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Dynamic Optimisation and Scenario Analysis of the Romanian Public Pension System*

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Abstract

The literature on the sustainability of publicly financed pension systems predominantly focuses on long-term demographic and fiscal projections, while considerably less attention is devoted to the explicit identification of optimal policy solutions that jointly minimise economic and social costs. This paper addresses this gap by embedding pension policy decision making in a dynamic optimisation framework based on the Bellman equation, enabling the identification of economically and socially optimal policy paths. The study examines whether the long-term sustainability of the Romanian public pension system can be enhanced through optimally timed policy interventions while limiting economic and social burdens. The proposed model integrates demographic dynamics, labour market behaviour, and fiscal constraints within a unified analytical framework. It optimises seven key decision variables, including the retirement age of women and men, the social security contribution rate, the early retirement rate, the proportion of active pensioners, and the employment rate. Scenario simulations for the period 2024-2036 demonstrate that maintaining the current retirement age cannot be achieved optimally through contribution-rate adjustments alone. The results emphasise the crucial role of extending pensioners' labour-market participation, which substantially reduces fiscal pressure and enhances long-term system sustainability. The methodology is adaptable to other national pension systems and supports integrated pension-policy design.

Keywords: *public pension systems, dynamic scenario analysis, optimisation, Romania, pension system policies*

JEL classification: *C53, H55, H62, I38*

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1. Introduction

The sustainability of pension systems is a multidimensional challenge (Balteș et al., 2018; Litterman & Sharpe, 2014), and this complexity makes short-term thinking and decision making inadequate (Bărbulescu, 2013). A multisectoral approach is required to achieve sustainability (Simonovits, 2003), which may also help improve the social distrust associated with public pension systems in Central and Eastern Europe (Chłoń-Domińczak, 2018). Consequently, forecasting tools and dynamic models are necessary to understand the system's dynamics and to simulate the long-term impact of decisions, thereby providing a rational basis for debate on pension reform (Disney, 2001) and reducing the pressure of changing demographic structures on public finances (Fougère & Mérette, 1999; Meier & Werding, 2010).

Literature on the sustainability of public pension systems predominantly relies on long-term demographic and fiscal projections and their expected consequences, while devoting considerably less attention to analyses that explicitly identify optimal policy solutions capable of simultaneously minimising economic and social costs. As a result, and as argued by Kahneman et al. (2021), decision making in noisy and uncertain environments often fails to minimise the costs of decisions. This study seeks to address this research gap by explicitly focusing on the optimisation of pension policy decision-making processes. The central research question is whether the long-term sustainability of the Romanian public pension system can be improved through optimally timed and jointly coordinated policy interventions, given a specific pension policy priority decision, while minimising economic and social adjustment costs. The aim is to identify decision alternatives that effectively support cost-efficient and socially acceptable policy choices. Accordingly, the aim of this paper is to develop and apply a Bellman-equation-based dynamic optimisation model that integrates social, economic, and legal constraints within a unified analytical framework. By jointly optimising seven key decision variables, namely the statutory retirement ages of women and men, the social security contribution rate, the national average gross wage, the early retirement rate, the proportion of active pensioners, and the employment rate, the model determines adjustment paths that are optimal from both economic and social perspectives. Scenario simulations for the period 2024-2036 aim to evaluate alternative policy strategies and to identify combinations of instruments that mitigate fiscal pressure and contribute to the long-term sustainability of the pension system. Although the empirical application focuses on Romania, the proposed methodology and optimisation framework are adaptable to pension systems in other countries, particularly in regions facing similar demographic and economic challenges. The implementation is carried out in the MATLAB programming environment.

From a system dynamics perspective, the analysis of the pension system is divided into three levels. Level 1 involves the statistical analysis of each parameter separately using relevant statistical indicators. Level 2 constructs a dynamic model to examine how the pension system changes when multiple parameters are varied simultaneously. This level determines the optimal functioning of the system based on a priority order formulated by decision makers. The paper focuses on this level by setting up scenarios for decision makers, studying the interactions among the parameters that form the system, and incorporating a penalty function and dynamic modelling to achieve an optimal outcome. These scenarios provide possible outcomes for decisions, model and predict the impact of different factors, and assist decision makers in selecting the best policy direction to ensure the sustainability of the pension system and the well-being of pensioners. Level 3 transforms the dynamic system into an adaptive system to identify its internal equilibrium, representing a further development of the current research.

This paper develops a dynamic model of the pension system based on the Bellman equation (Hillier & Lieberman, 2021), an approach that has not yet been encountered in the existing literature. The complexity of pension systems necessitates a shift from simpler static models to dynamic modelling, which not only considers the effect of changing a single parameter on the system's equilibrium, but also captures the interdependent shifts of parameters and the optimal timing for corresponding decisions to reach the optimal state of the objective function. The dynamic programming model facilitates the implementation of a country's pension model, with changes being easily integrated due to the model's adaptive nature.

Studies on the sustainability of the Romanian pension system have examined three major demographic challenges: population decline, population ageing (including declining birth rates), and migration trends expected to persist over the next three decades (Stancu et al., 2019). The pension system can be understood as a mapping of the demographic age structure (Koettl et al., 2014). Although Romania currently has a younger population than most European countries, creating a potential for a dynamic labour market (Stancu et al., 2019), fostering economic growth is not being exploited effectively. Over the next 50 years, however, Romania is projected to become one of the oldest populations in Europe, with severe social and economic impacts (Dobre et al., 2012). For instance, while the dependency ratio was 0.85 pensioners per worker in 2010, it is expected to rise to 1.5 pensioners per worker by 2060 (Dobre et al., 2012), indicating that population ageing negatively affects multiple dimensions of social and economic life (Eleftherios et al., 2019).

The Ministry of Finance has estimated that the pension system's budget deficit could reach 87.9 billion lei by 2050 (Stancu et al., 2019), requiring state-budget transfers that would have lasting impacts on the financing of future investments. Projections suggest that even an increase in the employment rate alone will not resolve the sustainability issue in the long run (Pânzaru, 2015). Although reducing migration is often proposed as a solution to the labour market imbalance, its impact on ensuring the sustainability of the pension system remains hypothetical (Pânzaru, 2015).

Regular projections of future pension liabilities are currently based on reasonable assumptions about macroeconomic and demographic trends, which can be used to simulate the contribution rates required to achieve the most favourable financial outcomes (Disney, 2001). The eighth edition of the European Commission's *The Ageing Report*, published in 2024, provides long-term projections of the budgetary impact of population ageing in Romania for the period 2022–2070 (European Commission, 2024).

The study tests the following hypotheses:

> H1: *In the Romanian public pension system in force in 2024, preserving the current retirement age as a primary policy objective cannot be achieved optimally solely through adjustments to the social security contribution rate.*
>
> H2: *The activation of the retired population in the Romanian labour market is a key determinant in attaining optimal outcomes under the analysed policy scenarios.*
>
> H3: *The magnitude of the real pension system deficit in the Romanian public pension system in 2024 can be reduced through appropriate policy interventions compared with the no-intervention baseline, as indicated by the optimal policy scenarios.*

The paper begins with a review of the relevant literature, outlining the theoretical background of Bellman's dynamic programming, followed by a detailed methodological section and the presentation of optimal scenarios. After that, the results are discussed, and the paper concludes with a summary and suggestions for future research.

2. Literature review

According to UN projections, the proportion of the world's population aged 60 and over, which was 8% in 1950 and 11% in 2009, is expected to reach 22% by 2050 (United Nations, 2010). Hyndman et al. (2021) attribute this trend to three primary factors: advancements in healthcare systems that have significantly increased life expectancy, the ageing of the baby-boomer generation born in the mid-20th century, and a marked decline in birth rates over the past three decades (Fehr et al., 2008).

