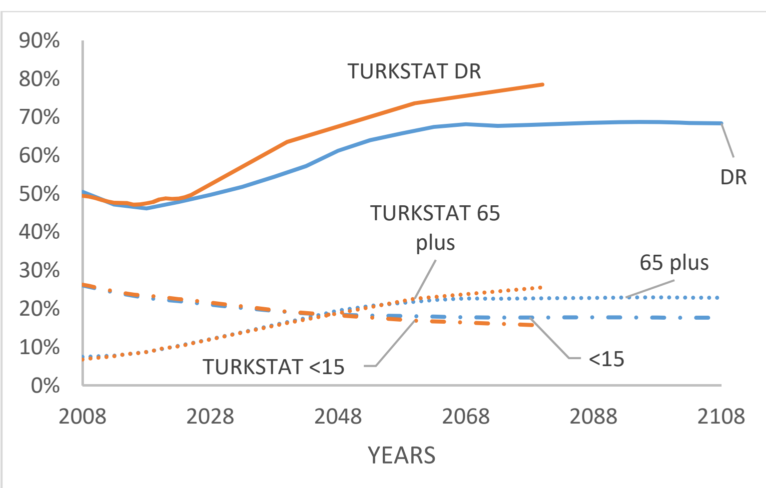

Figure 10 Population age structure indicators ($\boldsymbol{R^2}_{<15}$ = 0.9865, $\boldsymbol{R^2}_{65plus}$ = 0.9640, $\boldsymbol{R^2}_{DR}$ = 0.9748)

Overall the simulation outputs showcase a strong alignment with the data obtained from TURKSTAT and high values of R^2 reported in graphs also validate the resembelance in trends.

Henceforward, we turn our attention to the macroeconomic indicators (Figure 11, 12). Note that the numbers provided in the y-axis are standardized values, such that the behavioral patterns are presented across the years.

Given that the model does not allow any technology import and/or technology outsale (i.e. closing down an R&D capability), the technology level demonstrates a monotonically increase throughout the years. As the model dynamics indicate, the parents are supposed to invest more in the education of their offspring as a response to increasing technology levels, however a downward trend in education is observed between the years 30-45. This can be explained by the decreasing technological progress rate in the same time period. It is mirrored with a symetrical increase in TFR that actually showcases the coherence among the model dynamics. That is, parents decide on quantity over quality when the technological progress is relatively slow.

Human capital level of the population, on the other hand, is observed to have a non-increasing trend, which is an obvious indicator for the depreciation of the education investment against the technological improvement. As being a function of education and population size, technological progress rate follows a similar behavioral pattern with the education, but it has some oscillatory movements towards the end.

