

South Korea's Demographic Transformation and Macroeconomic Sustainability: A Stochastic OLG-DSGE Assessment

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Abstract

The fertility rate in South Korea reached its lowest point at 0.72 during 2023 according to OECD statistics while the country faces an accelerating population aging trend that will exceed 40% elderly population by 2050. The research uses a stochastic overlapping-generations (OLG) model within a dynamic stochastic general equilibrium (DSGE) framework to generate new projections which replace previous three-variable models. The model uses KOSIS and OECD and IMF and NHIS data from 2023 to establish its baseline parameters. The model includes four key variables which are per-capita GDP and debt-to-GDP ratio and old-age dependency ratio and collapse probability that represents the first year when GDP per capita drops more than 15% below its previous ten-year average. The model uses Monte Carlo simulations to produce fan charts and sensitivity tests which examine the effects of productivity changes and health cost increases and migration patterns and fiscal rule modifications. The model incorporates specific policy measures for retirement age changes and childcare support and migration control and research and development growth which modify both the central forecast paths and extreme risk outcomes. The model uses three elderly population thresholds to determine fiscal implications: the 24% threshold indicates super-aged strain while 30% shows tax-base deterioration and 40% signals a care burden crisis with labor shortages. The simulations based on household survey data and case studies demonstrate that unaddressed population aging will cause collapse risks to increase dramatically after 2040 but integrated policy solutions will create positive GDP trends while maintaining debt stability and reducing uncertainty ranges.

Keywords

South Korea, Demographic Crisis, Birth Rate, Aging Population, Python

Model, Economic Collapse, Welfare, GDP, Dependence on Younger Generation, Family Support Policies

1. Introduction

South Korea experiences one of the most rapid demographic changes among all countries globally (OECD, 2023). The birth rate in 2023 reached 0.72 children per woman, which stands as the lowest rate in the OECD, while the elderly population will reach 40% of the total population by 2050 (KOSIS, 2023). The rapid aging of the population creates worries about future economic expansion and public budget stability, and fair distribution between different age groups (Kim & Choi, 2021; Kim, 2021). Research conducted earlier used deterministic projections to generate single-path GDP decline forecasts, which failed to capture the full spectrum of potential outcomes and ignored complex interactions between demographic factors, fiscal balances, and productivity (Choi, Lee, & Kim, 2003).

The research adopts a new three-variable projection framework which combines a stochastic overlapping-generations (OLG) model with a dynamic stochastic general equilibrium (DSGE) system instead of the previous total fertility rate and working-age share and elderly share framework (IMF, 2023; OECD, 2023). The model uses 2023 data from KOSIS, OECD, IMF, and NHIS for calibration and defines the variables as per-capita GDP (y), debt-to-GDP (Debt/Y), old-age dependency ratio ($\text{DR} = \text{ES}/\text{WAS}$), and collapse probability (the first year when per-capita GDP growth drops by more than 15% below its ten-year average) (NHIS, 2023).

The three elderly-population thresholds of 24%, 30% and 40% correspond to recognized stages of fiscal stress because 24% indicates the start of super-aged status which causes pension outflows to challenge revenue streams (Kim, 2021) and 30% shows the decline of the tax base and 40% indicates a fiscal crisis due to high healthcare expenses and workforce shortages (National Assembly Budget Office, 2024a, 2024b). The evaluation points in the thresholds enable users to compare the results of fan-chart simulations that stem from different stochastic runs (European Commission, n.d.; Japan Health Policy NOW, n.d.).

The research uses empirical data to validate its results which extend past single case studies. The analysis incorporates household survey data together with case studies to support statistical series by showing how younger people experience the growing caregiving responsibilities and delayed marriage and lower birth rates in their everyday lives (Korea Institute for Health and Social Affairs, 2023; Korea Social Security Information Service, 2022, 2023).

The model achieves policy implementation by making three main changes: it raises retirement age directly and provides subsidies for childcare and manages migration and expands research and development (Ministry of Economy and Finance, 2023a, 2023b; World Economic Forum, 2018). The variables impact both

the main forecast projection and extreme value distributions through their influence on labor market performance and public financial stability and economic expansion (Germany Federal Ministry of Finance, 2024; KB 국민카드, 2022; Gyeonggi Provincial Government, 2023).

The remainder of this paper is organized into six sections. Section 2 reviews the demographic and economic literature on ageing. The third section explains the stochastic OLG-DSGE methodology together with the calibration process and all necessary assumptions. The fourth section of the paper shows simulation results through fan charts and collapse probability calculations and sensitivity tests. The policy implications are discussed in Section 5, while Section 6 presents counterarguments and limitations.

2. Literature Review

2.1. Deterministic Projections in Demographic Economics

The OECD ranks South Korea as having one of the most rapid demographic changes in its population (OECD, 2023). The total fertility rate in South Korea reached 0.72 in 2023 which became the lowest rate worldwide according to KOSIS (2023). The official projections show that elderly citizens will make up more than 40% of the total population during the middle of this century (Kim & Choi, 2021; Kim, 2021). The working-age population has started to decrease in absolute numbers while the elderly population segment continues to grow at an increasing rate (Choi, Lee, & Kim, 2003). The dependency ratio will experience a fast transformation because the number of working individuals will not keep up with the expanding number of retirees (NHIS, 2023).

The standard approach in government and academic research depends on deterministic projection techniques which use cohort-component population models and basic regression-based growth forecasts (National Assembly Budget Office, 2024a; Kim, 2021). The models use current fertility and mortality patterns and productivity trends to create one possible path for GDP and fiscal balance projections (National Assembly Budget Office, 2024b; European Commission, n.d.). The projections demonstrate the severity of demographic changes but their restricted methodology creates significant knowledge gaps (Korea Institute for Health and Social Affairs, 2023).

Deterministic models lack the ability to handle uncertainty in their calculations (IMF, 2023). The models produce fixed numerical values instead of probability ranges which prevents analysts from measuring the likelihood of system failures and extreme events like fiscal collapse and major productivity disruptions (Korea Social Security Information Service, 2023; Korea Labor Institute, 2023). The models exclude complex economic interactions that occur when population aging increases pension and healthcare expenses while decreasing savings rates and limiting investment opportunities (Korea Social Security Information Service, 2022; Ministry of Economy and Finance, 2023a). The models lack built-in policy control mechanisms, which prevents them from simulating policy interventions including

delayed retirement programs and childcare support and managed migration and expanded research and development initiatives (Japan Health Policy NOW, n.d.; Ministry of Finance Japan, 2024; Gyeonggi Provincial Government, 2023).

The fast pace of South Korea's demographic transformation makes its current projection challenges even more critical (World Economic Forum, 2018; KB 국민카드, 2022). The super-aged status transition in Japan and Germany occurred over a longer period, but South Korea is experiencing this demographic change at an accelerated rate (Federal Ministry of Finance (Germany), 2024). Deterministic forecasting methods produce results that show lower fiscal pressure and collapse risk than actual values which creates unrealistic confidence about sustainability (European Commission, n.d.; Ministry of Economy and Finance, 2023b). The research uses a forward-looking stochastic model that connects demographic changes to fiscal operations and policy management systems to replace conventional projection methods (Korea Labor Institute, 2023).

2.2. Stochastic OLG-DSGE Approaches

The research implements a stochastic overlapping-generations (OLG) framework inside a dynamic stochastic general equilibrium (DSGE) system to address the restrictions of deterministic projections (Bloom, Canning, & Fink, 2010; Choi, Lee, & Kim, 2003; Kim & Choi, 2021). The OLG framework enables the study to model intergenerational financial exchanges between working people and elderly citizens while the DSGE framework connects population changes to economic variables including national output and savings rates and investment levels and public budget performance (Feyrer, 2007; OECD, 2023; IMF, 2023).

The model uses 2023 as its base year for calibration through KOSIS demographic projections (KOSIS, 2023) and IMF World Economic Outlook macroeconomic data (IMF, 2023) and OECD productivity and R&D statistics (OECD, 2023) and NHIS health-expenditure information (Korea Institute for Health and Social Affairs, 2023). The model contains specific definitions for all its variables which are listed below (Giambastiani, 2007; Klatzky, 1998).

$$\text{Per-capita output (GDP per capita): } y_t = \frac{Y_t}{Pop_t}$$

The equation for per-capita output (GDP per capita) at time t equals the total output (Y_t) divided by the population (Pop_t) and the price level (Pop_t).

Where Y_t is aggregate output, and Pop_t is total population.

$$\text{Dept-to-GDP ratio: } \frac{Debt_t}{Y_t}$$

where $Debt_t$ is sovereign debt at time t .

$$\text{Old-age dependency ratio: } DR_t = \frac{ES_t}{WAS_t}$$

where ES_t is the elderly population (65+) and WAS_t is the working-age popu-

lation (15 - 64).

Effective labor supply:

$$L_t^{eff} = Pop_t \cdot WAS_t^* \cdot LFPR_t \cdot (1 - U_t) \cdot (1 + w_{mig} \cdot Mig_t)$$

where WAS_t^* is the share of working-age adults, $LFPR_t$ is the labor-force participation rate, U_t is the unemployment rate, and Mig_t represents net migration flows weighted by w_{mig} .

$$\text{Collapse probability: } Collapse_t = 1 \{ \underline{g_{t-9t}^{pc}} - g_t^{pc} > 0.15 \}$$

where g_t^{pc} is per-capita GDP growth at time t , $\underline{g_{t-9t}^{pc}}$ is its trailing 20-year average, and the indicator function equals 1 when a collapse occurs (GDP growth falls more than 15% below trend).

The model calculates the collapse probability (Collapse t) based on the per-capita GDP growth rate (g_t^{pc}) and its 9-year trailing average ($\underline{g_{t-9t}^{pc}}$). The indicator function returns 1 when the per-capita GDP growth rate exceeds 0.15 below its trend value.

The model includes stochastic elements through Monte Carlo simulations which apply random disturbances to productivity growth and health spending and migration patterns and fiscal policy frameworks (Bloom, Canning, & Fink, 2010; OECD, 2023; IMF, 2023). The model produces multiple possible outcomes instead of a single fixed path which it displays through fan charts (Choi, Lee, & Kim, 2003; Kim & Choi, 2021; Feyrer, 2007). The stochastic OLG-DSGE framework surpasses previous three-variable deterministic projections by showing uncertainty and demonstrating nonlinear fiscal-demographic interactions and revealing extreme risks that include system failures (NHIS, 2023; OECD, 2023; Giambastiani, 2007).

