FACULDADE
DE ECONOMIA
UNIVERSIDADE
DO PORTO

Fertility Preferences and Economic Evolution: Agent-Based Extension to Evolutionary Growth Theory

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Dissertation

Master in Modelling, Data Analysis and Decision Support Systems

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2025

Acknowledgments

I would like to thank Professor Pedro Campos and Professor Isabel Mota for their knowledge, support and valuable advice.

My gratitude also goes to Professor Maria Eduarda Silva, along with all professors and lecturers of the Master in Modelling, Data Analysis and Decision Support Systems at the Faculty of Economics, University of Porto, for their guidance and offered support.

I am also grateful to my colleagues for the assistance and encouragement provided throughout the Master's programme.

Abstract

This dissertation investigates whether populations with heterogeneous fertility preferences can trigger a reversal from modern economic growth back to Malthusian stagnation and identifies the critical thresholds in the quality-quantity trade-off that determine these long-run economic trajectories. By simulating Galor and Moav (2002) evolutionary growth model using system dynamics and agent-based modelling, this research examines how heterogeneous reproductive strategies within and across populations shape the transition from Malthusian stagnation to sustained growth and potentially back again. The study introduces a methodological framework that bridges micro-level fertility decisions with macro-level economic outcomes, incorporating individual heterogeneity in human capital and educational choices while maintaining tractable evolutionary dynamics.

The central finding challenges the presumed irreversibility of demographic and economic transitions: populations with strongly quantity-preferring fertility preferences can trigger economic regression to Malthusian conditions through a demographic selection mechanism, whereby high-fertility genotypes with minimal educational investment gradually dominate the population, driving average human capital toward zero and halting technological progress.

This work contributes to unified growth theory by providing the first agent-based microfoundation for evolutionary macro-dynamics, demonstrating how individual reproductive choices cascade through evolutionary selection and human capital accumulation to shape civilizational trajectories. The results suggest that the continuation of modern economic growth depends critically on maintaining populations whose fertility preferences support intergenerational investment in education, highlighting the fragility of economic modernity in the face of demographic change.

Keywords: Fertility transition, Micro-level factors, Macro-level factors, Micro-macro links, Agent-based models (ABMs), Evolutionary growth theory

Contents

List of Figures

Chapter 1

Introduction

Fertility (the process of childbearing in human populations) stands as one of the most consequential demographic phenomena, fundamentally shaping population size, growth rates and age structure. These demographic outcomes cascade through every facet of society: determining labour force dynamics, dependency ratios and the sustainability of pension systems; driving demand for education, healthcare and housing infrastructure; and influencing economic growth trajectories and fiscal planning horizons. Beyond its population-level impacts, fertility intersects profoundly with gender equality and women's autonomy, intergenerational wealth transfers, migration pressures, environmental resource consumption and the pace of cultural and social transformation. The measurement and analysis of fertility through standardized indicators include: period measures like the Total Fertility Rate (TFR) and Age-Specific Fertility Rates (ASFR), cohort-based analyses of completed fertility and parity progression. These metrics enable governments to project future service needs, assess the fiscal implications of demographic change and design evidence-based interventions ranging from childcare provision and parental leave policies to reproductive health programs (Preston, Heuveline, Guillot, et al. (2001); Bongaarts (2015)).

Fertility transition, defined as the shift from high to low fertility rates over time, has long occupied a central place in demographic research. This phenomenon is integral to the broader demographic transition framework, which links social, economic and cultural transformations to changes in reproductive behaviour. Scholars have increasingly recognized that fertility decline is driven by a multiplicity of factors, ranging from advancements in family planning and healthcare to shifts in individual aspirations and gender roles (Billari, Liefbroer, and Philipov (2006); Bongaarts (2001)). Such complexity requires the integration of diverse methodological approaches in order to fully capture the dynamics underlying reproductive decision-making.

Fertility decline across Europe since the mid-1960s reflects a continental demographic shift, yet its trajectory has been punctuated by periods of volatility. After steady reductions through the late 20th century, the EU-wide total fertility rate (TFR) exhibited a limited recovery in the early 2000s, only to stagnate by 2010 (TFR 1.57) and decline to 1.51 in 2013. A modest recovery to 1.57 in 2016 gave way to renewed decreases, reaching 1.51 again by 2020. The COVID-19 pandemic lead to a temporary increase to 1.53 in 2021 with TFR falling to 1.46 by 2022 — the lowest recorded level in decades (Eurostat (2024)). The decline of TFR from 2014 to 2023 in EU countries can be seen in Figures 1.1 and 1.2 (Eurostat (2025)).

