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Debt Sustainability in the Context of Population Ageing: A Risk Management Approach

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Abstract: The ageing of the population has negative effects on the gross domestic product (GDP), influencing various economic and social aspects. These effects, in turn, contribute to an increase in the debt-to-GDP ratio, raising concerns about the long-term sustainability of public debt. The objective of our study is to evaluate the possible dynamics of debt sustainability with a certain level of probability. The analysis employs the stochastic modelling of risk factors influencing the debt-to-GDP ratio, particularly emphasising the economic consequences of population ageing. Using advanced risk management techniques, we aim to provide a robust assessment of how future demographic outlooks impact debt sustainability.

Keywords: debt sustainability analysis; population ageing; stochastic optimisation; risk management

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1. Introduction

Population ageing is posing challenging concerns in many European countries, as well as in many advanced economies of the world. Current times are characterised by a low total fertility rate (TFR) in several European countries that is at the origin of a decline of the total population in the euro area in the next 15 years. At the same time, recent increases in life expectancy are driving significant population ageing, resulting in a higher old-age dependency ratio, defined as the number of individuals aged 65 or older relative to the working-age group, typically aged 20 to 64.

The resulting shift in the age structure raises concerns about the sustainability of an ageing, shrinking population, particularly regarding its impact on a country's pension system, productivity, and overall economic health in the long term. Indeed, older people generally work and save less, providing less labour and capital to the economy than younger individuals. They also have higher healthcare needs and may depend heavily on social pensions for their income.

In 2021, following the COVID-19 pandemic, the EU Council approved a document underscoring that: *"[. . .] ageing populations pose a major challenge for the long-term sustainability of public finances, exacerbated by the substantial rise in government debt levels following the COVID-19 pandemic crisis"*. The Council reaffirmed that *"coping with the challenges highlighted by the age-related expenditure projections will require Member States to take further policy actions to resolve specific country issues"* and urged *"Member States to implement the European Semester recommendations related to the sustainability of public finances, including in the context of the Recovery and Resilience Facility."* (Council of the European Union 2021).

When assessing debt sustainability, it is essential to adopt a multifaceted approach that encompasses economic, social, and institutional factors, particularly concerning demographic changes. For instance, Briceño and Perote (2020) highlight that fiscal sustainability in the Eurozone is influenced by various elements, including the effectiveness of government and social policies, which are particularly relevant given the increasing costs associated with demographics.

Additionally, unexpected economic shocks can intensify challenges related to debt sustainability, especially in countries with demographic and fiscal vulnerabilities. Della Posta et al. (2022) illustrate this interaction in the context of Italy, where the policies implemented in response to the pandemic further strained public debt levels.

In practical terms, if the fiscal costs associated with population ageing are not effectively managed, EU countries will experience mounting pressure on their debt-to-GDP ratios due to increasing public expenditures and constrained economic growth potential. In recent years, immigration has become the primary factor counteracting the EU's population decline. Without immigration from non-EU countries, low fertility rates would lead to a natural population decrease, reducing the EU population to approximately 466 million by 2060—a level last seen in the 1980s (Lutz et al. 2019).

While increased migration can help mitigate the effects of population ageing, they are insufficient to reverse the trend fully. Consequently, public sector reforms are crucial to strengthening public finances. This may involve reallocating funds from non-ageing-related areas to those affected by ageing or implementing additional tax measures to meet the requirements of the new EU fiscal framework.

The objective of the research is to evaluate the impact of population ageing on the government accounts of five EU Member States. The sample comprises Finland, France, Germany, Italy, and Spain, chosen for their varying initial debt positions and distinct projected ageing-related fiscal challenges. The analysis period spans from 2023 to 2054, with demographic impacts expected to become more pronounced starting in 2027.

Drawing upon the statistical analyses provided by the Ageing Working Group (AWG) of the European Commission (2023), we present and analyse how different scenarios for total fertility, migrations, and life expectancy could hit the sovereign debt sustainability in the countries investigated.

The harms of population ageing reduce the size of economic growth, while any benefits (such as increased migration) increase growth. However, some effects that are negative for GDP growth have a positive impact on the primary balance, generating a surplus. For example, ageing leads to lower demand for pension services due to the increase in the retirement age, while the beneficial effects of a reduction in ageing due to increased immigration increase expenditure on vocational training and health care.

Our model follows Zenios et al. (2021) to represent stochastic financial, economic, and fiscal variables as a discrete-time and state-space scenario tree. We analyze the evolution of public debt by deriving state-dependent dynamics for both debt stock and flows. Our investigation focuses on optimising the maturity structure of issued debt securities to minimise expected debt financing costs while sticking to sustainability risk criteria (Alberola et al. 2023). Debt remains sustainable when its stock follows a decreasing path over the long term with a high likelihood (Blanchard 2022), and refinancing needs stay within limits that markets can finance. The model balances the trade-off between financing costs and refinancing risk. Issuing debt at the lowest possible maturity reduces financing costs but increases refinancing risk, as large amounts may need to be refinanced simultaneously. On the other hand, extending debt maturity increases financing costs, raising the debt stock. Our optimisation approach identifies efficient debt issuance strategies within sustainability constraints.

We incorporate demographic scenarios into the model by adjusting GDP growth rates and fiscal balances, recognizing that lower growth increases the debt-to-GDP ratio and that fiscal surpluses reduce it. The net effect of the ageing scenarios determines the impact on debt sustainability in probabilistic terms, providing fan charts of each country's evolution of public debt analyzed.

The insights of our study carry important policy considerations. First, demographic changes present significant risks to public debt sustainability, particularly as the ageing population weakens fiscal resources. Second, it highlights the timing and magnitude of these government debt burdens, which are critical for assessing whether public finances are sustainable under the stability and convergence frameworks established by the EU. These insights are crucial for international organisations and entities responsible for managing sovereign debt, guiding policy formulation and risk mitigation strategies in response to demographic challenges.

Our main contribution to the existing literature is introducing demographic scenarios within a stochastic model with correlated economic, financial and fiscal variables, where the debt manager's objective is to minimise the expected value of the tail of the rollover risk distribution.

The structure of the paper is as follows: Section 2 summarises the relevant literature. Section 3 introduces the model framework. In Section 4, we apply the model to the EU countries under study. The results are analyzed in Section 5, and concluding remarks are presented in Section 7.

2. Related Literature

Population ageing has no trivial implications for the fiscal policy of a country and its economic growth, as it tends to lower both labour-force participation and savings rates, which are at the origin of rising government debt burdens. The analysis of such consequences is the focus of an increasing body of literature.

In Aksoy et al. (2019), a Panel VAR model for 21 OECD economies from 1970 to 2014 is used to estimate the long-run impact of the proportion of the population in each age group on growth, savings, investment, hours, interest rates and inflation. Population ageing is expected to slow down the growth rate of income per capita by 0.86 PPS per year during 2011–2030s, with the strongest predicted negative impact in the US at 1.22%.

Similar results are shown in Maestas et al. (2023) for US economic growth. They found that each 10% increase in the fraction of the population aged 60 and older decreased growth in GDP per capita by 5.5%, with a reduction due one-third to slower labour force growth and two-thirds to slower labour productivity growth.

Kotschy and Bloom (2023) analyse how population ageing impacts economic growth across 145 OECD and non-OECD countries from 2020 to 2050. Using an empirical growth model, they find that ageing will generally slow economic growth worldwide. However, this demographic drag can be partly offset by increasing labour supply through enhanced functional capacity among older individuals, allowing them to remain in the workforce longer.

Aiyar et al. (2016) explore the impact of an ageing workforce on European productivity. The authors find that a growing proportion of older workers favour a decline in total factor productivity growth, particularly in countries with a high proportion of workers aged 55 to 64. They argue that policies such as improved healthcare access, increased training opportunities, and investment in research and development are needed to mitigate this negative impact.

In a recent paper, Bodnár and Nerlich (2022) highlight that population ageing in the euro area creates significant economic and fiscal challenges. The shrinking working-age population reduces labour supply and slows productivity. Additionally, the growing preference for safe assets lowers natural interest rates, limiting monetary policy effectiveness. Fiscally, increased spending on pensions and healthcare, combined with a shrinking tax base, undermines long-term sustainability, particularly in high-debt countries, while restricting fiscal options for growth investments.

Our contribution aligns with the framework established by international institutions for country-specific Debt Sustainability Analysis (DSA). We also draw upon the work of various scholars and organisations such as Bouabdallah et al. (2017) for the European Central Bank (ECB), the Debt Sustainability Monitor of the European Commission (2024) and the Staff Guidance Note of the International Monetary Fund (2022).

Within the DSA framework, a key component is Stochastic Debt Sustainability Analysis (SDSA), which expands the evaluation of a sovereign's capacity to manage its debt by integrating the uncertainties related to critical economic variables.

SDSA generally adopts scenario analysis to include uncertainty affecting key economic factors, such as interest rates, output growth, and primary balance. These elements exhibit a degree of interdependence that can be included, considering their empirical correlations.

The stochastic approach to debt sustainability analysis is not entirely new. Early contributions in this field can be traced back to the works of Bohn (1998) and Mendoza and Ostry (2008). More recent literature has expanded on these foundational ideas. For instance, Garcia and Rigobon (2004) approach debt sustainability from a risk management angle.

Adopting a prescriptive approach, Tanner and Samake (2008) expand on prior analyses to investigate fiscal policy alternatives. They employ simulations to determine the primary surplus needed for debt-to-GDP ratio stability based on specific probabilities across various time horizons.