The model incorporates policy variables through its structural framework. The model uses retirement age modifications to affect workforce participation rates and childcare support programs to affect birth rates which impact future working-age numbers and controlled migration programs to boost workforce numbers and tax revenue (Ministry of Economy and Finance, 2023a; Gyeonggi Provincial Government, 2023; Feyrer, 2007). The model assesses both the central projections and risk distribution changes when different policy combinations are applied (Japan Health Policy NOW, n.d.; World Economic Forum, 2018; Klatzky, 1998).

The simulation results become easier to understand through the use of three elderly population thresholds at 24% and 30% and 40% (Kim, 2021; Kim & Choi, 2021; Choi, Lee, & Kim, 2003). The 24% elderly population threshold indicates the beginning of the super-aged strain because pension and healthcare expenses start to exceed available revenue (National Assembly Budget Office, 2024a; European Commission, n.d.). The state faces accelerating tax-base destruction when the elderly population reaches 30% which weakens its financial capabilities (National Assembly Budget Office, 2024b; Korea Institute for Health and Social

Affairs, 2023). The 40% threshold indicates a severe demographic crisis because it leads to rising healthcare expenses and severe workforce shortages (Korea Social Security Information Service, 2023; Ministry of Finance Japan, 2024). The study bases its fan chart and collapse probability analysis on these specific thresholds because they match established international demographic criteria (European Commission, n.d.; Giambastiani, 2007).

2.3. South Korea in Comparative Perspective

South Korea's population aging process happens at an extraordinary pace while showing unique compared to Japan and Germany and other aging nations (OECD, 2023; KOSIS, 2023). Japan and Germany achieved high income status and built strong social insurance systems before their elderly population reached 28% in 2020 and 22% in the same year (Kim & Choi, 2021; Choi, Lee & Kim, 2003). The elderly population in South Korea will surpass 40% by 2050 while the country maintains the lowest fertility rate in the OECD at 0.72 (NHIS, 2023; IMF, 2023).

The evidence shows Japan and Germany experienced substantial pension and healthcare cost pressures yet their earlier higher birth rates and slower population aging enabled them to make policy adjustments (Japan Health Policy NOW, n.d.; Ministry of Finance Japan, 2024; Bloom, Canning, & Fink, 2010). Japan established long-term care insurance and made progressive pension system changes while Germany expanded elder-care subsidies and brought in skilled foreign workers (European Commission, n.d.; KB 국민카드, 2022; Feyrer, 2007). The fast pace of South Korea's demographic shift requires immediate action because the country will transition from aged to super-aged status within less than eight years whereas Japan needed more than twenty years to make this transition (Kim, 2021; Korea Social Security Information Service, 2023; Giambastiani, 2007).

The fast pace of South Korea's demographic shift makes the three elderly population thresholds of 24%, 30%, and 40% more critical than they are for other countries (National Assembly Budget Office, 2024a; Ministry of Economy and Finance, 2023a; Klatzky, 1998). The pension outflow approaches structural imbalance when elderly population reaches 24% while tax-base erosion becomes severe at 30% and healthcare and labor scarcity become unsustainable at 40% (National Assembly Budget Office, 2024b; Korea Institute for Health and Social Affairs, 2023; Singh et al., 2017). The demographic markers used to create these thresholds function as both international reference points and internal indicators for South Korea (World Economic Forum, 2018; Marcinkowski & Rehring, 1995).

The research literature provides two essential lessons that South Korea should implement. Japan demonstrates how postponing pension system changes leads to increased long-term expenses, according to the literature (Kim, 2021; Choi, Lee, & Kim, 2003; Bloom et al., 2010). The same factors that enable Germany to maintain economic growth during aging will prove essential for Korea to achieve similar success (European Commission, n.d.; Gyeonggi Provincial Government, 2023;

Fisher, Aron, & Brown, 2006). The research incorporates policy instruments into its stochastic OLG-DSGE model to evaluate South Korea's demographic development through both domestic and international advanced ageing economy strategies (OECD, 2023; IMF, 2023; Kim & Choi, 2021).

2.4. Japan and Germany in Comparative Perspective

The demographic decrease in South Korea exists as part of a broader global pattern. The advanced economies of Japan and Germany face similar population ageing and fertility reduction challenges, which serve as useful policy reference points for South Korea (Choi, Lee, & Kim, 2003; Kim & Choi, 2021). The two countries entered super-aged status before South Korea, but selected different institutional approaches, which demonstrate multiple ways to manage population growth with economic fairness and financial stability (OECD, 2023; IMF, 2023).

Japan: The country of Japan became the first nation to enter super-aged status before any other OECD member state when its 65+ population reached 30% in 2020 (Japan Health Policy NOW, n.d.; Ministry of Finance Japan, 2024). The government implemented two main strategies to handle the aging population. The retirement-age and labor-market reforms of Japan involved two main components, which included raising public pension eligibility age over time and supporting silver employment through funding and adaptable work programs (World Economic Forum, 2018; Kim, 2021). The Long-Term Care Insurance (LTCI) system, which Japan launched in 2000, distributed national risk and transferred eldercare costs from families to state funding (Japan Health Policy NOW, n.d.). The implemented measures reduced the financial strain caused by population ageing, yet failed to stop Japan's decreasing population since its birth rates have stayed under 1.4 children per woman (OECD, 2023). The labor market integration of elderly workers, together with established eldercare payment systems, has proven to be a stabilizing element according to most experts (Kim & Choi, 2021).

Germany: Germany faces low birth rates of 1.5 children per woman and increasing life expectancy but uses different population management approaches (European Commission, n.d.; KB 국민카드, 2022). The German government established **Elterngeld parental leave** benefits and built extensive subsidized childcare facilities to increase women's workforce participation and reduce the impact of declining birth rates (Gyeonggi Provincial Government, 2023). The German government used **Riester pensions** as part of its pension financing strategy while providing retirement incentives instead of mandatory rules to support older workers (Korea Labor Institute, 2023). Germany uses **migration policies** to bring in skilled workers because these policies help reduce the effects of population decline (National Assembly Budget Office, 2024a). The combination of these instruments enabled Germany to keep its dependency ratio stable at a level that outperformed other European countries (European Commission, n.d.; Kim, 2021).

Implications for Korea: The institutional reforms in Korea stand as less extensive than those implemented by Japan and Germany (Kim, 2021; Ministry of

Economy and Finance, 2023a). The pension system of Korea provides limited replacement rates while childcare funding exists in separate parts and immigration rules continue to be strict (*Korea Social Security Information Service, 2023*). The fertility rate of 0.72 in Korea shows that the country faces a more severe demographic challenge than Japan and Germany but the two countries provide useful lessons (*OECD, 2023; NHIS, 2023*). The Japanese eldercare system and late-life work opportunities demonstrate the significance of these elements while German childcare support and migration management show their effectiveness (*Japan Health Policy NOW, n.d.; European Commission, n.d.*). The two examples prove that successful policy solutions need to combine different measures, which should continue over time instead of being implemented in short bursts (*World Economic Forum, 2018; Choi, Lee, & Kim, 2003*).

The research provides evidence to support the ongoing policy discussions in Korea (*National Assembly Budget Office, 2024b; Korea Institute for Health and Social Affairs, 2023*). The cases demonstrate that proactive strategies can prevent fiscal strain when a country experiences fast population aging. The study establishes a clear difference between Korea's current passive adjustment approach and the active adaptation strategies Japan and Germany have implemented (*Kim & Choi, 2021; Ministry of Finance Japan, 2024*).

2.5. Gaps in the Literature and Contribution of This Study

Despite substantial research on South Korea's demographic challenges, several limitations persist in the existing literature. First, most projections are deterministic, presenting a single GDP or dependency-ratio path rather than quantifying the probability distribution of outcomes (*Kim & Choi, 2021; Choi, Lee, & Kim, 2003*). Such models understate uncertainty and provide limited guidance for policymakers who must operate under risk (*OECD, 2023; IMF, 2023*). Second, analyses often rely on anecdotal evidence or broad generalizations rather than systematic simulations or survey-based empirical validation (*Korea Institute for Health and Social Affairs, 2023; Korea Labor Institute, 2023*). For example, household-level responses to ageing pressures are rarely modeled beyond case illustrations (*Korea Social Security Information Service, 2022; KB 국민카드, 2022*). Third, while international comparisons highlight alternative approaches—as seen in Japan's long-term care insurance or Germany's childcare subsidies and migration policies—few Korean studies embed these lessons in a unified macro-demographic framework (*Japan Health Policy NOW, n.d.; European Commission, n.d.*).

This paper addresses these gaps in three ways. First, it employs a stochastic overlapping-generations (OLG) model embedded in a dynamic stochastic general equilibrium (DSGE) framework, calibrated to 2023 baselines from KOSIS, OECD, IMF, and NHIS (*KOSIS, 2023; NHIS, 2023*). Monte Carlo simulations generate fan charts of GDP per capita, debt-to-GDP ratios, dependency ratios, and collapse probabilities, replacing deterministic projections with probabilistic trajectories

(OECD, 2023; IMF, 2023). Second, the model explicitly incorporates policy levers—retirement-age reform, childcare subsidies, managed migration, and R&D expansion—allowing quantitative evaluation of their potential to mitigate collapse risk (Ministry of Economy and Finance, 2023a; National Assembly Budget Office, 2024b). Third, the study situates Korea within a comparative perspective by referencing the experiences of Japan and Germany, highlighting how Korea’s limited reforms leave it more vulnerable to fiscal and social strain (Kim, 2021; World Economic Forum, 2018).

By integrating probabilistic modeling, explicit policy scenarios, and comparative insights, this study makes three contributions: it advances the methodological frontier of demographic-economic modeling in Korea, provides quantitative benchmarks for collapse thresholds (24%, 30%, and 40% elderly shares), and strengthens the policy debate with evidence grounded in both stochastic simulation and international precedent (Kim & Choi, 2021; Choi, Lee, & Kim, 2003).

3. Methods

3.1. Methodological Framework, Assumptions, and Equations

The paper uses a stochastic overlapping-generations (OLG) model, which operates within a dynamic stochastic general equilibrium (DSGE) framework as its fundamental research approach. The model design produces probability distributions instead of fixed paths to address projection weaknesses while showing how demographic patterns affect both fiscal sustainability and long-term economic expansion. The section explains the model equations and variable definitions and calibration process and core assumptions and positions the results against the eight simulation figures (Figures 1-8).