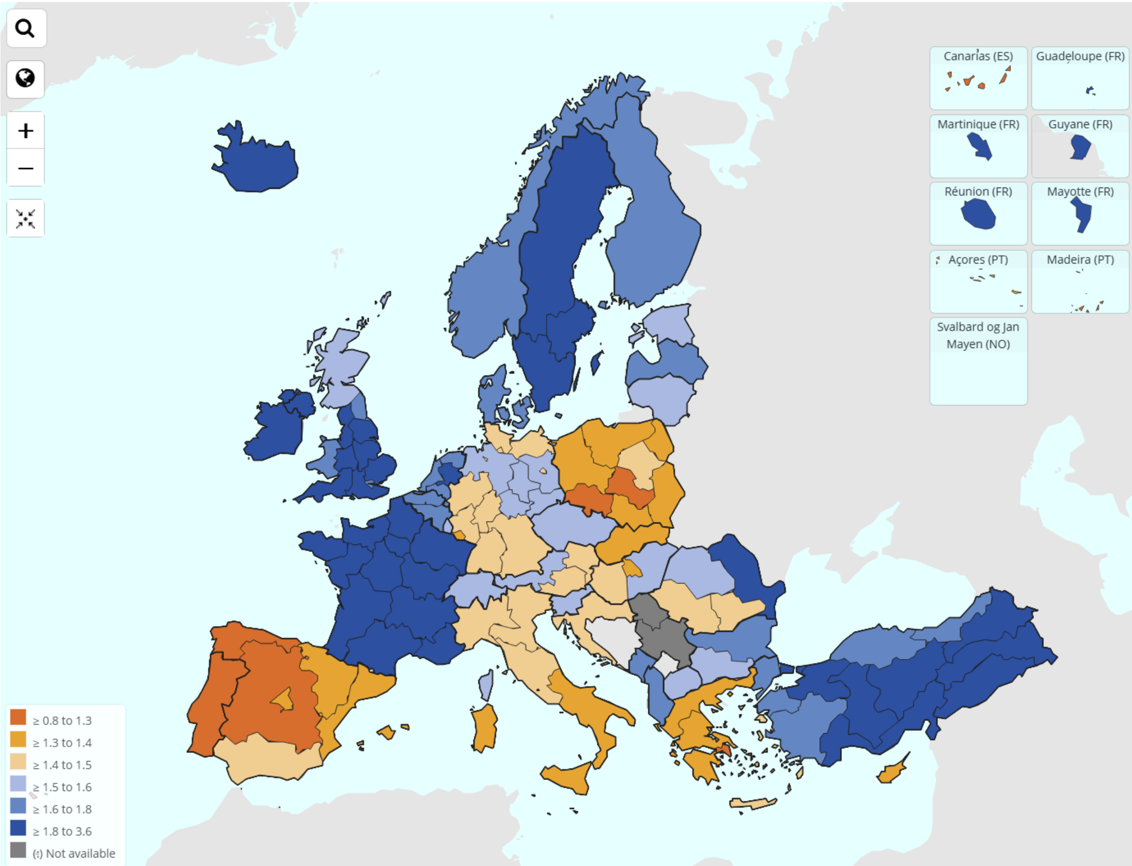

Figure 1.1: Total Fertility rate (live births per woman), 2014 (Eurosat data)

Portugal presents a particularly compelling case for the study of fertility transition. Over recent decades, the country has experienced profound political, economic and social changes, transitioning from a prolonged period of authoritarian governance to a modern democratic state. These transformations have been accompanied by rapid economic development, extensive educational improvements and evolving cultural norms, all of which have exerted significant influence on fertility patterns. This transition has unfolded with distinct characteristics, marked by rapid declines and regional disparities (Pimentel and Sousa Gomes (2022)).

Empirical investigations into Portugal's fertility decline reveal that economic progress

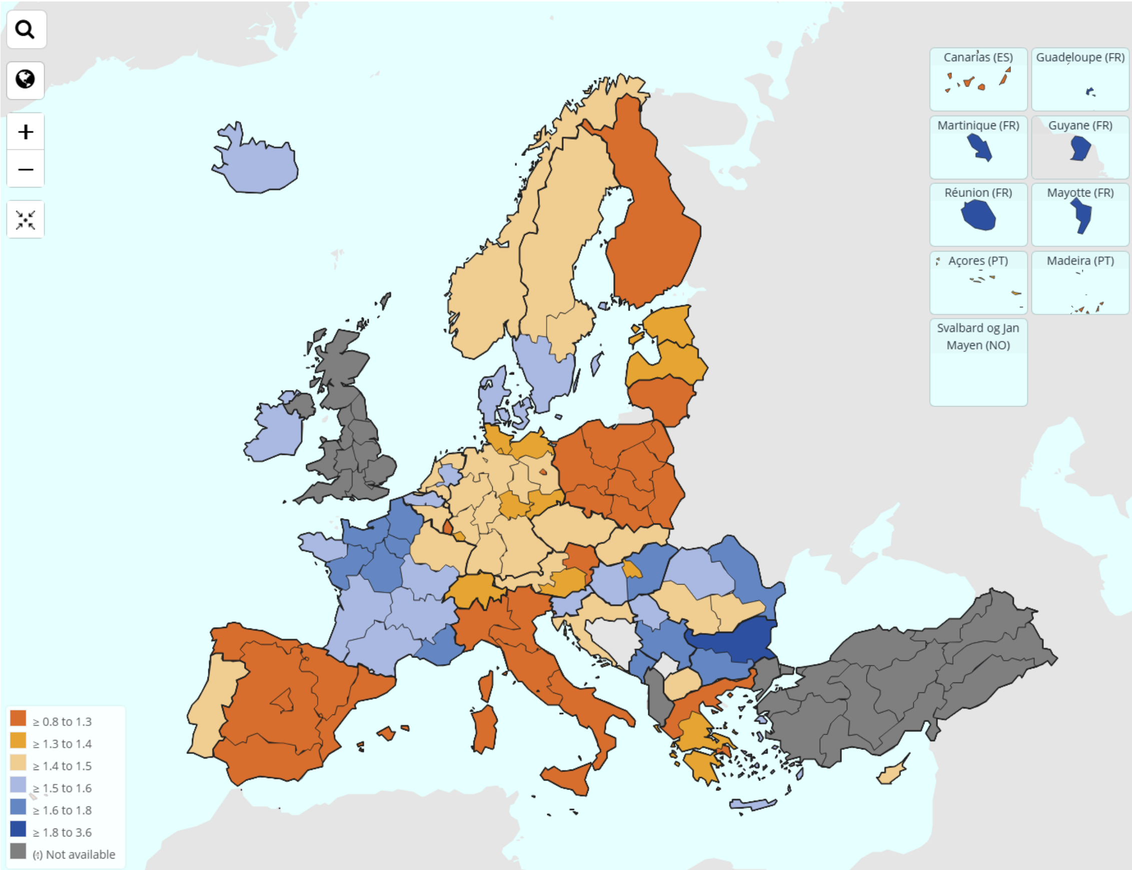

Figure 1.2: Total Fertility rate (live births per woman), 2023 (Eurosat data)

alone cannot account for the observed changes. Studies indicate that increased female labour market engagement, rising levels of education and the gradual liberalization of traditional family roles have collectively contributed to the fertility transition. Furthermore, regional disparities within Portugal underscore the importance of localized socioeconomic conditions and cultural contexts, suggesting that fertility patterns are as much a product of micro-level decision processes as they are of broader macroeconomic trends (de Oliveira (2006)).