2.1. Demographic trends and economic challenges in public pension systems

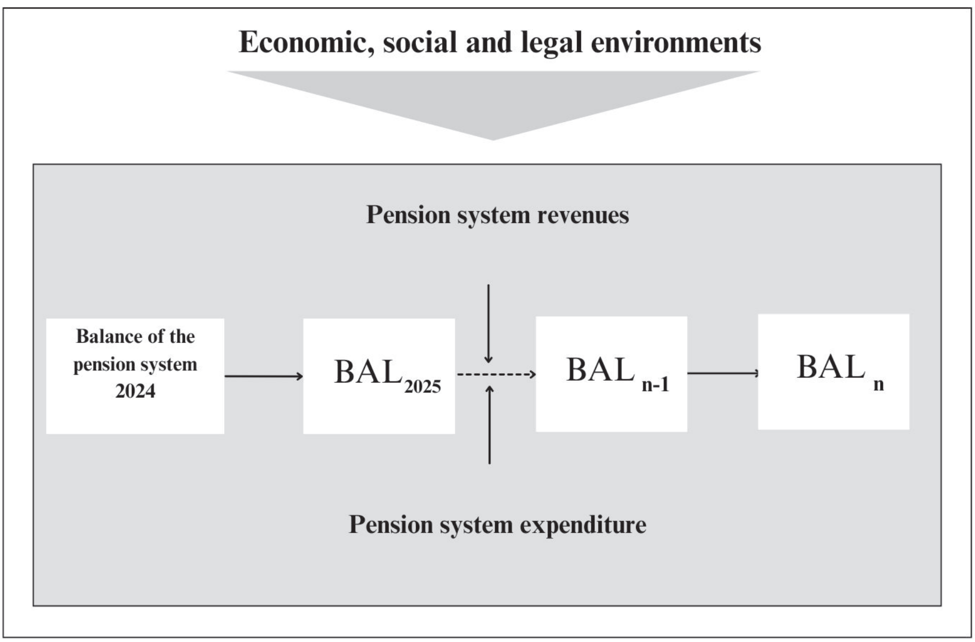
Hyndman et al. (2021) employ a stochastic population-projection method to analyse Australia's pension system. Their study is based on interrelated functional data models of mortality, fertility, and net migration, which together forecast the future structure of the population. This approach combines the functional demographic models of Hyndman and Ullah (2007) with the general stochastic population-projection framework of Hyndman et al. (2013) and utilises the age-structure projections from Hyndman and Booth (2008). Population ageing is quantified using the old-age dependency ratio. Similarly, Bazzana (2020) examines the effect of altering the retirement age on the sustainability of PAYG pension systems and the evolution of public debt. This economic perspective builds on the findings by Galasso (2008) and Godínez-Olivares et al. (2016), who show that increasing the retirement age can reduce pension system deficits, although Magnani (2011) and Miyazaki (2014) argue that this measure alone does not provide a long-term solution. Boado-Penas et al. (2020) find that linking the retirement age to life expectancy in the decision-making process, which is an approach adopted by many countries, can be effective, albeit as a parametric reform that must be combined with other measures to fully address the issue.

Bazzana (2020) concludes that extending the retirement age, and thus the working age, decreases the proportion of retirees, reduces pension expenditures, and lowers both the system deficit and the debt stock. This policy increases the number of active workers, yielding positive effects on overall output and tax revenue, though it may also create social tensions. Comparable outcomes are observed when the government opts to reduce pension contributions (Bazzana, 2020), a proposal also discussed by Boado-Penas et al. (2020). However, such an approach could lead to serious social challenges by impoverishing the elderly and widening the economic gap between active and inactive populations. A third option for deficit reduction could involve higher taxation on labour income (Bazzana, 2020).

The determinants of the pension system can be divided into economic, social, and legal environments, as illustrated in Figure 1. A lack of coherence among these factors leads to sustainability issues (Guardiancich, 2012), as the income, expenditure, and overall balance of the pension system depend on parameters from all three domains. This three-dimensional classification is applied in the simulation model of the Spanish pay-as-you-go (PAYG) pension system developed by Villanueva-García et al. (2025), who project the future evolution of the system up to 2060. A similar analytical framework is employed in the methodological approaches adopted by the OECD (2023) and the European Commission (2024).

In this paper, the social dimension corresponds to the demographic component defined by Villanueva-García et al. (2025). The most important determinants within this component include trends in the number of births and net migration flows, as well as mortality patterns and changes in life expectancy. The economic dimension captures labour market and macroeconomic processes, including employment and unemployment rates, the overall economic environment, productivity developments, and changes in the national average wage level. These factors directly influence the evolution of social security contribution revenues and, consequently, the financial balance of the pension system. The third dimension refers to the institutional and legal framework governing the operation of the pension system. This includes the statutory retirement age, the regulation of pension benefits and contribution rates, and the eligibility conditions for pension entitlements. This dimension plays a crucial role in shaping both the long-term sustainability of the system and the adequacy of pension benefits. The seven decision parameters analysed in this study – the statutory retirement age for women and men, the social security contribution rate, the national average gross wage, the early retirement rate, the proportion of active pensioners, and the employment rate – collectively span these three dimensions. The dimensions are interdependent, as are the seven decision parameters themselves, reflecting the complex and interconnected nature of demographic, economic, and institutional mechanisms within the PAYG pension system. In the context of pension system reforms, it is essential to consider transitional costs at both economic and social welfare levels, in addition to demographic and fiscal constraints, as these costs may be substantial relative to the long-run policy objectives (Heer et al., 2023). This consideration applies across different pension policy goals, and the model presented in this paper explicitly allows for the optimisation of the entire adjustment path rather than focusing solely on the final steady-state outcome.

Figure 1: Diagram of the pension system



Source: Author’s illustration

The basic projection model for the Romanian pension system is based on the World Bank's Pension Reform Options Simulation Toolkit (PROST) (European Commission, 2024). This model primarily assists in designing objective pension policies, although it does not generate optimal scenarios. Input data and forecasts for the model are provided by Eurostat.

2.2. Bellman equation, dynamic programming

In the modelling of issues related to pension systems, dynamic optimisation is a widely used approach. Fehr and Fröhlich (2023) formulate individual decision making within a recursive optimisation framework in a general equilibrium life-cycle model, where households choose among continued labour market participation, standard retirement, and the uptake of disability pensions. The application of the Bellman principle enables the numerical derivation of optimal decision rules under alternative institutional configurations. Their results indicate that increasing the statutory retirement age alone may induce a shift towards disability retirement, highlighting the need for coordinated optimisation of old-age and disability pension schemes.

Research on the optimal timing of statutory retirement age increases in a dynamic framework examines how retirement age reforms can be scheduled in a way that distributes actuarial losses across generations in an equitable manner, while also assessing the role of demographic structure and benefit formulae. Findings indicate that the welfare effects of raising the retirement age depend critically on the adjustment path and that dynamically optimised, gradual reforms are associated with substantially lower transitional costs than one-off, discrete policy interventions (Zhang & Zhu, 2024).

Ji et al. (2022) analyse the long-term operation of pension systems within a stochastic optimisation framework, applying a model that combines multistage stochastic programming with dynamic stochastic control. Their approach explicitly addresses demographic decline and ageing-related financing challenges, while allowing short- and medium-term uncertainties to be incorporated into the optimal management of public pension systems.

Short-term effects of increases in the statutory retirement age may exhibit substantial heterogeneity, which points to the need for a dynamic and intertemporally optimised approach to pension reforms (Nivalainen & Ilmakunnas, 2025).

Godínez-Olivares et al. (2016) develop a dynamic optimisation framework for a sustainable PAYG pension system, in which automatic balancing mechanisms determine the optimal time paths of the contribution rate, statutory retirement age, and pension indexation. Their results indicate that the sustainability of PAYG pension systems can be substantially improved through the jointly and dynamically optimised adjustment of multiple policy parameters, ensuring financial balance under demographic and economic fluctuations with lower volatility and reduced adjustment costs, while requiring minimal discretionary legislative intervention.

The Bellman equation provides the value of a decision problem at a given point in time by equating it to the sum of the immediate decision profit and the value of the subsequent decision problems resulting from that initial decision (Kirk, 1970). Its application originated in engineering control theory and applied mathematics, where research questions are frequently formulated as Multi-Stage Optimisation Problems (MSOPs) (Jones & Peet, 2021; Liu et al., 2019; Zeng & Wang, 2018). Over time, the Bellman equation has become an important tool in economics (Merton, 1973). Typically, the term *Bellman equation* is used to refer to a discrete-time dynamic-programming equation associated with an optimisation problem.

The characteristics of a dynamic programming problem, both in general (based on Hillier & Lieberman, 2021) and in relation to a pension scheme, can be outlined as follows.

Decomposability and interrelated decisions: The problem under consideration can be segmented into distinct sections, each requiring a strategic decision. In the case of a pension system, the state is represented by the pension system balance, which is directly influenced by strategic decisions made on an annual basis. Each year, therefore, constitutes a stage during which policymakers can influence the system's balance through their decisions.

Association of stages with states: Each stage is associated with a state that represents the expected conditions at that point in time. In the context of the pension system, this involves specifying the intervals within which relevant variables may fluctuate during a given year.

State transitions induced by decisions: A decision taken at one stage results in a new state for that stage, from which the next stage commences. In the pension scheme, a strategic decision made in one year alters the system's variables, thereby establishing a new state on which the decisions of the subsequent year are based.

Optimisation across multiple stages: The overall objective is to determine the optimal strategies for the problem by ensuring that the most effective decision is made at each stage. For the pension system, this means that each year must meet the system's target in an optimal manner by appropriately adjusting the parameters. Importantly, the focus is not solely on the final year; rather, the entire process is critical for achieving the desired outcome.

Independence and the Markov property: Decisions made in the current phase are independent from previous decisions; however, the current state contains all the necessary information (i.e., previous decisions and their outcomes) that is essential for determining the optimal subsequent steps. This characteristic, known as the Markov property or the optimality principle, implies that the optimal decision for the pension system in any given year depends solely on the current state.

