Expert Systems with Applications 40 (2013) 3481–3490

Contents lists available at SciVerse ScienceDirect

Expert Systems with Applications

journal homepage: www.elsevier.com/locate/eswa

Modeling gender evolution and gap in science and technology using ecological dynamics

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ARTICLE INFO

Keywords:
Artificial Bee Colony
Ecological evolution
Forecasting
Gender gap
Population dynamics
Science and technology
Swarm optimization

ABSTRACT

In this paper a model based on population biology is proposed in order to investigate the evolution of human resources (men and women) in science and technology as a share of labor market as well as the dynamics of their gap. An analytical and a simulation method using the Artificial Bee Colony optimization algorithm are described and used for the determination of the proposed model parameters. The presented model is applied to three case studies; Greece, Portugal and Europe-27.[3] The accuracy of the obtained results is confirmed through comparison with actual data. In addition, the model can also be used to accurately forecast future trends. It is illustrated that the gender gap is continuously decreasing, while in the last years, women seem to outperform men in the field of science and technology. The estimation and forecasting ability of the model can be used as an extremely valuable tool for decision and policy makers.

1. Introduction

In the last decades, an unrelieved evolution of technologies is observed. Societies are experiencing new and rapidly changing scientific and technological (S&T) achievements. It is a common belief that the progress in science and technology is usually an indicator of economic growth, environmental well-being and social development. However, a link between the S&T evolution and the socio-economic development is required. The main candidate able to fill in the gap between these activities is the human resources of the specific field (Chou, Hsu, & Yen, 2011; Kefela, 2010). A workforce with lifelong learning (updated skills) seems to be the key ingredient for the adoption of the rapid S&T changes as well as the development and diffusion of knowledge.

Recently, there has been an increased attention for qualitative and quantitative investigation of human resources in science and technology (Chou, Sun, & Yen, 2012; Davó, Mayor, & Blazquez de la Hera, 2011). Statistical information regarding S&T human resources is of great importance and high interest for several different parties from industry, government and public sector to academics. These data are useful in determining the current status and monitoring workforce's evolution.

Special interest has also been paid for the investigation of gender gap in science and technology. As described in the following section, several studies have been conducted regarding the inequalities in education and/or the occupation of the two genders in the field of S&T. It has been shown that although the differences between males and females are marginal in younger ages, there are obvious discrepancies in older population with males outperforming females.

Although human resources in science and technology (HRST) are extremely significant, their study was incorporated for several years in research and development (R&D) related analyses, creating thus a lack of systematic mechanisms capable for in depth examination and/or future tracking of HRST based issues. It has then become evident that more effort should be made to gather and process data enhancing HSRT knowledge. This endeavor can be exemplified by the numerous programs supported by the OECD and the European Commission. Milestone to this process was the Canberra manual proposed and developed by the organization for economic co-operation and development in 1995 (Nanopoulos, Sirilli, & Tanaka, 1995).

Canberra Manual incorporates the best national and international practice as a result of a wide inventory along with the use of the main standard international classifications. In fact, it provides a framework for processing HRST data, investigating trends and preparing up-to-date series for intended users aiming in the harmonization of data and the use of HRST indicators.

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[3] Economic and political union consisting of the following 27 member states (from 1 January 2007): Belgium (BE), Greece (EL), Luxembourg (LU), Denmark (DK), Spain (ES), Netherlands (NL), Germany (DE), France (FR), Portugal (PT), Ireland (IE), Italy (IT), United Kingdom (UK), Austria (AT), Finland (FI), Sweden (SE), Poland (PL), Czech Republic (CZ), Cyprus (CY), Latvia (LV), Lithuania (LT), Slovenia (SI), Estonia (EE), Slovakia (SK), Hungary (HU), Malta (MT), Bulgaria (BG), Romania (RO).

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http://dx.doi.org/10.1016/j.eswa.2012.12.056

In this work and in contrary to the majority of previous studies that are limited to statistically analyze and forecast human resources in science and technology as a whole or the evolution of each gender separately, the evolution of "population shares" in S&T as well as gender interactions are modeled, investigated and forecasted using the evolutionary theory of population biology and dynamics. In detail, the proposed model is based on Lotka–Volterra model describing the competition between species (Begon, Townsend, & Harper, 2006; Murray, 2007). Lotka–Volterra model is a widely used model especially in biology.

However, it has also been applied in several other areas, besides biology, providing precise estimates of the dynamics under consideration (Foryś, 2009; Lee, Lee, & Oh, 2005; Ying & Shi, 2008). A typical example is telecommunications market where the L–V model is used to examine providers' competitive behavior-market share (Kim, Lee, & Ahn, 2006; Lopez & Sanjuan, 2001; Michalakelis, Christodoulos, Varoutas, & Sphicopoulos, 2012). The results obtained by the model can be supportive to other already used techniques providing a comparison reference confirming their results.

The proposed model was applied in the case of two European countries; Greece and Portugal as well as in the case of Europe-27. It was shown that the model gives very good interpolation of the statistical data providing at the same time an accurate forecasting (It was compared to actual data of 2011) using the parameters obtained from both the analytical and simulation methods. The results showed that in the case of Greece and Portugal, human resources of the two genders in S&T as a share of active population will continue to increase in the following years tending to a steady-state. On the other hand human resources in the case of Europe-27 revealed a decreasing oscillatory behavior, possibly due to the contribution of countries with different characteristics, leading again to a steady-state.

Good performance of the proposed methodology would result in a twofold contribution. On the one hand, it would provide an alternative analysis and interpretation method of HRST data as well as of the interaction of the two genders in this area. On the other hand, it would act as valuable tool for policy and decision makers saving money from expensive and frequently unnecessary training of S&T skills.

This paper is organized as follows. At first a literature review is introduced regarding gender inequalities in HRST. Then the proposed model describing the relationship and the evolution of the two genders regarding human resources in science and technology is presented. Subsequently the solution procedure of the set of the nonlinear differential equations is described and details are given for the analytical method for the determination of model coefficients is given and the simulation method based on Artificial Bee Colony optimization algorithm. The linearization of the nonlinear problem as well as a closed form formula for the evolution of males and females in S&T is derived the following subsection. The results obtained by the application of the described model along with the two solving methods are finally presented and discussed before the concluding remarks.

2. Literature review and definition

Gender inequality has existed since the ancient times. Women were not involved in paid labor (Rossi, 1988) until 1830. Women began to participate in labor after the first industrial revolution that generated a great need for manpower (Ruskin, 2002). However, both technological revolutions brought up once again gender inequality issues.

The European Union (EU) since its establishment anticipated these gender inequality issues and therefore took steps towards equal rights between men and women. Nevertheless the two genders have not yet achieved to be equal to each other and it is a fact that women are still employed in inferior and less paid jobs. Gender inequality was extensively studied by Helgesen (1990) and many more researchers earlier than him.

