

Efficient Decumulation Strategy with Health Risk and Bequest

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Abstract

With the global shift from defined benefit to defined contribution pension systems, retirement planning is now fully borne on individuals elevating their exposure to longevity, health, and market risks. This transition has prompted more precautionary saving behaviour, as retirees become more conservative in fully consuming their wealth. This research proposes a decumulation strategy which combines long-term care insurance (LTCI) and guaranteed minimum death benefit (GMDB) purchased at retirement with a withdrawal-then-rebalance investment approach. Within this framework, the retirement fund is modelled using a regime-switching structure, while a target volatility strategy detects asset allocation to smooth wealth dynamics and reduces likelihood of extreme losses. The LTCI covers late-life healthcare costs, whereas the GMDB secures a minimum bequest, thereby supporting both consumption confidence and legacy objectives. Numerical experiments compare consumption patterns under this strategy with default drawdown strategies on account-based pension schemes and lifetime annuities. Results reveal that the proposed strategy provides smoother long-term consumption and better resilience to adverse financial shocks. Sensitivity analyses further explore variations in insurance allocation ratios, health state transitions, and target volatility levels are performed. Preliminary results suggest that moderate volatility targets strike an effective balance between risk and sustainability, and that the strategy remains robust across different health scenarios.

Keywords: Retirement decumulation, Dynamic withdrawal strategy, Target volatility strategy, Long-term care insurance, Guaranteed minimum death benefit, Regime-switching model, Post-retirement risk management.

1 Introduction

The global pension system is undergoing a structural transition from defined benefit (DB) to defined contribution (DC) schemes, shifting retirement investment and spending risks from institutions to individuals. This shift is particularly pronounced in countries such as Australia, where DC arrangements dominate the retirement landscape (Basu et al., 2010). Consequently, retirees are increasingly required to manage accumulated wealth during the decumulation phase while

facing multiple and interacting sources of uncertainty, which Alonso-García et al. (2022) identify as including longevity risk, market risk, and late-life health expenditure risk. In this context, the design of retirement income strategies calls for coordinated decisions on withdrawals, portfolio allocation, and insurance use, in line with policy efforts to develop retirement solutions that better reflect the circumstances and needs of actual retirees (Australian Government Treasury, 2022).

Against this background, retirement decumulation has become a central issue in pension finance. Based on their reviews of the major approaches to managing retirement income, MacDonald et al. (2013) and Bernhardt et al. (2018) classify existing studies into three broad strands: heuristic withdrawal rules, optimisation-based approaches, and annuitisation-based solutions. The first strand proposes practical withdrawal rules that are easy to communicate and implement, but typically abstracts from dynamic market conditions, health shocks, and insurance choices (Bengen, 1994; Milevsky et al., 2011; Piggott et al., 2005). The second strand derives retirement decisions from formal objective functions, such as utility maximisation, ruin minimisation, expected shortfall control, and bequest attainment, thereby providing theoretically coherent solutions to consumption and portfolio choice under uncertainty (Yaari, 1965; Bayraktar et al., 2016; Xu et al., 2023). However, such models often rely on preference parameters and modelling assumptions that are difficult to calibrate, interpret, and implement in practice, particularly for retirees with limited financial expertise (Vigna, 2014; Forsyth et al., 2019; Forsyth, 2022). The third strand focuses on insurance and retirement products designed to hedge specific post-retirement risks: life annuities mitigate longevity risk, long-term care insurance addresses late-life care expenditure risk, and death-benefit guarantees support bequest motives (Brown et al., 2011). Yet empirical and behavioural evidence indicates that demand for these products remains limited by liquidity concerns, precautionary saving motives, framing effects, and the persistent annuity puzzle (Mitchell et al., 2011; Peijnenburg et al., 2016; Peijnenburg et al., 2017).

Collectively, these strands provide important insights but yield only partial solutions. In the bulk of existing studies, withdrawal smoothing, portfolio protection, long-term care risk management, and bequest support are examined separately rather than within a unified framework (Bernhardt et al., 2018; Forsyth, 2022; Bär et al., 2023). In practice, however, these dimensions are closely interdependent: withdrawal decisions affect portfolio sustainability, investment losses can intensify late-life expenditure pressure, and insurance choices influence both liquid wealth and terminal bequests. Despite these interactions, relatively few studies develop post-retirement frameworks that jointly integrate dynamic withdrawal strategies,

portfolio risk control, long-term care protection, and bequest provision while remaining sufficiently transparent and practically interpretable for real-world retirement planning (Olivieri et al., 2022; Piggott et al., 2005; Brown et al., 2011).

This paper addresses this gap by developing an integrated decumulation strategy that combines a time-varying annuity-style withdrawal rule, a target volatility investment strategy, LTCI, and a GMDB. The proposed framework incorporates a multi-state health transition model and a regime-switching market model to evaluate consumption stability, wealth sustainability, long-term care protection, and bequest security under interacting post-retirement risks. By not treating full annuitisation as the central design principle, the framework remains relevant for retirement systems in which individuals retain control over accumulated savings, while also permitting subsequent comparison with annuity-based benchmarks.

The remainder of the paper is organised as follows. Section 2 outlines the design of the proposed decumulation strategy, including initial wealth allocation, insurance components, withdrawal rules, and wealth dynamics. Section 3 develops the stochastic modelling framework, comprising the multi-state health transition model, the regime-switching financial market, and the target volatility strategy. Section 4 presents the numerical results and comparative analysis across alternative scenarios. Section 5 concludes and discusses potential extensions.

2 Decumulation Strategy Design

At retirement, the individual faces a multiple objective decision problem involving investment, consumption, and insurance. The retiree allocates initial wealth across three components: LTCI, a GMDB, and liquid investable wealth. Thereafter, retirement wealth is progressively decumulated through a time-varying annuity-style withdrawal rule, while out-of-pocket long-term care expenditure and death benefits are directly incorporated into the wealth dynamics.

2.1 Initial Wealth Allocation

Let W_0 denote the retiree's total wealth at retirement. At time $t = 0$, a proportion $\omega_L \in [0, 1]$ of initial wealth is allocated to the purchase of LTCI, while a proportion $\omega_G \in [0, 1 - \omega_L]$ is allocated to the GMDB rider. The remaining wealth is held in a liquid account available for portfolio allocation and withdrawal. Accordingly, the investable wealth immediately after the insurance purchases is given by

$$W(0^-) = (1 - \omega_L - \omega_G)W_0, \quad (1)$$

where $W(0^-)$ denotes the liquid investable wealth after the insurance purchases at time $t = 0$. Equation (1) formalises the initial allocation of retirement wealth between insurance protection and liquid financial capital. Specifically, the LTCI allocation provides a hedge against future health-related expenditures, the GMDB allocation secures a minimum bequest, and the remaining wealth supports consumption and investment.

2.2 Insurance Structure

The proposed decumulation strategy incorporates two optional insurance riders purchased at retirement: LTCI and GMDB. These products complement the withdrawal and investment decisions by protecting against uncertain long-term care costs and the risk of leaving insufficient terminal wealth to beneficiaries.

2.2.1 Long-Term Care Insurance

Following Xu et al. (2023), the actuarially fair premium for a full-coverage LTCI contract is defined as the expected present value of long-term care (LTC) expenditure incurred in the functionally disabled states. Let $h_j(t)$ denote the health-care cost at time t in health state $j \in \{2, 4\}$, and let $\pi^t(s_0, j)$ denote the t -step transition probability from the initial state s_0 to state j . Then the full-coverage premium can be represented as

$$P = \sum_{t=1}^T \left(\prod_{k=1}^t \frac{1}{1 + r(k)} \right) [\pi^t(s_0, 2) h_2(t) + \pi^t(s_0, 4) h_4(t)]. \quad (2)$$

To account for LTC inflation, the health-care cost in the disabled states evolves according to

$$h_j(t) = h_j(1)(1 + q)^{t-1}, \quad j \in \{2, 4\}, \quad (3)$$

where q is the annual inflation rate for disability-related long-term care expenditure. The retiree may choose only partial LTCI coverage. Let $\theta \in [0, 1]$ denote the proportion of long-term care expenditure reimbursed by the policy. Consistent with the amount allocated to LTCI at retirement, the coverage ratio is defined as

$$\theta = \frac{\omega_L W_0}{P}. \quad (4)$$

When $\theta = 1$, the retiree purchases full actuarially fair coverage, while for $\theta < 1$ only a fraction of care costs is reimbursed.

2.2.2 Guaranteed Minimum Death Benefit

Following Ignatieva et al. (2016), the death benefit is defined as the greater of a guaranteed amount G and the value of the GMDB-linked investment account $F_G(t)$ at the time of death. Thus, if death occurs at time t , the benefit payment is

$$\max(G, F_G(t)). \quad (5)$$

The guaranteed amount is funded through an initial allocation of wealth to the GMDB rider. Specifically,

$$\omega_G W_0 = F_G(0) = G. \quad (6)$$

The GMDB guarantee is determined by the share of initial wealth committed to this rider. This contract therefore allows the retiree to preserve a baseline bequest while still permitting the GMDB-linked account to participate in financial market.