This aligns with recent advancements by Dubbert (2024), who utilises time-varying fiscal reaction functions to enhance the robustness of debt sustainability analysis in unpredictable fiscal environments.

Our analysis further builds on recent approaches like those by Zenios et al. (2021) for the European Stability Mechanism and Alberola et al. (2023) for the Bank for International Settlements.

A distinctive feature of our model is the integration of demographic factors into debt dynamics. Darvas et al. (2024) develop a similar analysis using the European Commission's debt sustainability methodology, linking long-term fiscal pressures to demographic shocks like general ageing costs, fertility rates, life expectancy, immigration, and TFP growth. Unlike Darvas et al. (2024), we provide a fully stochastic model that addresses the DSA from a risk management point of view.

In terms of sustainable debt levels, our work contributes to a rich body of literature (D'Erasmo et al. 2016), particularly by modelling the behaviour of an active fiscal policymaker. Unlike models incorporating endogenous default mechanisms, such as those proposed by Hatchondo et al. (2016) or Arellano and Ramanarayanan (2012), our approach assumes an exogenous primary surplus process.

Our model combines risk management principles with a multiperiod stochastic programming framework to optimise sovereign debt strategies. Building on the well-established concept of balancing risk and expected returns, as seen in regulatory frameworks like Basel III and Solvency II, we extend the work of Missale (1997) and Bolder (2003), who explored these dynamics in sovereign debt management. Drawing on Markowitz (1952)'s efficient frontier approach, we introduce a prescriptive model that embeds sustainability conditions to enhance debt management.

The methodology draws from the stochastic programming techniques developed by Dantzig (1963) and refined by Birge and Louveaux (2011). Previous applications in sovereign debt management are those for Turkey (Balibek and Köksalan 2010) and Italy (Consiglio and Staino 2012).

Our integrated approach not only fills a gap in the literature but also provides a pragmatic framework for understanding the complex interplay between demographic factors, fiscal policy, and debt management.

3. The DSA Model

In this section, we introduce the notation and the principal equations describing the Zenios et al. (2021) DSA model (ZeCoESM). We highlight two main features that characterise the ZeCoESM model: (i) an endogenous optimal choice of the debt financing strategy combined with (ii) a risk management approach by incorporating conditional value-at-risk (CVaR) as a risk measure.

3.1. Notation

A discrete multi-period scenario tree is used to represent and address uncertainty (see Figure 1 for a pictorial representation). Time steps are denoted by $t = 0, 1, 2, \ldots T$, where 0 is the present moment and T is the endpoint of the risk assessment horizon. The data are organised into a collection of "states" denoted as $\mathcal{N}_t$, each element $n \in \mathcal{N}_t$ being a possible economic state at time t. The number of states at time t is N_t, and the total number of states in the framework is N. Not every state at time t can be reached from any state at time $t-1$. The set of states along the unique "path" from the initial "root state" 0 to a state n is $\mathcal{P}(n)$. These paths leading to terminal states denoted as $n \in \mathcal{N}_T$ are called "scenarios".

Each state n has a unique ancestor, denoted as $a(n)$, with $a(0) = 0$ for the root state. A function $\tau(n)$ is used to identify the time period of states along a path, such that $\tau(n) = t$ for state n at time t, and $\tau(a(n)) = t-1$ for its ancestor. This temporal assignment ensures that all states m along the path $\mathcal{P}(n)$ are known for a state n at time t, since $\tau(m) < t$.

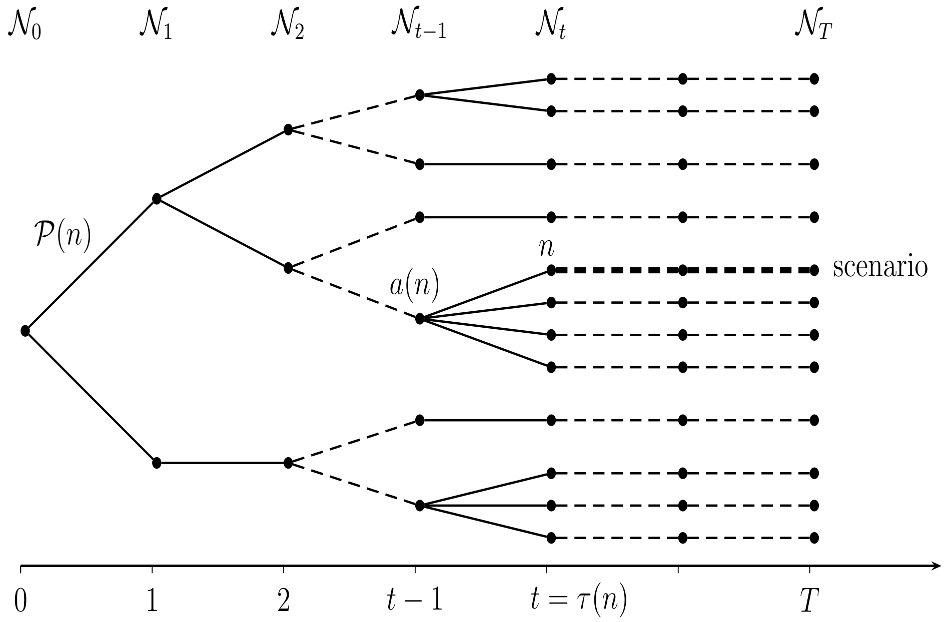


Figure 1. A scenario tree.

We represent with ξ a collection of discrete stochastic processes, each characterised by a tree structure as illustrated in Figure 1. At every node n, a specific realisation of the stochastic process ξ is represented by the vector ξ_n, denoting the value of the process at that particular point in the tree.

3.2. Model Equations

For clarity and ease of understanding, we initially formulated the core equations of the ZeCoESM model as deterministic functions of time. Later, we simplify the notation by omitting explicit time references and transform these deterministic processes into stochastic ones using tree-based modelling. This approach shifts the model's equations from yielding a single, predictable outcome to branching into multiple likely states, each with a certain probability.

Let Y_t, D_{t-1}, and PB_t represent the nominal output, the debt stock, and the primary balance of a sovereign country at time period t, respectively.

The nominal output Y_t is defined using its nominal growth rate g_t as follows:

$$Y_t = Y_{t-1}\,(1 + g_t), \tag{1}$$

where Y_{t-1} is the nominal output in the previous period.

The primary balance is formulated as a fraction of the GDP, denoted by $pb_t \cdot Y_t$. Here, pb_t is a quantity that may take positive or negative values, indicating surpluses or deficits in the primary balance, respectively.

The initial debt condition is D_0 and the *flow* variable GFN_t accounts for the *gross financing need* of the sovereign country, which is defined as:

$$GFN_t = i_{t-1}D_{t-1} + A_t - \underbrace{pb_t Y_t}_{PB_t}, \tag{2}$$

where i_{t-1} is the average nominal interest rate charged on government debt, and A_t is the part of the debt stock D_{t-1} that matures. The *debt stock* evolves according to:

$$D_t = (1 + i_{t-1})D_{t-1} - pb_t Y_t. \tag{3}$$

The sovereign country issues debt instruments of different maturities, denoted by $j = 1, 2, \ldots, J$, with $X_t(j)$ being the nominal amount of debt issued at t for maturity j. The *debt financing equation* is:

$$\sum_{j=1}^{J} X_t(j) = GFN_t. \tag{4}$$

The nominal interest rate of debt instrument j, issued at time t, is determined by adding specific premia to the risk-free rate (i_{ft}). Following the prevailing literature, these premia vary with their debt level; in particular, they are expressed as functions of the debt-to-GDP ratio, $d_t = \frac{D_t}{Y_t}$, and the maturity of the debt instrument. Consequently, the coupon rate for instrument j at time t is defined as:

$$r_t(j) = i_{ft} + \rho(d_t, j), \tag{5}$$

where $\rho(d, j)$ includes the *risk premium* and the *term premium* related to the maturity of the jth instrument (see Zenios et al. (2021) for details).

In the ZeCoESM model, the risk-free rate i_{ft}, the primary balance as a share of GDP pb_t, and the output growth rate g_t are considered exogenous factors. We model them as correlated stochastic processes, with their discrete versions depicted by a stochastic tree as illustrated in Figure 1. A realisation of these stochastic processes is represented by the vector $\xi_n = \left\{ i_{fn}, pb_n, g_n \right\}$, which indicates the risk-free rate, the primary balance to GDP ratio, and the output growth rate at a specific node $n \in \mathcal{N}$.

Given the stochastic process ξ and its tree representation, the Equations (1)–(5) transform into random processes that evolve along the scenario paths $\mathcal{P}(n)$. In this context, for any $n \in \mathcal{N}$, the stochastic variation is computed relative to its ancestor node $a(n)$. For example, Equation (3) for debt dynamics becomes:

$$D_n = \left(1 + i_{a(n)}\right) D_{a(n)} - pb_n Y_n, \tag{6}$$

where D_n is the debt at node n, $i_{a(n)}$ and $D_{a(n)}$ are, respectively, the servicing interest rate and debt at the ancestor node; pb_n and Y_n are, respectively, are the primary balance and the output at node n.