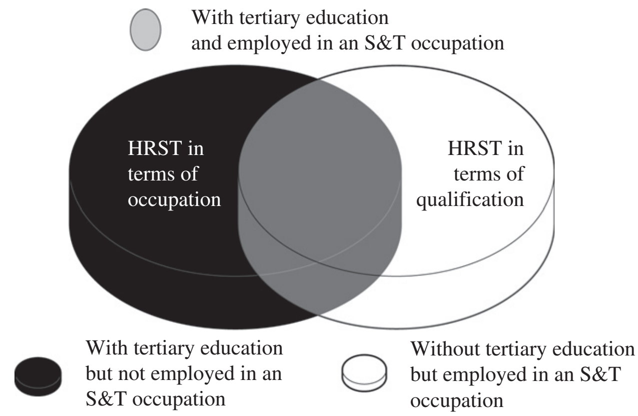

Fig. 1. Components of HRST.

In the last decades it was realized that the existing inequality between men and women that use new technologies and are employed to jobs related to science and technology (i.e. sciences related to mathematics, chemistry, engineering and biology etc.[4]) was not only due to gender differences but also due to age differences. More specifically, men and women between the ages of 16 and 24, have the same education and should therefore share the same labor opportunities but in contrast to that, when it comes to older people men outperform women.

Even though both genders equally use new technologies, fewer women chose to study in the field of natural sciences. At this point, it should be noted that between the ages of 25 and 64 over the years 2006–2008 in EU-27 there has been an increase of people related to science in new technologies of about 11% while at earlier ages this increase was even greater. Women working in R&D seem to be a minority in EU-25 with a percentage of only 28% that drops to 22.3% when regarding the field of technology and natural sciences in general (European Commission, 2008).

Before further analyzing women's disadvantages in labor over men it would be significant to define the term human resources in science and technology (HSRT). According to Eurostat:

"*This indicator gives the percentage of the total labor force in the age group 25–64, that is classified as HRST, i.e. having either successfully completed an education at the third level*[5] *in an S field of study or is employed in an occupation where such an education is normally required*".

As shown in Fig. 1, HSRT has two components; one consists of the people who work in fields related to new technologies without having a relevant educational background and the other of the people who work in related fields without tertiary education in the specific field. The rest are people that have studied fields related to science and technology and work in related issues (Nanopoulos et al., 1995).

In previous years, there is an increased interest of girls for tertiary education. This can also be proved by Eurostat statistical data showing that in the last two decades more women have graduated tertiary education. In 2007, 21.1% of women aged from 15 to 64 hold a degree, while the corresponding percentage of men is 20.1%. However the percentage of women choosing the field of

[4] http://www.uis.unesco.org/ScienceTechnology/Documents/38235147.pdf.

[5] ISCED levels 5, 6, 7 and 8, which are labeled as shortcycle tertiary, bachelor level or equivalent, master level or equivalent and doctoral level and equivalent, respectively.

natural sciences is less than that of men. Nevertheless from 2010, women holding a degree related to the fields of S&T are more than men. In contrast the percentage of working women is less than that of working men and in addition their jobs are less paid.

It is interesting that in Eu-27, 45% of Ph.D. holders are women and 41% of which is related to the field of natural sciences. Furthermore only 30% of employees in top managerial positions in big firms and organizations are women and this percentage is smaller in the case of S&T. Nonetheless, women do not fall short of men only in managerial positions in big firms but also in universities and research centers (Castaño, Sáinz, & González-Ramos, 2008). It is a common belief that the field of science worldwide is ruled by men leading to a gender gap that becomes smaller in industrially advanced countries and greater in developing and third world countries (Klassen, Stockard, Akbari, & Damooei, 2005; Othman & Latih, 2006). As a result gender inequality still exists. This can be clearly exemplified by Information and Communications Technology (ICT), an S&T sector where women are really under represented (Palma, 2001; Trauth, 2002; Wilson-Kovacs, Ryan, & Haslam, 2006).

There exists a vast bibliography related to this gender gap in high hierarchy job positions. It is a fact that natural sciences and their study, suits better men than women (Broos, 2005; Woodfield, 2002). However one should review such bibliographies in order to identify the reasons why men excel in labor generally and in managerial positions specifically. There exist several explanations and empirical researches that interpret gender gaps in workplaces (Billing & Alvesson, 1994; Morrison & Von Glinow, 1990). Many emphasize on several agents such as social and structural factors, psychological characteristics, social standards, vocational guidance, educational and professional choices. In 1993, Kanter states that managerial positions need determination, persistence in problem solving, analytical and synthetic way of thinking and being emotionless when facing a problem, creating thus a set of characteristics rarely found in women. On the other hand, the educational system might also be responsible for not helping women in their professional evolution since they are treated differently than men (Acker, 1989; Barret, 1980). Additionally the organizational culture of most businesses and organizations is fitted to male administration standards and therefore men tend not to trust women and stand in their way for higher ranks of the hierarchy (Broughton & Miller, 2009). Last but not least women handle and manage on their own all family matters, causing them to lose faith in themselves regarding labor and this makes other people to stop confide in them (Petraki-Kottis & Ventoura-Neokosmidi, 2011).

3. Proposed model and population dynamics

According to population biology, expressing the growth or decline of the population of a given species can be achieved by the rate of its change proportional to its current size. The simplest approach implies absence of any competitors ($i = 1$) and was given in Boyce and DiPrima (2008):

$$\frac{dy_i(t)}{dt} = r\left(1 - \frac{y_i(t)}{k}\right)y_i(t) \tag{1}$$

where $y_i(t)$ is the size of the given species population at time t, constant r is called the intrinsic growth rate and presents the growth rate in absence of any limiting factors and k is the upper bound that is approached yet not exceeded by growing populations starting below this value. Constant k is usually referred to as the saturation level or the environmental carrying capacity of the given species.

In view of studying more than one species that coexist in the same closed environment one would expect them to interact with each other in many ways. Usually when more than one species coexist they are expected to compete for the same resources and their population dynamics is affected. That is to say each species will impinge on the available resources of the other species affecting their growth rate and saturation population and vice versa. However, when considering a more specific case of two species interacting with each other, three types of interaction can be defined (Kot, 2001): (i) the growth rate of one population is decreasing while that of the other one is increasing denoting a predator–prey situation. (ii) the growth rate of each population is decreasing, showing that the populations are in competition. (iii) each population's growth rate is enhanced, presenting the case which is called mutualism or symbiosis.