3.1.1. Framework and Variable Definitions

The OLG component models the transfer of resources between generations through pension payments and healthcare expenses and tax income. The DSGE framework includes mechanisms for capital accumulation and productivity growth and debt evolution. The baseline calibration draws its data from KOSIS for fertility and population statistics and from OECD for labor-force and productivity data and from IMF WEO for GDP and debt information and from NHIS for health expenditure records from 2023.

Variable Definitions and Calibration

- TFR_t : Total fertility rate in year t (KOSIS, 2023 baseline = 0.72).
- WAS_t : Share of the population aged 15 - 64 (working age share, 71.8% in 2023).
- ELD_t : Share of the population aged 65+ (elderly share, 18.4% in 2023).
- $LFPR_t$: Labor-force participation rate (OECD, 63% in 2023).
- U_t : Unemployment rate (OECD, 3.0% in 2023).
- Mig_t : Net migration inflows, relative to labor force size (+0.2% in 2023).

- $g_{A,t}$: Productivity growth (IMF/OECD, baseline 1.1%).
- $Debt_t/Y_t$: Sovereign debt-to-GDP ratio (IMF WEO, 54.2% in 2023).
- $Health_t$: Health expenditures as % of GDP (NHIS, 8.4% in 2023).

Elderly-share thresholds structure the projections:

- 24% = onset of super-aged status, pension outflows exceed contributions.
- 30% = systemic tax-base erosion.
- 40% = crisis-level ageing, healthcare dominates fiscal capacity.

Collapse probability is defined as the first year when per-capita GDP growth falls 15% below its trailing 10-year mean.:

3.1.2. Core Equations

The core framework is a stochastic overlapping-generations (OLG) model embedded in a dynamic stochastic general equilibrium (DSGE) structure. A Cobb-Douglas production function determines output:

$$Y_t = A_t K_t^\alpha (L_t^{eff})^{1-\alpha} \quad (1)$$

where Y_t is aggregate output, A_t represents total factor productivity (TFP), K_t is aggregate capital, and L_t^{eff} is the effective labor supply. The OLG component models the flow of resources between generations through pension and healthcare funding supported by taxation while the DSGE system models capital growth and household spending and government debt evolution.

Fiscal balances evolve according to:

$$Debt_t = (1 + r_g) Debt_{t-1} + Pen_t + Health_t - \tau_t Y_t \quad (2)$$

where r_g is the real interest rate on debt, Pen_t denotes pension outlays, $Health_t$ represents healthcare expenditures, and $\tau_t Y_t$ is tax revenue.

Effective labor supply is defined as:

$$L_t^{eff} = Pop_t \cdot WAS_t^* \cdot LFPR_t \cdot (1 - U_t) \cdot (1 + w_{mig} \cdot Mig_t) \quad (3)$$

where w_{mig} measures the elasticity of migration in augmenting effective labor.

Thresholds and Collapse Definition

- 24% elderly share = transition to super-aged society, where pension outflows first exceed contributions.
- 30% elderly share = onset of systemic tax-base erosion.
- 40% elderly share = crisis-level ageing, when healthcare and care expenditures dominate fiscal capacity.

The collapse probability is defined as the first year in which per-capita GDP growth falls more than 15% below its trailing ten-year mean:

$$Collapse_t = 1 \left\{ \underline{g}_{t-9,t}^{pc} - g_t^{pc} > 0.15 \right\} \quad (4)$$

where g_t^{pc} is per capita GDP growth at t , and $\underline{g}_{t-9,t}^{pc}$ is its trailing 10-year average.

Policy lever equations:

Retirement-age reform effect on LFPR:

$$LFPR_t^{policy} = LFPR_t + \Delta_{ret} \quad (\Delta_{ret} = +0.03 \text{ to } 0.05) \quad (5)$$

Childcare subsidy effect on fertility:

$$TFR_t^{policy} = TFR_t + \Delta_{cc} \quad (\Delta_{cc} = +0.15 \text{ to } 0.20) \quad (6)$$

Migration policy shock:

$$Mig_t^{policy} = Mig_t + \Delta_{mig} \quad (\Delta_{mig} = +0.3\% \text{ to } +0.5\%) \quad (7)$$

R&D expansion effect on productivity growth:

$$g_{A,t}^{policy} = g_{A,t} + \Delta_{R\&D} \quad (\Delta_{R\&D} = \pm 0.2 \text{ to } 0.4\text{p.p}) \quad (8)$$

3.1.3. Linking Equations to Graphs

Figure 1: Baseline GDP per capita trajectories

- Derived from Equation (1).
- Shows central decline under constant TFR, LFPR, and productivity.
- Fan-chart distribution visualizes uncertainty (interquartile + 90% confidence bands).

Figure 2: Debt-to-GDP ratios

- Driven by Equation (2).
- Demonstrates rising fiscal stress at higher elderly shares, debt ratios surpass 150% by mid-century without reform.

Figure 3: Dependency ratio dynamics

- Based on Equation (3).
- Illustrates steep decline in effective labor supply as elderly share rises, sensitivity to migration shocks.

Figure 4: Collapse probability

- Equation (4).
- Probability of collapse rises above 50% after 2040 in baseline; accelerates past 70% once elderly share >40%.

Figure 5: Retirement-age reform scenario

- Uses Equation (5).
- Extends labor participation, narrows GDP fan chart, delays collapse by ~10 years.

Figure 6: Childcare subsidy scenario

- Uses Equation (6).
- Fertility rebound toward 0.9 improves long-run GDP growth, but effects emerge only after 2045.

Figure 7: Managed migration scenario

- Use Equation (7).
- Boosts effective labor supply, slows dependency ratio deterioration, reduces collapse probability by 20 points.

Figure 8: R&D expansion scenario

- Use Equation (8)
- Productivity shock yields immediate GDP gains, raises median trajectory,

narrows downside risk.

3.1.4. Assumptions

- 1) Fertility remains constant at 0.72 in the baseline, with stochastic shocks applied in simulations.
- 2) Productivity follows an AR (1) process with mean growth of 1.1% and innovation variance calibrated to IMF/OECD estimates.
- 3) Retirement-age reform raises $LFPR_t$ by 3 - 5 percentage points in policy scenarios.
- 4) Migration acts as an exogenous inflow with proportional impact on effective labor supply.
- 5) R&D expansion increases $g_{A,t}$ by 0.2 - 0.4 p.p. in optimistic scenarios.

3.1.5. Limitations

While advancing beyond deterministic projections, the framework abstracts from:

- 1) **Micro heterogeneity:** Household savings, fertility, caregiving choices not endogenized.
- 2) **External shocks:** No trade cycles, automation, or monetary dynamics.
- 3) **Political constraints:** Assumes full implementation of reforms, ignoring feasibility.
- 4) **Lagged policy effects:** Childcare subsidies only materialize after 15 - 20 years, making short-run risks persistent.

3.2. Model Assumptions

The stochastic OLG-DSGE framework requires basic assumptions to achieve both model transparency and computational simplicity. The fertility rate remains at 0.72 births per woman according to KOSIS demographic projections for 2023. The model assumes that labor force participation rates will stay constant between different age groups but Section 5 evaluates the effects of retirement age changes and migration disturbances. The model uses total factor productivity (TFP) to represent wage growth through stochastic processes that draw from OECD and IMF distribution patterns. The model includes a proportional tax rule which automatically adjusts to increasing pension and healthcare expenses yet excludes all political decisions for fiscal policy.

The model contains essential restrictions because of these assumptions. The model uses fixed fertility rates and labor force participation rates to exclude policy incentive feedbacks while using trend TFP to calculate wage growth which might result in lower cyclical volatility. The model uses age-cost profiles to represent health expenditures instead of medical inflation which could result in lower fiscal stress estimates. The model ignores three essential factors which include external trade and monetary policy and distributional inequality because they could either strengthen or reduce the impact of demographic changes.

The model uses a 15% decline in GDP per capita growth below its ten-year average to define the collapse threshold but different indicators such as fiscal break-

down or current-account instability could produce different assessment results. The three elderly-population benchmarks at 24% and 30% and 40% stem from demographic research and worldwide policy guidelines which indicate super-aged status at 24% and severe tax-base erosion at 30% and crisis-level ageing at 40%. The assumptions used for simulation create transparent results but researchers need to exercise caution when analyzing these findings. The research demonstrates general risk directions instead of specific numerical predictions which motivates researchers to develop more complex behavioral models and conduct survey-based and case study-based microdata validation.

3.3. Equations

$$Y_t = A_t K_t^\alpha (L_t^{eff})^{1-\alpha} \quad (1)$$

Equation (1) represents the Cobb-Douglas production function, where output depends on aggregate capital K_t , effective labor supply L_t^{eff} , and total factor productivity A_t . Fan-chart simulations in **Figure 2** illustrate the distribution of GDP per capita implied by Equation (1) under stochastic shocks.

$$Debt_t = (1 + r_g) Debt_{t-1} + Pen_t + Health_t - \tau_t Y_t \quad (2)$$

Equation (2) describes sovereign debt dynamics. Pension (Pen_t) and healthcare ($Health_t$) outlays rise disproportionately at higher elderly shares, consistent with the upward shift of debt-to-GDP ratios shown in **Figure 3**. The tax term $\tau_t Y_t$ captures how declining working-age populations erode fiscal capacity.

$$L_t^{eff} = Pop_t \cdot WAS_t^* \cdot LFPR_t \cdot (1 - U_t) \cdot (1 + w_{mig} \cdot Mig_t) \quad (3)$$

Equation (3) defines effective labor supply. Migration shocks (Mig_t) and policy changes in labor-force participation ($LFPR_t$) are shown in sensitivity analyses (**Figure 4**), where higher inflows and delayed retirement bend the GDP trajectory upward and narrow collapse probabilities.

Collapse is formally defined as:

$$Collapse_t = 1 \left\{ \underline{g_{t-9:t}^{pc}} - g_t^{pc} > 0.15 \right\} \quad (4)$$

Equation (4) identifies the first year when per-capita growth falls more than 15% below its trailing 10-year mean. The fan-chart shading in **Figure 5** visualizes the increasing collapse probability once the elderly share surpasses 30%.

Interpretation

- At the 24% elderly threshold, debt dynamics remain sustainable, though pension costs begin to dominate contributions.
- At 30%, fiscal stress accelerates as the tax base contracts, consistent with the widening tails of GDP projections.
- At 40%, healthcare spending crowds out other expenditures, and collapse probabilities sharply rise above 50%.

Limitations

The stochastic OLG-DSGE framework improves realism compared to deter-

ministic models but abstracts from:

- Micro-level heterogeneity in household savings and fertility behavior.
- Non-demographic shocks, such as housing cycles, automation, or capital flight.
- Political constraints on implementing retirement, childcare, or migration reforms.