Central to the ZeCoESM model is the concept of *endogenous debt*. In an expanded version of Equation (2), A_t is the combination of exogenous and endogenous elements. The exogenous part pertains to debt issued before the onset of our planning horizon. At the same time, the endogenous portion is determined by the optimal issuance decisions at each node m along the path $\mathcal{P}(n)$ leading to n. Similarly, interest payments on existing debt are dual-natured: partially exogenous, relating to coupon payments of bonds issued before $t = 0$, and partially endogenous, stemming from issuance choices in each state of the economy $m \in \mathcal{P}(n)$. Significantly, as detailed in Equation (5), the coupon rate is endogenously affected by the accumulated debt levels along the path $\mathcal{P}(n)$, thereby highlighting the effect of rising debt levels on credit spread.

Formally, Equation (2) is rewritten as:

$$GFN_n = A_n + I_n + EndA_n + EndI_n - pb_n Y_n, \tag{7}$$

where A and I describe the exogenous (legacy) expiring debt and interest payments; similarly, $EndA$ and $EndI$ refer to the endogenous expiring debt and interest payments.

The mathematical expression for these endogenous elements is detailed as follows:

$$EndA_n = \sum_{m \in \mathcal{P}(n)} \sum_{j \in \mathcal{J}} X_m(j)\, \mathbb{1}^A_{m,n}(j) \tag{8}$$

$$EndI_n = \sum_{m \in \mathcal{P}(n)} \sum_{j \in \mathcal{J}} X_m(j) r_m(j)\, \mathbb{1}^I_{m,n}(j), \tag{9}$$

where $\mathbb{1}^A_{m,n}(j)$ is an indicator function that takes a value of one if the j-th bond, issued at node m, expires at or before node n. Likewise, $\mathbb{1}^I_{m,n}(j)$ is an indicator function that takes a value of one if the j-th bond, issued at node m, pays a coupon at node n.

Risk Measure Definition

Gross financing need (GFN) is a critical indicator of debt sustainability as it signals a government's short-term liquidity requirements and refinancing risks. High volatility in GFN can indicate unstable fiscal policies and potential challenges in meeting debt obligations, especially under adverse market conditions. In this regard, if we consider GFN as a random variable, bounding GFN events occurring in the tail of its probability distribution is a rational objective for the debt manager officer (DMO) to trade off with the expected cost of a financing strategy.

We denote by $gfn_n = GFN_n / Y_n$ the sovereign country borrowing needs, re-scaled by the corresponding output Y_n, for any $n \in \mathcal{N}$. In Figure 2, we show a possible unconditional probability distribution of the random variable gfn.

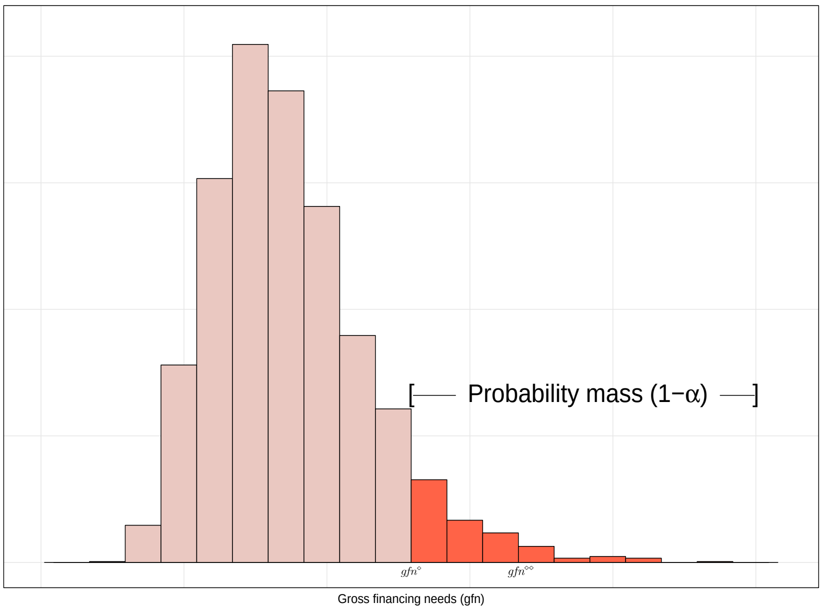


Figure 2. Probability Distribution of gfn. The dark orange region represents the $(1-\alpha)\%$ probability mass of the gfn distribution. Flow-at-risk (FaR) and conditional flow-at-risk (CFaR), at the $\alpha\%$ confidence level, marked as $gfn^{\diamond}$ and $gfn^{\diamond\diamond}$, respectively.

The quantile at the α percentile in Figure 2, $gfn^{\diamond}$, can be effectively linked to the concept of value-at-risk (VaR) in financial risk management. Given the character of flow measure of gfn, we term $gfn^{\diamond}$ as flow-at-risk (FaR). FaR represents the level of a borrowing need such that there is a $(1-\alpha)\%$ probability that the actual borrowing need will exceed this threshold.

Quantiles, by their nature, are non-linear and non-differentiable, which poses substantial difficulties in incorporating them into optimisation models that typically rely on linear or smooth non-linear functions. In contrast, the expected value of the tail of the probability distribution, also known as conditional value-at-risk, can be approximated by a linear function, making it more tractable for standard optimisation techniques.

Following Rockafellar and Uryasev (2000), we compute aggregate conditional flow-at-risk (CFaR) on the tree, denoted by $gfn^{\diamond\diamond}$, using the following linear system

$$gfn^{\diamond\diamond} = gfn^{\diamond} + \frac{1}{1-\alpha}\sum_{n\in\mathcal{N}} \pi_n z_n \tag{10}$$

$$z_n \geq gfn_n - gfn^{\diamond},\ n \in \mathcal{N} \tag{11}$$

$$z_n \geq 0,\ n \in \mathcal{N}, \tag{12}$$

3.3. The Optimisation Model

The DMO aims to minimise expected interest payments on its debt, subject to constraints on refinancing risk and debt stock dynamics. The expected cost is computed by tracking the *net interest payments* across the planning horizon. Denoting π^n as the probability of being in node n, and $\sum_{n\in\mathcal{N}} \pi_n = 1$, the expected cost of debt servicing is expressed as:

$$\sum_{n\in\mathcal{N}} \pi_n \left(\sum_{m\in\mathcal{P}(n)} \sum_{j\in\mathcal{J}} X_m(j) r_m(j)\, \mathbb{1}^B_{m,n}(j) \right) \tag{13}$$

Given the financing decisions on the tree, $X_n(j)$, the debt financing equation becomes

$$\sum_{j=1}^{J} X_n(j) = GFN_n, \quad \text{for } n \in \mathcal{N}_t, \text{ and } t = 0,1,2,\ldots,T. \tag{14}$$

We accommodate treasury policy constraints by implementing three financing strategies. The first, a *fixed-mix* strategy, uses constant weights $w(j)$ for a uniform financing approach across all periods. The second, an *adaptive fixed-mix* strategy, employs time-varying but state-invariant weights $w_t(j)$, allowing the strategy to evolve over time yet remain constant across all states in each period. The third, a *dynamic* strategy, involves both time- and state-dependent weights $w_n(j)$. In this approach, the issuer decides, observes the next period's state, and then optimally adjusts the strategy for that state, repeating this process.

With non-negative proportional weights $w_n(j)$, we have that:

$$w_n(j) = \frac{X_n(j)}{GFN_n}, \tag{15}$$

$$\sum_{j=1}^{J} w_n(j) = 1. \tag{16}$$

We determine the optimal financing strategy by parametrically solving Problem 1, where we constrain the CFaR by employing a range of specific values for ω.

Problem 1. *Minimisation of the expected net interest payments*

$$\underset{X_n(j),\, n\in\mathcal{N},\, j\in\mathcal{J}}{Minimise} \quad \mathbb{E}[C] = \sum_{n\in\mathcal{N}} \pi_n \left(\sum_{m\in\mathcal{P}(n)} \sum_{j\in\mathcal{J}} X_m(j) r_m(j)\, \mathbb{1}^B_{m,n}(j) \right)$$

s.t.

$$GFN_n = A_n + I_n + EndA_n + EndI_n - pb_n Y_n \tag{17}$$

$$GFN_n = \sum_{j\in\mathcal{J}} X_n(j) \tag{18}$$

$$gfn_n = GFN_n / Y_n \tag{19}$$

$$gfn^{\diamond} + \frac{1}{1-\alpha} \sum_{n\in\mathcal{N}} \pi_n z_n \leq \omega \tag{20}$$

$$z_n \geq gfn_n - gfn^{\diamond},\ \textit{for all}\ n \in \mathcal{N} \tag{21}$$

$$z_n \geq 0,\ \textit{for all}\ n \in \mathcal{N}. \tag{22}$$

The model's constraint (20) limits the conditional value-at-risk (CVaR) of gross financing needs using the parameter ω. By changing ω, we trace the efficient frontier that trade-off debt cost with refinancing risk, as illustrated in Figure 3. Lower refinancing risk is often achieved by issuing long-term debt, resulting in higher debt financing costs. This choice can lead to an upward shift in the debt-to-GDP ratio dynamics. Still, the debt is considered sustainable if these ratios stabilise or trend downwards with a high probability. Conversely, an upward trajectory in debt dynamics indicates a debt trap, potentially culminating in insolvency. We run the model to derive optimal debt financing decisions across various levels of refinancing risk. Afterwards, in a post-optimality analysis, we evaluate whether the debt stock remains sustainable with a high degree of probability.