Backward solution process: The solution process is initiated in a backward manner, beginning with the determination of the optimal strategy for the final stage. For the last *n* years of the process, the decision that optimises the objective function is determined first, followed by the optimal decision for year n–1, and so forth.

Recursive determination of the optimal strategy: Within a recursive framework, the optimal strategy at stage *n* is determined under the assumption that the optimal strategy for stage $n+1$ is already known.

Backward movement through states: Based on the recursive relationship, the solution process moves backwards from state to state, selecting the optimal strategy for each state until the initial state is reached.

3. Methodology and empirical data

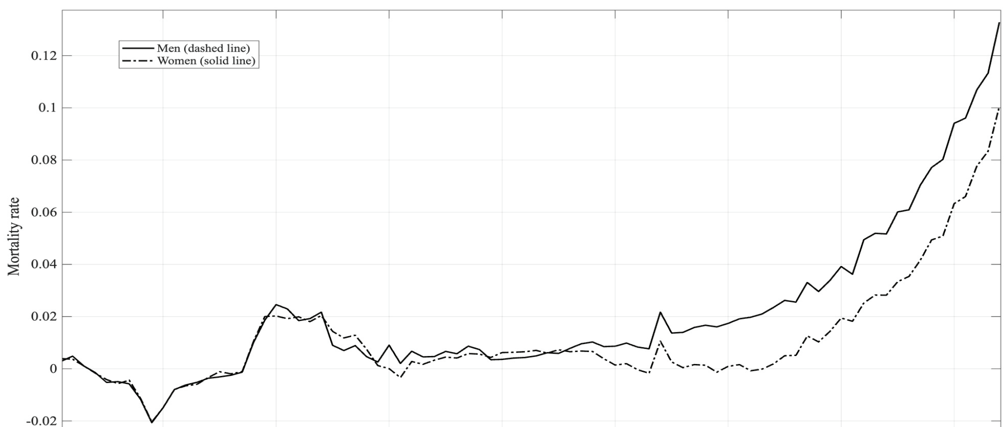
A dynamic pension model was developed to evaluate policy trade-offs and assess long-term fiscal and social sustainability. The model optimally adjusts seven key policy variables on an annual basis: retirement age for women (arw_n), retirement age for men (arm_n), contribution level (T_n), gross national average wage ($\bar{S}_n$), early retirement rate (e_n), the proportion of active pensioners (k_n), and the employment rate (u_n), based on the decision-maker's priorities. Each variable is optimised subject to a set of constraints derived from legislative and economic considerations, while additional parameters are estimated using secondary data from Eurostat and INSSE.

The information technology algorithm required for the implementation was previously presented in an integrated form together with the associated methodological framework (Lőrincz & Makó, 2025). As noted in that study, a subsequent publication was intended to address the application of the model. Accordingly, the present article applies the algorithm explicitly as an optimisation tool and examines its economic applicability through the presentation and interpretation of the scenarios generated during the implementation.

3.1. Population dynamics, empirical data

Population indicators constitute the fundamental input to the model, as they determine the demographic structure essential for pension financing (Simonovits, 2002). For the dynamic model under consideration, it was necessary to estimate the annual population numbers for each age group and sex. To this end, data were obtained from the national statistics office (INSSE) for the period 2010-2023. The change in population by age (transition-loss rate) is illustrated in Figure 2. This information is subsequently employed to project the future evolution of the population, thereby establishing a deterministic model. In the model, the grey-shaded plots represent the transition-loss rates for various age groups (*a*), sexes (*g*, where *w* indicates women and *m* men) and years (*n*) as part of the $MR_{a,n,g}$ distribution. The bold black lines, dashed for men and solid for women, represent the averaged transition-loss values for men ($AMR_{a,n,m}$) and for women ($AMR_{a,n,w}$). The figure shows a local maximum point after the age of 20, reflecting higher migration among individuals in this age group. Thus, the model accounts for migration in addition to mortality in the population projections by treating migration-induced cohort changes as part of an aggregate transition-loss parameter, which captures net population transition loss rather than biological mortality.

Figure 2: Age-specific population transition-loss rates by sex



Source: Author's illustration, based on INSSE population data for the period 2010-2023

Population data are organised in two gender-specific age-by-year population matrices. The matrix $Pop_m \in \mathbb{R}^{86\times14}$ represents the male population, while $Pop_w \in \mathbb{R}^{86\times14}$ represents the female population. In both matrices, rows correspond to single-year age cohorts (from age 0 to 84, with the last row representing the open-ended 85+ age group), and columns correspond to calendar years covering the period 2010–2023.

$$Pop_g = \begin{pmatrix} Pop_{0,2010,g} & \cdots & Pop_{0,2023,g} \\ \vdots & \ddots & \vdots \\ Pop_{85+,2010,g} & \cdots & Pop_{85+,2023,g} \end{pmatrix} \in R^{86*14}, g \in \{m, w\} \quad (1)$$

The notation $Pop_{a,n,g}$ denotes a scalar element of the corresponding population matrix, representing the number of individuals of age a and gender g in year n.

Based on these cohort-level population values the transition-loss rate $MR_{a,n,g}$, measuring the relative change in cohort size from year n to year $n + 1$ due to mortality and migration effects, is defined for each cohort as follows:

$$MR_{a,n,g} = \frac{(Pop_{a,n,g} - Pop_{a+1,n+1,g})}{Pop_{a,n,g}} \quad (2)$$

For the period 2010-2023, the transition loss rate $MR_{a,n,g}$ is computed and averaged to obtain the average transition-loss rate $AMR_{a,g}$:

$$AMR_{a,g} = \frac{1}{14} \sum_{n=2010}^{2023} MR_{a,n,g} \quad (3)$$

Future population evolution is then forecast as:

$$Pop_{a+1,n+1,g} = Pop_{a,n,g} * (1 - AMR_{a,g}) \quad (4)$$

Within the model, the total population for a given year n is partitioned into three segments: the underage ($YP_{n,g}$), the working-age ($UP_{n,g}$), and the elderly ($OP_{n,g}$). These are defined as follows:

$$Pop_{n,g} = YP_{n,g} + UP_{n,g} + OP_{n,g} \quad (5)$$

$$YP_{n,g} = \sum_{a=0}^{18} Pop_{a,n,g} \quad (6)$$

$$UP_{n,g} = \sum_{a=18}^{ar_n} Pop_{a,n,g} \quad (7)$$

$$OP_{n,g} = \sum_{a=arm_n}^{a\_max_{n,m}} Pop_{a,n,m} + \sum_{a=arw_n}^{a\_max_{n,w}} Pop_{a,n,w} \quad (8)$$

Retirement age constraints are defined as $65 \leq arm_n \leq 70$ for men and $63 \leq arw_n \leq 68$ for women. The max_n is the highest age in year n. These demographic projections are critical for understanding the labour force and pensioner segments, which, in turn, affect the financial dynamics of the pension system.

3.2. Financial balance and pension system mechanics

The model assumes a mandatory PAYG pension system financed primarily through social-security contributions. In cases where contributions do not cover pension expenditures, the deficit is financed from the state budget (Vallasek, 2015). The pension-system balance BAL_n for year n is the difference between its revenues REV_n and expenditures EXP_n:

$$BAL_n = REV_n - EXP_n \tag{9}$$

where revenue (REV_n) is calculated as:

$$REV_n = T_n{*}\bar{S}_n{*}C_n{*}12 \tag{10}$$

In this expression, T_n denotes the contribution rate (with T_1 = 20.25% and a constraint 15% ≤ T_n ≤ 30%), and $\bar{S}_n$ represents the gross national average wage (with $\bar{S}_1$ = 7,567 lei and a constraint 5,000 ≤ $\bar{S}_n$ ≤ 12,000). The number of employed individuals (C_n) is determined by:

$$C_n = LF_n{*}u_n{*}k_n{*}OP_n \tag{11}$$

In this formula, u_n denotes the employment rate (with an initial value of u_1 = 64% and a constraint 60% ≤ u_n ≤ 68%) and k_n the percentage of active pensioners (constraint 0% ≤ k_n ≤ 30%); k_n is calculated on the basis of the optimised parameters determined by the model. $\wp_n$ denotes the size of the working-age population, (in the Romanian case, $\wp_1$ amounts to 8,364,000 individuals). The labour force (LF_n) is then calculated as:

$$LF_n = \wp_n{*}(1 - ds_n{*}er_n) + NM_n \tag{12}$$

In this expression, ds_n is the disability rate based on Eurostat data, er_n represents the early retirement rate (with 0% ≤ er_n ≤ 5%) and NM_n refers to the net working-age migration. Changes in T_n and $\bar{S}_n$ affect the employment rate and net migration via elasticity factors ($eu_{\bar{S}_n}$ the coefficient of elasticity of employment rate with respect to gross wage, euT_n the coefficient of elasticity of the employment rate with respect to the contribution level, $em_{\bar{S}_n}$ coefficient of elasticity of net migration with respect to gross wage, emT_n the coefficient of elasticity of the net migration with respect to the contribution level)

$$\frac{u_n - u_{n-1}}{u_{n-1}} = \left(\frac{\bar{S}_n - \bar{S}_{n-1}}{\bar{S}_{n-1}}{*}eu_{\bar{S}_n} + \frac{T_n - T_{n-1}}{T_{n-1}}{*}eu_{T_n}\right) \tag{13}$$

$$\frac{NM_n - NM_{n-1}}{NM_{n-1}} = \left(\frac{\bar{S}_n - \bar{S}_{n-1}}{\bar{S}_{n-1}} * em_{\bar{S}_n} + \frac{T_n - T_{n-1}}{T_{n-1}} * em_{T_n}\right) \tag{14}$$