2.3 Time-Varying Annuity Withdrawal Rule

The central component of the decumulation strategy is a time-varying annuity withdrawal rule. At each decision time $t > 0$, the retiree withdraws an amount $C(t)$ for consumption before the remaining wealth is rebalanced between risky and risk-free assets. The withdrawal amount is determined by converting currently available wealth into annuity-style income, conditional on the retiree's current age and health state.

Let $s_t \in \{1, 2, 3, 4, 5\}$ denote the retiree's health state at time t , with $s_t = 5$ representing death. Let $\ddot{a}_{x+t}^{s_t}(t)$ denote the annuity-due factor at age $x + t$, conditional on health state s_t , where x is the retirement age. Let $W(t^-)$ denote the investable wealth immediately before withdrawal at time t , $h_{s_t}(t)$ the associated LTC cost, and $\theta \in [0, 1]$ the LTCI coverage rate. Then the withdrawal rule is expressed as

$$C(t) = \frac{W(t^-) - (1 - \theta) h_{s_t}(t) 1_{\{s_t \in \{2, 4\}\}}}{\ddot{a}_{x+t}^{s_t}(t)} 1_{\{s_t \in \{1, 2, 3, 4\}\}}. \quad (7)$$

Equation (7) defines time- t consumption as an annuity-style payout from net investable wealth. For $s_t \in \{2, 4\}$, the uninsured portion of long-term care expenditure, $(1 - \theta)h_{s_t}(t)$, is deducted prior to consumption. The withdrawal amount depends on both health-contingent expenditure needs and the health-state-specific annuity factor, allowing consumption to adjust to evolving survival prospects and health risks. No consumption occurs when $s_t = 5$.

This withdrawal rule may be interpreted as a dynamic annuity-style spending

policy. It updates consumption over time in response to changes in the retiree's health state, and provides a mechanism for smoothing consumption while retaining flexibility in the presence of investment and health shocks.

2.4 Wealth Dynamics

Let $S(t^-)$ and $B(t^-)$ denote the stock and bond holdings immediately before withdrawal at time t , with total pre-withdrawal wealth

$$W(t^-) = S(t^-) + B(t^-).$$

After consumption, out-of-pocket long-term care expenditure, and any death benefit payment triggered at time t , post-withdrawal wealth evolves according to

$$W(t^+) = W(t^-) - C(t) + \max(G, F_G(t))1_{\{s_t=5\}} - (1 - \theta) h_{s_t}(t)1_{\{s_t \in \{2,4\}\}}. \quad (8)$$

Equation (8) shows that retirement wealth changes through three channels: living consumption, uninsured long-term care costs, and the death benefit payment. Combined with the withdrawal rule in (7), it fully characterises the retiree's decumulation mechanism. In particular, consumption and care expenditure reduce on-path wealth when the individual is alive, while the GMDB creates an off-path terminal liability that is paid only upon death. The inclusion of LTCI and GMDB therefore affects both the level and the composition of retirement wealth over time.

2.5 Rebalancing

Following withdrawal, the remaining post-withdrawal wealth is reallocated between the risky asset and the risk-free bond according to the target volatility strategy. If $\alpha(t) \in [0, 1]$ denotes the fraction of wealth invested in the risky asset at time t , then the post-rebalancing holdings are represented as

$$S(t^+) = \alpha(t)W(t^+), \quad B(t^+) = (1 - \alpha(t))W(t^+). \quad (9)$$

Figure 1 summarises the timing convention of the model. Wealth first accumulates through market returns over the period, then consumption and health-related cash flows are applied, and finally the remaining wealth is rebalanced between stock and bond holdings.

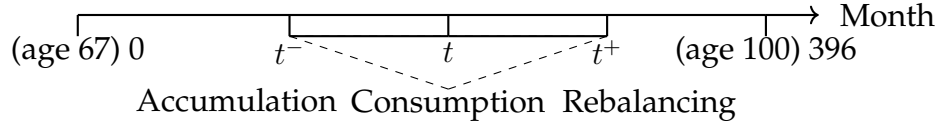


Figure 1: Time index for the consumption and rebalancing process.

3 Modelling Framework

Having specified the design of the decumulation strategy, we now develop the stochastic framework used to model the key sources of uncertainty and dynamic portfolio choice in retirement. The framework contains three main components: a multi-state health process for the retiree's health transitions, a regime-switching financial market model for asset returns and interest rates, and a target volatility strategy for adjusting risky-asset exposure over time. These components jointly determine the state variables entering the withdrawal rule and the wealth dynamics, and therefore form the basis for the subsequent numerical analysis.

3.1 Health State Process

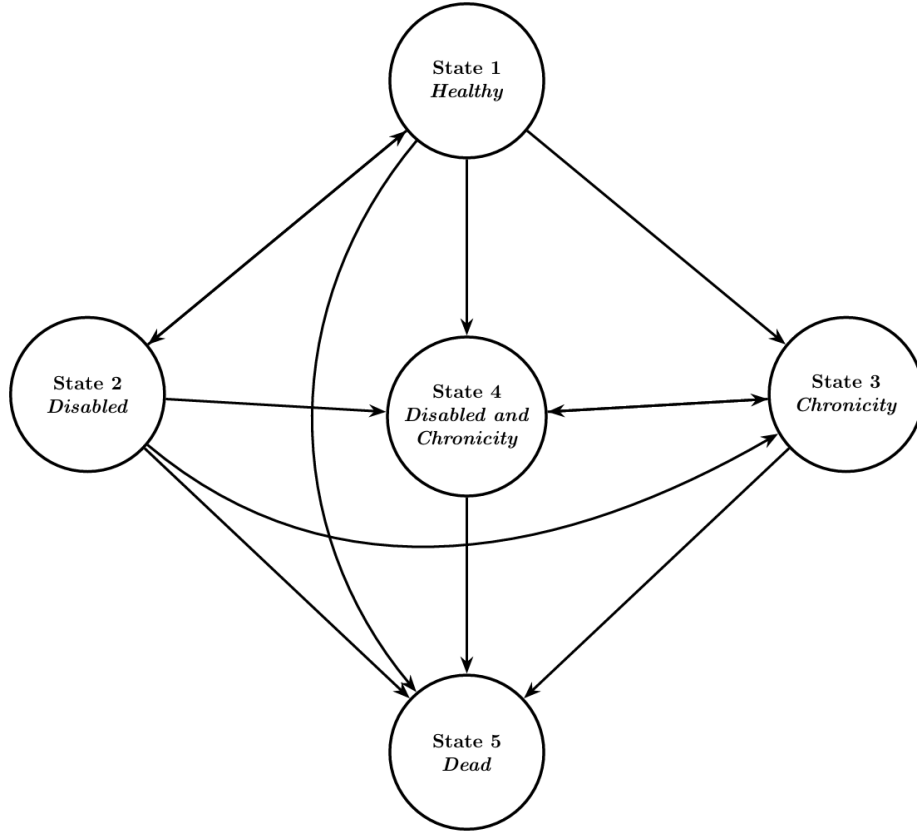


Figure 2: Five-state health transition model based on Park et al. (2023) and Sherris et al. (2021).

Following Sherris et al. (2021), we model the retiree's health status as a discrete-state continuous time Markov process $s_t \in \{1, 2, 3, 4, 5\}$, where each individual occupies one of five mutually exclusive states at any point in time, as shown in Figure 2. State 1 represents good health, referring to individuals who exhibit no functional limitations. State 2 corresponds to functional disability without chronic illness and is defined by the presence of at least two limitations in Activities of Daily Living (ADLs). State 3 captures chronic illness without functional impairment and includes individuals with a history of major chronic conditions such as heart disease, diabetes, lung disease, or stroke. State 4 reflects a more advanced stage of deterioration in which chronic illness and functional disability coexist. State 5 denotes death and serves as an absorbing state.

This five-state classification distinguishes chronic disease burden from functional impairment, which are the two principal dimensions of late-life health deterioration. The age-dependent transition probabilities are derived from estimated transition intensities based on Survey of Disability, Ageing and Carers (SDAC) data, following the empirical methodology of Park et al. (2023). Each transition intensity $\lambda_{i \rightarrow j}(t)$ from state i to state j is modelled as a log-linear function of age, gender, and calendar time:

$$\ln\{\lambda_{i \rightarrow j}(t)\} = \beta_{i \rightarrow j} + \gamma_{i \rightarrow j}^{age}x(t) + \gamma_{i \rightarrow j}^{female}F + \phi_{i \rightarrow j}t, \quad (10)$$

where $\beta_{i \rightarrow j}$ is the baseline log-intensity, $x(t)$ denotes age, F is a gender indicator, and $\phi_{i \rightarrow j}t$ captures systematic time trends across SDAC survey waves.