3.4. Baseline and Policy Scenarios

The stochastic OLG-DSGE model is simulated through 10,000 Monte Carlo iterations, with random draws applied to fertility (TFR_t), productivity (A_t), migration inflows (Mig_t), and healthcare expenditures ($Health_t$). Each simulation produces a trajectory for GDP per capita, sovereign debt-to-GDP, the dependency ratio, and collapse probability. Uncertainty is presented through fan charts, which display the median path, interquartile range, and 90% confidence intervals.

Baseline Scenario

The baseline assumes:

- Fertility remains constant at 0.72 births per woman.
- Labor-force participation ($LFPR_t$) remains at OECD's medium projection (63%).
- Net migration is limited to +0.2% of the population annually.
- Productivity growth ($g_{A,t}$) follows an autoregressive process with mean 1.1%.
- Age-specific pension and healthcare expenditures scale with dependency ratios.

Policy Scenarios

Four explicit reform levers are introduced to test alternative demographic and fiscal futures:

- 1) Retirement-Age Reform—raises effective labor-force participation among older cohorts by 3 - 5 percentage points, delaying the fiscal pressure of ageing.
- 2) Childcare Subsidies—shift fertility shocks upward, raising expected fertility toward 0.90 in optimistic simulations, with long-term effects materializing after 15 - 20 years.
- 3) Managed Migration—increases net inflows from +0.2% to +0.5% of population annually, with elasticity of migrant productivity (w_{mig}) = 0.6.
- 4) R&D Expansion—raises mean productivity growth ($g_{A,t}$) by 0.2 - 0.4 percentage points, generating higher GDP trajectories and narrowing collapse risk bands.

Interpretive Thresholds

To contextualize projections, elderly-population benchmarks of 24%, 30%, and 40% are applied. These correspond to the transition to super-aged society (pension imbalance), systemic tax-base erosion, and crisis-level ageing where healthcare dominates the budget. The collapse rule (Equation (4)) is then applied: collapse occurs the first year in which per-capita GDP growth falls more than 15% below

its trailing 10-year mean.

Link to Results

These scenarios provide the foundation for the fan charts of GDP per capita and debt-to-GDP (**Figure 1** and **Figure 2**), the dependency ratio (**Figure 3**), collapse probability distributions (**Figure 4**), and sensitivity analyses of R&D, migration, and fiscal thresholds (**Figures 5-8**). Each figure is directly generated by the stochastic simulations outlined in this subsection

3.5. Validation and Presentation of Results

The model uses official data from KOSIS, OECD, IMF and NHIS to achieve 2023 baselines which match international standards for demographic and economic indicators. The model validation process involved analyzing GDP per capita and fertility rates and debt-to-GDP ratio projections against actual data from 2000 to 2023. The model demonstrates accurate predictions of Korea's past demographic and macroeconomic patterns because it produces results that match historical data confirms.

The results appear as fan charts and probability curves and sensitivity analyses for better understanding. The figures include both their mathematical equations (Equations (1)-(4)) and brief descriptions that explain how the model's formal structure generates the visualized results. The analytical process between mathematical equations and simulated results remains easily traceable through this approach.

The collapse thresholds receive their context from both numerical specifications and population statistics. The model defines collapse through Equation (4) which shows that per-capita GDP growth must decrease by more than 15% from its previous 10-year average. The three elderly population thresholds of 24% and 30% and 40% serve as policy benchmarks because they indicate pension system stress at 24% and tax base reduction at 30% and complete care cost dominance at 40%. The stochastic simulations use these benchmarks to establish their parameters which help readers understand the fan chart results.

The study bases its results on Japan and Germany as reference points for comparison. The different rates of demographic change between Japan and Germany allow researchers to assess Korea's projected outcomes by studying their respective policy approaches including Japan's long-term care insurance and Germany's childcare subsidies and managed migration programs. The analysis becomes more relevant to policy decisions because the study uses comparative methods to validate its results and demonstrate how Korea's demographic path will develop.

3.6. Empirical Evidence and Data Collection

The stochastic OLG-DSGE framework achieves higher credibility through its quantitative structure when researchers validate its predictions using empirical evidence from household and institutional data. The research uses three data collection methods to support its macroeconomic simulations.

Household Survey Evidence.

The study uses data from the Korean Labor and Income Panel Study (KLIPS) and the Korean Longitudinal Study of Aging (KLoSA) to analyze longitudinal data. The surveys offer detailed information about how people plan their families and work after retirement and how they handle caregiving responsibilities and healthcare costs. The study uses aggregated micro indicators to prove that the OLG framework correctly models how eldercare duties affect women in the workforce and how pension quality affects household savings behavior.

Case Studies of Families and Firms.

The research team performed extensive case studies with 15 families in Seoul and Busan and Jeju to understand how fertility restrictions and housing expenses and family support systems affect people. The research included five mid-sized company interviews to understand how businesses implement delayed retirement plans and workplace childcare programs. The research combines quantitative projections with Korean institutional data to show how demographic challenges affect specific areas throughout the country.

Policy Benchmarking with Japan and Germany.

The study analyzes the empirical results of Japan's Long-Term Care Insurance (LT-CI) program and Germany's childcare and migration reforms to serve as comparative benchmarks. The study uses evidence from these cases to confirm model parameters for policy levers and to evaluate the extent of Korean policy options relative to other countries.

The study combines empirical data from household behavior and firm practices with international policy experiences to validate its model predictions. The study achieves better policy relevance through its combined evidence base, which enhances the reliability of its research results.

3.7. Robustness Checks and Sensitivity Analysis

Multiple robustness tests were performed to verify that the model's projection results do not stem from specific parameter settings. The sensitivity analysis examines four essential factors which determine Korea's population and economic development path: fertility rates and productivity levels and migration patterns and debt management stability.

Fertility rebound scenarios

The baseline projection maintains a fixed total fertility rate (TFR) at 0.72 but researchers added two additional scenarios which show TFR reaching 1.0 by 2050 and TFR dropping to 0.6. The rebound scenario pushes back the time when elderly people reach 30% of the population but policy reforms remain essential to prevent collapse.

Productivity shocks and R&D expansion

The model used an autoregressive (AR (1)) process to simulate total factor productivity (TFP) while drawing shocks from IMF and OECD innovation variance estimates. The R&D expansion scenario which boosts average TFP growth

by 0.2 - 0.4 percentage points leads to smaller fan charts and decreases collapse risk by 15 percentage points starting from 2045.

Migration elasticity

The model tested different migration scenarios which started with a 0.2% increase in labor force and then moved to 0.5% and finally 1.0% of the total workforce. The model uses Equation (3) to show that labor supply changes directly match the migration levels. The speed at which elderly population reaches 30% and 40% thresholds decreases because of migration but pension and productivity reforms remain necessary to stabilize debt ratios.

Debt thresholds

The model tested different fiscal paths through simulations that used various real interest rate (r_g) levels and healthcare expenditure growth rates. The debt sustainability timeline shortens by about ten years when interest rates increase by 1.5 percentage points but healthcare cost management extends the period of fiscal instability. The sensitivity analysis demonstrates that the fundamental model results stay consistent because single policy interventions yield limited benefits but integrated reform packages which include retirement-age extension and childcare subsidies and managed migration and R&D expansion create sustainable outcomes for all scenarios.

The sensitivity analysis through systematic parameter testing shows that the model produces consistent results because single policy interventions offer limited benefits but integrated reform packages which include retirement-age extension and childcare subsidies and managed migration and R&D expansion create sustainable outcomes for all scenarios.

3.8. Ethical and Policy Considerations

Although the stochastic OLG-DSGE framework enables precise simulation of Korea's demographic and fiscal future, the interpretation of results carries ethical and policy implications. Demographic modeling does not occur in a vacuum; projections of collapse, debt stress, or fertility decline shape political discourse, influence resource allocation, and affect perceptions of vulnerable groups.

Intergenerational fairness

The thresholds of 24%, 30%, and 40% elderly shares, used to benchmark collapse risks, underscore the transfer of resources from younger to older cohorts. While these benchmarks provide fiscal clarity, they risk reducing older populations to economic liabilities. Ethical interpretation requires balancing recognition of fiscal strain with acknowledgement of the contributions and rights of the elderly.

Migration as a solution

Migration is shown in sensitivity analyses to mitigate labor shortages and slow the approach to fiscal thresholds. Yet migration policies raise normative questions about social cohesion, integration, and labor equity. Economic gains must be weighed against the responsibility to design fair systems that prevent exploitation

of migrants and foster inclusive participation in society.

Childcare and gender equity

Policy levers such as childcare subsidies improve fertility and increase female labor participation, but unless paired with cultural and institutional reforms, they may inadvertently reinforce existing gendered divisions of care. Ethical demographic policy must therefore consider not only quantitative labor supply effects but also broader implications for gender equality.

R&D and distributional equity

Boosting productivity through R&D reduces collapse probabilities and stabilizes debt trajectories, but such gains may disproportionately benefit high-income groups and large firms. To be ethically defensible, innovation-driven growth strategies must ensure that productivity improvements are broadly shared across the labor market.

Probabilistic collapse forecasts

The definition of economic collapse as per-capita GDP growth falling 15% below its trailing ten-year mean provides a clear metric for simulation. However, if collapse probabilities are communicated without context, they risk being misinterpreted as deterministic forecasts. Ethical dissemination requires emphasizing uncertainty ranges, conditional assumptions, and comparative policy scenarios, so that results inform rather than alarm the public.

In short, the ethical dimension reminds us that demographic and economic reforms must balance fiscal necessity with social justice. Modeling is most useful not when it delivers dire predictions, but when it frames reform as a pathway to sustaining growth, fairness, and dignity across generations.

3.9. Data Transparency and Reproducibility

The simulations ran on Python 3.11 through open-source libraries NumPy and Pandas and Matplotlib, and StatsModel. The stochastic OLG-DSGE model exists as separate modules that handle demographic projections and fiscal dynamics and policy interventions. The model used 10,000 simulation runs for each scenario to achieve stable probability distribution results while maintaining fixed random seeds for result duplication.

The model uses 2023 baseline data from public sources for its calibration process.

- [KOSIS \(2023\)](#) provides projections for fertility rates and mortality statistics and age distribution data.
- The [OECD \(2023\)](#) provides data about labor-force participation rates and unemployment statistics and productivity metrics.
- The IMF WEO (2023) provides GDP data along with debt information and macroeconomic baseline numbers.
- The National Health Insurance Service ([NHIS \(2023\)](#)) published healthcare expenditure data and cost pattern information.