Expenditures (EXP_n) are computed based on the number of pensioners (P_n) and the national average pension ($\overline{PP}_n$) and old-age retirement rate (rr_n):

$$EXP_n = P_n * \overline{PP}_n * 12 \tag{15}$$

where the number of pensioners (P_n) is calculated as the number of elderly individuals (OP_n) multiplied by the proportion of the population eligible for pension benefits (rr_n):

$$P_n = OP_n * rr_n \tag{16}$$

Pension adjustments reflect the legal provisions established by Law 263/2010. Until 2030, pension increases account for both inflation and a diminishing proportion of real wage growth, with a transition to inflation-only adjustments thereafter. This mechanism aims to protect the beneficiaries of the system from impoverishment caused by the erosion of purchasing power due to inflation (Simonovits, 2016).

The Romanian Pension Law 360/2023, in force since 1 January 2024 (Romanian Parliament, 2023), defines annual pension indexation as the sum of full inflation compensation and 50% of real wage growth. In practice, however, the application of this rule remains is subject to fiscal and implementation constraints, and the legislation allows for its partial or temporary suspension. Given the current budgetary position of Romanian public finances, as well as the increasingly binding demographic and fiscal challenges affecting the pension system, the indexation mechanism applied in the analysis is restricted, from 2030 onwards, to the preservation of the real value of pensions only. This approach aligns with recent policy practice and enables a conservative and distortion-free assessment of pension system sustainability in an uncertain macroeconomic environment. Furthermore, the analysis explicitly aims to preserve at least the 2024 real-level benchmark across all decision parameters, thereby preventing real deterioration, which is also consistent with the determination of the pension contribution rate.

$$\overline{PP_{n-1}} = \begin{cases} \overline{PP_{n-1}} * \left[i_n + 1\left(\left(\frac{S_n}{S_{n-1}} - 1\right) * r\right)\right], & if \quad n \leq 2030, \\ \overline{PP}_n = \overline{PP}_{n-1} * [i_n + 1], & if \quad n > 2030 \end{cases} \tag{17}$$

$$If\ n \in [2024{,}2030],\ r = 0.3 - \left(0.05 * (n - 2024)\right) \tag{18}$$

3.3. Optimisation framework

The core of the model is an optimisation problem solved using dynamic programming. The algorithm proceeds backward from the final period *n* to period 1, identifying the optimal sequence of decisions for the variables arw_n, arm_n, T_n, $\overline{S}_n$, e_n, k_n and u_n that minimise a weighted penalty function. The penalty function quantifies deviations from the baseline (2024) values of these normalized variables, thereby reflecting the extent to which social welfare and economic sustainability are impaired relative to the 2024 situation. A decision matrix A is defined, where each row represents a year, and the columns contain the decision variables weighted by parameters *W*, *M*, *B*, *C*, *D*, *E*, and *G*. The sum of these weight parameters equals one. The weights parameters in the penalty function model the views of the decision makers. Magnitudes of the weights indicate the order of importance of these decision parameters. The normalization is performed with respect to the 2024 baseline (the first row of the matrix is set to zero):

$$A = \begin{matrix} \\ A_1 \\ \vdots \\ An \end{matrix} \begin{matrix} M & W & B & C & D & E & G \\ \left[\begin{matrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{arm_n - arm_1}{arm_1} & \frac{arw_n - arw_1}{arw_1} & \frac{T_n - T_1}{T_1} & \frac{\overline{S}_n - \overline{S}_1}{\overline{S}_1} & \frac{BAL_n - BAL_1}{BAL_1} & \frac{er_n - er_1}{er_1} & \frac{u_n - u_1}{u_1} \end{matrix} \right] \end{matrix} \quad (19)$$

The welfare (penalty) function for year *n* is defined as:

$$F_n = M\frac{arm_n - arm_1}{arm_1} + W\frac{arw_n - arw_1}{arw_1} + B\frac{T_n - T_1}{T_1} + C\frac{\overline{S}_n - \overline{S}_1}{\overline{S}_1} + D\frac{BAL_n - BAL_1}{BAL_1} + + E\frac{er_n - er_1}{er_1} + G\frac{u_n - u_1}{u_1} \quad (20)$$

The optimal dynamics are obtained by solving the Bellman equation:

$$F_{n-1}^{*}\left(arm_{n-1}^{*}, arw_{n-1}^{*}, T_{n-1}^{*}, \overline{S}_{n-1}^{*}, Pop_{n-1}^{*}, er_{n-1}^{*}, k_{n-1}^{*}, u_{n-1}^{*}\right) = F_n\left(arm_n, arw_n, T_n, \overline{S}_n, Pop_n, er_n, k_n, u_n\right) + F_n^{*}\left(arm_n^{*}, arw_n^{*}, T_n^{*}, \overline{S}_n^{*}, Pop_n^{*}, er_n^{*}, k_n^{*}, u_n^{*}\right) \quad (21)$$

An asterisk is used to mark values that are optimal over the remaining time horizon starting from period *n*. Accordingly, F_n^{*} denotes the lowest attainable value of the penalty function evaluated over all subsequent stages until the terminal period. The framework is subject to an extensive system of constraints, ensuring that the derived policy paths are both feasible and grounded in realistic institutional conditions.

$$\begin{cases} f(1) & 65 \leq arm_n \leq 70 \\ f(2) & 63 \leq arw_n \leq 70 \\ f(3) & 15\% \leq T_n \leq 30\% \\ f(4) & 5{,}000 \leq \overline{S}_n \leq 12{,}000 \\ f(5) & 0 \leq BAL_n \leq 0.5 * BAL_1 \\ f(6) & 0 \leq er_n \leq 3\% \\ f(7) & 60\% \leq u_n \leq 68\% \end{cases} \tag{22}$$

The goal is to solve the following optimisation problem:

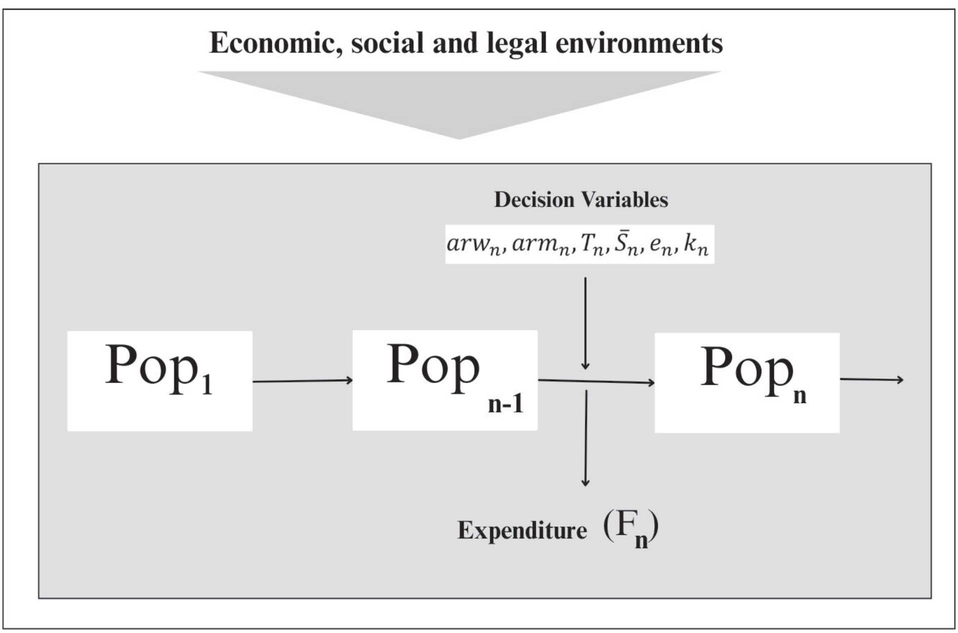
$$\begin{cases} F_1\left(arm_1, arw_{1,} T_{1,} \bar{S}_{1,} Pop_{1,} er_{1,} u_1\right) \rightarrow min \\ BAL_n \leq 0.5 * BAL_1 \end{cases} \tag{23}$$

State transitions are governed by:

$$\begin{cases} F_n = F_n\left(arm_n, arw_n, T_n, \overline{S}_n, Pop_n, er_n, k_n, u_n\right) \\ BAL_n = BAL_n\left(arm_n, arw_n, T_n, \overline{S}_n, Pop_n, er_n, k_n, u_n\right) \end{cases} \tag{24}$$

Figure 3 provides a graphical summary of the model structure.