Historically, Portugal maintained high fertility rates until the 1970s, when a dramatic decline began, aligning with broader Southern European trends yet exhibiting unique temporal and spatial patterns. Socioeconomic modernization and crises have further accelerated fertility decline. The 1970s marked a turning point, as urbanization, female labour force participation, and educational expansion reshaped family planning priorities. However, the 2008 financial crisis and subsequent austerity measures exacerbated these trends, with the total fertility rate plummeting to 1.21 children per woman by 2013 — a historic low (see Figure 1.3). Economic instability delayed childbearing decisions, amplified emigration, and intensified financial anxieties, reflecting the vulnerability of fertility rates to macroeconomic shocks. The COVID-19 pandemic compounded these pressures, driving births below 80,000 in 2021 and highlighting the persistent interplay between structural constraints and reproductive agency (Pimentel and Sousa Gomes (2022)).

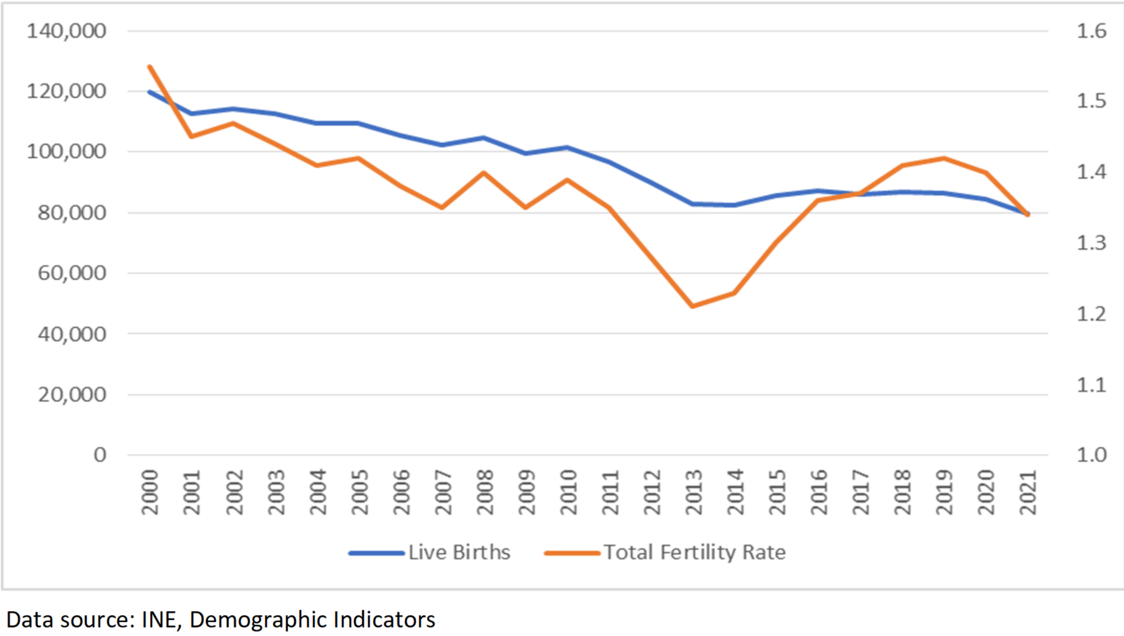

Figure 1.3: Live births and total fertility rate in Portugal 2000-2021 (Pimentel and Sousa Gomes (2022))

Cultural shifts, including changing gender roles and secularization, have also redefined fertility norms. The rise of out-of-wedlock births — from 22.2% in 2000 to nearly 50% by 2014 — signals a decoupling of marriage and childbearing, mirroring broader European trends toward individualized family formation (Pimentel and Sousa Gomes (2022)). Surveys reveal declining fertility intentions, with economic costs, career barriers for women and inadequate childcare support cited as key deterrents (Pimentel and Sousa Gomes (2022)). These findings align with theoretical models positing that fertility transitions necessitate not only material conditions but also cognitive shifts, such as numeracy and conscious family-size planning (Angeles (2010); de Oliveira (2006)).

The theoretical underpinnings of fertility transition research have evolved considerably since the classical demographic transition model was first articulated. While early models emphasized the direct relationship between economic development and declining fertility, subsequent frameworks, such as the second demographic transition, have emphasized the roles of individual autonomy, gender equity and changing values regarding family life (Lesthaeghe (2010)).

Recent methodological advancements in demographic research have introduced new tools for analysing such complex social phenomena. Traditional aggregate demographic models have been valuable in explaining general trends, yet they often obscure the heterogeneity inherent in individual-level fertility decisions. Agent-based models, by contrast, offer a promising approach to simulating how individual behaviours and interactions lead to emergent population-level patterns, thereby complementing classical models and providing deeper insights into the nature of fertility transitions (Bonabeau (2002)).

Despite the considerable progress made in understanding fertility transitions, significant gaps remain in reconciling macro-level socioeconomic indicators with the micro-level mechanisms of reproductive decision-making. This research aims to illustrate the complex interplay of economic and individual factors that have shaped the fertility transition. By combining insights from established demographic theories with innovative computational modelling techniques, the dissertation seeks to advance our understanding of the determinants of reproductive behaviour in a rapidly evolving social context.

This dissertation addresses the following research question: can populations with heterogeneous fertility preferences trigger a reversal from modern economic growth back to economic stagnation? This question is particularly relevant in the context of contemporary demographic challenges, where below-replacement fertility in native populations coincides with immigration from regions maintaining higher fertility preferences.