Let $Q^{int}(t) = [\lambda_{i \rightarrow j}(t)]$ denote the transition intensity matrix. The one-period transition probability from state i to state j is then obtained through the matrix exponential:

$$\pi^1(i, j) = [\exp(Q^{int}(t)\Delta t)]_{ij}, \quad \Delta t = 1. \quad (11)$$

Equation (11) provides the age- and state-dependent transition probabilities required to simulate future health trajectories and to construct state-specific survival-contingent quantities such as annuity-due factors.

3.1.1 Health-Care Costs by Health State

Health-care expenditure varies substantially across health states, particularly between chronic illness and functional disability. In the Australian aged-care system, functional disability is assessed according to limitations in Activities of Daily Living (ADLs), and the assessed care needs determine eligibility and the level of

government-funded support under the Support at Home program.¹ Consistent with policy practice, an individual in our model is classified as functionally disabled when at least two ADL limitations are present. To link disability severity to financial costs, we map ADL limitations to the Australian Support at Home funding schedule, as summarised in Table 1.

Table 1: Support levels, ADL requirements, and annual funding estimates (AUD). Source: AgedCareOnline (2025).

Level	ADLs Requiring Assistance	Annual Funding (AUD)
Level 1	0	\$10,696.72
Level 2	1	\$15,981.68
Level 3	1–2	\$21,919.77
Level 4	1–2	\$29,545.33
Level 5	2–3	\$39,535.04
Level 6	2–4	\$47,957.41
Level 7	5–6	\$58,122.13
Level 8	6	\$77,709.00

For numerical implementation, we set the first-year disability-related long-term care cost at AUD 50,000 for states $s_t \in \{2, 4\}$. This choice lies near the middle of the Australian aged-care funding range for moderate to severe care and serves as a parsimonious benchmark for functional disability expenditure.

By contrast, chronic illness without functional disability is assumed to generate negligible out-of-pocket long-term care expenditure, as the bulk of the associated costs are absorbed by the Australian public health system through Medicare and the Pharmaceutical Benefits Scheme (Australian Government Department of Health and Aged Care, 2025).

Thus, health-care expenditure arises only when the retiree is functionally disabled, that is, in either state 2 or state 4, while no such cost is applied in the healthy, chronic-only, or death states.

3.2 Regime-Switching Market Model

To capture the uncertainty and structural shifts in financial markets, we adopt a regime-switching framework in which key market parameters are modelled through a finite-state Markov process. This allows asset returns, interest rates, and volatilities to adapt to macroeconomic conditions such as bull and bear markets.

¹Australian Government Department of Health and Aged Care. *Support at Home Program: Assessment, Eligibility and Funding Levels*. Available at: <https://www.health.gov.au/our-work/support-at-home>.

3.2.1 Regime Representation and State Process

We describe the state of the financial market utilising an observable, continuous-time, finite-state Markov chain $\mathbf{X}(t) := \{X(t)\}_{t \in \mathcal{T}}$ defined on a filtered probability space $(\Omega, \mathcal{F}, \mathbb{P})$, with a finite state space $\mathcal{S} = \{\mathbf{e}_1, \dots, \mathbf{e}_N\} \subset \mathbb{R}^N$, where each $\mathbf{e}_j$ is a standard unit basis vector. The states represent distinct economic regimes (such as, bull and bear markets). Let $Q = [q_{ij}] \in \mathbb{R}^{N \times N}$ be the intensity matrix of the Markov chain, where q_{ij} denotes the instantaneous transition intensity from regime i to regime j . Following Shen et al. (2014), the Markov chain satisfies the semi-martingale representation:

$$\mathbf{X}(t) = \mathbf{X}(0) + \int_0^t Q^\top \mathbf{X}(s) ds + \mathbf{M}(t), \quad (12)$$

where $\mathbf{M}(t)$ is an $(\mathcal{F}^{\mathbf{X}}, \mathbb{P})$ -martingale, and $\mathbb{F}^{\mathbf{X}}$ denotes the natural filtration of $\mathbf{X}(t)$.

3.2.2 Asset Dynamics under Regime Switching

The financial market consists of a risk-free bond $B(t)$ and a risky asset $S(t)$, with dynamics described by a regime-switching model. The related parameters depend on the market regime. Specifically, we define

$$r(t) = \langle r, X(t) \rangle, \quad \kappa(t) = \langle \kappa, X(t) \rangle, \quad \sigma(t) = \langle \sigma, X(t) \rangle. \quad (13)$$

Here, r , κ , and σ are vectors of regime-specific parameters in $\mathbb{R}^N$. The process $X(t) \in \{\mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_N\} \subset \mathbb{R}^N$ is a continuous-time finite-state Markov chain that captures the market regime. The stock price follows a geometric Brownian motion process within each regime. The dynamics and recursion of the stock and bond prices under regime-switching are described by the following equations:

$$\frac{dS(t)}{S(t)} = \kappa(t) dt + \sigma(t) dW_t, \quad (14)$$

$$S(t + \Delta t) = S(t) \exp \left(\left(\kappa(t) - \frac{1}{2} \sigma(t)^2 \right) \Delta t + \sigma(t) \sqrt{\Delta t} Z_t \right), \quad (15)$$

where $W(t)$ is a Brownian motion and Z_t is a standard Normal random variable. The bond price is determined by a regime-dependent risk-free rate.

$$\frac{dB(t)}{B(t)} = r(t) dt \quad \Rightarrow \quad B(t + \Delta t) = B(t) e^{r(t) \Delta t}, \quad (16)$$

where $r(t)$ is the regime-dependent risk-free rate.

3.3 Target Volatility Strategy

To incorporate risk-managed investment behaviour into the decumulation framework, we adopt a target volatility strategy (TVS), as proposed in Olivieri et al. (2022). This approach links the allocation to the risky asset to observed market volatility, allowing the retiree to maintain portfolio risk close to a pre-specified target level over time. Such strategies are widely used in volatility-controlled investment products and retirement income design.

3.3.1 Strategy Definition

Following Olivieri et al. (2022), conditional equity volatility is estimated using an Exponentially Weighted Moving Average (EWMA) specification:

$$\sigma_t^2 = \lambda \sigma_{t-\Delta t}^2 + (1 - \lambda) r_t^2, \quad r_t = \ln S(t) - \ln S(t - \Delta t), \quad (17)$$

where σ_t^2 denotes the variance estimate at time t , r_t is the log-return of the risky asset, and $\lambda \in (0, 1)$ is a smoothing parameter. In line with the empirical implementation in Olivieri et al. (2022), we set $\lambda = 0.8$, which balances responsiveness and stability in volatility estimation.

The estimated volatility is annualised as

$$\hat{\sigma}(t) = \sqrt{252 \sigma_t^2}. \quad (18)$$

The allocation to the risky asset is then determined by

$$\alpha(t) = \min \left\{ \frac{\text{TV}}{\hat{\sigma}(t)}, 1 \right\}, \quad (19)$$

where TV is the target volatility level and $\alpha(t) \in [0, 1]$ denotes the fraction of wealth invested in the risky asset, with the remainder allocated to the risk-free bond.

This allocation rule reduces equity exposure in periods of high volatility and increases it when volatility is low, providing a simple and implementable mechanism for dynamic risk control.

4 Numerical Experiments

This section presents numerical experiments designed to evaluate the performance of the proposed decumulation framework, which integrates long-term care insur-

ance (LTCI) and a guaranteed minimum death benefit (GMDB) within a regime-switching financial market and a multi-state health system. The analysis is structured in three parts. First, a baseline specification is introduced to characterise the joint evolution of wealth, consumption, and bequest outcomes under the integrated strategy. Second, a sensitivity analysis examines how key design parameters influence financial sustainability and exposure to uninsured health costs. Finally, a case study compares alternative withdrawal rules across different initial wealth levels, with outcomes evaluated in the presence of the public Age Pension.

4.1 Baseline Setup

Age	Male			Female			Total		
	Number	Average account balance (\$)	Median account balance (\$)	Number	Average account balance (\$)	Median account balance (\$)	Number	Average account balance (\$)	Median account balance (\$)
Under 18	86,100	8,465	408	83,418	5,291	238	169,945	6,890	307
18–24	1,087,140	10,353	6,380	1,046,107	9,204	5,784	2,137,403	9,783	6,071
25–29	985,680	29,044	21,742	954,371	26,569	21,048	1,940,735	27,822	21,395
30–34	1,004,821	58,461	42,962	979,247	49,446	38,070	1,984,448	54,009	40,426
35–39	975,840	101,642	78,289	951,950	80,647	61,022	1,928,031	91,265	69,200
40–44	927,145	150,305	116,076	885,833	117,067	85,804	1,813,147	134,054	100,330
45–49	813,134	206,484	154,751	782,134	158,331	110,864	1,595,368	182,866	131,705
50–54	819,686	271,498	192,196	801,978	205,029	134,309	1,621,741	238,616	161,375
55–59	724,571	341,115	220,560	706,835	260,199	154,732	1,431,452	301,151	185,120
60–64	673,481	413,700	236,126	648,440	327,440	174,655	1,321,960	371,379	203,326
65–69	511,284	466,600	230,766	495,530	407,328	207,187	1,006,830	437,422	218,631
70–74	348,662	516,393	227,027	337,870	468,678	228,978	686,545	492,903	227,982
75 or more	396,164	562,305	200,477	359,509	484,818	195,201	755,676	525,439	197,878
Unknown	122	55,380	8,026	92	95,568	12,514	100,098	13,530	1,160
Total	9,353,830	202,644	71,914	9,033,314	164,206	57,688	18,493,379	182,781	63,339

Table 2: Average superannuation balances by age and gender in Australia. Source: Australian Taxation Office (2023).