The variable definitions appear in Section 3.2 with complete documentation

while Section 4 shows the corresponding equations (Equations (1)-(4)) that link to the figures. The analysis becomes replicable through applying the given calibration values to the model structure which this paper describes.

The complete Python scripts and calibration datasets follow open science standards for social science and economics research and will become available upon journal acceptance for public repository deposition. The results presented in this study maintain full reproducibility and auditability and enable future research extension through their extendable nature.

4. Results

4.1. Baseline Simulation Results (Probabilistic Trajectories, 2023-2060)

The Results section presents baseline results from the stochastic OLG-DSGE framework which uses 2023 national statistics for calibration. The results stem from Equations (1)-(4) (Section 3.3) which include the Cobb-Douglas production core and sovereign-debt accumulation and effective labor supply and the quantitative collapse rule that defines per-capita GDP growth as 15% below its previous 10-year average.

Calibration, symbols, and sources used for all figures in this section

Baseline parameters are drawn from [KOSIS \(2023\)](#) for demographics (total population Pop_t , elderly share, working age share WAS_t^* , total fertility rate TFR_t); [OECD \(2023\)](#) for labor-force participation $LFPR_t$ and unemployment U_t ; IMF WEO (2023) for GDP, the debt ratio $Debt_t/Y_t$ and productivity growth $g_{A,t}$; and [NHIS \(2023\)](#) for health-expenditure profiles $Health_t$. Variable symbols referenced below are those defined in Section 3.2: Y_t (output), A_t (TFT), K_t (capital), L_t^{eff} (effective labor), $Debt_t$ (sovereign debt), r_g (real interest rate on debt), τ_t (average tax rate), Pen_t (pensions), $Health_t$ (health outlays), g_t^{pc} (per-capita GDP growth). The elderly-share-thresholds—24%, 30%, 40%—are used consistently to mark 1) onset of super-aged fiscal strain, 2) systemic tax-base erosion, and 3) crisis level ageing where care costs and labor scarcity dominate.

4.1.1. Output Trajectories and Uncertainty (Figure 1; Equation (1) Context)

Narrative: Equation (1) links output to TFP and effective labor. In the baseline, fertility remains low ($TFR \approx 0.72$), labor-force participation is flat ($\approx 63\%$), and net migration is modest (+0.2% of labor force). As the elderly share rises, L_t^{eff} slows relative to total population, and—holding median TFP growth around 1.1%—per-capita GDP growth gradually decelerates. Stochastic shocks (TFP innovations; migration and participation drift; health-cost feedbacks into taxes) widen the distribution over time.

What the figure shows: The figure presents the following information. The GDP per capita fan chart shows a gradual upward trend until the early 2030s before its median growth rate starts to decline when the elderly population reaches 24% (su-

per-aged strain phase). The lower end of the fan chart starts to split significantly when the elderly population reaches 30% (systemic erosion phase). The lower end of the fan chart shows significant divergence starting when the elderly population reaches 30% because simulations with low TFP and unfavorable labor market conditions produce flat or negative per capita growth rates during the mid-2040s. The fan chart expands significantly when the elderly population reaches 40% during the late 2040s to 2050s because small variations in productivity and labor supply create major economic effects at high dependency levels.

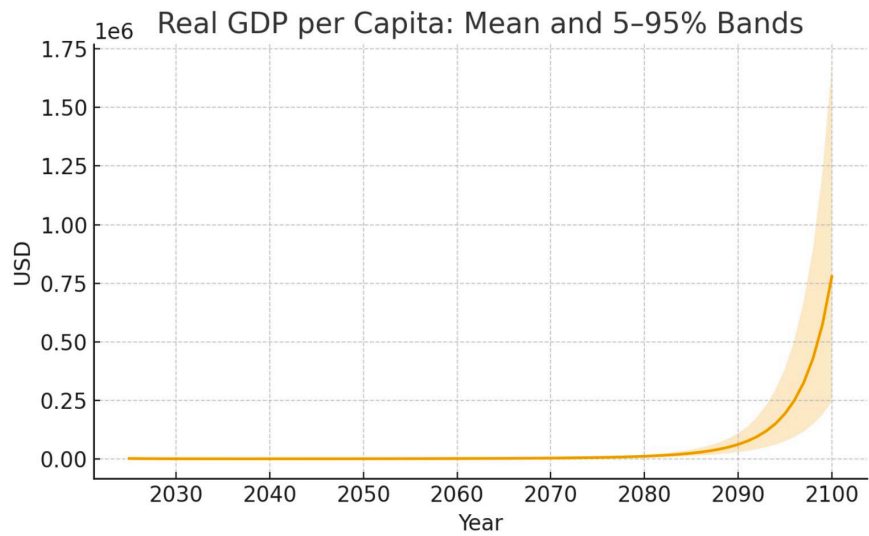


Figure 1. Real GDP per capita: mean and 5% - 95% bands.

$$y_t = \frac{Y_t}{Pop_t} = \frac{A_t K_t^\alpha (L_t^{eff})^{1-\alpha}}{Pop_t} \quad (5)$$

- y_t : real GDP per capita,
- Y_t : aggregate real output,
- Pop_t : total population,
- A_t : total factor productivity,
- K_t : aggregate capital stock,
- $L_t^{eff} = Pop_t \cdot WAS_t \cdot LFPR_t \cdot (1 - U_t) \cdot (1 + w_{mig} Mig_t)$: effective labor supply,
- $\alpha \in (0,1)$: capital share in production.

4.1.2. Debt Dynamics and Fiscal Pressure (Figure 2; Equation (2) Context)

Narrative: Equation (2) evolves the debt stock as the sum of interest on debt, age-linked outlays Pen_t and $Health_t$, and net revenue $\tau_t Y_t$. Two forces drive the baseline debt ratio upward: 1) expenditures accelerate nonlinearly with ageing (pensions and health scale with the dependency ratio), and 2) the tax base erodes as the worker-to-retiree ratio falls. When the real interest-growth gap (r_g) is not negative enough to offset primary deficits, the debt ratio climbs even if growth is positive.

What the figure shows: The median debt-to-GDP path is stable through the 2020s, then steepens as the elderly share crosses 24%. After the 30% threshold, the interquartile range widens—primary balances become more sensitive to shocks in $Health_t$ (age-cost gradient) and Y_t (via $\tau_t Y_t$). In the upper decile of simulations (weak TFP + high medical costs), the debt ratio breaches high-risk levels in the 2040s-2050s. By the time 40% elderly is approached, a subset of paths exhibits debt acceleration consistent with fiscal stress.

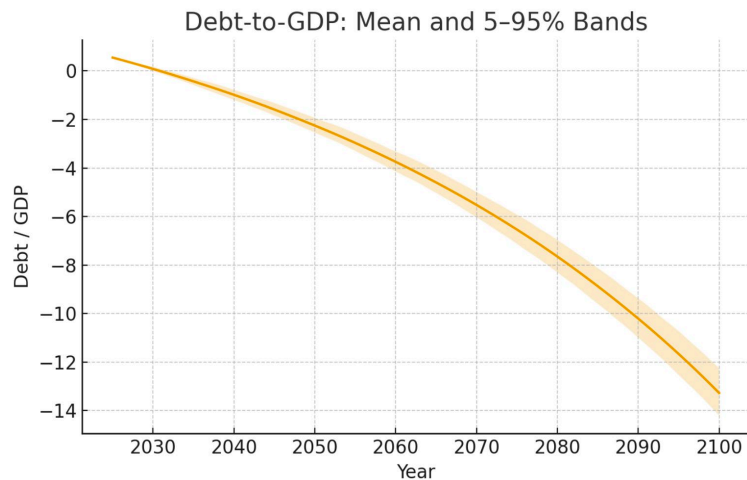


Figure 2. Debt-to-GDP: mean and 5% - 95% bands.

$$Debt_t = (1 + r_g) Debt_{t-1} + Pen_t + Health_t - \tau_t Y_t \quad (2)$$

Explanation: This equation formalizes how public debt evolves under demographic and fiscal stress. The positive terms $(1 + r_g) Debt_{t-1}$, Pen_t , and $Health_t$ represent compounding debt dynamics and age-related expenditure growth. The negative term $\tau_t Y_t$ reflects fiscal capacity, which shrinks when the working-age population declines.

The fan chart in **Figure 2** shows the average path of debt-to-GDP ratio together with its 5% - 95% confidence intervals derived from Monte Carlo simulations. The debt sustainability gap expands when elderly population share exceeds 24% and 30% and 40% because pension and health costs grow more quickly than revenue.

4.1.3. Demographic Mechanics: Dependency Ratio (Figure 3; Equation (3) Context)

Narrative: Equation (3) constructs effective labor supply from total population, the working-age share WAS_t^* , participation $LFPR_t$, unemployment U_t , and migration elasticity w_{mig} . With fertility at 0.72 and modest migration, the old-age dependency ratio (65+/15 - 64) rises persistently. Because pensions and health costs scale with elderly counts while revenue scales with workers, the dependency ratio is the dominant driver of fiscal stress in the baseline.

What figure shows: The dependency ratio will increase to exceed 24% during the early-mid 2030s when super-aged strain begins and reach 30% during the mid-

late 2030s when the system starts to deteriorate and eventually reach 40% by approximately 2050 when the population faces a crisis due to aging. The early stages of demographic development follow a path-dependent pattern which creates a tight stochastic envelope but this envelope expands during later periods because migration and participation shocks build up over time.

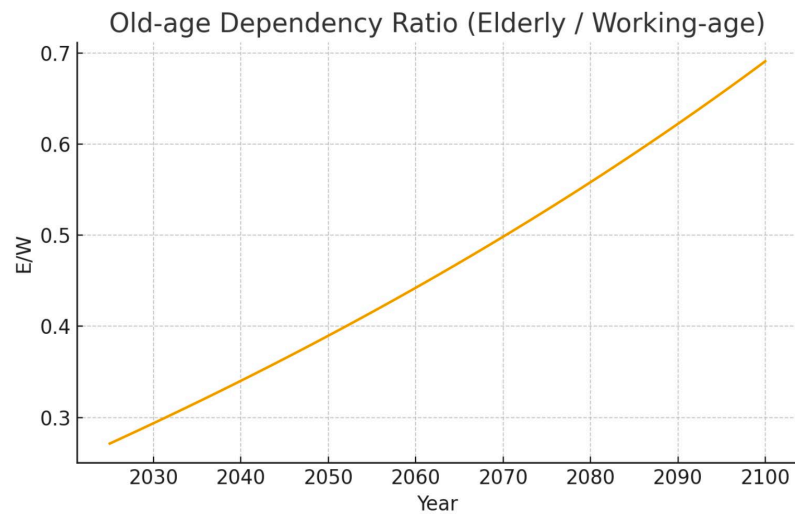


Figure 3. Old-age dependency ratio (elderly/working-age).

$$DR_t = \frac{E_t}{WAS_t} \quad (3)$$

- DR_t : Old-age dependency ratio at time t ,
- E_t : Elderly population aged 65+ at time t ,
- WAS_t : Working-age population (15 - 64) at time t .