Figure 3: Dynamic model of the pension system



Source: Author's illustration

The penalty function balances living standards and financial sustainability by penalizing deviations from the 2024 baseline in key areas such as retirement age, contribution levels, wage growth, pension system balance, early retirement rate, and employment rate. The assigned weights reflect the priorities of decision-makers: for instance, ensuring that retirement ages evolve in line with life expectancy trends while avoiding excessive pressure on the active workforce. Similarly, restrictions on wage growth and careful monitoring of pension deficits are essential to maintain fiscal stability.

In analysing the pension-policy options considered in the scenarios, several research questions emerge as central. What are the social and economic costs associated with maintaining the current retirement age? Is this scenario realistically achievable? Is it feasible, within the optimised scenario, to simultaneously maintain both the current retirement age and a stable contribution rate? To what extent can the pension system deficit be reduced if deficit reduction is treated as the primary objective? What optimal scenario is reached when the decision-maker assigns equal importance to all weight parameters? Finally, what interventions are necessary to implement these scenarios?

4. Results and discussion

The MATLAB programming environment was employed to implement the dynamic pension model. Initially, the evolution of the female and male populations was projected based on population data spanning from 2010 to 2023. On an annual basis, the model disaggregates the population into the underage, working age, and elderly segments according to the designated retirement age. The program begins its computation in the final year and proceeds backwards to 2024. During this backward induction, several potential trajectories leading to the 2024 state are determined based on the relations outlined in equation (23), while strictly adhering to the imposed constraints. Subsequently, in accordance with Bellman's equation (referenced as equation 21), the algorithm selects the optimal solution that minimises the penalty function using the currently assigned priority weights. With respect to the system of equations, Equations (1)-(8) constitute the Demographic Module, which provides the demographic forecasting framework of the model. Equations (9)-(18) form the Financial Balance and Pension System Dynamics module, while Equations (19)-(24) define the Optimisation Framework. Importantly, all three modules are jointly required to generate the simulation results: the outputs of the Demographic and Financial modules serve as essential inputs to the Optimisation Framework, and the combined interaction of all three modules underlies the scenario analyses and the resulting figures presented in the subsequent sections. The detailed integration of these modules with the underlying computational and programming framework has been published in an information-technology-focused scientific journal (Lőrincz & Makó, 2025).

Following the determination of the optimal solution, the resulting trajectory is illustrated through nine figures, each illustrating a key variable of the pension system. The x-axis represents calendar years from the baseline year 2024 to 2036, while the y-axis displays the policy-relevant variables central to the functioning of the pension system. The first two figures show the statutory retirement age for men and women, respectively, expressed in years. The third figure presents the social security contribution rate, expressed as a percentage. The fourth figure displays the national average gross wage, expressed in Romanian lei and measured in real terms relative to the 2024 baseline. The fifth figure illustrates population-related indicators, including the number of employed individuals and the number of pensioners. The sixth figure reports the magnitude of the pension system deficit, expressed in real terms relative to the year 2024. The seventh figure displays the early retirement rate, expressed as a percentage. The eighth figure shows the proportion of pensioners who remain active in the labour market, also expressed as a percentage, while the ninth figure presents the employment rate, expressed in percentage terms. In all figures, black dots indicate the range of feasible solutions, whereas solid black circles denote the optimal solutions attained in the corresponding years.

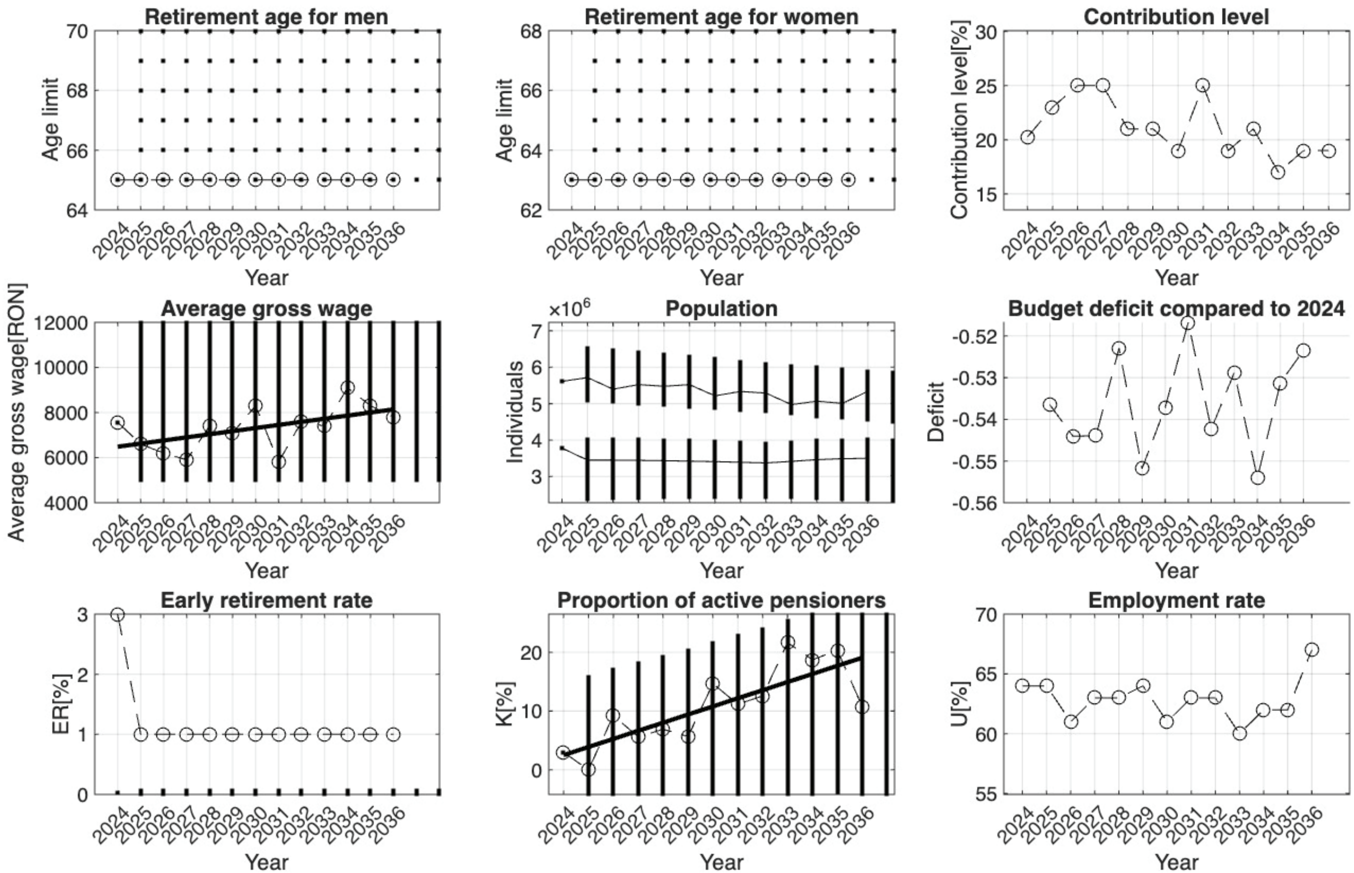
In terms of fiscal implications, public-pension expenditures accounted for 8.5% of GDP in 2022, with projections indicating an increase to 10.4% by 2030, as reported by the European Commission (2024). This significant escalation in costs underscores the urgency of addressing the financial challenges facing the pension system. To mitigate this critical period of fiscal strain, timely policy decisions are essential, and the various scenarios generated by the model offer valuable insights and potential policy responses.

Four distinct scenarios are presented within the study. It is important to emphasise that the values used in the model are expressed in real terms as of 2024. Consequently, in all cases, these values must be adjusted for inflation to ascertain their nominal levels, given that inflation constitutes a major risk factor for pension systems (Søren, 2017). Each scenario presents an optimal solution aimed at addressing the intertwined challenges of economic sustainability, social justice, and demographic shifts. In doing so, the model incorporates an appropriate weighting of the penalty function components while accounting for their interactions.

4.1. Sustaining social welfare regarding retirement age

The results related to the first scenario, which prioritises social welfare to support the most vulnerable segments of society while maintaining the current retirement age, are illustrated in Figure 4. By analysing the figure, it can be observed how the decision maker has to adjust each decision parameter in order to obtain the optimal solution for the strategy they have defined, as conveyed by the priority weights. The priority weights are: W=0.35; M=0.35; B=0.05; C=0.05; D=0.05; E=0.05; and G=0.05.