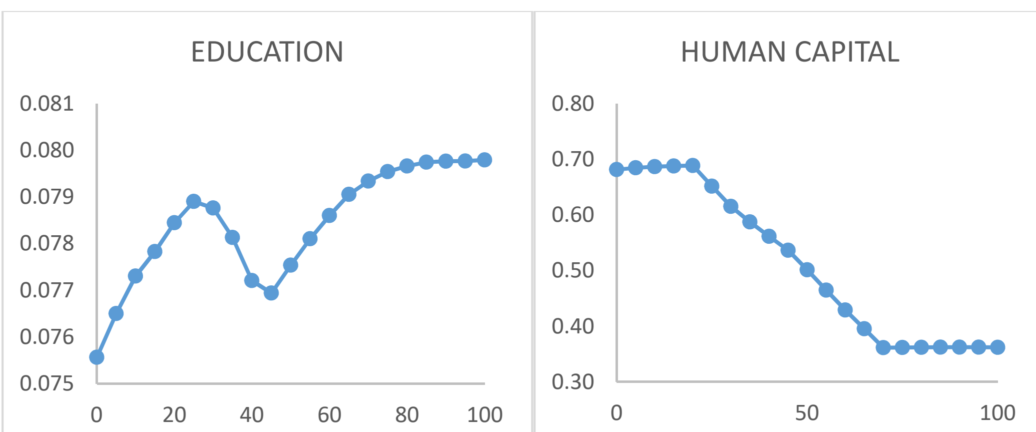

Figure 11 Education and human capital levels across years

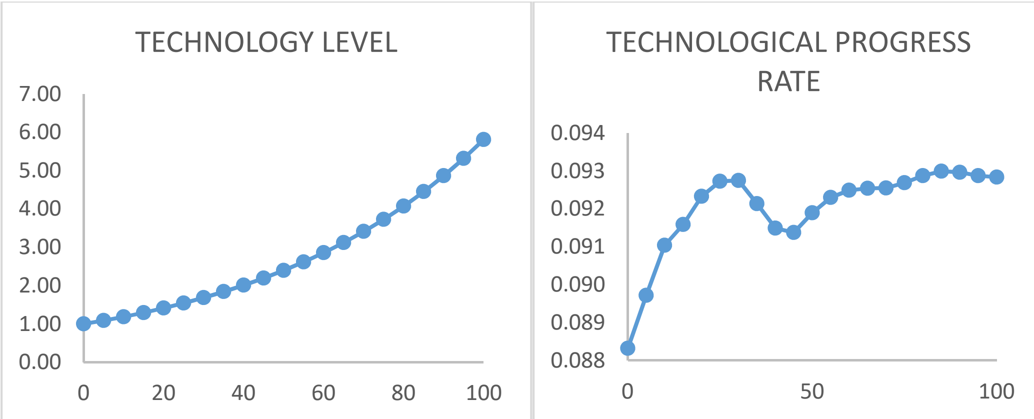

Figure 12 Technology level and technological progress rate across years

We have not included the graphs of age specific indicators. Nevertheless, our results reveal that the age-specific differences among the education and human capital levels disappear in the later years. This results resemble the educational regulations enforced in the developing countries. The educational differences among the age groups may diminish as the years of formal schooling is increased and the younger generations take the older's place.

We can conclude that the model dynamics present coherent behavioral patterns and the base case results more or less showcase the demographic dynamics of a developing country, in particular Turkey, in the 21st century.

MODEL VALIDATION AND SENSITIVITY ANALYSIS

In this section, we conduct further numerical experiments to test the validity of the model. This enables us to understand how the model reacts to unexpected events that cannot be explicitly observed in the model dynamics. We designed the validation process upon the standard validation methodologies for system dynamics models (Senge & Forrester, 1980; Barlas 1989, 1990, 1996 and Sterman, 2000). In the previous section, we have already mentioned output/behavioral validity. Below we first carry out extreme condition tests and then univariate sensitivity analysis for the key parameters, i.e. weight on fertility in the utility function (γ), the educational part of τ (ρ), the subsistence level of consumption ($\tilde{c}_i$) and the labor share in production (α).

Extreme Condition Tests

The aim is to explore whether the key outputs of the model perform effectively in the case of extreme manipulations. We first run the model on a very long time period (i.e. 500 years). Consequently, we observe that the model maintains its steady-state conditions with small oscillations. The result can be interpreted such that the model behavior is valid and robust even under the very long running periods, as it does not display any extreme oscillation and/or extreme values due to long-term accumulation of the stock variables. The model, on the other hand, foresees a stable economic and demographic environment for the future and it is unable to catch the trend changes, if any, in the long run. That points out the fact that there is a need for dynamic parameter setting and/or hypothetical interim manipulations in order to keep the model sensitive to the changes in trends in the long term.

As a second scenario, we analyzed the monotonically and almost smoothly increasing trend of technology. We interrupted the endogenous technological development every 4 periods and multiplied technological development progress rate by 10. In return, we observed jumps in technology levels where a hypothetical technology import was imposed. These jumps are followed by sharp declines at TFR and sharp inclines at education levels. Accordingly, uneven educational distribution among the age groups was observed in the upcoming years. That is, the cohorts born at the year of technology import have relatively higher education levels. The peaks at education levels also mirrored in human capital levels, but in a smoother way since the education level was depreciated by the high technological improvement.