The baseline specification serves as a benchmark for all subsequent numerical experiments. Initial retirement wealth is calibrated to the average superannuation account balance of Australian females aged 65–69, as reported by the Australian Taxation Office (2023), yielding $W_0 = 407,328$ AUD. At retirement, full long-term care insurance coverage is purchased, corresponding to a coverage ratio of $\theta = 1$. In addition, 20% of initial wealth is allocated to the guaranteed minimum death benefit rider. The remaining wealth, after accounting for the LTCI premium and GMDB allocation, is invested in financial markets under a target volatility strategy. This specification captures the trade-off between insurance protection and investable wealth, providing a consistent basis for the subsequent numerical analysis.

Demographic risk is modelled using a five-state Markov health transition model, which generates age-dependent probabilities of occupying each health state (Fig-

ure 3). The model captures the gradual deterioration of health over the life cycle, with declining probabilities of good health and increasing likelihood of chronic illness, disability, and death. The simulation horizon is truncated at age 100, which encompasses the overwhelming majority of lifetimes while preserving statistical reliability at advanced ages. Health states are observed annually and assumed to remain constant within each year, ensuring consistency between health transitions and annual cost realisations.

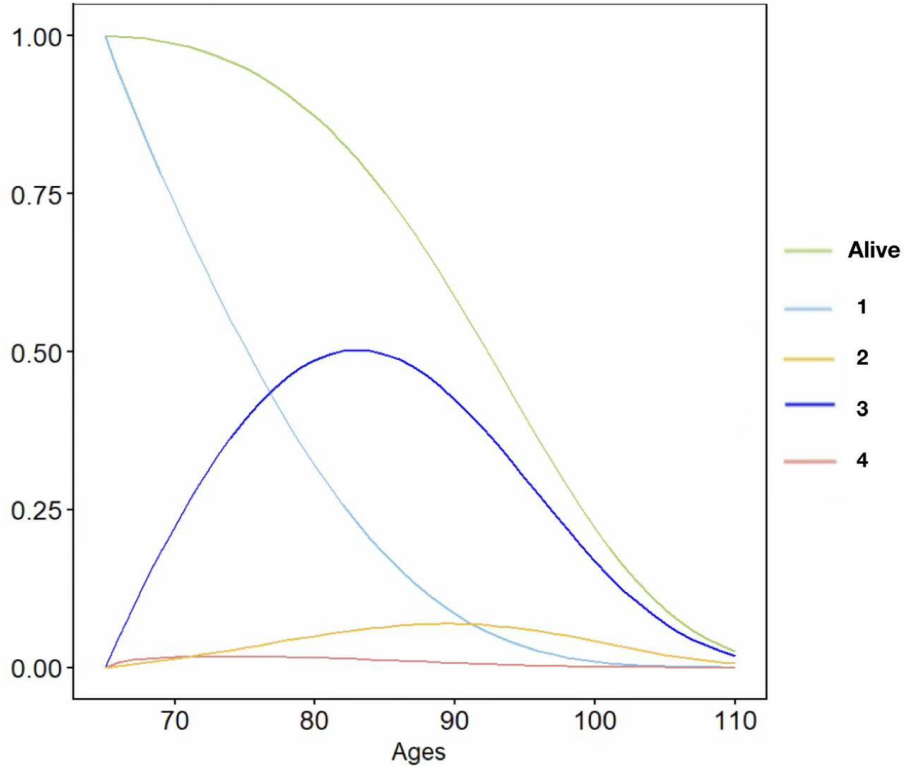


Figure 3: Age-specific health-state probabilities for females implied by the five-state Markov health model calibrated to SDAC transition data.

The financial market is described by a two-state Markov regime-switching model following Shen et al. (2014). The bull regime is associated with higher expected returns and lower volatility, whereas the bear regime features lower returns and heightened volatility. Asset dynamics are therefore regime-dependent through drift, volatility, and risk-free rates. Within this environment, the TVS adjusts the equity share endogenously to maintain a constant target volatility of 20%, thereby linking portfolio allocation directly to prevailing market conditions.

The regime-switching structure introduces persistent variation in both returns and risk, which is particularly relevant over long retirement horizons. Periods of elevated volatility and negative returns coincide with bear regimes, while bull regimes generate smoother growth paths. This dynamic environment provides a natural setting in which volatility targeting becomes economically meaningful.

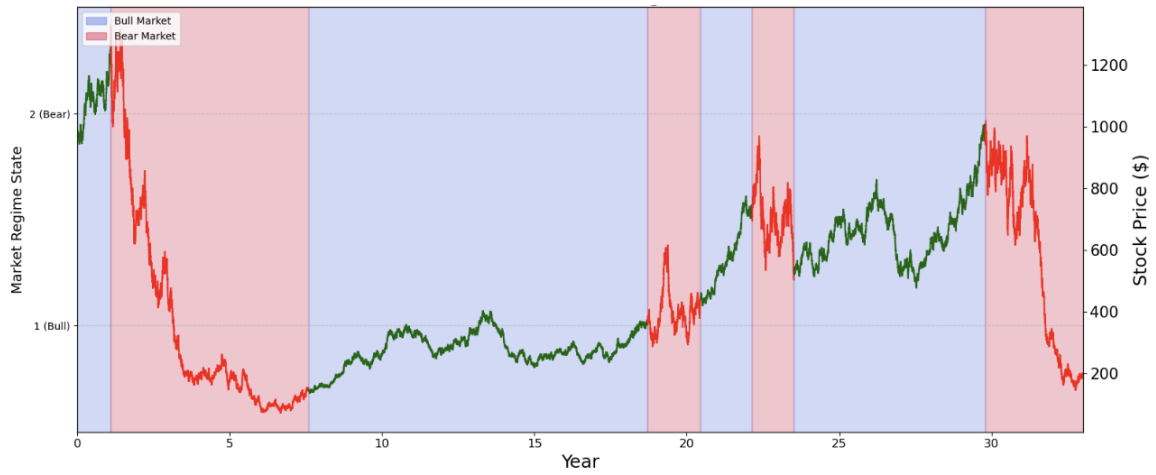


Figure 4: Example 33-year single simulation of the two-state Markov regime-switching market model.

Consumption decisions are governed by state-dependent annuity-due factors derived from the health transition model (Figure 5). These factors decline with age in all health states due to shortening life expectancy and differ significantly across states, with lower values for individuals in poor health. As a result, withdrawal rates adjust both over time and across health conditions, linking consumption directly to survival prospects.

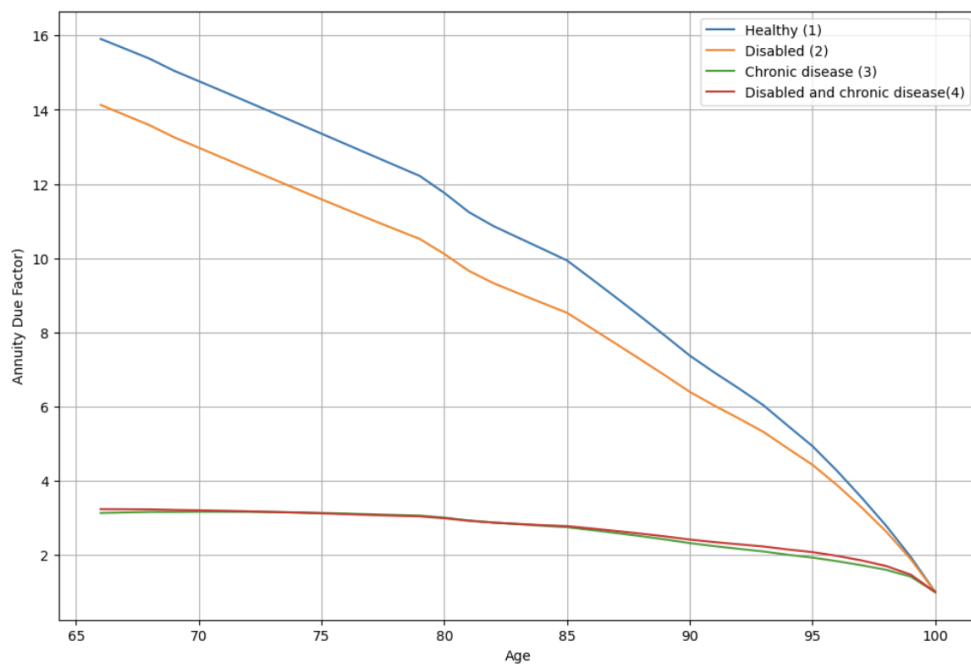


Figure 5: Annuity-due factors by health state.