The methodology employs a multi-level computational approach. It begins with a system dynamics replication of Collins, Baer, and Weber (2014) simulation of the Galor and Moav (2002) evolutionary growth model. This model is then extended through agent-based modelling, allowing examination of how individual-level fertility decisions (micro level) aggregate to population-level evolutionary dynamics (macro level). The framework incorporates immigrant populations with varying fertility preferences, enabling systematic sensitivity analysis.

This work makes several contributions to the unified growth and demographic transition literature. Galor and Moav (2002) provided the theoretical foundation for evolutionary selection in fertility preferences. While Collins et al. (2014) demonstrated these dynamics through simulation, their analysis lacked systematic investigation of the stability of modern growth under demographic shocks from migration. This dissertation differs by providing comprehensive sensitivity analysis, revealing previously unidentified threshold effects and non-monotonic relationships between fertility preferences and economic outcomes. Furthermore, the agent-based extension represents the micro level approach to evolutionary growth theory, bridging the gap between individual heterogeneity and macro level dynamics that previous aggregate models could not capture.

The dissertation is structured as follows. Chapter 2 reviews the literature on fertility determinants, micro-macro population forecasting methods, agent-based models for fertility and unified growth theory of fertility transitions. Chapter 3 presents the methodology, detailing the core Galor-Moav model, its system dynamics implementation and the agent-based extension. Chapter 4 presents simulation results across different migration scenarios. Chapter 5 discusses the implications for fertility preferences, scale effects and model limitations. Chapter 6 concludes with reflections on the fragility of modern economic growth and the critical balance between demographic dynamics and human capital investment required for sustained prosperity.

Chapter 2

Literature Review

2.1 Factors Influencing Fertility

Fertility decisions are shaped by a complex interplay of factors, ranging from economic conditions to cultural norms. In Europe and other developed regions, researchers have documented the emergence of what is termed ”lowest-low fertility”, where birth rates fall below levels necessary for population replacement, a phenomenon that has stimulated extensive scholarly debate (Billari (2005); Kohler, Billari, and Ortega (2002)).

Economic uncertainty and labour market instability have emerged as significant determinants of fertility behaviour. The financial risks associated with childbearing and rearing have led many individuals and couples to postpone or forgo having children (Kohler et al. (2002); Matysiak, Sobotka, and Vignoli (2021)). Recent evidence suggests that employment uncertainty, particularly among young adults facing precarious work conditions, has become a primary driver of fertility postponement across Europe (Alderotti, Vignoli, Baccini, and Matysiak (2021)). Periods of economic downturn or instability correlate with marked decreases in fertility rates (Sobotka, Skirbekk, and Philipov (2011)).

A critical economic dimension that has gained prominence in recent fertility research is the rising cost of human capital investment in children. As technological advancement accelerates and labour markets become increasingly skill-intensive, parents face mounting pressure to invest heavily in their children's education to ensure their competitive advantage (Doepke, Hannusch, Kindermann, and Tertilt (2023)). This ”quantity-quality trade-off,” first theorized by Becker and Lewis (1973), has intensified in the 21st century as educational requirements for economic success have escalated (Doepke and Kindermann (2019)). Parents increasingly opt for smaller families to concentrate resources on fewer children, ensuring each child receives substantial educational investment (Gobbi (2013)).

Welfare state provisions and family policies play a crucial role in shaping reproductive choices. Comprehensive support systems, including subsidized childcare services, generous parental leave and flexible work arrangements, can mitigate the adverse effects of economic uncertainty and enable individuals to better balance work and family responsibilities (Kohler, Billari, and Ortega (2006)). Recent comparative studies across European countries reveal that nations with more extensive family support policies exhibit higher fertility rates (Billingsley and Ferrarini (2014)).

Cultural and normative shifts have contributed significantly to changing fertility patterns. The evolving social expectations surrounding family life, marriage and individual fulfilment have led to more individualized life trajectories where traditional family models are no longer universally pursued (Billari (2005)). These changes intersect with the notable trend of postponement of childbearing, which has become increasingly common as individuals prioritize educational and career achievements (Kohler et al. (2002); Sobotka (2017)). Recent research distinguishes between tempo effects (timing changes) and quantum effects (number of children), revealing that much of the observed fertility decline may be attributed to postponement rather than permanent reductions in desired family size (Bongaarts and Sobotka (2012)).

Housing market conditions have emerged as critical determinants of fertility, with high housing costs and limited access to stable accommodation significantly delaying family formation (Mulder and Billari (2010)). These economic pressures are particularly acute in urban settings, where migration and urbanization have influenced fertility patterns by altering social networks and access to resources. The migration to urban areas, where living costs are higher and family support structures may be weaker, contributes to lower fertility rates through changes in lifestyle and economic pressures (Billari (2005); Kulu (2013)).

The availability of intergenerational support significantly influences fertility decisions, with geographical proximity to extended family positively associated with fertility outcomes (Aassve, Meroni, and Pronzato (2012)). In societies where familial support networks are robust, the burdens associated with childrearing may be alleviated, thereby fostering higher fertility levels. Conversely, the erosion of these support systems in modern urban environments can lead to reduced fertility.

In summary, the factors influencing fertility are multifaceted and deeply interwoven, encompassing economic, social, cultural and policy dimensions. A comprehensive understanding of these determinants is essential for developing effective strategies to address fertility declines (Eurostat (2024); Kohler et al. (2006)).

2.2 Micro-Macro Links in Population Forecasting

Population forecasting is a critical field in demography, linking individual-level behaviours and macro-level population trends. The micro-macro connection in population forecasting emphasizes the integration of individual decisions, such as fertility choices, migration and mortality, with broader demographic outcomes like population growth, age structure and spatial distribution. This relationship underpins the effort to improve forecasting accuracy by bridging granular data at the micro-level with overarching trends observed at the macro level (Willekens (2005); Billari (2015)). While macro-level models offer insights into aggregate population trends, they often miss the heterogeneity embedded in individual trajectories, which biographic forecasting seeks to capture (Willekens (2005); Van Bavel and Grow (2016)).