Sensitivity analysis

We performed univariate sensitivity analysis with respect to the parameters of weight on fertility in the utility function (γ), the educational part of τ (ρ), the subsistence level of consumption ($\tilde{c}_i$) and the labor share in production (α). Sensitivity analysis is done within a range of $\mp 50\%$ of the base case value of each parameter with 0.01 incremental changes. For instance, since the base value for weight on fertility (γ) is 0.5280, the associated sensitivity analysis is conducted by simply running the model with varying γ values within a range of [0.27, 0.79] with a granularity of 0.01 units.

Note that, the subsistence level of consumption ($\tilde{c}_i$) is not a single value, but it is age-specific. We used the $\mp 50\%$ rule to set the sensitivity range as is the case in the aforementioned parameters, but with a 5% granularity.

To ease the exposition, sensitivity analysis is mainly conducted to observe the behavior of TFR across the years under changing parameters. Yet, the model dynamics do not reveal any unexpected behavior and move in harmony and we mention corresponding variables (e.g. technology, income, education), as necessary, while explaining the behavior of TFR.

Increasing the weight of fertility in the utility function (γ) represents the case where individuals gets higher satisfaction from child rearing, rather than their own consumption. The results reveal that TFR fluctuates between 0.9 and 3.07 and the TFR line shifts upward with increasing weight on fertility. Although income levels lower down due to the dynamics in human capital, education and technology; individuals intend to have more children. Figure 13 visualizes changing TFR across years under changing weight on fertility. Although we work with a granularity of 0.01, we depict the results over a few scenarios that display the general trend. Each line corresponds to a separate run with a different parameter value shown in the legend.

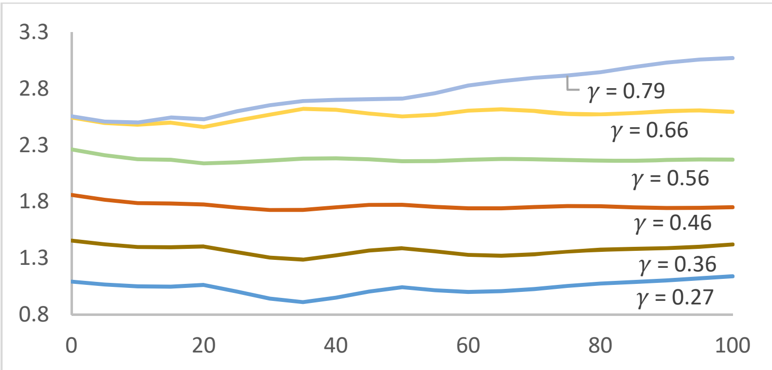

Figure 13 Sensitivity of TFR (Total Fertility Rate) w.r.t $\boldsymbol{\gamma}$

Remember that ρ represents the hereditary knowledge transfer from parents to the offspring and it is a proportion of the fixed amount of time parents spend for child rearing (τ). In that sense, higher values of ρ means that it is found to be adequate for a child to know what their parents know already as is the case in an agrarian society. Thus, the increase in educational part of τ (ρ) lead the parents to ignore formal schooling and a downward shift is observed in education levels, which is accompanied by an upward shift in fertility (Figure 14). Figure 14 also depicts that the marginal effect on TFR values gets smaller with the increasing values of ρ.