Wealth evolves at a monthly frequency according to investment returns, health-related expenditures, and a “withdraw-first, rebalance-later” rule. Taken together, these elements define a unified framework in which financial risk, longevity risk,

and health risk interact.

Table 3: Baseline parameter values for initial wealth allocation, regime-switching financial markets, volatility targeting, health expenditures, and retirement withdrawal strategies.

Parameter	Symbol	Value
<i>Initial Wealth Allocation</i>		
Initial Wealth	W_0	407,328
Initial LTCI Allocation	ω_L	0.19923
LTCI Coverage Ratio	θ	1.0
Initial GMDB Allocation	ω_G	0.20
Initial Investable Wealth	W_{invest}	$(1 - \omega_L - \omega_G)W_0$
Initial GMDB Investment	G_0	$\omega_G W_0$
<i>Regime-Switching Financial Market</i>		
Drift (Bull Regime)	κ_1	0.08
Volatility (Bull Regime)	σ_1	0.20
Risk-Free Rate (Bull Regime)	r_1	0.04
Drift (Bear Regime)	κ_2	0.04
Volatility (Bear Regime)	σ_2	0.40
Risk-Free Rate (Bear Regime)	r_2	0.02
Transition Intensity (Bull to Bear)	a_{12}	0.40
Transition Intensity (Bear to Bull)	a_{21}	0.30
Initial Market Regime	R_0	1
<i>Target Volatility Strategy</i>		
Target Volatility	TV	0.20
EWMA Decay Factor	λ	0.80
Initial Estimated Volatility	$\hat{\sigma}_0$	0.20
Trading Days per Year	N_d	252
Trading Days per Month	N_m	21
Portfolio Rebalancing Frequency	–	Monthly
<i>Health Costs and LTCI</i>		
Annual Health Cost (State 2)	$h_2(1)$	50,000
Annual Health Cost (State 4)	$h_4(1)$	50,000
Health Cost Inflation Rate	q	0.019
LTCI Full Coverage Fair Price	P	81,153.88
<i>Retirement and Withdrawal Parameters</i>		
Initial Retirement Age	x_0	67

4.2 Base Scenario Analysis

The baseline results illustrate the interaction between investment dynamics, withdrawal behaviour, and insurance features. A key mechanism is the endogenous adjustment of portfolio risk under the TVS. In response to changes in estimated volatility, equity exposure is reduced during periods of market stress and increased during more stable conditions.

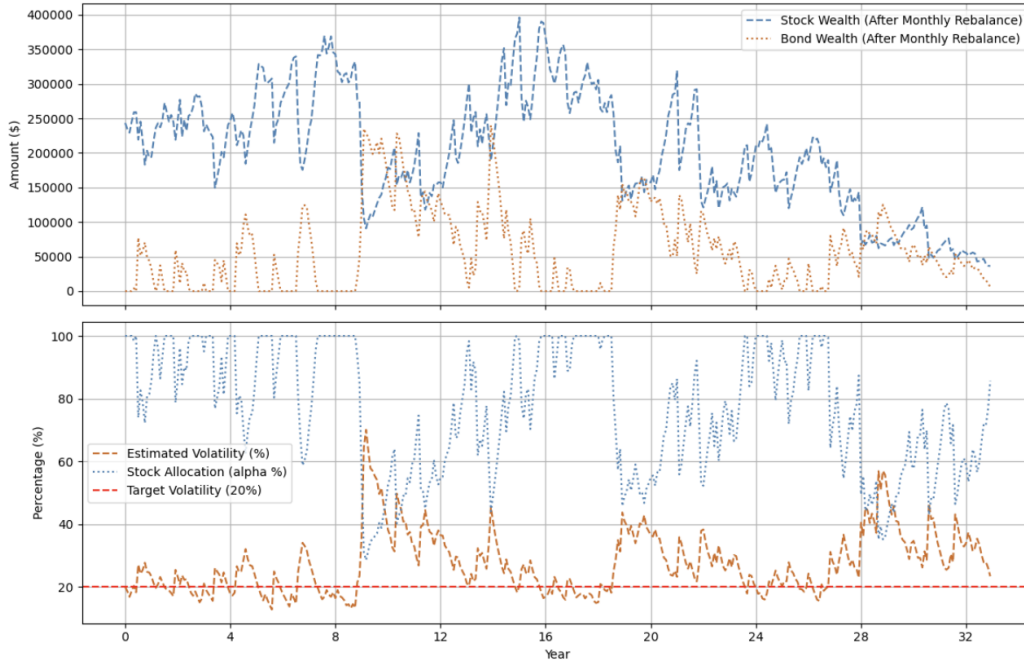


Figure 6: Simulated monthly stock and bond wealth together with estimated volatility and equity weight produced by the target volatility strategy with $TV = 0.2$.

The GMDB introduces an additional layer of protection in the event of early death. Payouts are close to the guaranteed level for short horizons, reflecting limited investment exposure, but increase with age at death as the linked account benefits from longer participation in financial markets.

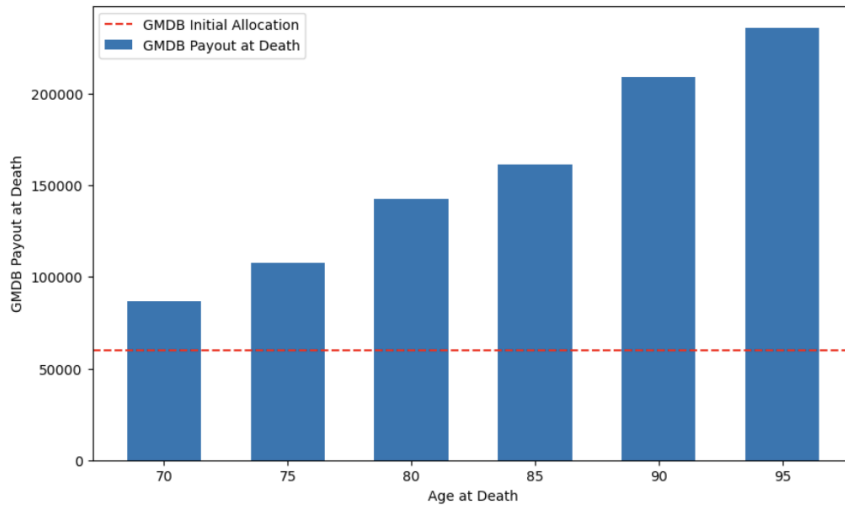


Figure 7: Simulated GMDB payouts at death across ages, based on the contract with initial guaranteed amount G and a GMDB-linked investment account simulated under the TVS.

The cross-sectional distribution of wealth highlights the cumulative impact of these mechanisms. While the distribution shifts downward over time due to withdrawals, a persistent upper tail remains, driven by favourable investment and

health trajectories. This heterogeneity underscores the importance of modelling both financial and health risks jointly.

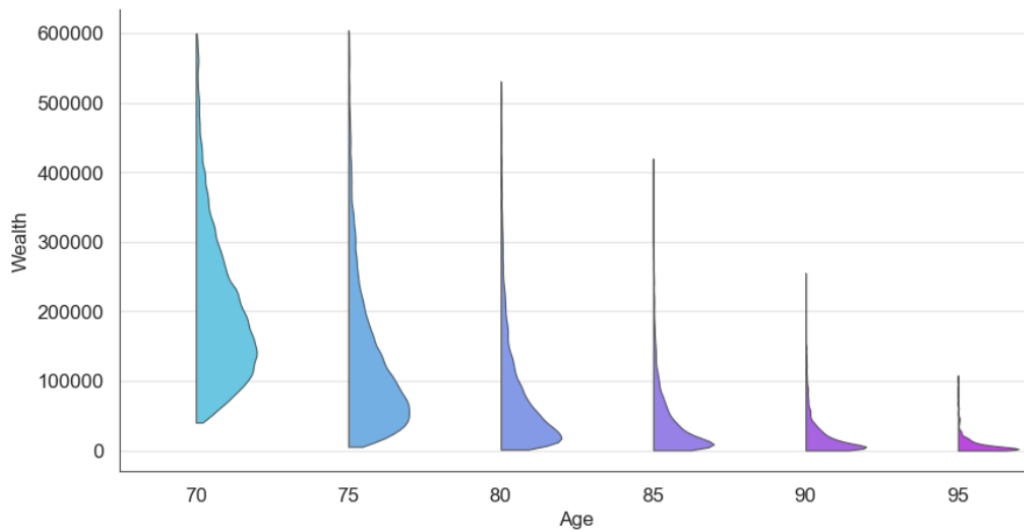


Figure 8: Cross-sectional distribution of simulated living wealth at selected ages obtained from 10,000 Monte Carlo paths under the baseline scenario.