Figure 4: First scenario: sustaining social welfare regarding retirement age

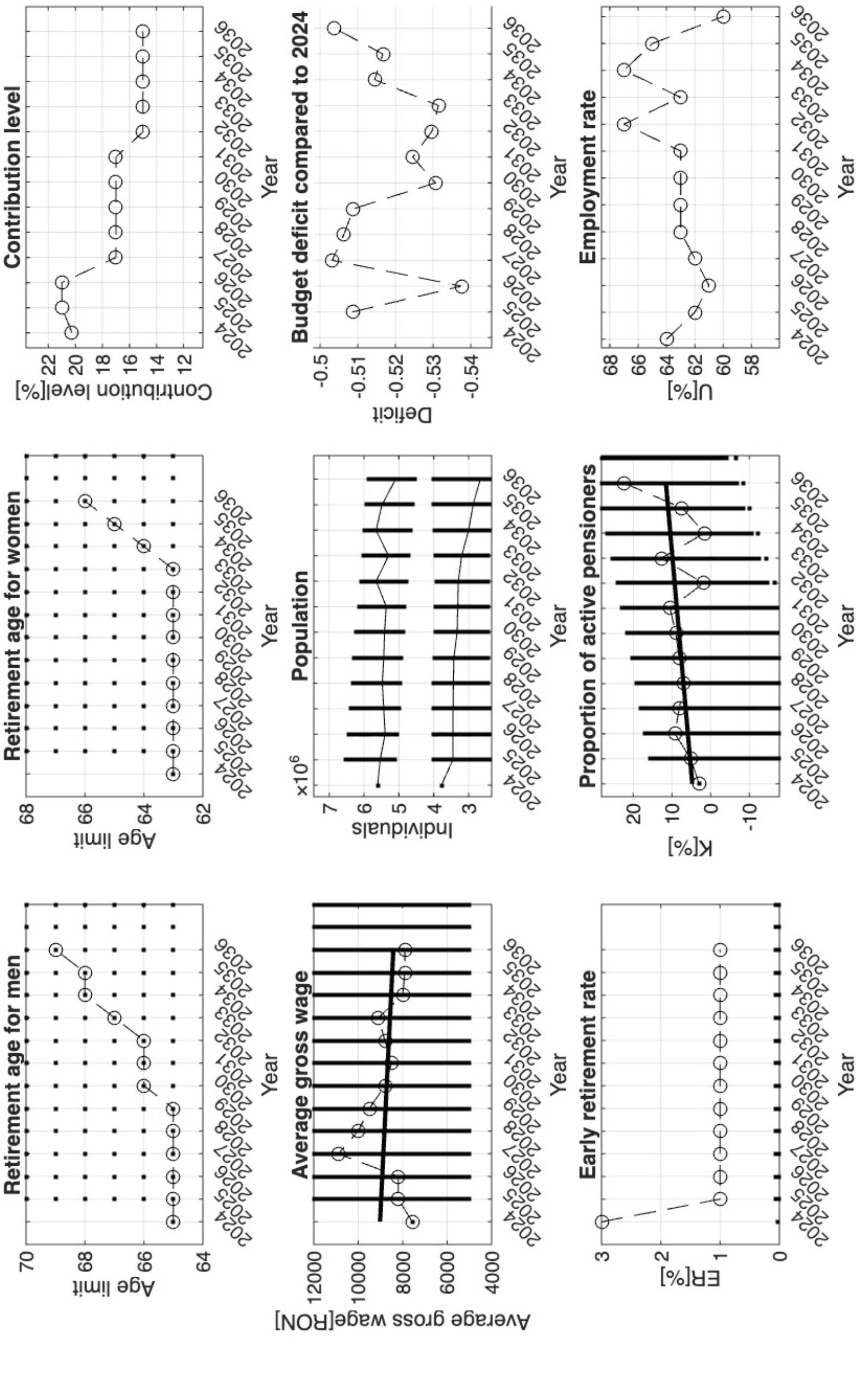


Source: Author’s calculations

Consequently, 70.5% of the weighting parameters focus on achieving the designated objective. With respect to the retirement age, the optimal solution remains at the current levels: 65 years for men and 63 years for women. The optimal trajectory is instead achieved through adjustments in contribution rates, average wages, early retirement rates, active retiree ratios, and employment rates. In 2026-2027 and in 2031, a maximum contribution rate of 25% is required for the first pillar, which then gradually decreases to 19%, falling below the current level. Alternatively, from 2029, policymakers may opt to allocate the 1.25% reduction from the 2024 level to the second pillar. Regarding average wages, a national average of 9,000 lei in 2024 real terms is projected as a local maximum for 2034. Concerning the system's deficit, reductions of at least 52% (in 2031) and up to 55% (in 2033) are achievable compared to the 2024 baseline. The early retirement rate remains constant at 1% throughout the period. The proportion of active retirees is expected to gradually increase, reaching 22% by 2033. For the employment rate, only a 3% improvement from the 2024 level is necessary by 2036. Implementing this scenario requires ensuring dynamic economic growth, stimulating employment, and encouraging the retention and reintegration of the retired population into the labour market.

The first scenario has a negative impact on employees, as higher contribution rates reduce their net wages. To counterbalance these effects, real wage growth must be stimulated through vigorous economic policies aimed at boosting productivity. Furthermore, labour-market wages can be improved by emphasising adult education and retraining programmes, thereby enhancing human capital and mitigating the wage reductions caused by increased contributions. Training the labour force should therefore be a priority policy objective, as investment in human capital can raise wages (Schultz, 1971). Another important step in achieving the optimal scenario is to motivate retirees to remain active in the labour market. According to Article 54 of the Implementation Norms of the Pension Law (Law No. 360/2023), an even more favourable outcome may be achieved if pensioners voluntarily postpone retirement in anticipation of higher future pension benefits. In addition to this, it is important to note that increasing the value of the pension only by inflation and decoupling it from the national average gross wage risks widening a social gap between the active and inactive population and may contribute to the impoverishment of the pensioner age group. This has a coercive effect on pensioners to supplement their pension benefits with wages and not to leave the labour market. In this context, adequate health status and the state's healthcare system become critical considerations for enabling longer labour-market participation.

Figure 5: Second scenario: sustaining broad social welfare



Source: Author's calculations

4.2. Sustaining broad social welfare

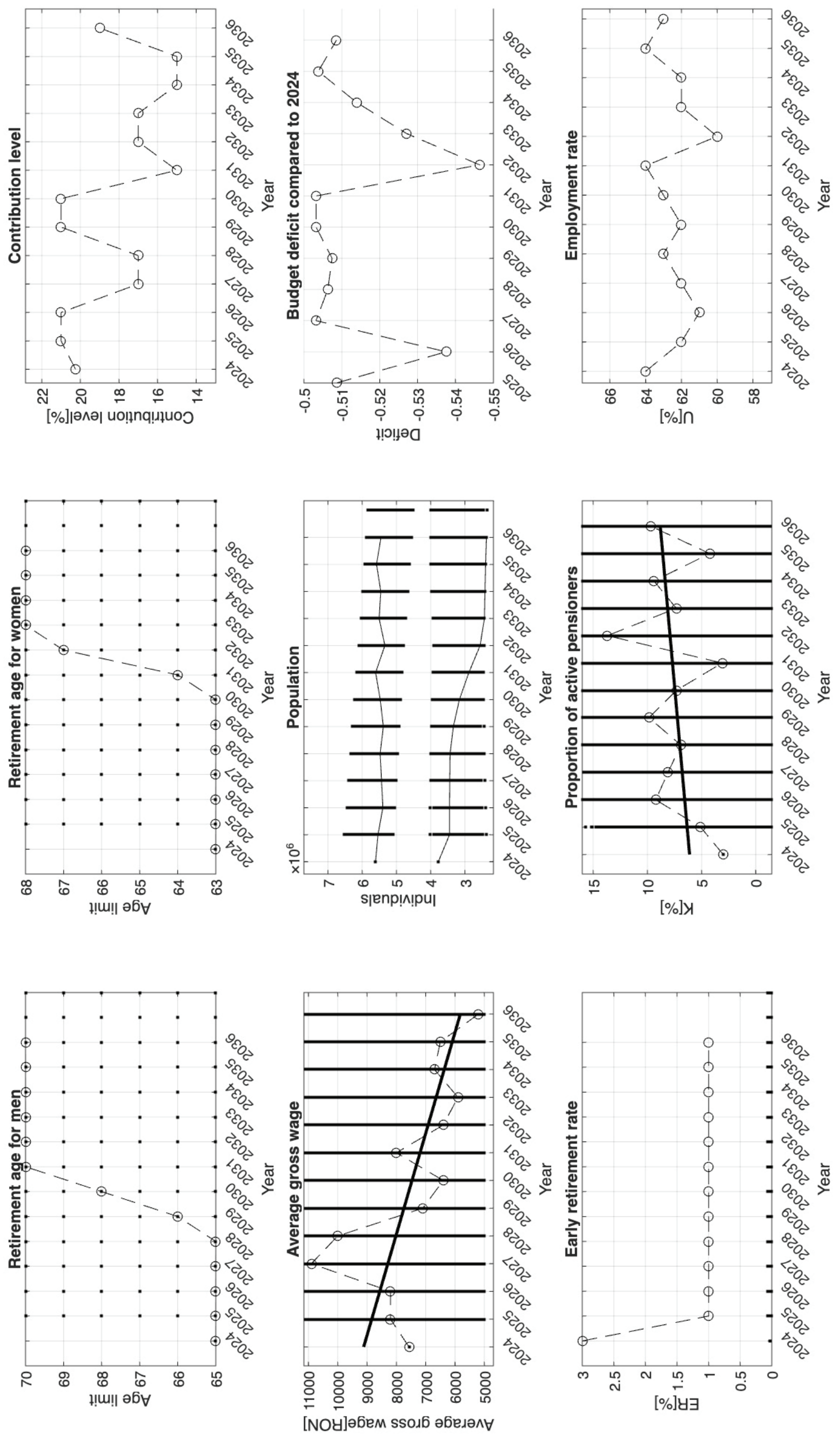
In the second scenario, the objective is to maintain the current level of broad social welfare with minimal reduction, considering both the retirement age and the contribution burden on employees. The results are illustrated in Figure 5. The following priority weights were applied: M=0.25; W=0.205; B=0.125; C=0.07; D=0.085; E=0.15; G=0.07.