Biographic forecasting, as described by Willekens (2005), represents a promising approach to addressing the micro-macro gap by focusing on life courses and individual demographic events. It moves away from traditional aggregate-level models by simulating life trajectories based on probabilities derived from observed data. This allows for a more dynamic and nuanced understanding of population changes, taking into account how individual-level decisions and behaviours influence collective outcomes. For example, fertility rates are not simply a product of societal norms but are shaped by personal circumstances, education and economic conditions, which biographic models can explicitly integrate (Willekens (2005)). Recent methodological advances have enhanced these approaches through the integration of sequence analysis and life course complexity measures, enabling more sophisticated modelling of individual trajectories and their aggregate implications (Ritschard and Studer (2018)).

One of the challenges in linking micro and macro perspectives is the need for detailed data on individual behaviours and the contextual factors influencing them. Surveys, longitudinal studies and administrative data provide rich sources for understanding these dynamics (Zinn (2016)). However, translating micro-level findings into macro-level forecasts requires sophisticated modelling techniques, such as agent-based models (ABMs) or microsimulation approaches. These models enable researchers to capture the feedback loops between individual behaviours and macro-level trends, such as how changes in policy might affect birth rates or migration patterns over time (Billari (2015); Klabunde and Willekens (2016)).

The integration of micro- and macro-level approaches also raises important methodological and theoretical considerations. While macro-level forecasts traditionally rely on extrapolations of past trends, micro-level approaches demand a deep understanding of causal mechanisms driving individual decisions. For instance, a macro forecast might predict declining fertility based on historical trends, while a micro-level analysis could reveal countervailing factors, such as increased access to childcare or shifts in societal attitudes toward parenting, that might stabilize or even increase fertility rates (Billari (2015); Morand et al. (2010)). The development of multi-level models has provided new tools for capturing these cross-scale dynamics, allowing researchers to examine how contextual factors at different levels influence individual behaviour (Courgeau, Bijak, Franck, and Silverman (2016)).

Moreover, micro-level approaches offer the advantage of incorporating uncertainty and variability into population forecasts. Individuals do not follow deterministic paths and their behaviours are influenced by diverse factors ranging from cultural norms to random life events. By modelling this heterogeneity, biographic forecasting and related techniques can generate probabilistic forecasts that better account for the range of possible futures. This stands in contrast to deterministic macro-level forecasts, which often fail to capture the complexity of demographic systems (Willekens (2005); Bijak and Bryant (2016)). Recent advances in stochastic forecasting have combined agent-based approaches with Bayesian methods to better quantify uncertainty at both individual and population levels (Raftery, Li, Ševčíková, Gerland, and Heilig (2012)).

Recent advances in computational tools and data availability have further enhanced the feasibility of micro-macro integration in population forecasting. The increasing use of big data, machine learning and high-performance computing allows for the analysis of large-scale datasets and the simulation of complex systems (Billari, Zagheni, et al. (2017); Cesare, Lee, McCormick, Spiro, and Zagheni (2018)). These technologies not only improve the precision of forecasts but also open new avenues for exploring the interactions between micro-level behaviours and macro-level outcomes in unprecedented detail (Billari (2015); Willekens (2005)). Digital trace data from social media and mobile phones provide new sources of demographic information that can complement traditional data sources (Alburez-Gutierrez et al. (2019)).

In the context of Portuguese population dynamics, agent-based modelling was employed to evaluate the interactions between individual behaviours and macro-level trends, particularly focusing on the sustainability of the social security system (da Silva Fernandes (2015)). This model incorporates micro-level data, such as individual employment histories, education levels, and retirement contributions, to simulate broader demographic shifts and economic outcomes. For example, the model examined the effects of changes in fertility, mortality, and migration patterns on the Portuguese population structure, revealing a trend toward an increasingly aged population. Such trends have significant implications for the dependency ratio and the economic sustainability of the social security system. By integrating individual decision-making processes with aggregate demographic indicators, the model provided insights into how policies affecting labour market participation and immigration could mitigate some of these challenges. Similar approaches have been applied in other European contexts, demonstrating the value of micro-macro integration for understanding pension system dynamics and population ageing (Marois, Sabourin, and Bélanger (2019)).

This work by da Silva Fernandes (2015) also illustrates how this integrated approach captures the nuances of macroeconomic scenarios on individual outcomes. By simulating scenarios with varying levels of emigration and economic growth, the model identified critical tipping points for social security sustainability. For instance, in high-emigration scenarios, the active-inactive dependency ratio reached unsustainable levels, highlighting the importance of policies that retain working-age individuals within the country. Conversely, in scenarios with moderate immigration and robust GDP growth, the dependency ratio stabilized, demonstrating how targeted policy interventions could align micro-level decisions with macroeconomic stability. These findings underscore the potential of agent-based modelling to bridge the micro-macro divide, offering actionable insights for policymakers addressing complex demographic and economic challenges (Axtell et al. (2002)).

In conclusion, bridging the micro-macro gap in population forecasting represents a crucial step toward more accurate and meaningful demographic insights. By combining individual-level data with aggregate trends, researchers can develop forecasts that reflect the true complexity of population dynamics. This approach not only improves our understanding of demographic change but also enhances the capacity to address pressing societal challenges through informed policy interventions. The continued development of integrated modelling approaches, supported by advances in data availability and computational methods, promises to further strengthen the connection between individual behaviours and population-level outcomes.

2.3 Agent-Based Models of Fertility

Agent-based models (ABMs) have become a central tool for studying fertility because they represent individuals, their network ties and the life-course contingencies through which micro decisions accumulate into macro-level demographic change. The tradition of agent-based computational demography established that bottom-up simulation can test theories of social interaction, feedback and timing in ways that equation-based or purely macro models cannot (e.g., marriage markets, peer influence, tempo effects) (Balbo, Billari, and Mills (2013)).