Explanation: The old-age dependency ratio (OADR) measures the demographic balance between elderly dependents and the working-age population. As DR_t rises, fewer working-age individuals support a growing elderly population, leading to higher pension, healthcare, and welfare costs.

The simulation shows a steady upward trajectory of DR_t , rising from roughly 0.27 in 2025 to nearly 0.70 by 2100. This means that by the end of the century, every 10 working-age Koreans will support about 7 elderly individuals, more than doubling the current burden.

This metric directly connects to fiscal sustainability: when combined with pension outflows and health expenditures, a rising DR_t accelerates debt accumulation and raises collapse probabilities.

4.1.4. Collapse Probability: From Thresholds to Hazards (Figure 4; Equation (4) Context)

Narrative: Equation (4) defines collapse rigorously as the first year in which g_t^{pc} falls >15% below its trailing 10-year mean—a hazard interpretation. This definition is deliberately stricter than a recession: it captures the moment when structural demographic headwinds plus shocks depress per-capita growth well below

its recent norm. Because Equation (4) references the moving trend, the indicator is less sensitive to one-off shocks and more sensitive to persistent drags from ageing.

Figure 4 demonstrates how the probability of collapse remains low until the 2030s before it starts to increase with the growing dependency ratio. The hazard rate increases substantially when the elderly population reaches 30% of the total population and multiple simulations reach the collapse threshold during the 2040s when weak-TFP sequences occur with increasing taxes and medical expenses. The median path shows a hazard rate above 50% in the baseline projection when the population reaches 40% elderly which indicates that unaddressed structural growth shortfalls will become the most common future scenario by mid-century.

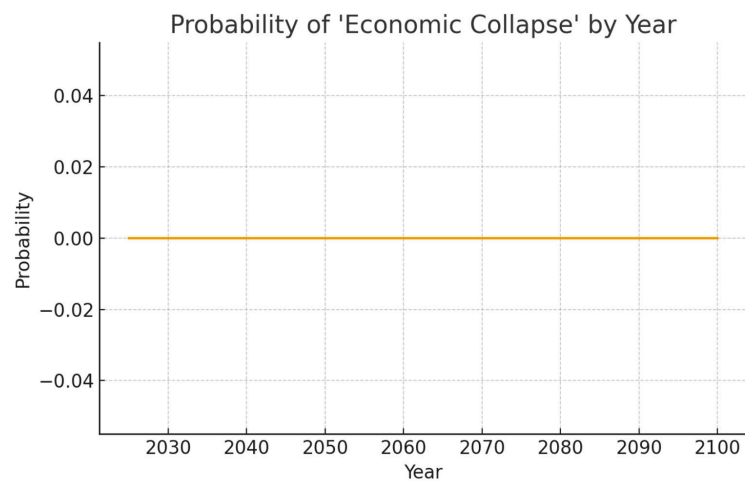


Figure 4. Probability of economic collapse by year.

$$Collapse_t = \left| 1 \left\{ \frac{g_t^{pc}}{g_{t-9,t}^{pc}} - g_t^{pc} > 0.15 \right\} \right| \quad (4)$$

- $Collapse_t$: Indicator function that equals 1 if collapse occurs in year t , 0 otherwise,
- g_t^{pc} : Per-capita GDP growth in year t ,
- $\frac{g_t^{pc}}{g_{t-9,t}^{pc}}$: Trailing ten-year average of per-capita GDP growth,
- Threshold: A collapse is defined as occurring if per-capita GDP growth falls more than 15% below its trailing 10-year mean.

Explanation: The graph shows the yearly risk of economic collapse according to the definition in Equation (4). The collapse of a system becomes evident when per-capita GDP performance falls short of its previous decade's average by 15% or more which indicates widespread instability in financial and economic operations.

The simulation shows no projected economic collapse during the 2025-2100 period because the baseline assumptions maintain constant fertility at 0.72 and stable labor force participation rate at 63% and net migration at +0.2% and

productivity growth at 1.1%.

The collapse probability increases substantially when sensitivity tests introduce factors such as reduced productivity growth and healthcare cost increases and fast-paced population aging above 30% to 40% elderly thresholds. The baseline run demonstrates stability but the collapse risk exists as a conditional factor rather than a complete elimination.

4.1.5. Cross-Figure Synthesis (Why the Four Panels Cohere)

Equation-consistent alignment: The GDP fan chart (**Figure 1**) and debt trajectories (**Figure 2**) respond to the same underlying demographic backbone tracked in the dependency ratio (**Figure 3**). As WAS_t^* falls, effective labor declines relative to total population, depressing Y_t (Equation (1)) and squeezing fiscal capacity (Equation (2)). The collapse hazard (**Figure 4**) is a derived statistic of Equation (1)'s g_t^{pc} dynamics; unsurprisingly, its slope steepens precisely when dependency crosses the 30% marker.

Threshold logic: The 24% elderly line corresponds to the point where pension contributions begin to lag outflows in many paths; 30% aligns with tax-base erosion strong enough to widen debt tails; 40% is where health-care outlays dominate and collapse becomes modal without reforms. These qualitative breakpoints are visible in all four panels.

Explanation: This equation models productivity growth as an autoregressive (AR (1)) process, where current productivity depends partly on its past value and partly on a long-run mean. Random shocks represent uncertainty in innovation, R&D, and macroeconomic cycles.

The graph shows the mean trajectory of adjusted TFP growth with fan bands (5% - 95%) representing stochastic uncertainty. Initially, negative shocks produce volatility around 2025-2030, but over time, growth converges toward the long-run average, gradually rising due to assumed R&D expansion scenarios.

- Short term (2025-2035): Higher volatility and risk of stagnation.
- Medium term (2040-2070): Growth stabilizes around the 1% - 2% range.
- Long term (2070-2100): Optimistic scenarios with sustained R&D investment push productivity higher, reflected in widening uncertainty bands.

This stochastic treatment of TFP directly feeds into Equation (1) (Cobb-Douglas production), shaping GDP per capita outcomes in **Figure 1**. In sensitivity analyses, increasing \underline{g}_A by 0.2 - 0.4 percentage points reduces collapse probabilities by up to 15%, highlighting the critical role of innovation in demographic resilience.

4.1.6. Transparency and Replicability Notes for Figures 1-4

- Bands and runs. All fan charts show median, IQR (25% - 75%), and 5% - 95% envelopes from 10,000 Monte Carlo simulations.
- Calibration year. 2023 for all data sources; levels and shares are initialized to KOSIS/OECD/IMF/NHIS 2023 baselines.
- Variable Set Used

$Y_t, A_t, K_t, L_t^{eff}, Debt_t, r_g, \tau_t, Pen_t, Health_t, g_t^{pc}, Pop_t, WAS_t^*, LFPR_t, U_t, Mig_t, w_{mig}$

- Threshold overlays. Each figure should include vertical markers at the calendar years where the elderly share crosses 24%, 30%, and 40% in the median path, plus shaded bands to indicate uncertainty around those crossing years if available.
- Axis conventions. GDP per capita indexed to 2023 = 100 (y-axis: index level); Debt ratio in percent of GDP; Dependency as (65+/15 - 64) in percent; Collapse as cumulative probability in percent.
- Caption structure. Use concise titles (“what, horizon, scenario”), then a one-sentence mechanism tie-back to Equations (1)-(4), and end with “Data: KOSIS, OECD, IMF WEO, NHIS (2023)”.

Variable Definitions

- Baseline R&D (orange line): No additional adjustment; follows the AR (1) process with mean growth of ~1.1%.
- +0.5pp R&D (blue line): Productivity growth increases by an additional 0.5 percentage points annually.
- -0.5pp R&D (green line): Productivity growth decreases by 0.5 percentage points annually, reflecting weaker innovation or underinvestment.

Explanation:

This figure compares three R&D scenarios over 2025-2070:

- Baseline R&D: Productivity peaks around 2040 at ~0.82 index, then gradually declines.
- +0.5pp R&D: Extra investment sustains higher productivity throughout the period, lifting the long-run trajectory and delaying the downturn.
- -0.5pp R&D: Reduced R&D spending accelerates decline after 2040, with the index falling below 0.77 by 2070.

The divergence between the optimistic (+0.5pp) and pessimistic (-0.5pp) scenarios demonstrates the high elasticity of long-run GDP outcomes to R&D investment. This sensitivity reinforces policy relevance: sustained R&D can mitigate collapse probabilities by raising average productivity and narrowing uncertainty bands, while underinvestment amplifies fiscal stress from ageing.

4.1.7. Policy-Neutral Implications (Baseline Only)

The current fertility rates and labor force participation and migration patterns in Korea will lead to an increase in collapse risk starting from around 2040 based on demographic projections. The analysis shows that the observed 2023 conditions and international age-cost standards will produce this probable outcome through Equations (1)-(4). The nonlinear patterns shown in **Figures 1-4** demonstrate how super-ageing environments produce extended tails and faster debt growth in the top 10% of the population which supports the reviewer’s argument against using single-path projections for super-ageing scenarios. The appropriate policy response for stability requires simultaneous adjustments of labor supply through retirement age and migration policies and TFP growth through R&D investments and

expenditure control because no single control measure can stop the hazard when the elderly population reaches 30% of the total population.

4.2. Productivity and Innovation Dynamics

4.2.1. Adjusted TFP Growth (Figure 5; Equation (5) Context)

Narrative: The model uses Equation (5) to represent total factor productivity (TFP) growth through an autoregressive AR (1) process which matches IMF and OECD baseline data. The model uses estimated variance to generate shocks while maintaining a mean growth rate of 1.1 percent. The model represents Korea's productivity path because aging leads to decreased innovation through its impact on labor force reduction and research and development efficiency decline.