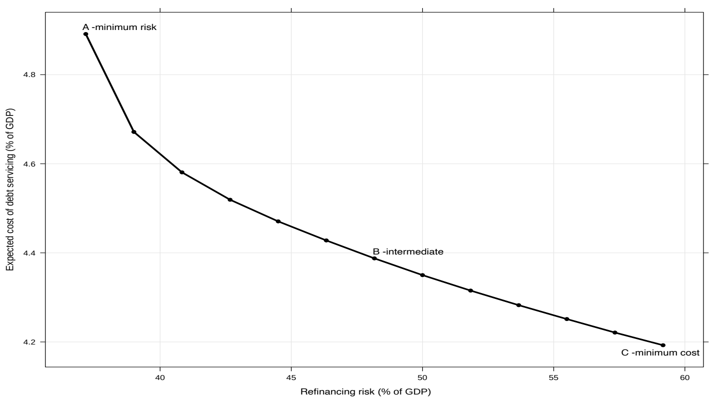


Figure 3. Pareto efficient frontier depicting the relationship between the expected cost of net interest payments and different levels of conditional flow-at-risk (CFaR), illustrating the trade-off between cost and risk.

4. DSA Input Data and Scenario Generation

Our analysis covers a panel of European countries selected for their economic outlook, fiscal challenges, and demographic trends. Specifically, we focus on Finland, France, Italy, Germany, and Spain. These nations represent key examples of how diverse economic conditions and demographic shifts influence debt sustainability and policy responses in the region.

Indeed, nations with high public debt may need help to fund extra expenses due to, for example, diminishing total productivity or migratory flows. At the same time, those with more fiscal space can implement a broader range of strategies, including raising fertility levels and promoting labour force participation.

Our analysis covers 2023 to 2054, as the impacts of demographic changes will become more pronounced from 2027 onward.

We require various inputs to run our DSA model. These inputs consist of historical data to calibrate a stochastic tree that describes the stochastic evolution of interest rates, GDP, and the primary balance.

We also require an estimation of the economic impacts—both positive and negative—resulting from demographic shifts and their influence on GDP growth. These include additional expenditures or potential savings linked to changes in the demographic composition of the population. Such an estimate would account for the effects of an ageing population, variations in labour force participation, and fluctuations in productivity, all of which directly affect economic output. Furthermore, it should encompass the projected costs or savings associated with age-related public services, such as healthcare and pensions, as these will fluctuate depending on the evolving demographic profile of each country.

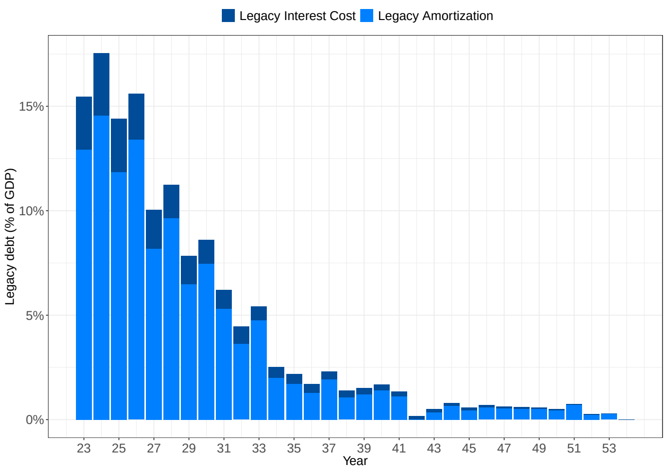
4.1. Debt Structure

Analysing a country's ability to repay its public debt depends on its total debt and how it is distributed over time. Even if the level of public debt is the same, a trajectory with sudden peaks in the amount to be financed can create liquidity problems.

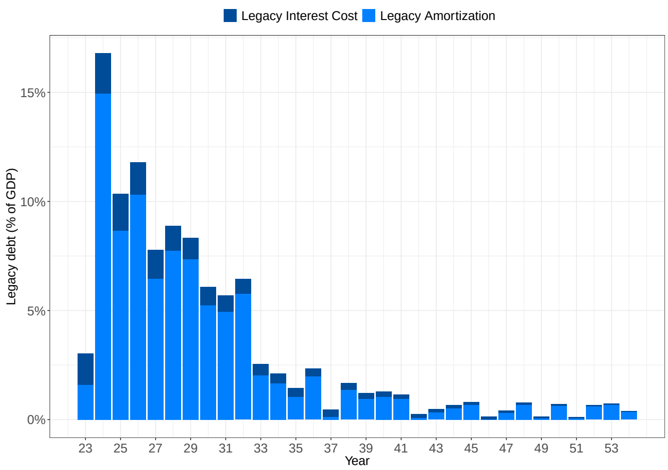
For example, a country facing a large debt repayment in a short period may find itself in difficulty, especially if it does not have adequate liquidity reserves or if the capital market becomes less accessible. This scenario can increase pressure on interest rates, increasing the cost of debt servicing and potentially triggering a negative financing spiral.

The ZeCoESM model takes these dynamics into account. In addition to considering the total amount of debt, temporal evolution is required as a specific input. By incorporating the time structure of debt into the ZeCoESM model, we can provide a more accurate assessment of a country's debt sustainability. In this way, policymakers can identify critical periods when debt servicing could become particularly burdensome and take preventive measures to mitigate liquidity and default risks.

In Figure 4, we display the debt for each country, highlighting the maturing amortisation (A) and interest (I) payments (source: FactSet).

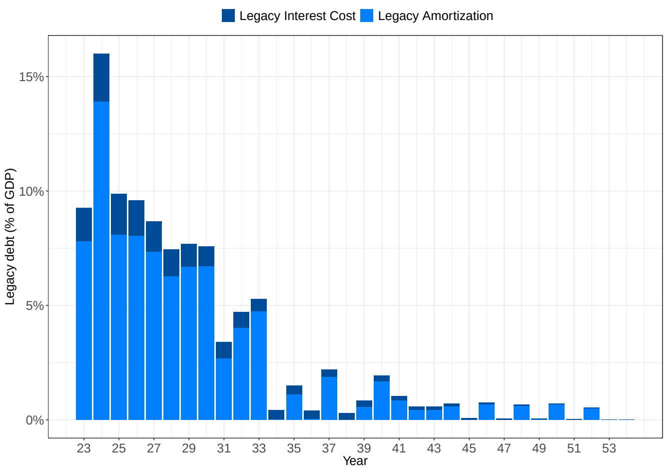


(**a**) Italy

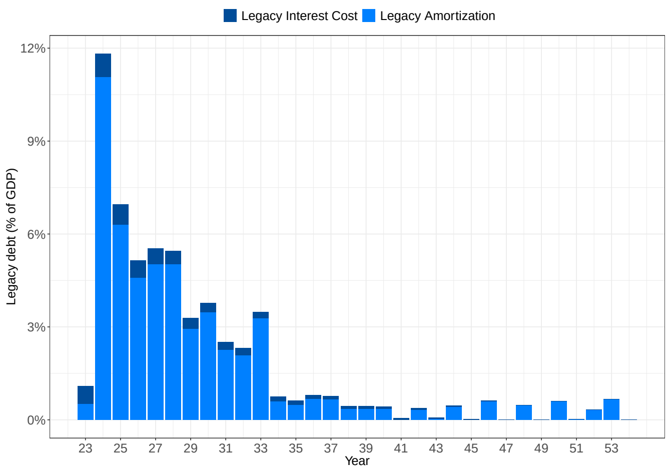


(**b**) France

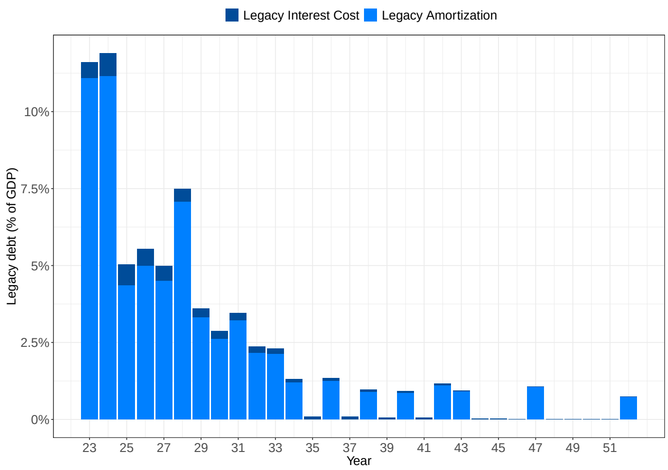
Figure 4. *Cont.*



(**c**) Spain



(**d**) Germany



(**e**) Finland

Figure 4. Debt structure for each country and its decomposition in amortisation (A) and interest payments (I). (Source: FactSet).

4.2. Risk-Free Rate

Our simulation model determines the issuance rate of future debt securities as in Equation (5): a risk-free rate, exogenous to the model, plus a spread determined endogenously as a function of the debt level.

In our analysis, we used the AAA Eurozone spot yield curve of 2 January 2023, from which we extracted the 10-year forward rates taken as risk-free. Figure 5 presents the spot structures of AAA rates sourced from the ECB website[1] and the correspondent 10-year forward rate.