Within this literature, FPsim represents a recent and influential advance focused on family planning as the proximate driver of fertility outcomes. FPsim is a woman-centred, open-source ABM that follows agents across the reproductive life course and explicitly models fecundability, sexual activity, contraceptive choice and efficacy, postpartum dynamics and pregnancy outcomes under uncertainty. Parameters are age-, stage-, and context-specific, with calibration to setting-level data and probabilistic state transitions that capture heterogeneous life histories. This design allows experiments on targeted interventions that would be infeasible in aggregate models (O'Brien et al. (2023)).

A second stream uses ABMs to unpack social influence on childbearing. Berndt, Rodermund, and Timm (2018) develop a decision architecture that integrates intrinsic "value of children," social pressure and social support within agent networks. Their experiments show that removing social contagion mechanisms depresses births relative to the reference scenario, with age-dependent effects: support matters earlier, pressure strengthens later. This demonstrates how peer environments shape timing and parity even when life-course constraints and preferences dominate baseline propensities (Berndt et al. (2018)).

At the household micro level, Luo, Wang, Yang, Yang, and Gong (2020) propose MASI-ITIB, an ABM linking within-family influence on fertility intentions to realised births. Agents (prospective mother, father, kin, friends) update intentions through weighted ties of varying polarity and strength; behaviour emerges when both parents' intentions cross thresholds, subject to biologically motivated constraints such as post-partum non-susceptibility and recovery intervals. The model illustrates how small changes in initial intentions or influence weights can propagate to longer inter-birth intervals and different completed fertility under policy shifts (Luo et al. (2020)).

ABMs have also been used to examine macro–micro feedback under very low fertility. Kim, Ransikarbum, Kim, and Paik (2016) implement a low fertility trap framework in which ageing, economic capability and demographic structure interact through agents' life-cycle states. Initial experiments for South Korea suggest that higher ageing ratios can induce postponement and lower fertility as younger agents buffer economic burdens, with the authors advocating hybridisation with microsimulation and system dynamics for policy analysis (Kim et al. (2016)).

Finally, earlier ABM contributions have demonstrated that networked interaction can reproduce observed shifts in first-birth timing and mediate policy effects. Diaz, Fent, Prskawetz, and Bernardi (2011) show that peer-group influence and endogenous networks can explain Austria's changes in first-birth probabilities, while Fent, Aparicio Diaz, and Prskawetz (2013) use an ABM to study how social structure conditions the effectiveness of family allowances on intended and realised fertility. Together these studies reinforce a broader point: ABMs add most value when linking micro rules, networks and policy regimes to population-level fertility patterns through transparent, testable mechanisms (Grow and Van Bavel (2015)).

2.4 Unified Growth Theory and Fertility Transitions

The evolution of human economic development can be characterized by three distinct developmental regimes: Malthusian stagnation, Post-Malthusian acceleration and Modern Growth. The Malthusian stagnation epoch dominated from the emergence of humanity until the Industrial Revolution, during which technological progress was minimal and any productivity gains were absorbed by population growth, maintaining living standards near subsistence levels for millennia. The Post-Malthusian acceleration phase emerged in the nineteenth century as technological advancement accelerated, generating both population growth and modest improvements in per capita income, though fertility rates remained elevated. The Modern Growth regime, beginning in the late nineteenth and early twentieth centuries in Western economies, marked an unprecedented transformation characterized by sustained economic growth, declining fertility rates and dramatic improvements in living standards - a phenomenon known as the demographic transition (Ashraf and Galor (2011)).

These three stages show clear patterns in population growth, technology change, human skills, income growth and the tie between income and population (see Figure 2.1). In the Malthusian stage, population and technology grow slowly, human skills stay low, income grows little and higher income leads to more people. Income per person shows no real change. In the Post-Malthusian stage, population and technology start to rise, human skills remain low at first, income grows more and the positive link between income and population stays. Income per person begins to increase slowly. In the Modern Growth stage, population growth levels off or drops, technology and human skills rise fast, income grows steadily and higher income now links to fewer people. This shift happens because of the demographic transition, where population growth falls as education levels rise (Galor (2005)).

The unified growth model, as articulated in Galor and Weil (2000) and further refined by Galor and Moav (2002), stands out for its capacity to encapsulate all three developmental regimes within a single framework, while clarifying the mechanisms that facilitate transitions between them. Traditional economic models typically examine these phases in isolation, viewing the Malthusian era as a static equilibrium interrupted by exogenous events such as the Industrial Revolution, or concentrating exclusively on contemporary growth dynamics without integrating historical contexts Galor (2005). Unified Growth Theory (UGT) aims

Three Distinct Regimes of Economic Development

	Malthusian Epoch	Post-Malthusian Regime	Sustained Economic Growth
Population growth	→	↗	→
Technological change	→	↗	↗
Human capital formation	→	→	↗
Growth of income	→	↗	↗
Relationship between income level and population	+	+	−
Growth of income per capita	→	→-↗	↗

→ insignificant

Figure 2.1: Stages of Economic Development by Galor (2005)

to explain the long-term changes in economic growth. It covers the shift from thousands of years of little progress to steady increases in income. The theory uses basic economic ideas to match the main features of the whole growth process Galor (2005). A key model in this theory comes from Galor and Weil (2000). Their work combines changes in technology, population and human skills. It shows how population growth, technology and income per person have changed over time. UGT describes three main stages in history: the Malthusian stage, the Post-Malthusian stage and the Modern Growth stage. Each stage has a different link between income levels and birth rates (Galor (2005)).

In the Malthusian stage, as Galor and Weil (2000) explain, technology improves slowly. Any rise in output goes mostly to more people, keeping income per person near basic needs. Based on ideas from Malthus (1967), better living standards lead to faster population growth through more births and fewer deaths. Fixed resources like land make returns drop as more people share them. This keeps income steady. History supports this: world population grew at just 0.02 percent per year from the year 1 to 1000, and 0.1 percent from 1000 to 1500, with income per person showing little change (Maddison (2007), as cited in Galor (2005)). Real wages changed little over centuries (Humphries and Weisdorf (2019)). Birth rates rise with income, due to fewer delays in marriage and less hunger or disease, as seen in Europe before industry (Foreman-Peck (2011)).