In the present work, human resources in science and technology (HRST) as a share of the economically active population in the age group 25–64 are chosen for our study group. More specifically the indicator chosen presents a percentage of the total labor force in the age group 25–64, that is classified as HRST, according to the definition given in the previous section. Both women and men are studied separately being regarded as two biological species competing for survival and growth. On the other hand, one might consider the workforce of women and men in HRST as two species that interact with each other to the advantage of all. This is the case of mutualism or symbiosis and both of these species play a crucial role in promoting or even maintaining their population. Even though the importance of this kind of population interaction is equally important to that of competition and prey-predator interactions, mutualism or symbiosis have not yet been widely studied (Murray, 2007). The simplest mutualism model for species y_1 and y_2 is equivalent to the classical Lotka–Volterra predator–prey model presented in (1) for $i = 1,2$. In this model all constants are positive and since dy_1/dt and dy_2/dt are also positive and y_1, y_2 would simply grow unboundedly. However, more realistic models should at least show a mutual benefit to both species and have some positive steady state. Therefore a more practical example is discussed in May (1975) that results in the following set of equations:

$$\begin{aligned}\frac{dN_1}{dt} &= a_{10}N_1 + a_{11}N_1^2 + a_{12}N_1N_2 \\ \frac{dN_2}{dt} &= a_{20}N_2 + a_{21}N_2^2 + a_{22}N_1N_2\end{aligned} \tag{2}$$

In (2) coefficients a_{10} and a_{20} represent the growth coefficients of the corresponding populations N_1 and N_2. Coefficients a_{11} and a_{21} measure the intraspecies interaction while a_{12} and a_{22} measure interspecies interaction.

4. Methodology and solution procedure

In order to model the evolution of the number of women and men in science and technology as a share of the labor force, one should solve the system of differential equations shown in (2). However, the first step towards this process is to estimate the unknown coefficients a_{ij} using actual statistical data.

4.1. Estimation of model coefficients

In the following subsections, two methods, an analytical and a simulation method, are described. Both methods are based on the minimization of an objective function. A recently proposed optimization algorithm, Artificial Bee Colony, is used in the case of the simulation method.

4.2. Analytical method

The analytical method (Shatalov, Greeff, Joubert, & Fedotov, 2008) begins with time integration of equation in (2). This transforms the system of differential equations into the following form:

$$
\begin{aligned}
N_1(t) - N_1(0) &= a_{10}\int_0^t N_1(\tau)d\tau + a_{11}\int_0^t N_1^2(\tau)d\tau \\
&\quad + a_{12}\int_0^t N_1(\tau)N_2(\tau)d\tau \\
N_2(t) - N_2(0) &= a_{20}\int_0^t N_2(\tau)d\tau + a_{21}\int_0^t N_2^2(\tau)d\tau \\
&\quad + a_{22}\int_0^t N_2(\tau)N_1(\tau)d\tau
\end{aligned} \tag{3}
$$

where $\tau \in [0,t]$. Using the above transformation, the estimation of the coefficients a_{1j} can be treated independently from that of a_{2j}. Hence, coefficients a_{10}, a_{11} and a_{12} and coefficients a_{20}, a_{21} and a_{22} will be evaluated from the first and the second equation of (3) respectively along with the use of actual data. It should be noted that the integrals in (3) will be approximately estimated using the trapezoidal method. For example, the third integral of the first equation in (3) at the ith time instant can be written as:

$$
I_3^{(i)} = \int_0^{t_i} N_1(\tau)N_2(\tau)d\tau \approx \begin{bmatrix} \frac{t_1-t_0}{2}(N_1(0)N_2(0)+N_1(t_1)N_2(t_1))+ \\ +\frac{t_2-t_1}{2}(N_1(t_1)N_2(t_1)+N_1(t_2)N_2(t_2))+\cdots+ \\ +\frac{t_i-t_{i-1}}{2}(N_1(t_{i-1})N_2(t_{i-1})+N_1(t_i)N_2(t_i)) \end{bmatrix} \tag{4}
$$

It should be noted that at $t_0 = 0$, $I_i = 0$ for $i = 1,2,\ldots,6$. Using the approximate estimations of the integrals I_i in each time instance $t \in [0,t_N]$, where N is the number of actual data, a system of N linear equations for each equation in (3) is derived. In the case of the first equation in (3), the obtained system is:

$$
\begin{aligned}
&a_{10}I_1^{(1)} + a_{11}I_2^{(1)} + a_{12}I_3^{(1)} = N_1(t_1) - N_1(t_0) \\
&a_{10}I_1^{(2)} + a_{11}I_2^{(2)} + a_{12}I_3^{(2)} = N_1(t_2) - N_1(t_0) \\
&\ldots \\
&a_{10}I_1^{(N)} + a_{11}I_2^{(N)} + a_{12}I_3^{(N)} = N_1(t_N) - N_1(t_0)
\end{aligned} \tag{5}
$$

In other words one can assume that $N_1(t_i)$, $i = 1,2,\ldots,N$ is the actual data while

$$
\widehat{N}_1(t_i) = N_1(t_0) + a_{10}I_1^{(i)} + a_{11}I_2^{(i)} + a_{12}I_3^{(i)} \tag{6}
$$

is an estimation of $N_1(t_i)$. Hence, in order to determine the coefficients a_{1j}, the mean squared error (objective function) between the observed–actual data and the estimations should be minimized.

$$
MSE = \frac{1}{N}\sum_{i=1}^{N}\left[a_{10}I_1^{(i)} + a_{11}I_2^{(i)} + a_{12}I_3^{(i)} - \Delta N_1^{(i)}\right]^2 \tag{7}
$$

The coefficients a_{1j} for which the MSE is minimized can be found by setting the corresponding partial derivatives equal to zero. This leads to the following system of linear equations.

$$
\begin{aligned}
\frac{\partial MSE}{\partial a_{10}} &= a_{10}\sum_{i=1}^{N}\left(I_1^{(i)}\right)^2 + a_{11}\sum_{i=1}^{N}I_1^{(i)}I_2^{(i)} + a_{12}\sum_{i=1}^{N}I_1^{(i)}I_3^{(i)} - \sum_{i=1}^{N}I_1^{(i)}\Delta N_1^{(i)} = 0 \\
\frac{\partial MSE}{\partial a_{11}} &= a_{10}\sum_{i=1}^{N}I_1^{(i)}I_2^{(i)} + a_{11}\sum_{i=1}^{N}\left(I_2^{(i)}\right)^2 + a_{12}\sum_{i=1}^{N}I_2^{(i)}I_3^{(i)} - \sum_{i=1}^{N}I_2^{(i)}\Delta N_1^{(i)} = 0 \\
\frac{\partial MSE}{\partial a_{12}} &= a_{10}\sum_{i=1}^{N}I_1^{(i)}I_3^{(i)} + a_{11}\sum_{i=1}^{N}I_2^{(i)}I_3^{(i)} + a_{12}\sum_{i=1}^{N}\left(I_3^{(i)}\right)^2 - \sum_{i=1}^{N}I_3^{(i)}\Delta N_1^{(i)} = 0
\end{aligned} \tag{8}
$$