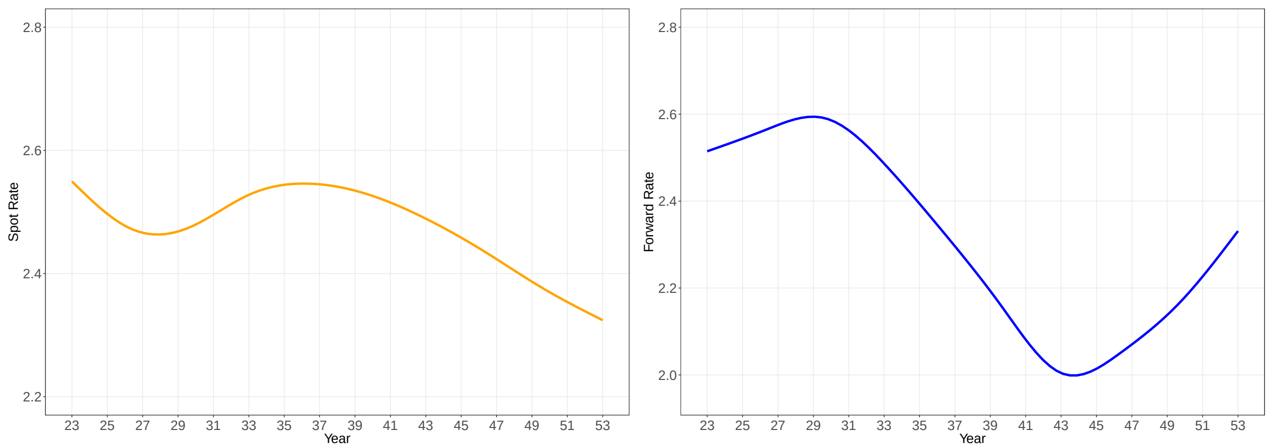
4.3. Growth and Primary Balance

The stochastic tree in the ZeCoESM model plays a crucial role in determining the random dynamics of key variables such as the interest rate, GDP, and the primary balance. This tree originates from the so-called "baseline scenarios", representing long-term projections based on different data sources.

These baseline scenarios can be derived from various sources, including historical data, consensus forecasts, or extrapolations from other economic models.

Regarding GDP, for example, in the current analysis, the baseline scenario is grounded in Eurostat's demographic forecasts, projecting long-term growth for the EU countries under current policy conditions and no major policy shifts (European Commission 2023).

Key assumptions include a gradual fertility increase (from 1.5 to 1.62 births per woman by 2070), modest life expectancy gains (with half of the additional years spent in good health), and net migration stabilising at 1 million people per year post-2022. Productivity growth is set at 0.8%, down from previous assumptions, while healthcare and long-term care costs follow GDP per capita, with rising demand due to an ageing population. Labour participation rates for those aged 55–74 are expected to increase, reflecting reforms encouraging extended work life.

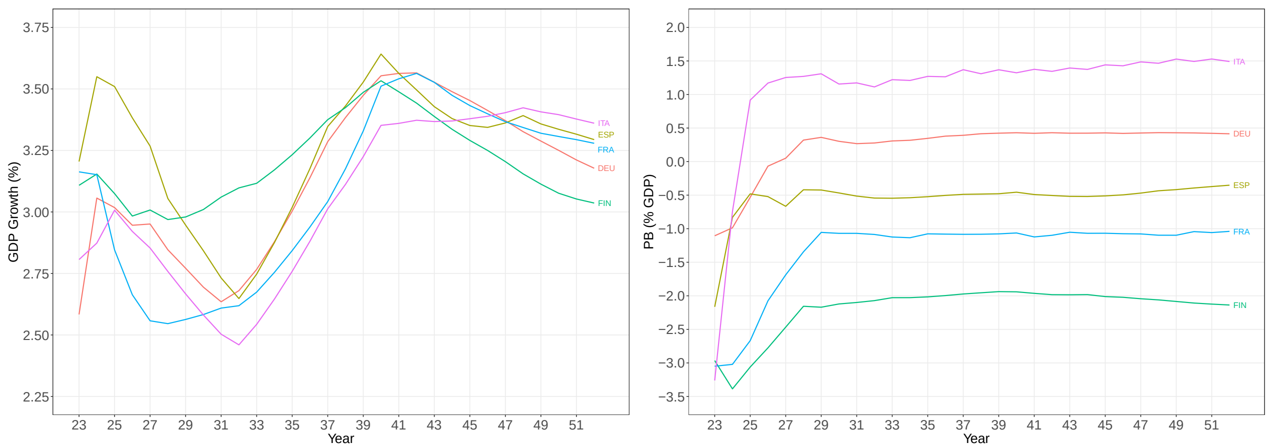


(**a**) Spot (**b**) Forward

Figure 5. Spot (**a**) and 10-years forward (**b**) rates of the Euro area.

Regarding primary balance, our baseline scenario is grounded on IMF's World Economic Outlook (WEO)-April 2024-up to 2029 (International Monetary Fund 2024).

Figure 6 presents the baseline projections, displaying GDP growth (Figure 6a) and primary balance (Figure 6b) for each country in the panel, adjusted to account for ageing effects.



(**a**) GDP growth (**b**) Primary balance

Figure 6. Baseline projections for GDP growth (**a**) based on Eurostat's demographic forecasts under stable policy conditions and primary balance (**b**) adjusted for ageing costs using WEO forecasts, incorporating expenditure changes associated with an ageing population. (Source: European Commission (2023) and International Monetary Fund (2024)).

Given the inherent uncertainties in long-term projections, using terminology and data in European Commission (2023), we perform sensitivity tests around the baseline scenario in our DSA model to evaluate how the projections shift with scenarios, presumably leading to higher debt sustainability risk. In particular, we explored the following alternative shock scenarios:

Reduced Fertility: This scenario assumes a 20% decline in fertility relative to the baseline. Such a drop contributes to slower GDP growth.

Lower Immigration: With immigration reduced by roughly one-third (about 350,000 fewer immigrants compared to the baseline), this scenario leads to lower GDP growth, as a smaller labour force slows economic expansion.

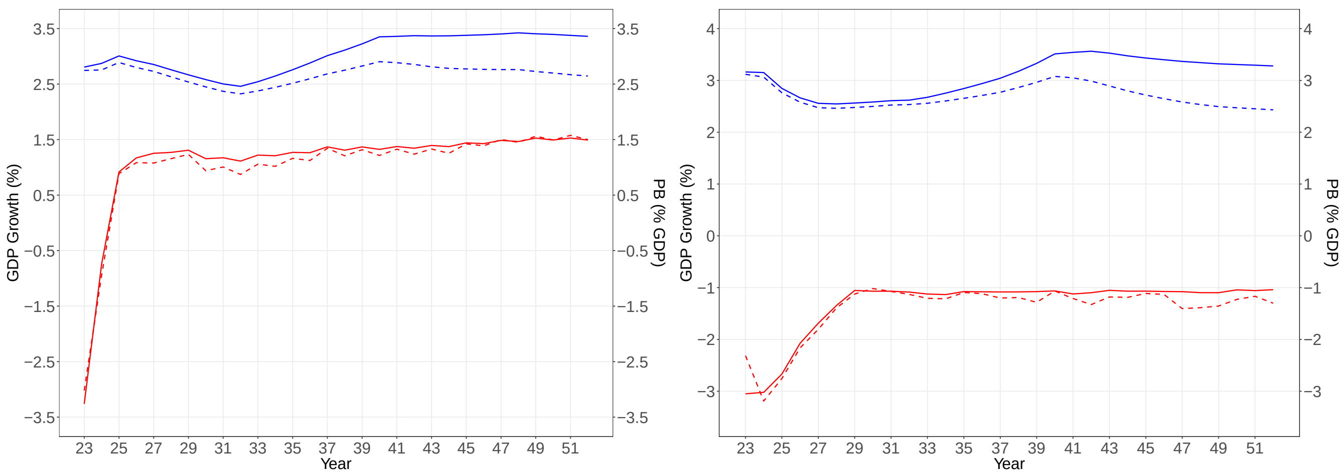
Extended Life Expectancy: Life expectancy is projected to increase by an additional two years by 2070 beyond the baseline, modestly raising age-related expenditures.

Reduced TFP Growth: This scenario assumes total factor productivity (TFP) growth tapers to 0.6% instead of 0.8% from 2040 onward, further dampening GDP growth. The lower productivity growth rate amplifies ageing-related expenses.

Increased Healthcare and Long-Term Care Costs: This "risk scenario" anticipates a significant rise in healthcare and long-term care costs, driven by factors such as high-income elasticity of demand for health services and an increased reliance on formal long-term care.

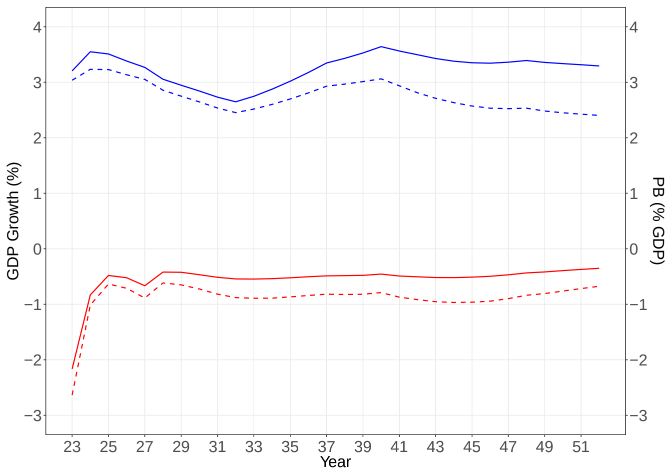
The cumulative impact of these scenarios leads to a marked economic slowdown and worsening fiscal conditions. To gauge the full extent of these combined shocks, we assess debt sustainability under a "cumulative effect" scenario, which integrates all previously outlined stress factors and thoroughly evaluates their aggregate impact on fiscal stability.

Figure 7 compares GDP growth and primary balance outcomes for each country under the baseline and cumulative effect scenarios. GDP growth trajectories are shown on the left axis, while the corresponding primary balances appear on the right axis, providing a clear view of how each country's fiscal health is affected by compounded demographic pressures.