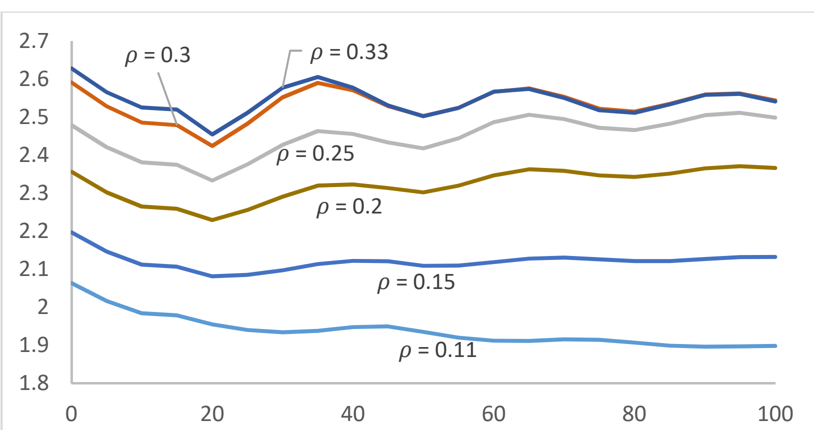

Figure 14 Sensitivity of TFR (Total Fertility Rate) w.r.t $\boldsymbol{\rho}$

Fertility levels are observed to be insensitive to declines in subsistence level of consumption, however, increases in $\tilde{c}_i$ shift TFR down until the year 45 (Figure 15). After 45 years the average individual income reaches a level, where parents are wealthy enough to be able to afford subsistence level of consumption and having children. An interesting result is observed at the oscillations after 45 years. They change direction such that the lowest TFR line becomes the highest at the first oscillatory region (between years 45-55) and vice versa for the following regions. That can be explained by the marginal effect of the education level on the technological progress rate. In particular, with a lower level of fertility, if average income reaches a level where one can both afford having more children and invest in their education, the effect of that educational investment on technological progress is observed to be relatively higher. In that sense, higher progress rates surpass fertility levels for the next oscillatory period by the increase in the need for higher educational investment.

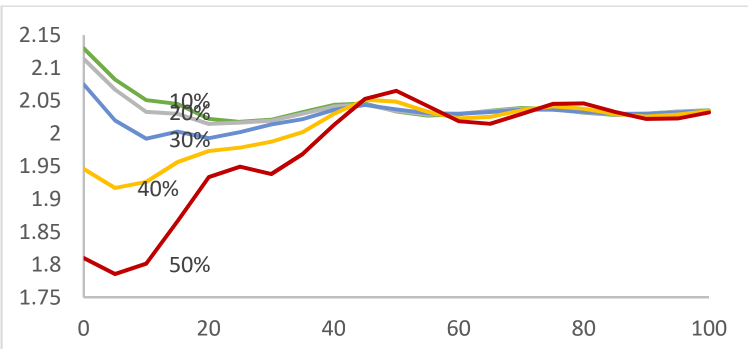

Figure 15 Sensitivity of TFR (Total Fertility Rate) w.r.t $\tilde{\boldsymbol{c}}_{\boldsymbol{i}}$

Lastly we examined TFR sensitivity with respect to labor share in production (α). These results are not displayed on the graph, as we observed that fertility levels are insensitive to the changes in labor share within the $\mp 50\%$ limits, [0.13,0.39]. We did further analysis and found out that TFR is effected by the changes in α values when it is larger than 0.5. After that threshold point, income levels and accordingly TFR values are observed to shift downward. We infer that values of labor share at the threshold creates a production system, where the contribution of the labor and the fixed resources in the production function are equally weighted and above that threshold value, a new economic system displaying different behavioral patterns comes to the scene.

Sensitivity analysis, overall, demonstrates that the model dynamics move in coherence and as expected under different parameter settings. The behavioral patterns are either preserved as in the base model run or they can be explained in consistency with the model dynamics itself.