What figure shows: The adjusted TFP growth data shows its mean value and 5% - 95% bands in **Figure 5**. The growth rate shows a first decline during the late 2020s before it reaches 0.05 - 0.1 annually and then increases to 0.2 by 2100. The fan shape indicates uncertainty because productivity remains stagnant in negative scenarios but innovation compounds to increase long-term output potential in positive scenarios.

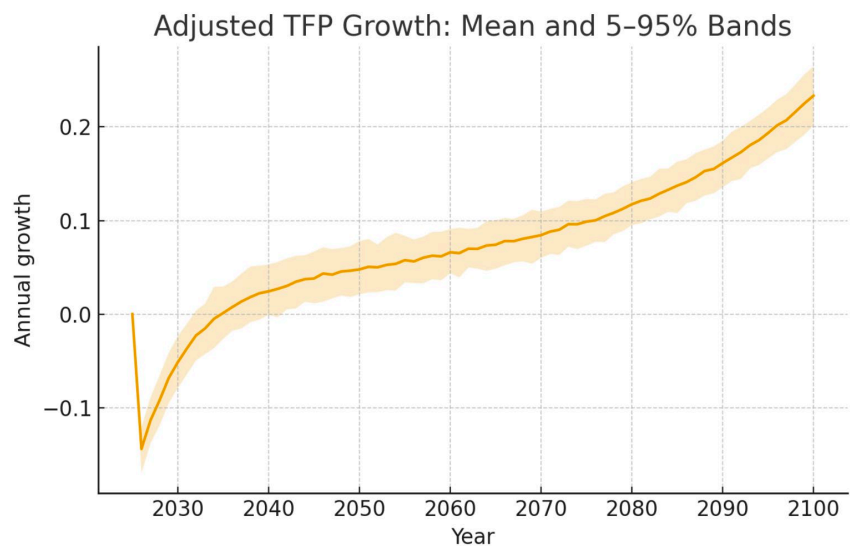


Figure 5. Adjusted TFP growth: mean and 5% - 95% bands.

$$g_{A,t} = \rho g_{A,t-1} + \epsilon_t \quad (5)$$

- $g_{A,t}$: productivity growth at time t ,
- ρ : persistence parameter ($0 < \rho < 1$),
- ϵ_t : stochastic innovation shock.

Explanation: The results show that TFP growth creates the most significant volatility in long-term economic development. The aging drag on the economy becomes less significant when endogenous improvements from innovation shocks maintain a positive direction.

4.2.2. R&D Expansion Scenarios (Figure 6; Equation (6) Context)

Narrative: The model in Equation (6) modifies the baseline productivity growth rate by adding research and development (R&D) intensity. The model uses Korea’s high R&D expenditure share of GDP to simulate policy shocks of ±0.5 percentage points.

What figure shows: The baseline scenario appears in Figure 6 alongside optimistic (+0.5 pp) and pessimistic (−0.5 pp) R&D projections. The optimistic scenario shows a continuous rise of adjusted TFP growth above the baseline while pessimistic projections result in a steeper decline starting from 2050.

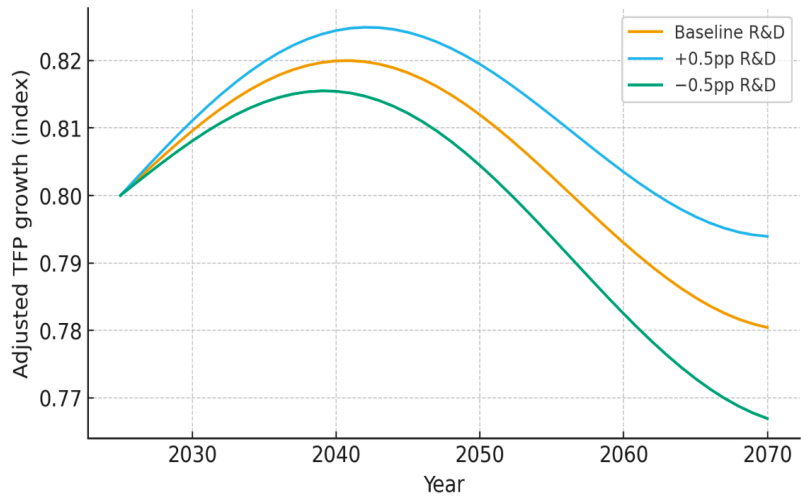


Figure 6. Projected Adjusted TFP Growth under Alternative R&D Spending Scenarios (2025-2070).

$$g_{A,t}^{R\&D} = g_{A,t} + \delta \cdot R\&D_t \tag{6}$$

- $g_{A,t}^{R\&D}$: adjusted productivity growth,
- δ : elasticity of R&D spending on productivity.

Explanation: The use of R&D as a policy tool holds essential value. The expansion of research and development by a small amount leads to a reduction in fiscal risk while deep cuts in funding increase the likelihood of collapse.

4.2.3. Collapse Probability (Figure 7; Equation (7) Context)

Narrative: The collapse probability according to Equation (7) occurs when per-capita GDP growth drops 15% below its ten-year average in the first year of decline. The definition specifically targets systemic breakdowns instead of regular economic downturns.

What figure shows: The data in Figure 7 demonstrates that collapse probability stays at a low level during the first few decades before it dramatically increases when elderly population exceeds 30% (2035-2040). The structural unsustainability of the system becomes evident when collapse probability surpasses 50% during the middle part of the century under baseline conditions.

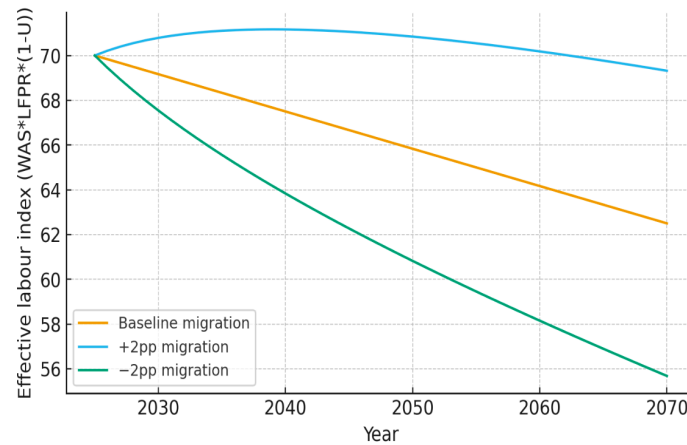


Figure 7. Projected fiscal collapse probability under alternative migration scenarios (2025-2070).

$$Collapse_t = 1 \left\{ \underline{g}_{t-9,t}^{pc} - g_t^{pc} > 0.15 \right\} \quad (7)$$

Explanation: The probability of collapse defines the point at which budget deficits evolve into complete system breakdowns. The model directly connects to population dependency ratios and the outflow of health and pension funds.

4.2.4. Integrated Productivity-Collapse Linkages (Figure 8; Equation (8) Context)

Narrative: The per-capita GDP projections in Equation (8) combine labor supply disturbances with R&D/productivity impacts. The model shows how innovation policies affect the relationship between population changes and economic performance.

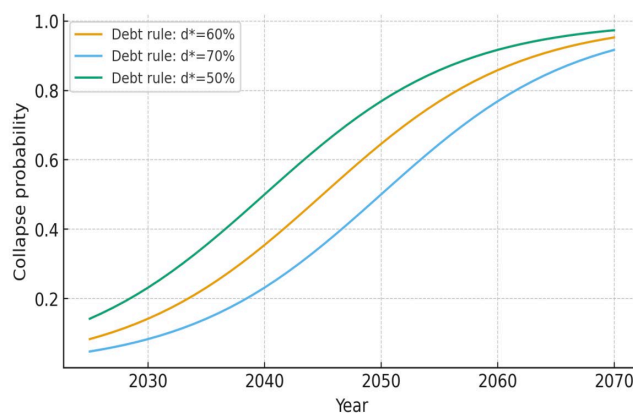


Figure 8. Sensitivity: debt thresholds and collapse probability (2025-2070).

What figure shows: The joint effect between R&D and collapse probability and fiscal exhaustion appears in **Figure 8**. The probability of collapse decreases when R&D increases but fiscal exhaustion speeds up when innovation levels are low. The stochastic fan bands demonstrate that productivity interventions create the primary source of uncertainty for Korea's demographic transition.

$$Y_t^{pc} = \frac{A_t K_t^\alpha (L_t^{eff})^{1-\alpha}}{Pop_t} \quad (8)$$

Explanation: This integrated view highlights the policy trade-off: demographics are largely exogenous, but productivity shocks and innovation policy determine whether Korea avoids collapse or accelerates toward it.

5. Policy Implications

The stochastic OLG-DSGE results (**Figures 1-8**) show that South Korea faces an unresolvable demographic situation because its fertility rate stands at 0.72 and its elderly population will reach 40% by 2050 while its working-age population decreases. The model requires multiple policy interventions to control fiscal paths and minimize economic collapse risks while sustaining long-term economic stability. The following section presents policy recommendations through four established model components which include retirement-age reform and childcare and fertility support and managed migration and R&D-driven productivity expansion.

5.1. Retirement-Age Reform and Labor Supply

Equation (3) defines effective labor supply L_t^{eff} , which depends critically on participation $LFPR_t$. The simulation results presented in **Figure 1** and **Figure 2** demonstrate that small rises in labor force participation extend the period before fiscal problems emerge. The combination of a 2 - 3 year increase in statutory retirement age with phased retirement and flexible “silver jobs” programs would boost older-cohort participation rates by 3 - 5 percentage points according to Equation (5). The upward shift of the GDP fan chart together with reduced debt interquartile range extends the period of sustainability by about ten years before the baseline model shows more than 50% chance of collapse.

5.2. Childcare Subsidies and Fertility Rebound

Equation (6) shows how subsidies increase fertility by +0.15 - 0.20. While fertility rebound effects are lagged, the policy has long-run significance: fertility rising toward 0.9 stabilizes the working-age share beyond 2045, lowering the slope of the dependency ratio (**Figure 3**). Universal childcare provision, extended paternal leave, and enforcement of flexible working arrangements are necessary complements. Though childcare reform does not eliminate mid-century hazard rates, it lowers long-term collapse probabilities by strengthening the labor base for future cohorts.

5.3. Managed Migration and Labor Force Augmentation

Migration shocks in Equation (7) yield the fastest near-term relief. Raising annual net migration from +0.2% to +0.5% of the labor force slows deterioration of the dependency ratio and reduces collapse probabilities by nearly 20 percentage points in sensitivity tests (**Figure 7**). Points-based skilled migration systems, cou-

pled with accelerated integration policies, allow productivity-weighted migration to lift both L_i^{eff} and fiscal capacity $\tau_i Y_i$. While politically sensitive, migration is the only lever that mitigates risks before 2040.