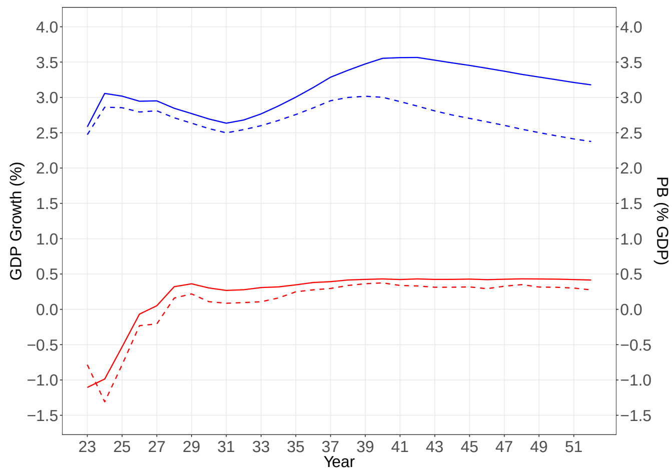


(**a**) Italy (**b**) France

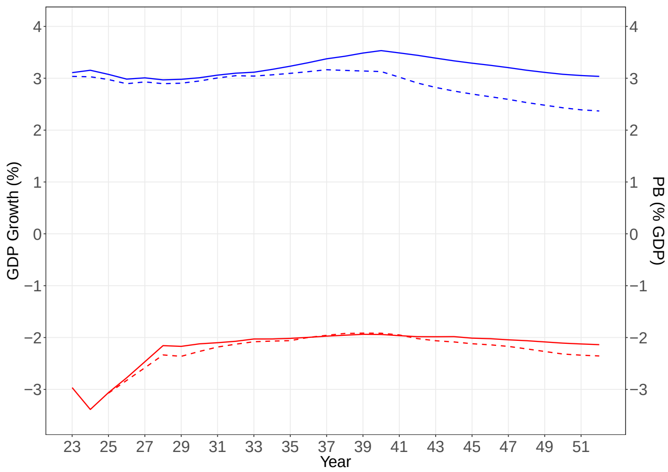
Figure 7. *Cont.*



(**c**) Spain



(**d**) Germany



(**e**) Finland

Figure 7. Comparison of GDP growth (left axis, blue) and primary balance (right axis, red) for each country under the baseline (solid line) and cumulative (dashed line) effect scenarios.

4.4. Tree-Based Uncertainty Modelling

The scenario tree is calibrated using a moment-matching method (see Consiglio et al. (2016); Høyland et al. (2003)). Specifically, we solve a global optimisation problem to estimate the state variables and conditional probabilities at each state, ensuring that their mean values, standard deviations, and correlations are consistent with input data.

The chosen standard deviations and correlation matrix shape the stochastic dynamics of exogenous economic factors—GDP growth, interest rates, and primary balance. By setting correlations, we establish a weak interdependence between these factors, allowing us to model plausible joint scenarios without introducing complex interrelations within the model itself. This approach keeps the model solution manageable while capturing realistic dynamics. For instance, although our sustainability model does not assume an endogenous link between primary balance and GDP growth (where fiscal tightening often slows economic growth), the correlations enable us to simulate coherent scenarios that reflect potential co-movements of GDP and primary balance in a realistic manner.

To highlight the effects of demographic scenarios on public debt sustainability, we apply an invariant stochastic framework across all countries in the panel, utilizing identical standard deviations and a unified correlation matrix. This approach minimises interference from country-specific volatility and correlation differences, enabling a more transparent comparison of outcomes. Table 1 presents the standard deviations and correlation matrix applied throughout the analysis.

Table 1. Standard deviations and correlation matrix used to model stochastic factors across all countries (source: Zenios et al. (2021)).

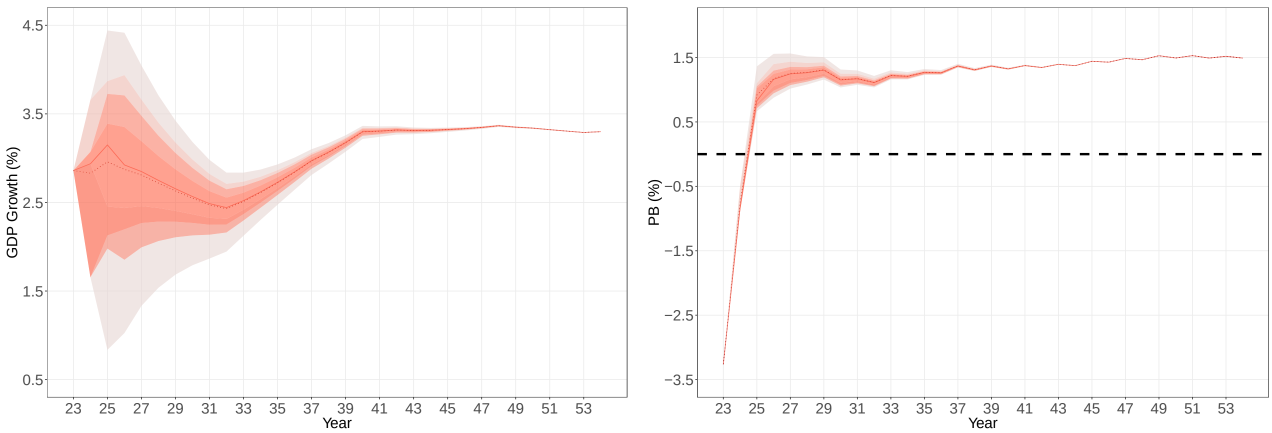
	Correlation		
	Growth	**Primary Balance**	**10y Forward Rate**
Growth	1.00		
Primary balance	0.25	1.00	
10y Forward rate	−0.20	−0.03	1.00
Standard deviation	0.75	0.15	0.85

For risk-free interest rate states, we align the mean values with market expectations derived from the forward yield curve (see Figure 5).

For GDP growth and primary balance, the tree is calibrated based on the baseline scenarios reported in Figure 6. The same procedure is applied for each shock described in Section 4.3 and for the combined effect scenario.

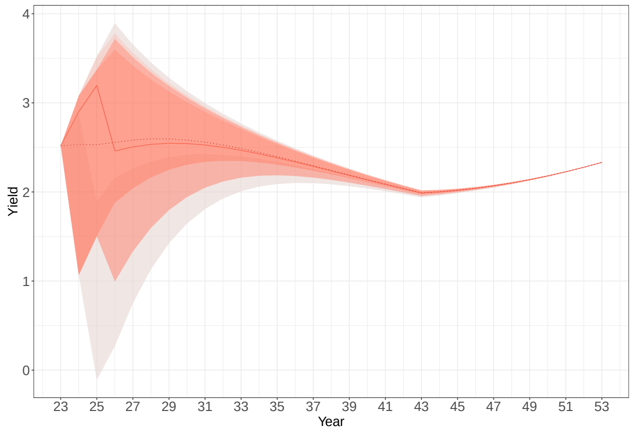
The scenario tree is flexible, allowing for a variable number of branches at each period, and its structure is not constrained to a binomial format. By simultaneously estimating state levels and conditional probabilities, we can achieve an accurate fit of moments with a relatively compact set of scenarios.

The fan charts in Figure 8 illustrate the scenario tree of the three exogenous factors in our model. To maintain computational tractability, the tree is structured so that for the first five years, each node branches four times, with no additional branching afterwards, resulting in a total of 64 scenarios. These factors, which represent the stochastic dynamics of Italy under the "baseline scenario," gradually converge toward the long-run values displayed in Figure 6.



(**a**) GDP growth (**b**) Primary balance

Figure 8. *Cont.*



(**c**) Yield curve

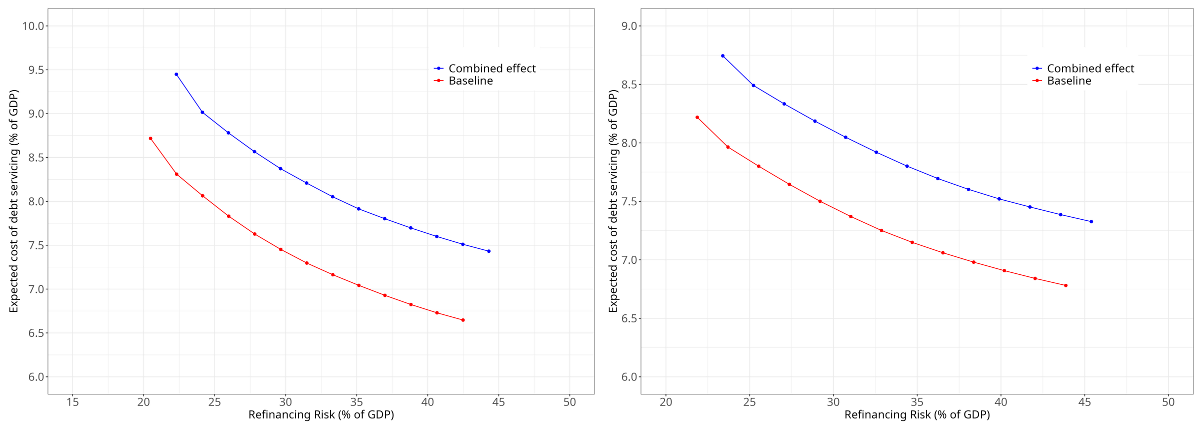
Figure 8. Fan charts illustrating the scenario tree for Italy's three exogenous factors under the baseline scenario. The shaded region, spanning the 10th to 90th percentiles, illustrates the uncertainty in projections. The shading grows lighter towards the extreme quantiles, indicating less probable outcomes. The chart includes two key lines: the median (dashed red line) and the expected value (solid red line), highlighting the central tendency and the overall distribution of outcomes.