CONCLUSION

In this study, we develop an integrated economy-demography model that assumes endogenous fertility, education, human capital and technology under exogenous mortality. The model is based on an economic growth model (Galor and Weil, 2000) that proposes a framework explaining the history of economic and demographic dynamics in a continuum. However, the unified growth theory has certain limitations that complicate its practical use for policy makers in the field of decision making about family size. The economy-demography model reformulates the model of Galor and Weil (2000) from a demographic perspective. We then construct the economy-demography model in a system dynamics setting. We conduct numerical experiments and validity tests so as to demonstrate the realism of the proposed model.

The economy-demography model provides a deeper insight on demographic dynamics over macroeconomic indicators. In that sense, policy makers could make use of this framework in order to explore the possible outcomes of interventions related to family size. With the direct results of the model, one can easily comment on the changes in population dynamics depending on the macroeconomic indicators in short to medium term.

According to the base model run, extreme condition tests and sensitivity analysis, we can conclude that the proposed model yields promising results in terms of conventional demographic measures. However, the model is data intensive and due to the lack of data availability we could not showcase detailed historical fit for some of the variables. Thus, we do not claim that the proposed model has high resolution projective power. We rather assert that the numerical study is performed for illustrative purposes to comment on the behavioral trends and it would be a future direction to conduct historical fit and test the projective power of the proposed economy-demography model. Yet, we compare the model results with Turkish past data (i.e. years 2008-2019) and also with TURKSTAT projections where it is possible. We demonstrate that our results are very promising, showing a high level of fit in terms of trends with the benchmark data. However, approximately after 50 years the model reaches steady-state around which oscillations take place afterwards. Thus, we can conclude that implementing a dynamic parameter setting instead of a stationary one would be a good solution for long-term efficacy. Moreover, integrating migration as a factor within the model would enhance the projective power.

A limitation of the study relates to the representation of technology as endogenous. The model ignores the external effects on technology level and the experimental results yield almost a smooth and continuous development in technology. However, in developing countries it is very common to experience jumps in technology level by technology imports. Also, according to the economic conditions, it is possible to observe a technology downscale due to factory closures. In order to catch up with these real life dynamics in technology, attempts to improve the conceptual model and/or the parameter settings could be a valuable contribution.

Despite these limitations, the study leads us to conclude that by preserving age/sex structure, giving age-specific results within reasonably small time steps and providing the conventional demographic drives of fertility (TFR and ASFR) as a function of macroeconomic indicators; the economy-demography model, deployed in a system dynamics framework, presents an interdisciplinary perspective for policy makers in economics and demography.

The authors declare that they have no conflicts of interest.

ACKNOWLEDGEMENTS

We would like to thank to Editors: Jim Duggan, Yaman Barlas and Thomas Gaston for their guidance to improve our work. Their comments and suggestions have been very helpful and encouraging. We are also very grateful to the other anonymous reviewers for their rigorous comments and suggestions. S. Armagan Tarim had the financial support of Science Foundation Ireland under Grant number 12/RC/2289-P2 which is co-funded under the European Regional Development Fund.

REFERENCES

Auping, W. L., Pruyt, E., & Kwakkel, J. H. (2015). Societal ageing in the Netherlands: a robust system dynamics approach. *Systems Research and Behavioral Science*, *32*(4), 485-501.

Barlas, Y. (1989). Multiple tests for validation of system dynamics type of simulation models. *European Journal of Operational Research*, *42*(1), 59-87.

Barlas, Y. (1990). An autocorrelation function test for output validation. *Simulation*, *55*(1), 7-16.

Barlas, Y. (1996). Formal aspects of model validity and validation in system dynamics. *System Dynamics Review*, *12*(3), 183-210.

Barro, R. J. (1974). Are government bonds net wealth? *The Journal of Political Economy*, 1095-1117.

Barro, R. J. (2001). Human capital and growth. *American Economic Review*, 12-17.

Barro, R. J., & Becker, G. S. (1989). Fertility choice in a model of economic growth. *Econometrica: Journal of the Econometric Society*, 481-501.

Becker, G. S. (1960). An economic analysis of fertility. In *Demographic and economic change in developed countries* (pp. 209-240). Columbia University Press.