This means that 80% of the weighting parameters serve a dual purpose. Regarding the retirement age for males, it is projected to increase to 66 years by 2030, to 67 years by 2033, and to 69 years by 2036. Thus, the increase commences in 2030 – a year deemed demographically critical. As for females, the retirement age must rise by one year annually after 2033, reaching 66 years by 2036. Consequently, a three-year gap emerges between the two statutory retirement ages. The contribution rate attains a local maximum of 21% during 2025-2026, then declines to 17% between 2027 and 2031, and further decreases to 15% in the period 2032-2036. This reduction improves the well-being of the employed, although it simultaneously worsens the situation of retirees. National average wages are expected to increase gradually until 2027, reaching a real-value local maximum of 10,900 lei (in 2024 terms), then falling to 8,500 lei by 2031 and to 7,900 lei by the end of the period under consideration. The deficit can be maintained at a level that is at least 50% lower than the real deficit of 2024, with a local minimum reduction of 54%. The proportion of pensioners receiving age-related reductions remains constant at 1% throughout the period. Meanwhile, the share of active retirees follows a linear upward trend, reaching a maximum of 22% by the end of the period. This parameter is thus considered to be the key factor in the implementation of the scenario. The employment rate must improve by 3% by the end of the period relative to 2024, although it is projected to drop to 63% in the critical year of 2030. In this scenario, the current retirement age is no longer sustainable, and the reduction in the contribution rate can only be achieved at the expense of, and alongside, the activation of the retired population.

4.3. Economic sustainability

As presented in Figure 6, the third scenario examines what happens to the parameters when deficit minimisation is the main pension policy objective, with the following coefficient values: M=0.05; W=0.05; B=0.05; C=0.05; D=0.7; E=0.05; and G=0.05.

Figure 6: Third scenario: economic sustainability



Source: Author's calculations

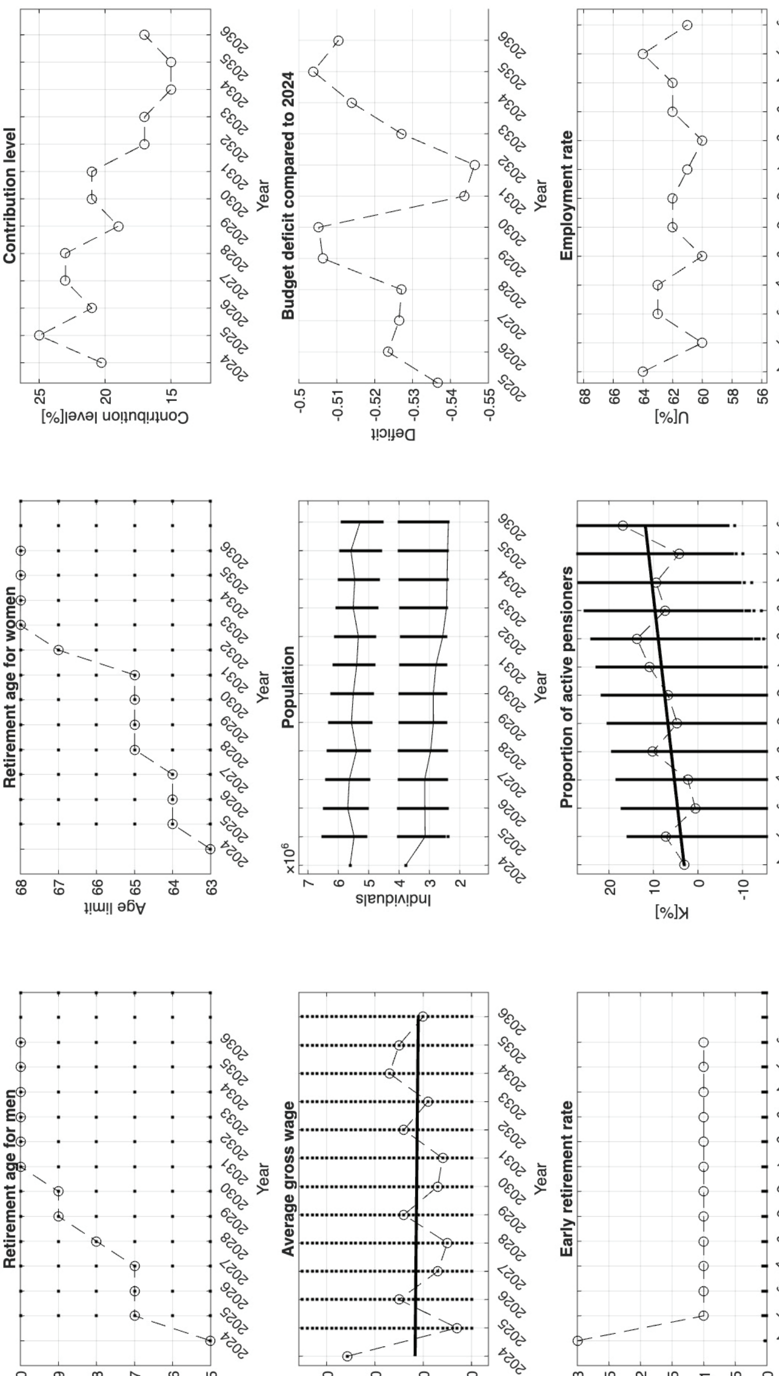
In this scenario, the retirement age remains at the current level until 2028 for men and 2030 for women, after which it increases to 70 years for men in 2031 and to 68 years for women in 2033. The contribution rate reaches a local maximum of 22%, but at its local minimum during the period under review (2034-2035), it drops to 15%. The national average gross wage reaches 10,900 lei in 2027; however, a linear trend with a negative slope can be fitted to the data, indicating a declining wage level in real terms, consistent with a recessionary scenario. The population's labour potential is fully utilised. The deficit is reduced by 50-55% in real terms compared to the deficit in 2024. The share of early retirees remains at 1%. For retirees, an employment rate of 13.7% is needed by 2032 at the local maximum, followed by a maximum of 10% in subsequent years. Regarding the employment rate, a ratio between 60-64% is required, without exceeding the 2024 value.

The third scenario represents a recessionary outlook, characterised by a declining trend in real wages and a falling employment rate. Nonetheless, even in this challenging economic environment, the deficit is successfully reduced – achieving an average reduction level of approximately 50%, similar to the previous scenarios – primarily through measures such as increasing the retirement age and increasing the employment of retirees.

4.4. Equal priority scenario

The optimal solution for equal priority weights is presented in Figure 7. For both sexes, the increase in retirement age is staggered, with the critical year 2030 requiring an age of 69 for men and 65 for women. The male retirement age will reach its upper limit by 2031 and the female by 2033.