5. Results

Our sustainability model dynamically optimises public debt issuance at each point in time, providing a more extensive solution space for decision-making. This approach allows for exploring a range of issuance policies instead of a single policy configuration, facilitating the creation of a Pareto-optimal frontier. This frontier represents a balance between risk—indicated by the tail of the gross financing need (GFN) distribution—and the expected debt issuance cost. Upward shifts in this efficient frontier signal scenario, where, holding other factors constant, a higher risk level corresponds to the same issuance cost, or a higher cost reflects the same level of assumed risk.

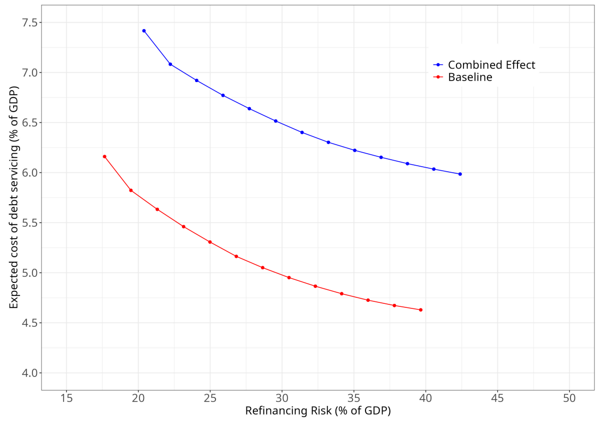
5.1. Efficient Frontiers

Figure 9 illustrates the efficient frontier for each country under both the baseline scenario and the cumulative effects of the joint shock. The observed reductions in economic growth, alongside generally rising deficits, lead to an upward shift in the efficient frontier. This shift highlights the increased risk associated with higher debt levels, underscoring a clear progression towards heightened debt vulnerability.

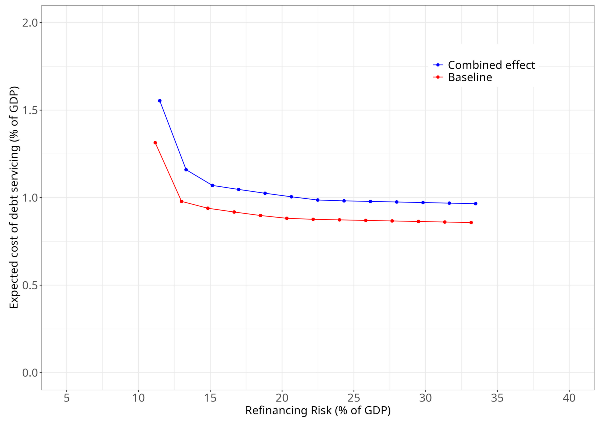


(**a**) Italy (**b**) France

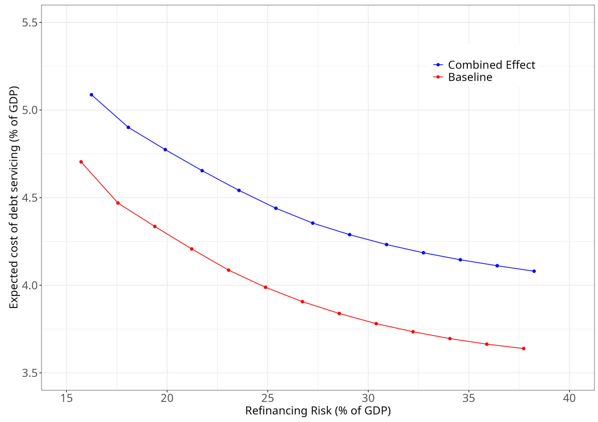
Figure 9. *Cont.*



(**c**) Spain



(**d**) Germany



(**e**) Finland

Figure 9. Efficient frontiers for each country under the baseline and cumulative effect scenarios. The upward shifts in the frontier, driven by reduced economic growth and rising deficits, highlight increased debt risk, illustrating a progression toward heightened fiscal vulnerability with greater debt issuance costs or risk tolerance.

5.2. Debt Dynamics

Each point along the efficient frontier represents a distinct debt trajectory over a thirty-year horizon, reflecting the optimal issuance of bonds across various maturities. This section examines the impact of demographic shocks on debt sustainability, focusing on the intermediate issuance strategy of the efficient frontier. As outlined by Blanchard (2022), ensuring debt sustainability requires that the debt-to-GDP ratio remains stable with high probability; this translates to a non-increasing 75th percentile of the debt-to-GDP distribution. Figure 10 overlays the projected debt-to-GDP dynamics under the baseline scenario (coral shading) and the cumulative demographic effects scenario (blue shading), illustrating the comparative debt trajectories for each scenario.

We observe that demographic shocks substantially heighten the vulnerability of public debt, resulting in a steeper trajectory for the 75th percentile of the debt-to-GDP ratio. This indicates that as population ageing accelerates, larger budgetary adjustments will be necessary to maintain fiscal stability, diminishing available fiscal space and limiting the government's capacity to respond to future economic challenges.

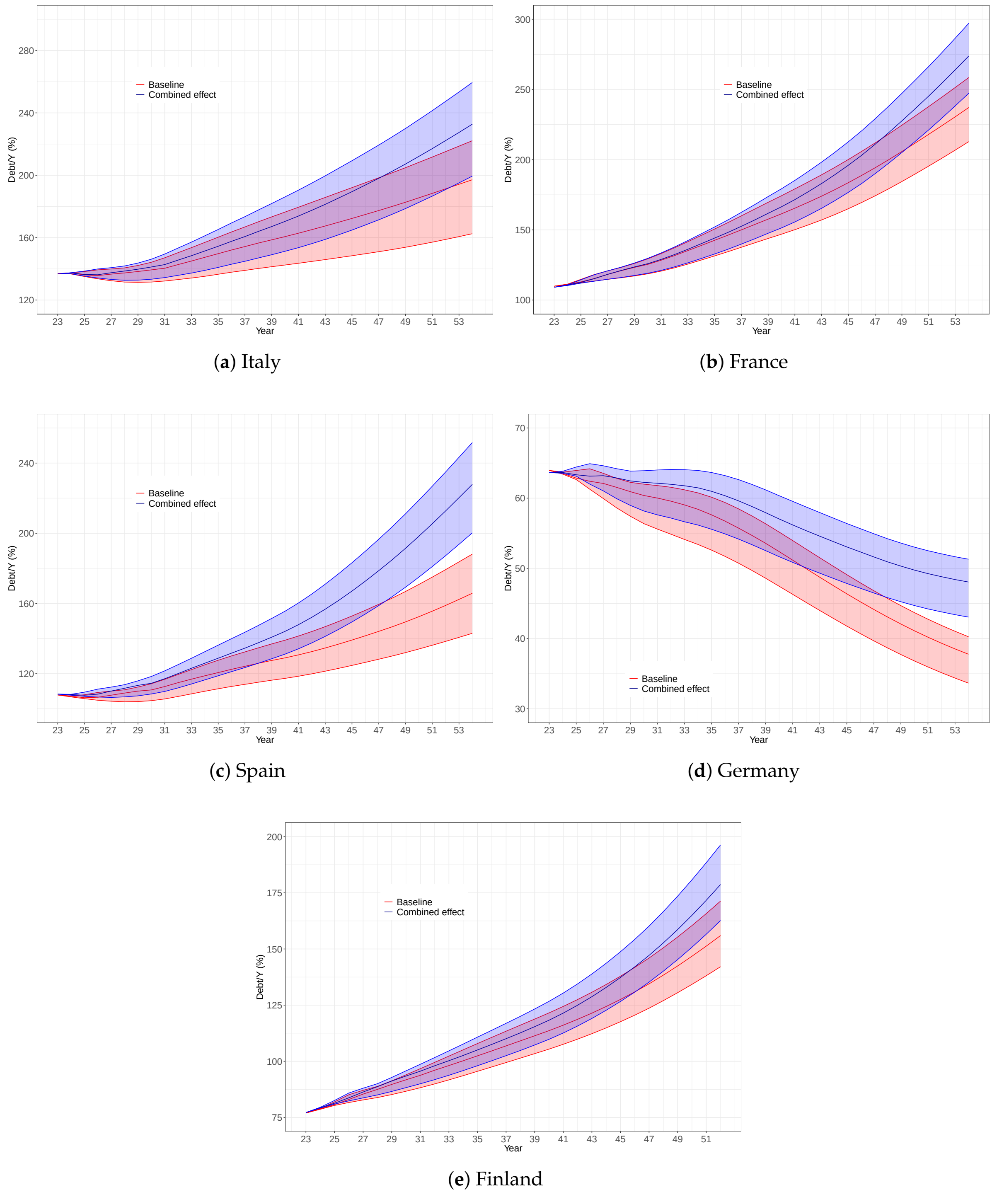


Figure 10. Projected debt-to-GDP trajectories over a thirty-year horizon under baseline (coral shading) and cumulative demographic effects scenarios (blue shading). The cumulative impact of demographic shocks results in a steeper 75th-percentile trajectory, indicating increased fiscal vulnerability and reduced fiscal space.