Thus, the coefficients of the first equation of (2) equal to the unique solution of (8) given by:

$$
[a_{10}, a_{11}, a_{12}]^T = \begin{bmatrix} \sum_{i=1}^{N}\left(I_1^{(i)}\right)^2 & \sum_{i=1}^{N}I_1^{(i)}I_2^{(i)} & \sum_{i=1}^{N}I_1^{(i)}I_3^{(i)} \\ \sum_{i=1}^{N}I_1^{(i)}I_2^{(i)} & \sum_{i=1}^{N}\left(I_2^{(i)}\right)^2 & \sum_{i=1}^{N}I_2^{(i)}I_3^{(i)} \\ \sum_{i=1}^{N}I_1^{(i)}I_3^{(i)} & \sum_{i=1}^{N}I_2^{(i)}I_3^{(i)} & \sum_{i=1}^{N}\left(I_3^{(i)}\right)^2 \end{bmatrix} \times \begin{bmatrix} \sum_{i=1}^{N}I_1^{(i)}\Delta N_1^{(i)} \\ \sum_{i=1}^{N}I_2^{(i)}\Delta N_1^{(i)} \\ \sum_{i=1}^{N}I_3^{(i)}\Delta N_1^{(i)} \end{bmatrix} \tag{9}
$$

The coefficients of the second equation of (2) can be derived following a similar to the above procedure.

4.3. Simulation method

In order to estimate model's coefficients through simulation, a recently proposed optimization algorithm, Artificial Bee Colony optimization, is implemented in MATLAB. This kind of algorithm is applied aiming to minimize the objective function defined as the mean squared errors (Eq. (7)) between the observed (actual data) and the estimated values given by (6).

The Artificial Bee Colony algorithm (ABC) was proposed by Karaboga (2005) as an optimization method of multivariable continuous objective functions. ABC algorithm belongs to the wider family of swarm optimization algorithms. These are based on swarm intelligence that models the collective behavior of self-organized interacting swarms. Immune system, particle swarm, flock of birds and ant colony are some examples of swarm optimization methods (Sedighizadeh & Masehian, 2009). It has been shown that ABC performance is comparable to other population-based methods (Goldberg, 1989; Karaboga & Akay, 2009). Furthermore, ABC received increased attention in the last years and has been used in several problems (Pan, Tasgetiren, Suganthan, & Chua, 2011; Szeto, Wu, & Ho, 2011) due to its simple and ease of implementation as well as its reduced number of control parameters. However, the biggest advantage of ABC algorithm is its independency on the initial values of the examined variables.

In fact, ABC algorithm resembles the foraging operation of honeybees and their swarming around the hive. The interaction between three types of bees: employed, onlooker and scout results in the collective intelligence of the colony. This interaction is presented by the waggle dance of bees during food procuring. It should be noticed that employed bee is a bee currently procuring a food source; onlooker bee is staying in the hive in order to decide a source food while scout bees are those that randomly search for new food sources. The solutions obtained by the ABC algorithm are corresponded to food sources while the fitness of the solution is described by the amount of nectar of the investigated food source. The interaction of bees with food sources and the sharing of information about the direction and distance to patches of flower and nectar amount through waggle dance lead to the best solution.

ABC algorithm is an iterative process that requires three parameters by the user: (a) number of food sources (solutions), (b) number of iterations (MCN) and (c) number of cycles before a constant solution (with no improvement) is replaced by a new one, randomly selected by the scout bees. The number of employed and onlooker bees are set equal to the number of solutions that is an employed bee corresponds for every food source.

The initial solutions (during the first step of ABC) are randomly selected as follows:

$$
x_{ij} = LB_j + (UB_j - LB_j)^*\varphi_{ij}, j = 1,2,\ldots,n \quad \text{and} \quad i = 1,2,\ldots,SN \tag{10}
$$

where LB_j and UB_j is the minimum and maximum value of dimension j and φ_{ij} is a uniformly distributed random number in the range of [0,1]. The employed bees are sent to the initial sources, evaluate their fitness functions and then return to their hive in order to inform the bees waiting on the dance area about the amount of nectar of the examined sources.

At the next step, the employed bees return to the last known sources and chose a new source in this neighborhood.

$$v_{ij} = x_{ij} + (x_{ij} - x_{kj})^{*}\varphi_{ij}, j \in [1, 2, \ldots, n] \quad \text{and}$$
$$k \in [1, 2, \ldots, SN],\ k \neq i \tag{11}$$

where x_{ij} is the current position (source) of the employed bee and φ_{ij} is a uniformly distributed random number in the range of $[-1, 1]$. It should be noted that the deviation from the current position x_{ij} decreases as the difference between x_{ij} and x_{kj} decreases. Hence, the step adaptively decreases as the algorithm converges. After the selection of the new position, its fitness function should be evaluated and compared through a greedy selection mechanism. The current position should be replaced by the new one in the case that its fitness function is smaller than that of the new source.

An onlooker bee selects a food source x_i by calculating its probability:

$$p_i = \frac{f_i}{\sum_{i=1}^{SN} f_i} \tag{12}$$

where f_i is the fitness function of source i that is the nectar information gathered by the employed bees. It is evident that the source with the highest fitness function has a bigger probability to be selected. Similar to the employed bees, the onlookers generate a new source using (11) which is finally selected if its amount of nectar is higher or equal than that of the current source.

If a source cannot be further improved in a predetermined number of cycles, it is abandoned and replaced with a new one produced by scouts through (10). It should be noted that at most one scout searches for new food source at each cycle of the ABC algorithm.

The basic ABC algorithm is shown in Fig. 2 while its main steps are summarized in the following list:

1. Define the objective and fitness functions of the problem.
2. Initialize control parameters.
3. Allocate food sources to the employed bees.
4. Place the onlooker bees on the food sources according to the amount of their nectar.
5. New food sources are investigated by scouts.
6. Memorize the best source so far.
7. Terminate the process and show the best source if the stopping criteria are satisfied; otherwise return to step 3.