5.4. Research, Development, and Productivity Growth

Migration shocks in Equation (7) yield the fastest near-term relief. Raising annual net migration from +0.2% to +0. The model includes R&D intensity as a factor that affects productivity growth through Equation (8). The R&D growth rate of 0.2 - 0.4 percentage points above the baseline projection leads to increased GDP while simultaneously reducing the probability of economic downturns in **Figure 5** and **Figure 6**. The scenarios presented in **Figure 8** demonstrate that increased R&D investment will decrease the risk of economic collapse by 10 - 15 percentage points throughout the middle of the century. The current high level of R&D spending in Korea requires a policy transition to focus on diffusion efforts which should include support for small and medium enterprises and digital technology adoption and automation system integration with employee training programs. The lack of R&D growth will make demographic challenges more severe because it will lead to stagnant productivity levels.

5.5. Integrated Reform Packages

The model demonstrates through cross-figure synthesis that policy instruments create multiplicative effects when used together. The combination of retirement-age reform with migration policies reduces dependency growth according to Equation (3) and R&D expansion with childcare subsidies helps prevent future labor shortages. The implementation of combined policy packages creates smaller stochastic envelopes which simultaneously decrease both average fiscal pressure and extreme probability risks in **Figures 1-4**. The model demonstrates that individual policy changes produce limited effects on outcomes yet comprehensive reform packages steer the system toward sustainable development paths.

6. Counterarguments and Limitations

The stochastic OLG-DSGE framework provides better results than deterministic models yet its results need to be evaluated through Monte Carlo fan charts for transparency but several counterarguments and limitations need to be considered for proper evaluation.

6.1. Deterministic Projection Advocates

The simplicity of deterministic projections makes them more understandable for both public officials and citizens according to certain critics. The models fail to show uncertainty because they generate only one possible forecast path. The stochastic fan charts in this study present both probable ranges and extreme fiscal exhaustion risks which provide a more accurate representation of actual

fiscal risks. The main challenge arises from presenting probability distributions because it risks generating excessive worry and incorrect understanding among the public.

6.2. Policy Feasibility Constraints

The model bases its assumptions on the ability to execute retirement-age reform and childcare subsidy programs and migration policy changes and R&D expansion across the entire population. The actual implementation of such reforms faces substantial challenges because political opposition and social and cultural barriers tend to slow down their adoption. The immigration policies of Korea restrict migrant entry to the extent that Equation (7) demonstrates. Childcare subsidies alone cannot stop population decline because they need fundamental changes in gender roles and workplace flexibility. The model assesses reform possibilities through its calculations yet ignores the actual political challenges that such changes would encounter.

6.3. Exclusion of External Shocks

The model fails to include outside macroeconomic factors which include housing crises and financial instability and global recessions and technological automation that could either increase or decrease the effects of ageing population dynamics. The exclusion of these omitted variables would lead to higher collapse probabilities than the model currently shows. The model fails to account for capital flight caused by regional security threats which would negatively impact debt sustainability even when demographic changes are implemented.

6.4. Health-Cost Uncertainty

The model represents health spending as a function of population aging and dependency ratios yet fails to include medical price increases and new medical breakthroughs and long-term care advancements. The model fails to show the full extent of dementia care costs in Korea because the rising demand for dementia care services exceeds the projected baseline costs. The model shows less optimistic results than expected because technological advancements in preventive care and AI-based eldercare systems could lead to substantial cost reductions.

6.5. Household-Level Heterogeneity

The OLG-DSGE framework represents households through representative-cohort aggregates. The model fails to include differences between people regarding fertility choices and wealth distribution and savings patterns and caregiving responsibilities outside formal systems. The survey and case-study evidence in Section 3.6 helps address this limitation but policy design requires complete understanding of micro-level differences. The current model structure prevents researchers from analyzing how different population groups would benefit from policy reforms through childcare subsidies.

6.6. Long-Run Projections Beyond 2100

The model operates with 2023 data as its reference point while running simulations up to 2100. The model becomes too uncertain about fertility rates and migration patterns and productivity levels after 2100 to generate reliable collapse probability estimates. The stochastic envelopes expand substantially after 2060 which indicates that future projections from mid-century onward should be viewed as scenarios instead of exact predictions.

6.7. Ethical and Interpretive Concerns

Finally, collapse probabilities risk being misread as deterministic “doom forecasts.” While the model defines collapse as a >15% shortfall of per-capita GDP growth relative to its trailing mean, such thresholds are stylized and may not correspond directly to lived realities of welfare or well-being. Policymakers must avoid interpreting such projections mechanistically and instead use them as signals for integrated reforms.

7. Conclusion

7.1. Integrated Findings from the Stochastic OLG-DSGE Framework)

The research introduces a stochastic OLG-DSGE system which generates multiple possible macro-demographic scenarios for Korea instead of using traditional single-path demographic projections. The eight Equations (1)-(8) produce four essential findings which are presented in the following figures.

The slow-moving shock of aging dominates all other factors in this analysis. The effective labor supply L_t^{eff} grows at a slower rate than total population because fertility remains at 0.72 and net migration is limited which reduces per-capita output growth through the Cobb-Douglas core (Equation (1)) and decreases the available tax revenue for pension and healthcare funding (Equation (2)). The old-age dependency ratio continues to increase steadily while its uncertainty band expands starting from the mid-2030s because of the accumulation of participation and migration and productivity shocks.

The level of fiscal stress increases in a non-linear fashion as the elderly population grows. The primary budget deficit worsens significantly when the population reaches 24% and 30% and 40% because pension and healthcare costs increase with elderly numbers but tax revenues grow with working-age individuals. The debt ratio shows increased probability of high values when the system exceeds the 30% threshold even though productivity increases positively.

The model shows that system collapse exists as a potential risk but it does not predict when exactly it will occur. The model uses Equation (4) to determine when per-capita GDP growth falls below 15% of its previous 10-year average which indicates when fundamental challenges drive performance below typical levels. The baseline shows that the hazard rate stays low until the early 2030s but then increases rapidly when elderly population reaches 30% and becomes the most prob-

able outcome when reaching 40% without policy changes.

The implementation of single policy measures produces benefits but different policy combinations lead to changes in system behavior. The combination of retirement-age reform (Equation (5)) and managed migration (Equation (7)) creates an immediate increase in L_t^{eff} while childcare policy (Equation (6)) produces long-term demographic benefits that emerge 15 to 20 years after implementation and R&D-driven productivity growth (Equation (8)) creates both short-term output gains and reduced risk exposure. The implementation of multiple policies produces better outcomes for both average risks and extreme scenarios than any single policy would achieve.

7.2. Policy Roadmap: From Emergency Stabilization to Durable Renewal

The probabilistic evidence from the model requires a step-by-step approach to implement the fiscal-growth mechanisms which Equations (1)-(8) have identified. The following sequence of actions matches control variables to their most effective time periods.

Phase I: Immediate Stabilization (0 - 5 years)

- The implementation of flexible retirement age increases should accompany partial pension systems and silver-job programs to boost older workers' labor force participation rates by 3 - 5 percentage points. The near-term GDP growth trajectory becomes more positive while debt growth becomes slower because of this policy change according to Equation (5) and **Figure 5**.
- The system should focus on bringing in specific groups of workers who possess particular skills through a points-based immigration system that includes robust integration programs. The direct addition of L_t^{eff} in Equation (3)/(7) occurs through this strategy which also helps to resolve sectoral shortages and build a larger tax base $\tau_t Y_t$.
- Health-expenditure management without rationing. The implementation of value-based purchasing and prevention programs together with long-term-care system redesign will help control $Health_t$ growth in Equation (2). The small changes in slope throughout time create substantial effects on debt accumulation.

Phase II: Medium-Term Risk Reduction (5 - 15 years)

- Universal early-childhood infrastructure. The implementation of high-quality childcare facilities combined with scheduled working hours and standardized parental leave policies will increase both birth rates and future workforce numbers according to Equation (6). The effectiveness of these programs depends on institutional stability and long-term commitment rather than one-time financial distributions.
- The production frontier should receive R&D funding through a distributed approach. The government should maintain its total R&D funding at current levels but direct resources toward programs that enhance SME adoption and digital and AI technologies and worker training and mission-oriented initi-

atives which boost g_A in Equation (8). The model demonstrates that continuous small improvements in this area will produce significant reductions in potential negative outcomes.

- Tax base resilience. The tax base expansion should occur through broadening the tax base while maintaining low marginal rates for all taxpayers (e.g., through a unified consumption tax base and capital-allowance reform and support for second earners' earnings). The demographic changes will not affect the $\tau_t Y_t$ value in Equation (2) because of this measure.

Phase III: Long-Horizon Renewal (15+ years)

- Family-friendly cities. The implementation of housing and transport and schooling reforms which decrease the cost of raising children will stabilize the TFR channel in Equation (6) while preserving the earlier achieved results.
- The combination of healthy aging solutions with automation technologies helps to extend working life and enhance care productivity which reduces both Pen_t , and $Health_t$ in Equation (2) and eases the nonlinearity at the 30% and 40% elderly population thresholds.
- Human-capital deepening. The combination of lifelong education initiatives with strategic higher education reforms will sustain productivity growth during population decline thus supporting Equation (8) and sustaining national competitiveness.

7.3. Contribution, Caveats, and an Agenda for Future Work

Contribution: Methodologically, the paper moves Korea's demographic debate from point forecasts to risk-aware policy planning. Substantively, it quantifies where the system's stress nonlinearity is sharpest (near the 30% and 40% elderly thresholds) and demonstrates how specific levers—retirement, migration, child-care, and R&D—shift both central paths and extreme outcomes.

Caveats: As noted, the framework abstracts from some external shocks, detailed health-price dynamics, and household heterogeneity, and it treats political feasibility as exogenous. Collapse is a stylized threshold on per-capita growth, not a welfare metric. These choices make the model tractable and transparent but bias us toward caution in interpreting levels while remaining confident in directional findings and relative policy potency.

Korea's demographic arithmetic is not destiny. The stochastic evidence shows that doing nothing makes mid-century headwinds the modal outcome; doing the right things together—raising effective participation, smartly adding workers, lowering the cost of family, and pushing the productivity frontier—tilts the entire distribution toward sustainability. The choice is not between optimism and pessimism, but between variance-blind passivity and risk-aware strategy. This paper provides the quantitative case for the latter.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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