5.3. Overall Assessment

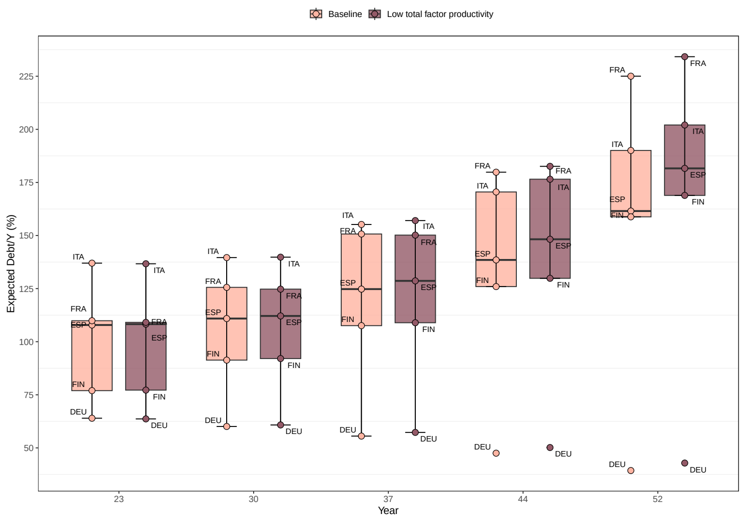
The cumulative impact of demographic scenarios on the debt stock, illustrated in Figure 10, heightens debt-accumulation dynamics, particularly for countries starting with higher initial debt levels. This non-linear effect arises primarily from the feedback mechanism defined by the issuance rate of the relation (5), where increases in the debt-to-GDP ratio endogenously raise the spread, thus accelerating debt growth.

Not all shock scenarios are likely to occur simultaneously, and analysing each shock, one at a time, provides valuable insights for policy decisions. For example, one could consider the effects of the reduced migratory flow to study policies for welcoming foreign workers according to the needs of the productive world. Alternatively, incentive policies for older workers, such as distance working, could be studied. However, it is essential to recognise that when multiple shocks combine, their impact is amplified by the self-reinforcing debt mechanism that drives spreads higher.

Figure 11 presents the snapshots of the debt-to-GDP ratio at specific time points, contrasting these with the baseline scenario. Each point represents the expected debt-to-GDP ratio at a given time, conditioned on the specific time period. The box plots illustrate the range of impacts across countries for each demographic scenario, capturing variations within the panel. Key factors influencing debt dynamics include GDP growth rate changes and primary balance adjustments, each shaped by demographic shocks.

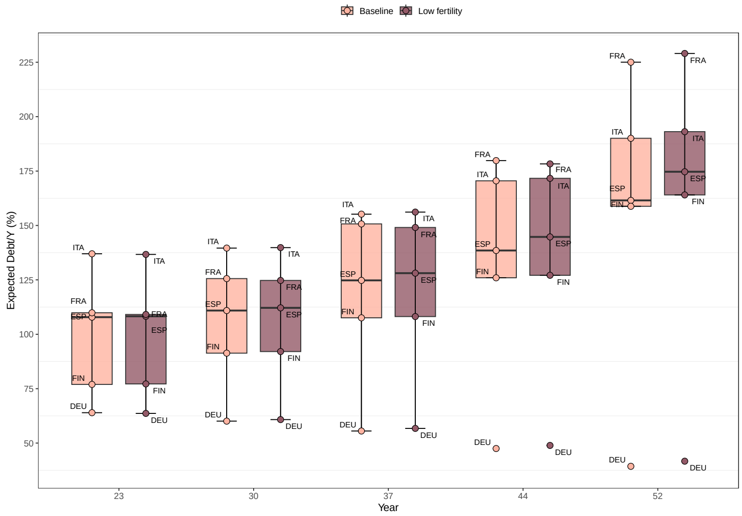
Our findings align with those of Darvas et al. (2024), showing that demographic shifts call for an increase in the structural primary balance to manage rising fiscal pressures. This adjustment, as evidenced in our analysis, results in a higher debt-to-GDP ratio, underscoring the fiscal challenges posed by demographic changes. Specifically:

- **Minimal Impact on Low-Debt Countries**: In countries with lower initial debt levels, such as Germany and Finland, demographic shocks show a limited impact, with the debt-to-GDP ratio in each scenario remaining only slightly above the baseline projection.
- **Significant Vulnerability in High-Debt Countries**: Italy and France exhibit heightened sensitivity to demographic scenarios, particularly after 2040. Both countries display substantial deviations from the baseline in the "low migration" scenario, whereas the impact of the "low fertility" scenario is considerably milder. This muted effect of low fertility is likely because projected declines in fertility rates are already factored into the baseline, reducing the relative deviation.

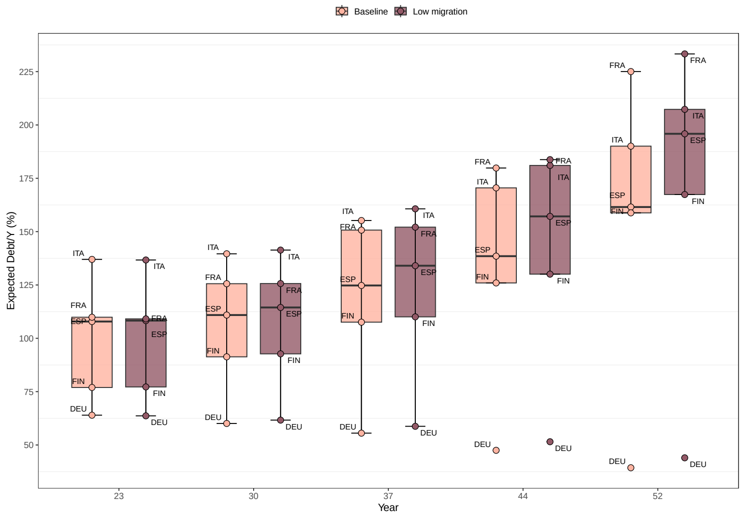


(**a**) Low TFP

Figure 11. *Cont.*



(**b**) Low Fertility



(**c**) Low Migration

Figure 11. Snapshots of the debt-to-GDP ratio over time under various demographic scenarios compared to the baseline. Each point represents the expected debt-to-GDP ratio at a given time, with box plots illustrating the range of impacts across countries in the panel. Low-debt countries, such as Germany and Finland, show minimal deviation from the baseline, whereas Italy and France are particularly affected, especially under the "low migration" scenario, with significant divergence observed after 2040.

6. Limitations and Future Research

Our study provides insights into how demographic changes impact public debt sustainability in Europe, but several limitations suggest areas for future research. A primary limitation is the assumption of an exogenous primary surplus process, which excludes feedback between debt levels and fiscal policy adjustments. As suggested by Hatchondo et al. (2016) and Arellano and Ramanarayanan (2012), incorporating endogenous default mechanisms could offer a more realistic representation of fiscal policy responses to changing debt dynamics.

While we explore scenarios such as low fertility, reduced migration, and increased life expectancy, future research could expand to include technological advances, labour market shifts, and climate change. These factors would broaden the model's robustness and applicability. Additionally, our model uses a simplified correlation structure among economic variables to maintain computational tractability. Future studies could explore more complex relationships between fiscal policy, economic growth, and demographics, enhancing the model's depth.

This study's focus on five European countries—Finland, France, Germany, Italy, and Spain—also limits its scope. Expanding the analysis to include countries in other regions, particularly those facing significant demographic challenges, would provide broader insights. Data limitations are another constraint; future work could use more granular data, such as age-specific labour force participation and healthcare costs, for refined analysis and more accurate projections.

An important caveat regards the assessment horizon. Its extension (2023 to 2054) is challenging, as forecasting over three decades involves uncertainty, especially with non-linear trends. However, this long-term perspective is essential for fully capturing the gradual impacts of demographic changes on debt sustainability. The analysis mitigates these uncertainties through sensitivity tests and scenario analyses, considering various plausible assumptions. While long-term projections have limitations, they provide valuable insights, alerting policymakers to potential challenges. Importantly, these projections should be considered trends and updated as new data emerge, ensuring that the analysis remains significant.

Finally, while our study focuses on debt sustainability risks from demographic changes, future research could evaluate the effectiveness of policy interventions, such as pension reforms, immigration policies, and investments in healthcare and education. Assessing these interventions would enhance the model's practical relevance and inform strategies to address the fiscal challenges posed by demographic shifts.

7. Conclusions

We assessed the implications of population ageing on debt sustainability in five EU Member States: Finland, France, Germany, Italy, and Spain. These countries were selected due to the significant differences in their initial debt profiles and anticipated costs associated with ageing, which imply diverse fiscal adjustments. The research applies a model to capture the effects of demographic scenarios on each country's debt-to-GDP ratio, focusing on three core demographic factors: fertility rates, migration, and life expectancy projections. This approach is built upon statistical analyses provided by the European Commission's (2023) AWG and considers both negative and positive impacts on growth and primary balance. For instance, while an ageing population generally reduces GDP growth, migration inflows can partially mitigate this effect. Our paper identifies how demographic trends could challenge the fiscal sustainability of these countries and explores policy interventions that may stabilise their public debt trajectories.

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Data Availability Statement: Restrictions apply to the availability of the research data, as they were confidentially provided by the Working Group on Ageing Populations and Sustainability of the Economic Policy Committee. The codes used in the analysis are proprietary. However, data may be made available to interested readers upon request, subject to approval of the data owners.

Conflicts of Interest: The authors declare no conflict of interest.

Note

1 https://www.ecb.europa.eu/stats/financial_markets_and_interest_rates/euro_area_yield_curves/html/index.en.html, accessed on 21 November 2024.

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