Overall, the baseline results demonstrate how the interaction between regime-dependent returns, volatility targeting, and insurance shapes retirement outcomes.

4.3 Strategy Comparison with Age Pension

This subsection compares three alternative withdrawal strategies in the presence of the means-tested Australian Age Pension and evaluates their implications for retirement income adequacy relative to the ASFA² “comfortable” and “modest” retirement income benchmarks. The strategies considered are:

1. **Efficient drawdown strategy**, in which consumption is determined by the time-varying annuity rule based on the health-state-specific annuity factors developed in this study.
2. **Age-based withdrawal rate strategy**, which follows the legislated ATO minimum drawdown percentages applied to the remaining superannuation balance at each age.³

²Association of Superannuation Funds of Australia, <https://www.superannuation.asn.au/consumers/retirement-standard/>.

³Australian Taxation Office, *Key superannuation rates and thresholds: Payments from superannuation*, available at: <https://www.ato.gov.au/tax-rates-and-codes/key-superannuation-rates-and-thresholds/payments-from-super>.

3. **Full annuitisation strategy**, in which all remaining investable wealth after insurance purchase is converted at retirement into a level lifetime annuity that pays a fixed monthly amount while the retiree remains alive.

For the purpose of this comparison, two initial wealth levels are considered: Case I with baseline wealth $W_0 = 407,328$ AUD and Case II with higher wealth $W_0 = 600,000$ AUD. In both cases, retirees are assumed to purchase full LTCI coverage at retirement and allocate 20% of their initial wealth to a GMDB rider, with the remaining wealth invested in financial markets. The 20% allocation serves as a benchmark assumption rather than a fixed or universally optimal proportion. In practice, the allocation to GMDB can be adjusted according to individual preferences, particularly the strength of retirees' bequest motives. Retirees with stronger bequest motives may choose a higher allocation to GMDB, while those who prioritize consumption during retirement may prefer a lower allocation. To accommodate such heterogeneity, we provide an interactive retirement planning tool⁴ that allows users to adjust initial retirement parameters according to their individual circumstances and preferences. For the comparison of the three withdrawal strategies, the GMDB allocation is held constant at 20% to ensure that differences in wealth trajectories and consumption outcomes primarily reflect the withdrawal rules rather than differences in insurance allocation.

We model the Age Pension for a single pensioner aged 67 or above and resident in Australia, consistent with the eligibility conditions specified by Services Australia.⁵ The maximum Age Pension rate, including supplements and effective from 20 September 2025, is taken as the benchmark full payment for a single person, equal to 1,178.70 AUD per fortnight, or 2,566.36 AUD per month. Total monthly income is defined as the sum of private withdrawals and any Age Pension entitlement. This total income is then evaluated against the ASFA retirement income standards in order to assess the adequacy of each strategy.

At each time t , the Age Pension entitlement $AP(t)$ is determined as the minimum of the pension amounts calculated under the income test and the assets test:

$$AP(t) = \min \{AP_I(t), AP_A(t)\}, \quad (20)$$

where $AP_I(t)$ and $AP_A(t)$ denote the Age Pension under the income test and the assets test, respectively. Under the *income test*, assessable income includes deemed

⁴The interactive retirement planning tool was developed using a GitHub repository and deployed via Streamlit Community Cloud. It allows users to customize initial retirement parameters based on their individual circumstances and preferences. The tool is available at: <https://retirement-income-planner-67uatrdtkkadezpxyzrkru.streamlit.app/>

⁵Services Australia, *Age Pension*, available at: <https://www.servicesaustralia.gov.au/age-pension>.

income from financial assets (Services Australia, 2025b). For a single pensioner with financial assets balance $A(t)$, annual deemed income is given by

$$I^{\text{deem}}(A(t)) = 0.0075 \min(A(t), 60,400) + 0.0275 \max(A(t) - 60,400, 0),$$

where 60,400 AUD is the deeming threshold for singles as of 20 September 2025. This annual amount is converted to a fortnightly figure and then combined with any other assessable income. For a single pensioner, no reduction applies when assessable income is at or below 218 AUD per fortnight; above this threshold, the pension is reduced by 0.50 AUD for each additional 1 AUD of assessable income. The monthly Age Pension under the income test is calculated as

$$AP_I(t) = \max \left\{ 0, AP_{\max} - \frac{26}{12} \times 0.5 \max \left(\frac{I^{\text{deem}}(A(t))}{26} - 218, 0 \right) \right\},$$

where $I^{\text{deem}}(A(t))$ denotes the annual deemed income from financial assets, and $AP_{\max} = 2566.36$ AUD per month denotes the maximum Age Pension payment for a single pensioner.

Under the *assets test*, assessable assets exclude the principal residence but depend on homeownership status (Services Australia, 2025a). For a single homeowner, the monthly Age Pension entitlement under the assets test is given by

$$AP_A(t) = \max \left\{ 0, AP_{\max} - \frac{26}{12} \times \frac{3}{1000} \max(A(t) - 321500, 0) \right\},$$

where $A(t)$ denotes assessable assets at time t .

In the simulations, we focus on single homeowners and treat the retirement account as the main assessable financial asset. For a single homeowner, the full pension is payable when assessable assets do not exceed 321,500 AUD. Above this threshold, the pension is reduced by 3 AUD per 1,000 AUD of assets in excess of the threshold. Lifetime annuities receive concessional treatment under both tests. Under the income test, only 60% of ongoing annuity income is treated as assessable income. Under the assets test, 60% of the purchase price is counted as an assessable asset up to age 85, after which the assessed proportion falls to 30% of the original purchase price.

In the case of the fully annuitised strategy, both tests are evaluated. However, because only 60% of the life-annuity payment is treated as assessable income, the income test consistently produces the lower and therefore binding Age Pension entitlement. Since annuity income remains constant over time, the resulting Age Pension entitlement is also constant. In each simulation period, the Age Pension payable is therefore computed as the minimum of the income-test-based

entitlement and the assets-test-based entitlement, ensuring that the interaction between private decumulation decisions and public transfers is captured consistently throughout the retirement horizon.

Table 4: Initial wealth, LTCI loading for full coverage, annuity income under full annuitisation, and ASFA benchmark income levels for Cases I and II.

Case	W_0	Full w_L	Annuity	Comfortable	Modest
I	407,328	0.19923	1,191.19	4,440.75	2,876.83
II	600,000	0.135256	1,950.82	4,440.75	2,876.83

Table 4 summarises the two cases, reporting the LTCI loading w_L required for full coverage, the annuity income obtained by fully annuitising the residual investable wealth, and the ASFA “comfortable” and “modest” income benchmarks.

Figure 9 plots total monthly income, including Age Pension entitlements, for Case I. Total monthly income is defined as the sum of private withdrawals $C(t)$ and the Age Pension entitlement $AP(t)$, given by

$$C_{\text{total}}(t) = C(t) + AP(t). \quad (21)$$

The efficient drawdown strategy provides relatively higher income in early retirement than the age-based withdrawal rule, while adjusting withdrawals to remaining wealth and health state specific annuity factors. As private assets decline, higher Age Pension entitlements partly offset lower private withdrawals.

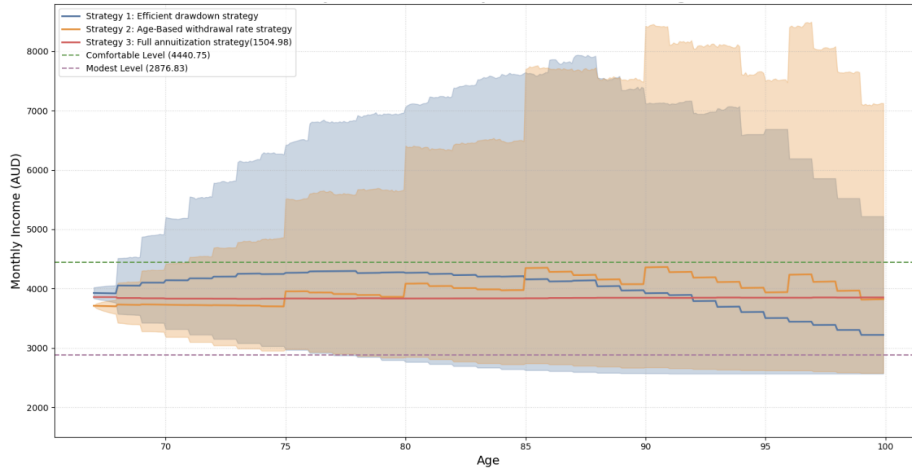


Figure 9: Simulated total monthly income, including Age Pension entitlements, under the three withdrawal strategies in Case I. The initial wealth is $W_0 = 407,328$ AUD, the full-annuitisation income is 1,191.19 AUD per month, and ASFA benchmark monthly income levels are 4,440.75 AUD (comfortable) and 2,876.83 AUD (modest).