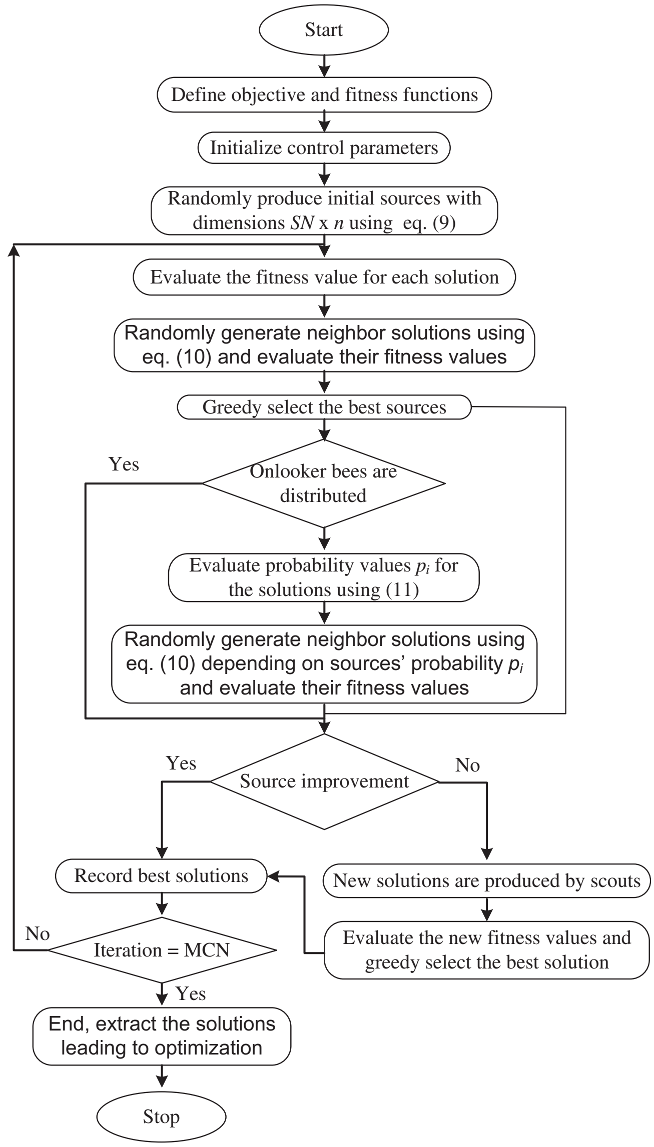

Fig. 2. The ABC algorithm main step block diagram.

4.4. System linearization

After having estimated the coefficients of system (2) a linearization procedure must be adopted in order to derive a linear system of equations (Boyce & DiPrima, 2008). In order to do so, the first step is to define a stable solution for system (2) which can be rewritten in the following form:

$$\begin{aligned} \frac{dN_1}{dt} &= N_1(a_{10} + a_{11}N_1 + a_{12}N_2) \\ \frac{dN_2}{dt} &= N_2(a_{20} + a_{21}N_2 + a_{22}N_1) \end{aligned} \tag{13}$$

This system has 2^i possible equilibrium points (solutions), where i equals the number of the system's equations. In the case of system (13), there exist 4 possible solutions only one of which contains non-zero values for parameters N_1 and N_2. In order to identify these solutions, the derivatives of the left-hand side are set to zero and the remaining system (i.e. the equations inside the parentheses) is solved in terms of N_1 and N_2.

$$N_1 = \frac{a_{21}a_{10} - a_{12}a_{20}}{a_{22}a_{12} - a_{21}a_{11}} \tag{14}$$
$$N_2 = \frac{a_{11}a_{20} - a_{10}a_{22}}{a_{22}a_{12} - a_{21}a_{11}} \tag{15}$$

The system can be transformed to its closest linear system when the values of populations N_1 and N_2 are close to this solution. In order to do that the left-hand side of the system (2) is expanded around the equilibrium point $\left(N_1^{(0)}, N_2^{(0)}\right)$ by its tangent around that fixed point.

$$\begin{aligned} \frac{dN_1}{dt} &= F_1(N_1, N_2) \approx F_1\left(N_1^{(0)}, N_2^{(0)}\right) + \left(N_1 - N_1^{(0)}\right)\left.\frac{\partial F_1}{\partial N_1}\right|_{\left(N_1^{(0)}, N_2^{(0)}\right)} \\ &\quad + \left(N_2 - N_2^{(0)}\right)\left.\frac{\partial F_1}{\partial N_2}\right|_{\left(N_1^{(0)}, N_2^{(0)}\right)} \\ \frac{dN_2}{dt} &= F_2(N_1, N_2) \approx F_2\left(N_1^{(0)}, N_2^{(0)}\right) + \left(N_1 - N_1^{(0)}\right)\left.\frac{\partial F_2}{\partial N_1}\right|_{\left(N_1^{(0)}, N_2^{(0)}\right)} \\ &\quad + \left(N_2 - N_2^{(0)}\right)\left.\frac{\partial F_2}{\partial N_2}\right|_{\left(N_1^{(0)}, N_2^{(0)}\right)} \end{aligned} \tag{16}$$

By definition $F_1\left(N_1^0, N_2^0\right) = F_2\left(N_1^0, N_2^0\right) = 0$ therefore (16) can be simplified to:

$$\begin{aligned}\frac{dN_1}{dt} &\approx \left(N_1 - N_1^{(0)}\right)\frac{\partial F_1}{\partial N_1}\Big|_{\left(N_1^{(0)},N_2^{(0)}\right)} + \left(N_2 - N_2^{(0)}\right)\frac{\partial F_1}{\partial N_2}\Big|_{\left(N_1^{(0)},N_2^{(0)}\right)} \\ \frac{dN_2}{dt} &\approx \left(N_1 - N_1^{(0)}\right)\frac{\partial F_2}{\partial N_1}\Big|_{\left(N_1^{(0)},N_2^{(0)}\right)} + \left(N_2 - N_2^{(0)}\right)\frac{\partial F_2}{\partial N_2}\Big|_{\left(N_1^{(0)},N_2^{(0)}\right)}\end{aligned} \tag{17}$$

The system (17) is now transformed into the following linear system:

$$\frac{d}{dt}\begin{bmatrix} M \\ W \end{bmatrix} = \mathbf{J} \times \begin{bmatrix} M \\ W \end{bmatrix} \tag{18}$$

where $M = N_1 - N_1^{(0)}$ and $W = N_2 - N_2^{(0)}$ and the matrix $\mathbf{J}$ is the Jacobian matrix of the system at the equilibrium point $\left(N_1^{(0)}, N_2^{(0)}\right)$,

$$\mathbf{J} = \begin{bmatrix} \frac{\partial F_1}{\partial N_1}\Big|_{\left(N_1^{(0)},N_2^{(0)}\right)} & \frac{\partial F_1}{\partial N_2}\Big|_{\left(N_1^{(0)},N_2^{(0)}\right)} \\ \frac{\partial F_2}{\partial N_1}\Big|_{\left(N_1^{(0)},N_2^{(0)}\right)} & \frac{\partial F_2}{\partial N_2}\Big|_{\left(N_1^{(0)},N_2^{(0)}\right)} \end{bmatrix} \tag{19}$$

According to Poincare–Lyapunov theorem (Boyce & DiPrima, 2008) if the eigenvalues of matrix $\mathbf{J}$ are not equal to zero or are not pure imaginary numbers, then the trajectories of the system around this point behave the same way as the trajectories of the associated linear system. More specifically if the eigenvalues are negative or complex with negative real part, then the fixed point is a sink, or if the eigenvalues are positive or complex with positive real part, then the fixed point is a source point and if the eigenvalues are real numbers with different sign then the equilibrium point is a saddle point.