The move to the Post-Malthusian stage starts with faster technology growth. This outruns population increases. In Western Europe from 1500 to 1820, total output grew at 0.32 percent per year, but most went to more people (0.27 percent), so income per person rose only 0.05 percent yearly (Maddison (2007), as cited in Galor (2005)). Birth rates still go up with income, with more marriages and better health from good food (Fogel (1997)). Yet, new technology stops resources from running out too much, allowing slow gains in living standards. This stage keeps the old link between income and population but adds some lasting growth per person. It ended in the 1970s for Latin America and Asia, but continues in Africa (Galor (2005)).

The change to the Modern Growth stage breaks this pattern. Now, population growth no longer rises with income. Galor and Weil (2000) say this happens because fast technology makes skills more valuable. Parents then choose fewer children but invest more in their education. Birth rates drop sharply, while school years rise a lot (Murtin (2013)). This choice, plus more capital and new ideas, leads to high growth per person. In Western Europe from 1950 to 1973, total output grew at 4.63 percent, with income per person at 3.93 percent and population at 0.70 percent (Maddison (2007), as cited in Galor (2005)). The model ties these stages together in one system. Hidden build-up of skills in the Post-Malthusian stage sets up the drop in births and modern growth.

Galor and Moav (2002) build on this by adding evolution to explain why parents shift to fewer, better educated children. While Galor and Weil (2000) see this shift as a reaction to technology changes from outside, Galor and Moav (2002) make preferences change from within through natural selection. They add differences in genes for parent choices: one type prefers more children, another prefers better educated ones. In the Malthusian time, survival pressures favour traits that fit better technology. Families with higher income from quality choices have more children who survive. Over time, more people prefer quality, boosting skills and speeding up technology. This explains the drop in births as a result of evolution, where quick changes make education pay off more, matching history (Galor and Klemp (2019); Vogl (2016)). By adding biology to economics, Galor and Moav (2002) give a stronger base for birth changes in UGT. It shows why the old income-population link lasts longer in some groups and stresses gene variety for keeping modern growth.

Chapter 3

Methodology

3.1 Core Model

The foundational model developed by Galor and Moav (2002) is an overlapping generations economy that incorporates evolutionary biology into economic growth theory. It demonstrates the interplay between natural selection on human traits and the transition from Malthusian stagnation to sustained economic growth. The model shows that differential reproductive success among genotypes with varying preferences for child quality versus quantity drives changes in population composition, ultimately triggering human capital accumulation and technological acceleration. Agents live for two periods: childhood, during which they are educated by parents and acquire human capital, and adulthood, where they allocate time between labour market participation, consumption and child-rearing decisions. Reproduction is asexual, ensuring direct transmission of genetic traits, and the population consists of two distinct genotypes, denoted $i = a, b$. Genotype a exhibits a stronger preference for child quality (higher education investment), while genotype b leans toward quantity (more children with less investment per child).

The production side of the economy features a constant-returns-to-scale technology that combines efficiency units of labour H_t and a fixed factor, land X, augmented by the level of technology A_t. Aggregate output Y_t is given by:

$$Y_t = H_t^{1-\alpha}(A_t X)^{\alpha}, \quad \alpha \in (0, 1),$$

where $1 - \alpha$ represents the elasticity of output with respect to labour. The aggregate labour input in efficiency units is $H_t = L_t \bar{h}_t$, with L_t as the total population (number of workers) and $\bar{h}_t$ as average human capital. Output per worker is thus:

$$y_t = \frac{Y_t}{L_t} = \bar{h}_t^{1-\alpha}(A_t X/L_t)^\alpha = \bar{h}_t^{1-\alpha} x_t^\alpha,$$

where $x_t = A_t X/L_t$ denotes the land-labour ratio, reflecting resource availability per worker. Assuming no property rights over land, the return to land is zero and the wage per efficiency unit of labour equals the marginal product:

$$w_t = (1-\alpha)\bar{h}_t^{-\alpha}(A_t X)^\alpha L_t^{-(1-\alpha)} = x_t^\alpha.$$

An individual's potential income, if all time is devoted to work, is $z_t^i = w_t h_t^i$, where h_t^i is the human capital level of genotype i.

Preferences are modelled via a utility function that balances consumption and the quantity and quality of offsprings:

$$u_t^i = (1-\gamma)\ln c_t^i + \gamma\left(\ln n_t^i + \beta^i \ln h_{t+1}^i\right),$$

where c_t^i is adult consumption, n_t^i is the number of children, h_{t+1}^i is the human capital of each child, $\gamma \in (0,1)$ weights the utility from children relative to consumption, and $\beta^i \in (0,1]$ (with $\beta^a > \beta^b$) parametrizes the relative preference for quality. This formulation captures the quality-quantity trade-off central to the model.

The budget constraint reflects time allocation: adults have one unit of time, with $\tau + e_{t+1}^i$ as the time cost per child ($\tau > 0$ is fixed rearing cost, and $e_{t+1}^i \geq 0$ is education investment per child). Thus:

$$c_t^i + w_t h_t^i n_t^i(\tau + e_{t+1}^i) \leq w_t h_t^i = z_t^i,$$

or equivalently, in terms of feasible consumption:

$$c_t^i \leq z_t^i\left[1 - n_t^i(\tau + e_{t+1}^i)\right].$$

Human capital formation for the next generation is a function of parental investment in education and the technological progress:

$$h_{t+1}^i = h(e_{t+1}^i, g_{t+1}),$$

where $g_{t+1} = (A_{t+1} - A_t)/A_t$ is the rate of technological progress. The function $h(\cdot)$ is increasing and concave in e_{t+1}^i (diminishing returns to education) but decreasing in g_{t+1}

(technological change erodes existing skills, necessitating adaptation). Technological progress itself is endogenous, driven by the average education level in the population:

$$g_{t+1} = \phi(\bar{e}_t),$$

where $\phi(\cdot)$ is increasing, reflecting scale effects from human capital.