Becker, G. S. (1962). Investment in human capital: A theoretical analysis. *The Journal of Political Economy*, 9-49.

Becker, G. S. (1974). A theory of social interactions. *Journal of Political Economy, LXXXVII 1063-93.*

Becker, G., & Barro, R. J. (1988). A reformulation of the economic theory of fertility. *The Quarterly Journal of Economics (1988) 103 (1): 1-25.*

Becker, G. S., & Lewis, H. G. (1974). Interaction between quantity and quality of children. In *Economics of the family: Marriage, children, and human capital* (pp. 81-90). UMI.

Becker, G., Murphy, K., & Tamura, R. (1990). Economic growth, human capital and population growth. *Journal of Political Economy*, *98*(5), S12-S37.

Boldrin, M., & Jones, L. E. (2002). Mortality, fertility, and saving in a Malthusian economy. *Review of Economic Dynamics*, *5*(4), 775-814.

Caldwell, J. C. (1976). Toward a restatement of demographic transition theory. *Population and Development Review*, 321-366.

Doepke, M. (2004). Accounting for fertility decline during the transition to growth. *Journal of Economic Growth*, *9*(3), 347-383.

Doepke, M. (2005). Child mortality and fertility decline: Does the Barro-Becker model fit the facts? *Journal of Population Economics*, *18*(2), 337-366.

Easterlin, R. A. (1966). On the relation of economic factors to recent and projected fertility changes. *Demography*, *3*(1), 131-153.

Easterlin, R. A. (1978). The economics and sociology of fertility: A synthesis. *Center for Advanced Study in the Behavioral Sciences.*

Eberlein, R. L., & Thompson, J. P. (2013). Precise modeling of aging populations. *System Dynamics Review*, 29(2), 87-101.

Eckstein, Z., Mira, P., & Wolpin, K. I. (1999). A quantitative analysis of Swedish fertility dynamics: 1751–1990. *Review of Economic Dynamics*, 2(1), 137-165.

Fallah-Fini, S., Rahmandad, H., Chen, H. J., Xue, H., & Wang, Y. (2013). Connecting micro dynamics and population distributions in system dynamics models. *System dynamics review*, 29(4), 197-215.

Fernandez-Villaverde, J. (2001). Was Malthus right? Economic Growth and Population Dynamics. PIER Working Paper No. 01-046. Available at SSRN: https://ssrn.com/abstract=293800 or http://dx.doi.org/10.2139/ssrn.293800

Forrester, J. W., & Forrester, J. W. (1971). *World dynamics* (Vol. 59). Cambridge, MA: Wright-Allen Press.

Forrester, J. W. (2013). Economic theory for the new millennium (2003). *System Dynamics Review*, *29*(1), 26-41.

Galor, O. (2005). The demographic transition and the emergence of sustained economic growth. *Journal of the European Economic Association*, *3*(2-3), 494-504.

Galor, O. (2011). *Unified growth theory*. Princeton University Press.

Galor, O., & Moav, O. (2002). Natural selection and the origin of economic growth. *Quarterly Journal of Economics*, 1133-1191.

Galor, O., & Weil, D. N. (2000). Population, technology, and growth: from Malthusian stagnation to the demographic transition and beyond. *American Economic Review*, 806-828.

Gargiulo, F., Ternes, S., Huet, S., & Deffuant, G. (2010). An iterative approach for generating statistically realistic populations of households. *PloS one*, 5(1), e8828.

Geard, N., McCaw, J. M., Dorin, A., Korb, K. B., & McVernon, J. (2013). Synthetic population dynamics: A model of household demography. *Journal of Artificial Societies and Social Simulation*, *16*(1), 8.

Hansen, G. D., & Prescott, E. C. (2002). Malthus to Solow. *American Economic Review*, 1205-1217.