The general solution of the system (18) is:

$$\begin{bmatrix} M \\ W \end{bmatrix} = c_1 \begin{pmatrix} v_{11} \\ v_{12} \end{pmatrix} e^{\lambda_1 t} + c_2 \begin{pmatrix} v_{21} \\ v_{22} \end{pmatrix} e^{\lambda_2 t} \tag{20}$$

where c_1, c_2 are arbitrary constants and v_{ij} are the elements of the eigenvectors derived from the Jacobian matrix $\mathbf{J}$. In addition, since the system under investigation is an initial value problem, substitution of these initial values to Eq. (20) allows the calculation of constants c_1 and c_2 resulting in the final solution.

5. Results and discussion

In this section the proposed model is applied in order to describe the gender evolution and gap of HRST in the case of two European countries; Greece and Portugal as well as the European-27. These two countries were chosen as their common socio-economic characteristics may facilitate the conduction of common or similar conclusions. Furthermore Europe's-27 results may provide an indicator of European trends in a very attractive sector.

Calculations were performed on annual data describing human resources in science and technology as a share of labor force. Two species will be used, i.e. men and women, in all cases. The selected data set was found in Eurostat's Database from 2002 until 2010. In fact data between 2002 and 2009 are used for the estimation of the model coefficients. Data of the last year is utilized in order to verify the model's ability to forecast future trends. The authors are willing to reexamine the model's forecasting ability when more data will be available. Although the data set may seem to contain few data points in order to produce accurate estimates both the ABC algorithm and the analytical method remain unaffected and reveal high performance.

The evaluation procedure is going to be described in detail for the case of Greece while for Portugal's and Europe's-27 cases only the final results are going to be presented since they were derived with exactly the same way.

Human resources in science and technology as a share of the economically active population in the age group 25–64 for the three chosen cases are shown in Table 1. The first column corresponds to the year under consideration while the second and the third, of each case, to the men and women HRST shares respectively.

The first step towards the HRST modeling is the identification of equation's (2) coefficients a_{ij}, $i = 1,2$ and $j = 0,1,2$. This will be achieved with the application of the ABC algorithm as well as with the analytical method, described in previous, on the available dataset. The coefficients derived using the aforementioned methods are illustrated in Table 2.

As shown in Table 2, the results of both methods coincide very well. For simplicity, the ABC's coefficients are assumed to be the model's coefficients that will be used in the rest of the paper. It should be noted that important information can be derived regarding the process dynamics from coefficients of Table 2. For example, in the case of Greece, high values of a_{10} and a_{20} lead to the rapid growth of the corresponding genders' HRST shares. On the other hand, the small values of the rest coefficients indicate low intraspecies and interspecies interaction rates. This can be attributed to unprecedented evolution of science and technology fields that lead to a constantly increasing number of both university students and new jobs in this area over the last decade avoiding the competition among opposite and same gender for an S&T position.

Substituting the corresponding coefficients in Eq. (6) for the case of men (N_1) and in a similar equation for women, one can easily evaluate the estimates of the S&T shares. In Figs. 3 and 4, men and women in science and technology as a share of labor force are shown respectively. Actual data are illustrated as solid line while estimated data are depicted in dots. The R^2 coefficient of the fitting between estimated and actual values equals to 94% and 99% for men and women respectively, demonstrating the high accuracy of the whole process.

It is highlighted once again that model's coefficients were evaluated over the training period 2002–2009. As shown in Figs. 3 and 4, the estimated values (28.73 and 37.25) of year 2010 almost coincides with the actual values (28.9 and 37.2 – Table 1) for men and women respectively giving a first insight of the forecasting ability of the proposed model.

As mentioned in the previous section, the system of (13) has 4 critical points, when the derivatives of the left-hand side equal to zero. However, at the three of the four equilibrium solutions there is at least one N_i equal to zero and thus they must be ignored. The remaining non-zero solution in the case of Greece was found to be $(N_1, N_2) = (26.5573, 37.1641)$. The eigenvalues of Jacobian matrix (19) are evaluated at the calculated critical point in order to investigate its stability. This analysis showed that the critical point is stable since the eigenvalues are complex with negative real part (critical point is a sink). The calculated eigenvalues for this case are $(\lambda_1, \lambda_2) = (-0.1798 + 0.1600i, -0.1798 - 0.1600i)$. The fact that the calculated critical point is a sink bears significant value for the forecasting analysis since populations N_1, N_2 of men and women in science and technology as a share of labor force will

Table 1
Actual data of men and women in science and technology as a share of labor force (source: Eurostat).

Year	Greece		Portugal		Europe-27	
	Men	Women	Men	Women	Men	Women
2002	23.6	30.1	15.7	19.9	32.9	37.7
2003	24.4	31.3	16.5	20.3	33.6	38.7
2004	27.1	32.9	19.5	23.2	34.6	40.1
2005	26.5	33.5	19.7	23.5	35.2	41
2006	27.7	35.1	19.9	24.3	35.9	42
2007	28.2	35.6	19.9	24.5	36.3	42.9
2008	28.4	36.5	20.6	26	36.5	43.4
2009	28.3	36.8	21	26.3	36.9	44.1
2010	28.9	37.2	21.1	27	36.9	44.7

Table 2
Model coefficients produced using the ABC algorithm and the analytical method.

Coefficient	Greece		Portugal		Europe-27	
	ABC	Analytical	ABC	Analytical	ABC	Analytical
a_{10}	0.355303	0.35526	0.495908	0.49591	0.0385823	0.03847
a_{11}	−0.001294	−0.001287	−0.024823	−0.024823	0.012917	0.012929
a_{12}	−0.008635	−0.008639	0.000933	0.000933	−0.011582	−0.01159
a_{20}	0.179603	0.179609	0.225341	0.22534	0.006683	0.006683
a_{21}	0.005538	0.005489	−0.001612	−0.001613	0.015599	0.015599
a_{22}	−0.008794	−0.008755	−0.006549	−0.006549	−0.012955	−0.012955

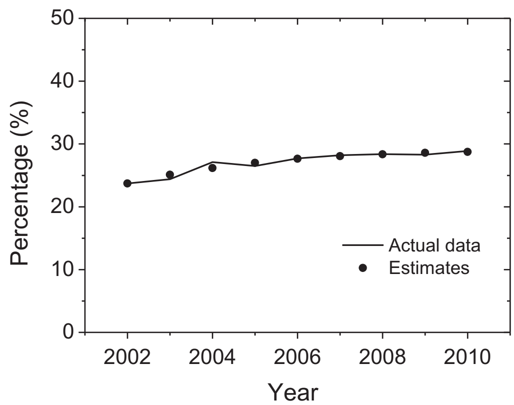

Fig. 3. Estimation results of men in science and technology as a share of labor force in Greece.