Compared with full annuitisation, the efficient drawdown strategy retains liquidity and allows withdrawals to respond to changes in remaining wealth. Over-

all, it supports higher early retirement income while maintaining flexibility and later-life Age Pension support.

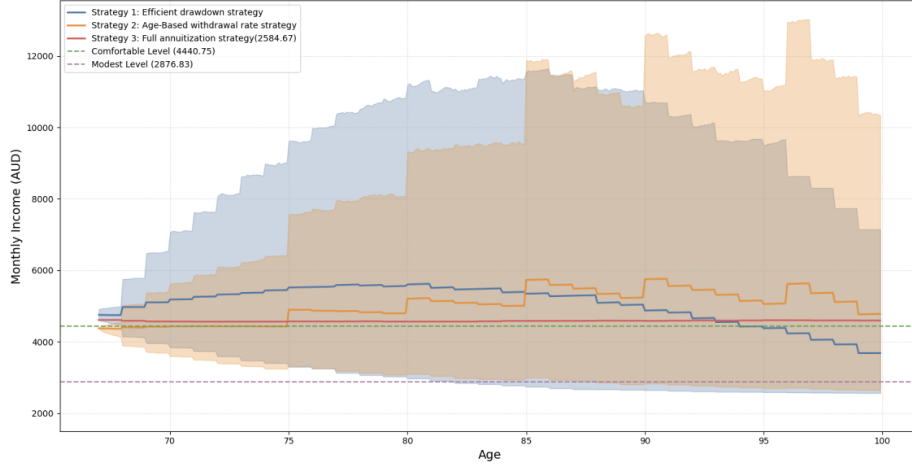


Figure 10: Simulated total monthly income, including Age Pension entitlements, under the three withdrawal strategies in Case II. The initial wealth is $W_0 = 600,000$ AUD, the full-annuitisation income is 1,950.82 AUD per month, and ASFA benchmark monthly income levels are 4,440.75 AUD (comfortable) and 2,876.83 AUD (modest).

Figure 10 presents the corresponding results for Case II. Higher initial wealth shifts the income distributions upward, especially in early and mid-retirement, while the Age Pension continues to provide a partial income floor at older ages once private assets have been drawn down. Comparing Figures 9 and 10 highlights how initial wealth, withdrawal design, and the means-tested Age Pension jointly determine the evolution of total retirement income over the life cycle.

Overall, the results from both initial-wealth cases indicate that the efficient drawdown strategy differs from the benchmark strategies primarily in its treatment of liquidity and withdrawal adjustment. Relative to full annuitisation, it retains investable wealth throughout retirement and permits withdrawals to adjust in response to changes in the remaining asset balance. Relative to the age-based minimum withdrawal rule, it generates a less constrained income profile, particularly during the earlier stages of retirement. In conjunction with LTCI and means-tested Age Pension support, the strategy is associated with a more responsive pattern of retirement income over the life cycle.

4.4 Sensitivity Analysis of Key Parameters

Building on the baseline scenario, we next investigate how changes in target volatility (TV) and LTCI allocation affect unpaid health costs, how different long-term care inflation assumptions shape the wealth distribution, and how initial wealth and LTCI design jointly influence the probability of bankruptcy.

Table 5: Discounted lifetime unpaid health costs for combinations of target volatility TV and LTCI allocation w_L , computed as averages over simulated paths.

TV	$w_L = 0$	$w_L = 0.05$	$w_L = 0.1$	$w_L = 0.15$
0.1	19269.27	14034.15	9705.04	6583.50
0.2	21632.20	16080.30	11195.23	7432.29
0.3	24592.92	18606.60	13137.59	8719.78
0.4	26287.45	20117.27	14361.88	9536.30

Table 5 summarises discounted lifetime unpaid health costs for different combinations of target volatility TV and LTCI allocation w_L . Unpaid costs represent disability-related expenditures that are not covered by available wealth or LTCI benefits. Two regularities emerge: first, for any fixed volatility target, unpaid costs decline monotonically with the LTCI allocation. Increasing LTCI from $w_L = 0$ to $w_L = 0.15$ (corresponding to an increase in θ from 0 to 0.753) substantially reduces unpaid costs, reflecting the direct insurance effect of LTCI against adverse health shocks. Second, for any given LTCI allocation, higher volatility targets increase unpaid costs. A more aggressive portfolio raises exposure to adverse investment outcomes and weakens the retiree’s ability to finance future care expenditures out of liquid wealth. Collectively, the results indicate a trade-off between return-seeking through greater portfolio risk and protection against health-related financial shortfalls.

To complement this measure of uninsured expenditure risk, Figure 11 presents the spatial distribution of bankruptcy probabilities across regions within Australia⁶. Bankruptcy is defined as the exhaustion of liquid retirement wealth while the retiree is still alive, with death treated as a censoring event.

Figure 11 reveals substantial regional variation in bankruptcy risk, indicating that retirement sustainability depends not only on individual decisions but also on regional economic conditions, cost structures, and exposure to health-care expenditure. This heterogeneity suggests that a uniform policy framework may be inadequate, particularly for financially vulnerable regions that may benefit from improved access to LTCI, premium subsidies, or additional public support. Initial wealth and LTCI also play complementary roles, with wealth providing broad financial resilience and LTCI protecting against large and uncertain care costs. Retirement policy should therefore account for regional heterogeneity and integrate wealth and insurance based mechanisms to improve sustainability and reduce in-

⁶Regional data used to construct the map are obtained from the Australian Government Open Data platform, based on the *Taxation Statistics 2022–23* dataset published by the Australian Taxation Office (ATO). Dataset resource: <https://www.data.gov.au/data/dataset/taxation-statistics-2022-23/resource/2b6e0599-ad64-4663-ac5b-518f39487823>.

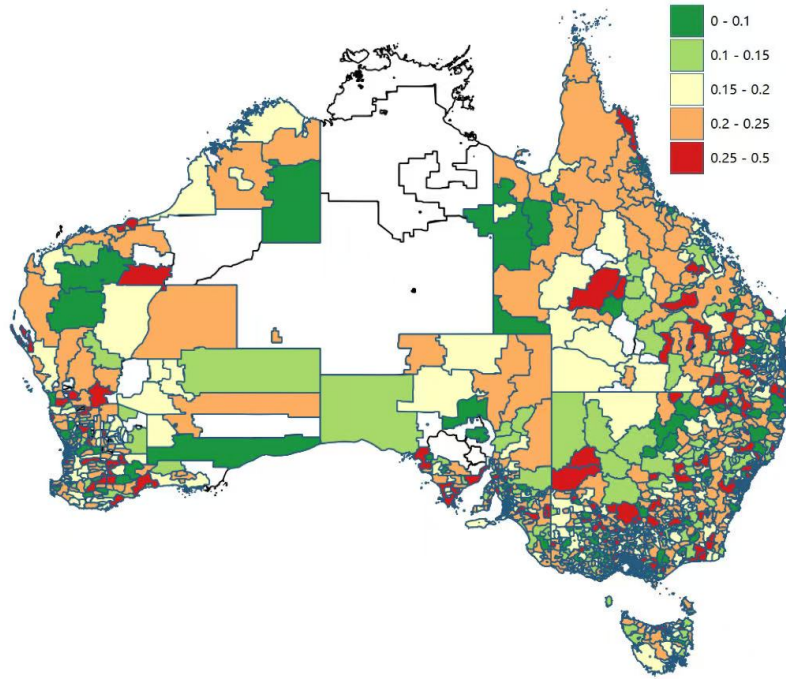


Figure 11: Spatial distribution of bankruptcy probability across regions. Colors indicate probability ranges of wealth exhaustion while alive under the simulated retirement framework.

equality in retirement outcomes.

Table 6 reports the 10th, 50th, and 90th percentiles of remaining wealth for each inflation–age combination, conditional on positive remaining wealth. For a fixed inflation rate, both the median and upper quantiles tend to decline with age, reflecting ongoing withdrawals, realised long-term care expenditures, and the progressive shortening of the remaining lifetime horizon. As retirement advances, a larger fraction of lifetime care costs has already been realised, and the distribution of wealth shifts downward accordingly.

However, the relationship between long-term care inflation and conditional remaining wealth is not strictly monotonic. For example, at age 77, the 90th percentile of remaining wealth increases from AUD 380,295.82 under 2% inflation to AUD 422,173.06 under 8% inflation. Similarly, at age 87, median remaining wealth is AUD 74,659.26 under 6% inflation, compared with AUD 63,217.30 under 2% inflation. This pattern may partly reflect a selection effect, as retirees whose wealth is exhausted and who may consequently be unable to finance necessary long-term care are excluded from the conditional wealth distribution. Consequently, higher conditional wealth quantiles under certain inflation scenarios do not necessarily indicate improved financial sustainability, but may instead reflect the exclusion of financially vulnerable retirees.

Overall, the sensitivity analysis shows that health-related financial risk in re-

Table 6: Quantiles of remaining wealth net of combined long-term care payments by inflation rate and age, obtained from simulated paths conditional on positive remaining wealth.