Jones, C. I. (2001). Was an industrial revolution inevitable? Economic growth over the very long run. *Advances in Macroeconomics*, *1*(2).

Kalemli-Ozcan, S. (2002). Does the mortality decline promote economic growth? *Journal of Economic Growth*, *7*(4), 411-439.

Kalemli-Ozcan, S. (2003). A stochastic model of mortality, fertility, and human capital investment. *Journal of Development Economics*, *70*(1), 103-118.

Kalemli-Ozcan, S. (2008). The uncertain lifetime and the timing of human capital investment. *Journal of Population Economics*, *21*(3), 557-572.

Lagerlöf, N. P. (2003). From Malthus to modern growth: Can epidemics explain the three regimes? *International Economic Review*, *44*(2), 755-777.

Lagerlöf, N. P. (2006). The Galor–Weil model revisited: A quantitative exercise. *Review of Economic Dynamics*, *9*(1), 116-142.

Lee, R. (2003). The demographic transition: three centuries of fundamental change. *The journal of Economic Perspectives*, *17*(4), 167-190.

Liao, P. J. (2011). Does demographic change matter for growth? *European Economic Review*, *55*(5), 659-677.

Mateos-Planas, X. (2002). The demographic transition in Europe: a neoclassical dynastic approach. *Review of Economic Dynamics*, *5*(3), 646-680.

Meadows, D. H., Meadows, D. H., Randers, J., & Behrens III, W. W. (1972). The limits to growth: a report to the club of Rome (1972).

Meadows, D. L., Behrens, W. W., Meadows, D. H., Naill, R. F., Randers, J., & Zahn, E. (1974). Dynamics of growth in a finite world. *Cambridge, MA: Wright-Allen Press.*

Meadows, D. H., Meadows, D. L., & Randers, J. (1992). Beyond the limits: global collapse or a sustainable future. *Earthscan Publications Ltd.*

Meadows, D., Randers, J., & Meadows, D. (2004). Limits to growth: the 30-year update. *Chelsea Green Publishing.*

Pedercini, M., & Barney, G. O. (2010). Dynamic analysis of interventions designed to achieve millennium development goals (MDG): The case of Ghana. *Socio-Economic Planning Sciences*, *44*(2), 89-99.

Republic of Turkey Ministry of Interior Directorate General of Migration Management: http://www.goc.gov.tr/icerik3/gecici-koruma_363_378_4713

Rowland, D. T. (2003). Demographic methods and concepts. *OUP Catalogue*.

Senge, P. M., & Forrester, J. W. (1980). Tests for building confidence in system dynamics models. *System dynamics, TIMS studies in management sciences*, *14*, 209-228.

Silverman, E., Bijak, J., Hilton, J., Cao, V. D., & Noble, J. (2013). When demography met social simulation: a tale of two modelling approaches. *Journal of Artificial Societies and Social Simulation*, *16*(4), 9.

Sterman, J. D. (2000). Business dynamics: systems thinking and modeling for a complex world (Vol. 19). Boston: Irwin/McGraw-Hill.

Tamura, R. (1996). From decay to growth: a demographic transition to economic growth. *Journal of Economic Dynamics and Control*, *20*(6), 1237-1261.

Tamura, R. (2002). Human capital and the switch from agriculture to industry. *Journal of Economic Dynamics and Control*, *27*(2), 207-242.

Tamura, R. (2006). Human capital and economic development. *Journal of Development Economics*, *79*(1), 26-72.

United Nations, Department of Economic and Social Affairs, Population Division (2015). World Population Ageing 2015 (ST/ESA/SER.A/390).

Weil, D. N. (2004). Economic Growth. *Prentice Hall.*

Weisdorf, J. L. (2004). From stagnation to growth: Revisiting three historical regimes. *Journal of Population Economics*, *17*(3), 455-472.

World Bank. *World Development Indicators*, The World Bank Group, https://data.worldbank.org/country/turkey, accessed 31/12/2019