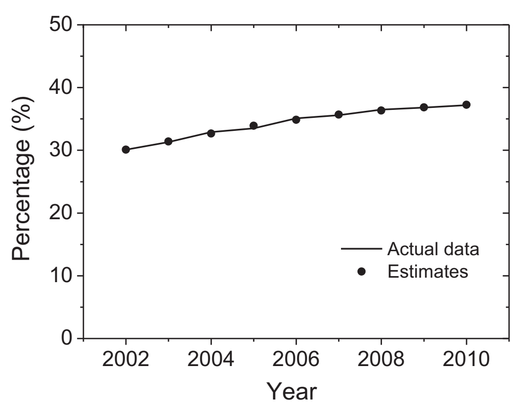

Fig. 4. Estimation results of women in science and technology as a share of labor force in Greece.

eventually settle to the values of the solution. This is of great importance for the policy and decision makers in order to properly design their strategy according to the future conditions and trends of the field of science and technology.

According to Poincare–Lyapunov theorem and since the eigenvalues of the Jacobian matrix (19) are not zero nor pure imaginary, the trajectories of system (2) around this point behave the same way as the trajectories of the associated linear system. Therefore the system is almost linear close to the critical point.

After simple mathematical manipulations (Eqs. (16)–(19)), it is straightforward to derive the general solution (20) for the case of Greece.

$$\begin{bmatrix} M \\ W \end{bmatrix} = c_1 \begin{pmatrix} 0.7276 \\ 0.4617 - 0.5074i \end{pmatrix} e^{(-0.1798+0.1600i)t} + c_2 \begin{pmatrix} 0.7276 \\ 0.4617 + 0.5074i \end{pmatrix} e^{(-0.1798-0.1600i)t} \tag{21}$$

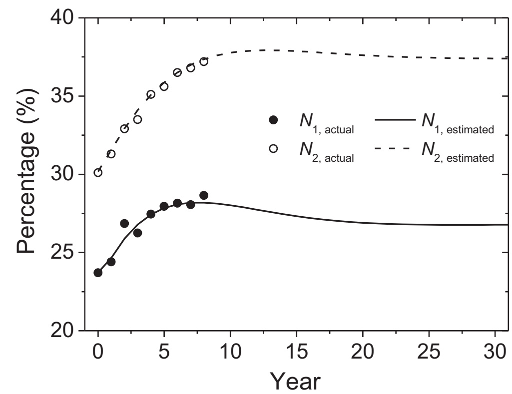

Fig. 5. Estimated evolution and forecasting of human resources in science and technology as a share of labor force in Greece.

where $M = N_1 - 26.5573$ and $W = N_2 - 37.1641$ and c_1 and c_2 are arbitrary constants. These constants can be calculated by substituting the initial values of M and W (at $t = 0$) in (21). Therefore, the resulting final solution for the case of Greece is:

$$\begin{bmatrix} M \\ W \end{bmatrix} = \begin{pmatrix} -1.08 - 3.22\mathrm{i} \\ -2.93 - 1.29\mathrm{i} \end{pmatrix} e^{(-0.1798+0.1600i)t} + \begin{pmatrix} -1.08 + 3.22\mathrm{i} \\ -2.93 + 1.29\mathrm{i} \end{pmatrix} e^{(-0.1798-0.1600i)t} \tag{22}$$

Next, illustrated in Fig. 5 is the men and women HRST evolution over time, based on the system described by (22). In order to be more specific the transformation of $M = N_1 - 26.5573$ and $W = N_2 - 37.1641$ in (22) is reversed and the constructed model estimates that the HRST share after ~15 years of men reaches an equilibrium of about 26%, while the corresponding figure for women is approximately 37%. As shown in Fig. 5, it is obvious that the share of women will slightly increase in the next years followed by a marginal drop until its predicted stabilization. On the other hand the share of men exhibits an asymptotical decay towards the forecasted equilibrium point.

According to the preceding analysis for the case of Greece one can easily derive the final solution for the case of Portugal:

$$\begin{bmatrix} M \\ W \end{bmatrix} = \begin{pmatrix} -4.08 \\ -0.58 \end{pmatrix} e^{-0.5204t} + \begin{pmatrix} -0.498 \\ -8.332 \end{pmatrix} e^{-0.1942t} \tag{23}$$

From (23) it is deduced that the eigenvalues are real negative leading to a sink solution $(N_1, N_2) = (21.0758, 29.2159)$. This can also be confirmed by Fig. 6 where both men and women HRST share are constantly increasing towards their equilibrium. This is reached again after ~15 years.

As an indication of the average HSRT evolution in European level, a similar model has been constructed using actual data for the 27 member states of the European Union. The calculated

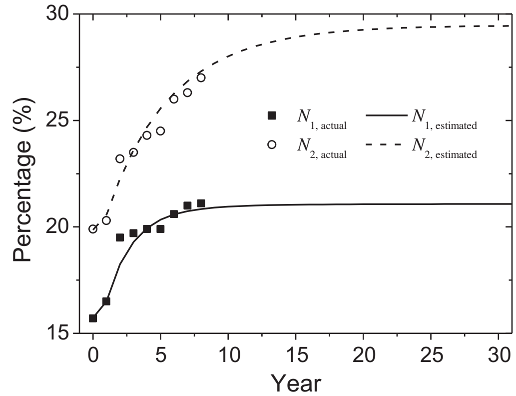

Fig. 6. Estimated evolution and forecasting of human resources in science and technology as a share of labor force in Portugal.

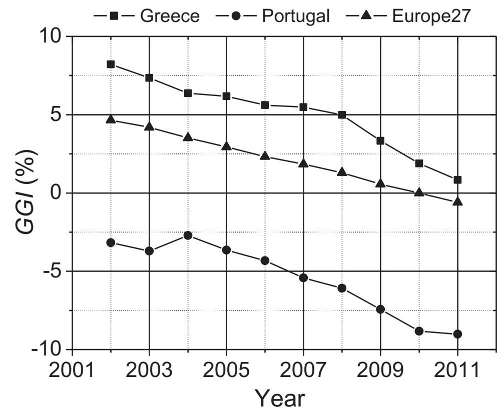

Fig. 8. Gender gap in science and technology.

coefficients of system (2) are shown in the last columns of Table 2. Performing the linearization procedure of this system the following final solution is obtained:

$$\begin{bmatrix} M \\ W \end{bmatrix} = \begin{pmatrix} 0.983 - 3.611i \\ 0.046 - 4.796i \end{pmatrix} e^{(-0.0456+0.1190i)t} + \begin{pmatrix} 0.983 + 3.611i \\ 0.046 + 4.796i \end{pmatrix} e^{(-0.0456-0.1190i)t} \quad (24)$$

The eigenvalues for Europe-27 were calculated $(\lambda_1, \lambda_2) = (-0.0456 + 0.1190i, -0.0456 - 0.1190i)$ revealing the stability of the derived critical point $(N_1, N_2) = (31.6342, 38.6077)$. Contrary to previous results the HRST share's evolution exhibits a damped oscillation that tends to the estimated equilibrium point. This may be attributed to the fact that Europe-27 consists of a set of inhomogeneous countries as regards to their HRST characteristics. The described behavior is illustrated in Fig. 7.