Long-term care Inflation	Age	Remaining Wealth Quantiles		
		Quantile _{0.1}	Quantile _{0.5}	Quantile _{0.9}
2.0%	72	100,362.61	211,335.07	397,236.58
	77	54,587.85	158,180.76	380,295.82
	82	26,301.40	112,338.42	334,962.58
	87	12,448.29	63,217.30	250,558.16
	92	4,794.96	32,416.79	157,596.84
	97	863.40	9,637.39	57,015.67
4.0%	72	102,644.71	211,015.61	395,572.01
	77	53,348.70	151,927.54	391,064.10
	82	30,286.18	107,061.18	330,027.40
	87	14,408.37	57,269.56	240,364.66
	92	4,098.84	28,004.48	139,142.76
	97	567.91	9,351.32	42,977.26
6.0%	72	101,309.20	206,976.77	399,424.67
	77	55,036.43	159,853.07	409,426.81
	82	26,880.49	106,724.53	342,493.16
	87	14,159.15	74,659.26	271,207.57
	92	5,790.87	37,040.22	160,270.74
	97	1,284.92	11,957.71	71,922.32
8.0%	72	100,873.59	202,779.66	388,159.21
	77	55,789.54	162,596.45	422,173.06
	82	27,881.47	112,473.37	377,486.86
	87	14,110.17	66,829.21	265,206.15
	92	6,005.59	31,615.50	154,081.62
	97	1,003.02	9,171.95	56,693.03

tirement is jointly shaped by portfolio choice, insurance coverage, cost inflation, and initial wealth. Increasing the LTCI allocation reduces both unpaid health costs and the probability of bankruptcy, whereas adopting a higher target volatility raises financial fragility by increasing exposure to adverse market outcomes. Long-term care inflation further affects wealth dynamics by accelerating expenditure growth, although its effect on conditional wealth quantiles is non-linear because of selection among surviving paths. These findings underscore the importance of jointly calibrating investment risk, LTCI coverage, and expenditure risk when assessing the robustness of retirement decumulation strategies.

5 Discussion and Conclusions

This study develops an integrated decumulation framework that links health dynamics, regime switching financial markets and insurance products within a unified retirement model. The core of the framework is an efficient drawdown rule, where consumption is determined by health state specific annuity factors and remaining wealth, combined with TVS for investment. LTCI, GMDB and the Australian Age Pension are incorporated to address, respectively, aged care, bequest and public policy dimensions of retirement risk.

The numerical analysis shows how these components interact. In the baseline with LTCI and GMDB, the TVS dampens the transmission of market shocks into consumption, while LTCI and GMDB absorb long-term care and bequest risks and support a relatively smooth, gradually declining consumption path. Sensitivity tests indicate that higher LTCI allocations substantially reduce unpaid health costs, whereas higher target volatility increase the probability that wealth becomes insufficient to cover care needs. Inflation in aged-care costs accelerates wealth depletion and concentrates high aged-care costs among paths with strong investment performance, underscoring the need to calibrate investment risk, LTCI coverage and inflation assumptions jointly. When the full coverage LTCI is combined with the Age Pension, the efficient drawdown strategy consistently delivers higher consumption than age based minimum withdrawals and full annuitisation at younger ages after retirement.

Looking ahead, three extensions appear particularly valuable for enhancing the realism and applicability of the framework. First, the macro-financial structure can be strengthened by jointly modelling inflation and implementation frictions. This study shows that medical inflation materially affects late-life affordability. Future research can represent general and medical inflation as stochastic processes that interact with market regimes, allowing portfolio returns, care costs and withdrawal

targets to be evaluated consistently in real terms. Incorporating transaction costs, discrete rebalancing intervals or no-trade regions, consistent with the dynamic trading framework of Gârleanu et al. (2013), also enables a systematic assessment of the robustness of TVS under operational constraints and helps identify parameterisations that remain welfare enhancing after accounting for trading frictions.

Second, the insurance component can be endogenised and contract mechanics refined. The current analysis treats LTCI and GMDB allocations as exogenous. An important extension is to optimise GMDB allocation and long-term care coverage jointly with investment and withdrawal decisions, conditional on initial wealth and health profiles. Evidence from Finkelstein et al. (2006) and Ameriks et al. (2020) highlights the role of private information, state dependence and late-life utility in shaping LTCI demand, motivating a behaviourally grounded approach to participation. As the optimisation problem is both state dependent and path dependent, reinforcement learning provides a powerful method for learning implementable coverage and drawdown rules from simulated trajectories of wealth, health transitions and market regimes as illustrated in Ozhamaratli et al. (2022). Additional realism can be gained by modelling waiting periods and reimbursement structures explicitly, thereby improving the representation of short-run disability cash-flow risk and strengthening alignment with market products.

Third, the framework can be extended to capture late-life risk and life-cycle coherence more fully. The simulations indicate that vulnerability is concentrated at advanced ages, when disability risk rises and remaining wealth becomes low and volatile. Embedding a late-life income floor, for example through a deferred annuity that commences at an advanced age, links the model to the literature on longevity pooling and group self annuitisation, exemplified in Piggott et al. (2005). Integrating the decumulation analysis with a pre-retirement accumulation phase that incorporates income risk, contribution behaviour and health evolution also yields a coherent life-cycle structure in which retirement wealth and health arise endogenously. This linkage enables direct comparison of retirement consumption paths with pre-retirement living standards and strengthens the welfare interpretation of front-loaded consumption early in retirement.

Collectively, these extensions deepen the empirical foundation of the framework, broaden its relevance for product and policy design and advance the development of personalised strategies that jointly manage market, inflation, longevity and long-term care risks throughout the retirement life cycle.

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Algorithm 1 Simulate Asset Prices with Regime-Switching

Input: Market parameters κ, σ, r under two regimes; initial values S_0, B_0, T, dt

Output: Equity path $\{S_t\}$, Bond path $\{B_t\}$, Regimes $\{r_t\}$

Initialize $S_0 \leftarrow S_0, B_0 \leftarrow B_0$

Simulate $\{r_t\}$ using Algorithm 1

for $t = 1$ to N **do**

 Select (κ, σ, r) according to r_{t-1}

$\Delta W \sim \mathcal{N}(0, dt)$

$S_t \leftarrow S_{t-1} \cdot \exp\left[(\kappa - \frac{1}{2}\sigma^2)dt + \sigma\Delta W\right]$

$B_t \leftarrow B_{t-1} \cdot \exp(r \cdot dt)$

end for

Algorithm 2 EWMA-based Volatility Targeting

Input: Equity values $\{S_t\}$, target volatility TV , smoothing parameter λ

Output: Allocation $\{\alpha_t\}$, estimated volatilities $\{\hat{\sigma}_t\}$

Compute $r_t = \log(S_t/S_{t-1})$

Initialize $\sigma_0^2 = \sigma_{\text{init}}^2/252, \hat{\sigma}_0 = \sigma_{\text{init}}$

for $t = 1$ to N **do**

$\sigma_t^2 \leftarrow \lambda\sigma_{t-1}^2 + (1 - \lambda)r_t^2$

$\hat{\sigma}_t \leftarrow \sqrt{252 \cdot \sigma_t^2}$

$\alpha_t \leftarrow \min\left(\frac{TV}{\hat{\sigma}_t}, 1.0\right)$

end for

Algorithm 3 Integrated Retirement Decumulation Strategy

Input: Initial wealth W_0 , LTCI allocation ω_L , GMDB allocation ω_G , coverage ratio θ , health path $\{s_t\}$, annuity factors $\{\ddot{a}_{x+t}^{s_t}\}$, asset returns, allocations $\{\alpha_t\}$

Output: Wealth path $\{W_t\}$, consumption path $\{C_t\}$, LTC payments, GMDB payoff

$$G \leftarrow \omega_G W_0$$

$$W_0^I \leftarrow (1 - \omega_L - \omega_G) W_0$$

$$F_G(0) \leftarrow G$$

Allocate W_0^I between stock and bond according to α_0

for $t = 1$ to T **do**

 Update stock and bond holdings using simulated market returns

 Update GMDB-linked investment account $F_G(t)$

if $s_t = 5$ **then**

$$DB_t \leftarrow \max(G, F_G(t))$$

 Record death benefit and terminate the path

else

$$W(t^-) \leftarrow S(t^-) + B(t^-)$$

if $s_t \in \{2, 4\}$ **then**

$$H_t \leftarrow (1 - \theta) h_{s_t}(t)$$

else

$$H_t \leftarrow 0$$

end if

$$C(t) \leftarrow \frac{\max(W(t^-) - H_t, 0)}{\ddot{a}_{x+t}^{s_t}}$$

$$W(t^+) \leftarrow \max(W(t^-) - C(t) - H_t, 0)$$

$$S(t^+) \leftarrow \alpha_t W(t^+)$$

$$B(t^+) \leftarrow (1 - \alpha_t) W(t^+)$$

end if

end for