Figure 7: Equal priority scenario



Source: Author's calculations

The contribution rate is projected to reach 25% by 2025, after which it gradually declines to 15%, with the possibility of stabilising at 17% in the final years of the period. The difference between the 2024 contribution level and the optimal level may be considered a positive addition when allocated to the second pillar. At the 2024 real level, the gross national average wage is expected to range between 5,300 and 6,700 lei; thus, being lower than the 2024 level, no additional resources need to be allocated to this area under the optimal scenario. During this period, the deficit of the Romanian state pension system is projected to decrease by 50-54% relative to the 2024 deficit, reaching its lowest level by 2032. The proportion of early retirees remains constant at 1% throughout the entire period. Meanwhile, the share of active pensioners gradually increases, reaching its peak of 17% at the end of the period. The employment rate is expected to remain between 60% and 64%, thereby not exceeding its current level. An inverse relationship can be observed between the employment rate and the proportion of active pensioners, as the system compensates for the reduced pool of contributors through the employment of pensioners. This balanced approach reflects the compromises between fiscal sustainability and social justice during a more recessionary period, when real wage growth is not feasible.

The simulation results confirm that policy interventions confined to a single dimension are insufficient to ensure long-term sustainability, as adjustments implemented in one domain inevitably generate spillover effects in the others. The findings align with the existing literature, which emphasises that the impact of demographic processes is substantially mediated by labour market conditions and institutional arrangements (Villanueva-García et al., 2025).

The institutional and legal dimensions also play a pivotal role. The results demonstrate that statutory retirement age regulations, eligibility conditions, and contribution rules fundamentally shape both the sustainability of the pension system and the adequacy of pension benefits. This is in line with findings from dynamic optimisation studies showing that isolated increases in the statutory retirement age may trigger unintended behavioural responses, such as shifts towards disability or early retirement (Fehr & Fröhlich, 2023; Nivalainen & Ilmakunnas, 2025).

From a methodological perspective, the results further contribute to literature on the dynamic optimisation of pension reforms. Studies examining the optimal timing of retirement age increases indicate that gradual, dynamically optimised reform paths are associated with substantially lower welfare losses than one-off, discrete policy interventions (Zhang & Zhu, 2024).

5. Conclusions

The study presents four optimal scenarios based on predefined priority criteria for pension system policies, enabling an examination of the system's dynamics along seven variable parameters: retirement age for women and men, contribution rate, gross national average wage, early retirement rate, proportion of active pensioners, and employment rate. The novelty of the approach lies in its optimisation process; using the Bellman functional within a penalty function integrated into the model, the decision maker can specify the weight parameters associated with each decision variable to formulate additional optimal pension system policies. Thus, the model not only determines the values of its components but also illustrates how these parameters should evolve and when strategic decisions should be made, to minimise the social and economic costs relative to the state of the Romanian public pension system in 2024, based on the established priority factors.

The added value of this study lies in its ability to bridge the gap between descriptive pension system projections and normative policy design. Unlike conventional simulation models that evaluate predefined reform paths, the proposed framework endogenously derives optimal policy trajectories by jointly considering demographic, economic, and institutional interactions within a dynamic optimisation setting. By explicitly accounting for transition costs and intertemporal trade-offs, the model provides decision makers with guidance not only on which policy parameters should be adjusted, but also on the appropriate timing and sequencing of reforms. This approach enhances the analytical relevance of pension system modelling by aligning long-term sustainability objectives with short- and medium-term social and economic constraints, thereby offering a more realistic and policy-relevant basis for pension reform design.

The results of the optimal scenarios indicate that, while maintaining the current retirement age may offer protection to vulnerable elderly groups, such protection is only feasible if it is accompanied by an increase in contribution rates – a measure that could, however, negatively impact the net wages of the employed. To mitigate these adverse effects, it is essential to stimulate real wage growth through robust economic policies aimed at enhancing productivity, complemented by strategic investments in adult education, since investments in human capital increase its value (Schultz, 1971). In the optimal solution, an increasing dynamic in this area is observable, thereby supporting the first hypothesis, which states that maintaining the current retirement age as a primary objective cannot be optimally achieved solely by modifying the social security contribution rate. Moreover, in line with the second hypothesis, all examined scenarios underscore that policy measures designed to promote the extended labour market participation of pensioners must be prioritised, as they are crucial for reducing fiscal pressure and ensuring the overall sustainability of the system. This is particularly important given the anticipated adverse labour market effects associated with the retirement of baby boomers. In the near future, an imperative for decision makers is to adopt flexible employment regulations and introduce tax incentives that could effectively encourage pensioners to remain in or re-enter the labour market. Hungary provides a notable example, having already implemented tax reductions for pensioners. Furthermore, revising Romania's current practice of excluding pensioners employed in the public sector could further motivate them to remain active. The provisions of Article 54 of Law 360/2023, which include the option of voluntarily deferring retirement in exchange for higher future pension benefits, could serve as an effective policy instrument.

It is also important to recognise that adjusting pension benefits solely based on inflation, without linking them to the gross national average wage, may widen the socio-economic gap between the active and inactive segments of the population. Such a gap might compel pensioners to supplement their income through additional employment, raising broader questions regarding the sustainability of social protection systems and the challenges related to elderly health and healthcare provision. Based on the examined scenarios, regarding the economical sustainability of the system, a minimum 50% decrease of the real value of the 2024 deficit could have been achieved each year even in recessionary economic circumstances, confirming the third hypothesis. In this case, the optimal solution is to raise the retirement age. When the same priority weights are assigned to the decision parameters, the gradual increase in the retirement age represents the greatest challenge.

When compared with the findings of other studies, the findings presented in this paper reinforce the view that achieving both the fiscal sustainability and social equity in pension systems requires an integrated, multifaceted policy approach. The model confirms that balancing the objectives of deficit reduction, wage stability, and retirement age adjustments require a carefully calibrated combination of economic and social policy interventions, thereby justifying the use of the optimising models presented in this study.

A limitation of the study is that the simplified model relies on historical data and specific assumptions, which may not fully capture future economic and demographic uncertainties. Future research should aim to incorporate stochastic elements into the model and pursue empirical validations in diverse contexts. Moreover, comparative analyses involving multiple countries or regions could further refine our understanding of the interactions between pension policy and broader socio-economic outcomes.

In summary, the dynamic pension model provides valuable insights into the trade-offs involved in pension system reform. The study lays a solid analytical foundation for designing policy interventions that balance fiscal discipline with social welfare. Moreover, it outlines clear directions for future research to enhance the model's applicability and empirical reliability.

The current model is robust, as it incorporates computed inputs based on projected population trends for the coming years. A future development goal could be to transform the model into a probabilistic framework that incorporates random variables. It would also be advisable to include further forward-looking decision parameters. In addition, the examination of gender differences in retirement age and the modelling of the effects created by eliminating these differences represent further potential research directions. Finally, as mentioned in the introduction of this paper, transforming the dynamic system into an adaptive system to find its internal equilibrium could be another possibility of future model development.

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Dinamička optimizacija i analiza scenarija rumunjskog javnog mirovinskog sustava

Annamária Lőrincz[1]

Sažetak

Literatura o održivosti javno financiranih mirovinskih sustava pretežno je usredotočena na dugoročne demografske i fiskalne projekcije te njihove očekivane posljedice. Znatno se manje pozornosti posvećuje izričitoj identifikaciji optimalnih javnopolitičkih rješenja koja istodobno minimiziraju ekonomske i socijalne troškove. Cilj je ovog rada odgovoriti na nedostatak u istraživanjima integriranjem donošenja odluka o mirovinskoj politici u okvir dinamičke optimizacije temeljen na Bellmanovoj jednadžbi, čime se omogućuje identifikacija ekonomski i društveno optimalnih politika. U radu se ispituje može li se dugoročna održivost rumunjskog javnog mirovinskog sustava poboljšati optimalnim vremenskim usklađivanjem političkih intervencija, uz istodobno ograničavanje ekonomskih i socijalnih opterećenja. Predloženi model integrira demografsku dinamiku, ponašanje na tržištu rada i fiskalna ograničenja u jedinstveni analitički okvir. Optimizira se sedam ključnih varijabli odlučivanja, uključujući dob umirovljenja žena i muškaraca, stopu doprinosa za mirovinsko osiguranje, nacionalnu prosječnu bruto plaću, stopu prijevremenog umirovljenja, udio aktivnih umirovljenika te stopu zaposlenosti. Simulacije scenarija za razdoblje 2024.-2036. pokazuju da se održavanje trenutačne dobi za umirovljenje ne može optimalno postići isključivo prilagodbama stope doprinosa. Rezultati naglašavaju ključnu ulogu produljenog sudjelovanja umirovljenika na tržištu rada, koje znatno smanjuje fiskalni pritisak i doprinosi dugoročnoj održivosti sustava. Prikazana metodologija i analizirani scenariji nisu relevantni samo za Rumunjsku, već se mogu prilagoditi i mirovinskim sustavima drugih zemalja, čime se podupire integrirani i višedimenzionalni pristup oblikovanju mirovinskih politika.

Ključne riječi: *javni mirovinski sustavi, dinamičke scenarijske analize, optimizacija, Rumunjska, politike mirovinskog sustava*

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