It would be of great importance to model and study the gender gap in the field of science and technology. Towards this direction the HRST shares should be transformed into net figures of men (N_{men}) and women (N_{women}) in S&T. This can be achieved by multiplying men and women shares with the corresponding active population of men and women respectively (source EUROSTAT). It should be noted that active population of men is actually greater than that of women in case of Greece and Europe-27. The evolution of the gender gap can be investigated by the introduction of the following gender gap index (GGI):

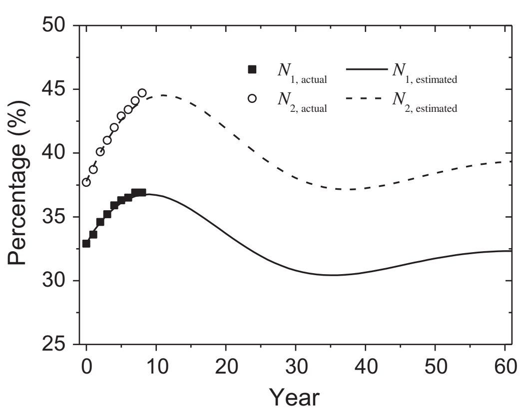

Fig. 7. Estimated evolution and forecasting of human resources in science and technology as a share of labor force in Europe-27.

$$GGI = \frac{N_{men} - N_{women}}{N_{total}} \quad (25)$$

where N_{total} represents the sum of the N_{men} and N_{women}.

The evolution of the gender gap of the three aforementioned cases is depicted in Fig. 8. The gaps in the cases of Greece and Europe-27 exhibit a decrease from 2002 and so on and approximately eliminate at 2010. It is interesting to note that after 2010 women outperform men. However in the case of Portugal, the superiority of women is evident in all years under consideration. The obtained results can be further expanded beyond 2011, if one can provide a forecasting for active population.

The derived results are not completely surprising since nowadays more and more women resort to natural sciences and/or sciences dealing with technology. At the same time, specific "taboos" have begun to gradually collapse. As a result, more jobs related to science and technology are covered by women. However, most of them remain in the lower and middle ranks of the hierarchy. Very few women succeed in breaking the glass ceiling and reaching the top. In fact, they are obliged often to accept clerical jobs that do not relate to their qualifications, while most of those who get managerial positions enter and stay at the lower end of the ladder. This demonstrates that quite a great deal of work remains to be done in that area (Petraki-Kottis & Ventoura-Neokosmidi, 2011).

6. Conclusions

A model to describe the interactive evolution of men and women in science and technology as a share of labor force was proposed in this work. The model was based on evolutionary ecology while the solution of the described system of differential equations was derived via an analytical method and a simulation optimization method based on ABC algorithm that proved to be equally accurate. The results obtained by solving the presented model in three cases, Greece, Portugal and Europe-27 revealed its ability to precisely estimate and forecast the evolution of both HRST as well as the gender gap. An equilibrium of HRST as a share of labor force was predicted in all cases. It also depicted an elimination of gender gap followed by women superiority in the next years.

It should be highlighted once more that the proposed model was designed without any specific exclusion in order to take into account all kinds of interactions. However, the resulting small values of the corresponding coefficients reveal weak interspecies and intraspecies interactions. This can be attributed to the explosive evolution of science and technology fields leading to a constantly increasing number of both university students and new jobs in this area over the last decade. Therefore, men and women did not have to compete within or between them for an S&T position, thus reducing the corresponding exchange rates.

It should be additionally mentioned that this is a very interesting topic worth further research and investigation. When the S&T population reaches a constant value, the dynamics of the model should be reconsidered. That is to say feed the model with updated data in the parameter calculation and study their influence over the model dynamics.

The proposed model leads to analytical expressions enabling further theoretical manipulations (e.g. inclusion to other models using S&T share as an independent variable). In addition it can be the basis for further research leading to more advanced models including uncertainties through stochastic modeling. Such models can be used to emulate future trends and dynamics without the need of new calculations incorporating updated data.

The model described in the present manuscript is of significant importance in strategic planning of training and occupation in order to maintain a sufficient S&T workforce to meet future needs. Its role can be twofold to either support and encourage or discourage possible future actions of governments, public sector and academics. Policies and strategic planning should be focused on several factors such as the investment in human resources training and development, demand for knowledge by the private sector, rich environment for higher knowledge institutions, and ICT infrastructures that facilitate the flow and dissemination of knowledge and information.

The first step towards this direction is to conduct a road map for the development of programs, projects and policies forming the long-term vision of S&T. This can be achieved by organizing fora and workshops in which several ideas can be exchanged between experts.

In this endeavor, governments play an extremely important role by funding and facilitating careers in the S&T field. Tertiary education in this area can be significantly improved by establishing training fellowships, scholarships and exchange grants for scientists and professors. On the other hand, both governments and private enterprises can attract HSRT through economic incentives such as advantageous salaries and tax benefits.

In parallel, research and development programs, think tanks, training and joint post-graduate programs can also be contributed to this end in a pan-European or global level. This also facilitates international cooperation among university, industry and other public/private entities as well as researcher mobility enabling sharing of research capacity and expertise. It should be noted that in order to support mobility several policies should be taken into account such as calm down visa limitations. In addition, the promotion of centres of excellence in key technologies, international science and technology (S&T) networks and "clusters" of knowledge-based industries would be of great importance since it enables networking of research institutes, universities and knowledge-based businesses facilitating the connection between basic research results with innovation.

Furthermore, both governments and private enterprises should invest in developing new or up-grading and strengthening existing information and communication technology infrastructures and networks. These systems should be properly designed to support S&T cooperation in target areas and promote greater sharing of S&T information, training and research programs, and research facilities. At the same time, training and education to facilitate broader use of ICT should be taken into account.

In addition, increased attention should be paid in emergent HRST. Creative and talented young people should be encouraged to take up careers in science and technology. Seminars and training programs should be designed and funded promoting science and technology. Global competition for talents can also be organized in order to attract young people.

Last but not least are the support efforts to increase the public awareness of S&T activities. Since there is strong diffidence regarding the impact of technology on humans' life, the management of ethical issues seems to be the only way to calm down fears and win public support for science and technology.

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