Optimization yields interior solutions for fertility and education under certain parameter conditions (e.g., income above subsistence). The first-order conditions imply that education e^i_{t+1} is higher for quality-preferring types ($e^a_{t+1} > e^b_{t+1}$) and increases with technological growth rates, as faster progress raises returns to skill adaptation. Fertility n^i_t rises with potential income z^i_t (Malthusian effect) but is moderated by quality preferences: type a has fewer children than type b at the same income level. Specifically, solving the utility maximization subject to the budget gives:

$$n^i_t = \frac{\gamma}{1 + \gamma(\beta^i - 1) + \frac{e^i_{t+1}}{\tau + e^i_{t+1}}}$$

In the Malthusian regime, slow technology ($g_{t+1} \approx 0$) favours quantity types, maintaining stagnation. As initial technological sparks (e.g., from population scale) emerge, quality types gain fitness via higher income and fertility, shifting composition toward education-biased preferences. This feedback loop accelerates human capital, technology and the demographic transition, where fertility declines as quality investments dominate, aligning with modern below-replacement rates (Galor and Moav (2002)).

3.2 Model Extensions

Collins et al. (2014) extend the analytical model of Galor and Moav (2002) through numerical simulations to quantitatively analyse its dynamics. This computational methodology, similar to Lagerlöf (2006) simulation of Galor and Weil (2000) model, enables the replication of historical growth patterns and assessment of equilibrium stability. By specifying functional forms for human capital formation and technological progress, the simulations generate time series for key variables, demonstrating the transition from Malthusian stagnation to modern growth.

To operationalize the model for simulation, Collins et al. (2014) adopt explicit functional forms. Human capital in the next generation is modelled as:

$$h_{t+1}^i = \frac{me_{t+1}^i + a}{e_{t+1}^i + rg_{t+1} + a},$$

where $m > 1$ represents the asymptotic maximum human capital attainable through education, $a > 0$ denotes baseline human capital independent of investment and $r > 0$ captures the erosion of skills due to technological change g_{t+1}. This specification ensures $h(\cdot)$ is increasing and concave in education e_{t+1}^i while decreasing in g_{t+1}.

Technological progress is modelled as:

$$g_{t+1} = k\bar{e}_t^d,$$

with $\bar{e}_t$ as the population average education level, $k > 0$ scaling the innovation rate, and $d > 0$ governing the elasticity of progress to education.

Optimization proceeds numerically due to the nonlinearity of these forms. The education choice e_{t+1}^i maximizes utility by satisfying the marginal condition:

$$\beta^i \frac{\partial h_{t+1}^i / \partial e_{t+1}^i}{h_{t+1}^i} = \frac{1}{\tau + e_{t+1}^i},$$

derived from the first-order conditions, balancing quality benefits against time costs.

Fertility n_t^i is then determined from the budget constraint post-education choice:

$$n_t^i = \frac{\gamma}{(\tau + e_{t+1}^i)(1 + \gamma\beta^i)}$$

The parameter values for the base case model are calibrated to achieve a transition of population, technology and income that reflects the Industrial Revolution, as detailed in Table 1 of Collins et al. (2014). The preference parameters are selected such that $\beta^a = 1$ and $\beta^b = 0.9$, ensuring a stronger quality preference for genotype a and yielding a maximum fertility rate of 5 children per parent, consistent with pre-industrial levels. The weight on children in the utility function is $\gamma = 0.259$, producing Malthusian equilibrium fertility rates around 2.5 children per parent, aligning with historical data. The time cost of child rearing is $\tau = 0.2$, facilitating a plausible quantity-quality trade-off. For production, the output elasticity of labour is $1 - \alpha = 0.6$ (implying $\alpha = 0.4$), reflecting the significant role of land in pre-industrial economies. Human capital parameters include $m = 2$ as the asymptotic maximum (allowing a tenfold increase from baseline), $a = 0.99 * \tau$ for baseline human capital without education and $r = 0.108$ to emphasize technological erosion effects. Technological progress parameters are $k = 8.88$ and $d = 0.5$, enabling slow initial progress that accelerates with rising education. Initial conditions are set to $h_0 = 1$ for initial human capital, $A_0 = 1$ for technology level and $X = 1$ for the fixed resource (land), representing a Malthusian starting point. Simulations over extended horizons produce a prolonged Malthusian phase with near-zero per capita growth, followed by a take-off as quality-preferring genotypes increase in frequency, elevating education levels, accelerating technological progress and inducing fertility declines, mirroring Western European economic trajectories from antiquity to the 20th century (Maddison (2005)).

The first step of this study was to replicate this simulation of Collins et al. (2014). A key methodological decision in this replication concerns the calculation of aggregate labour supply H_t. Collins et al. (2014), following Galor and Moav (2002), incorporate labour force participation fractions f_t^i in their formulation:

$$H_t = L_t^a f_t^a h_t^a + L_t^b f_t^b h_t^b,$$

where f_t^i is the fraction of time used by genotype i for labour:

$$f_t^i = \begin{cases} 1 - \gamma & \text{if } z_t^i \geq \tilde{z}, \\ \dfrac{\tilde{c}}{z_t^i} & \text{if } \tilde{c} \leq z_t^i \leq \tilde{z}. \end{cases}$$

This study instead adopts the simpler formulation used by Galor and Weil (2000):

$$H_t = L_t^a h_t^a + L_t^b h_t^b.$$

This simplification is justified on both theoretical and computational grounds. First, the inclusion of labour participation fractions creates minimal qualitative differences in the model's long-run dynamics, as genotypes converge to similar participation rates $f_t^i = 1 -$ once income exceeds the critical threshold $\tilde{z}$. The primary effect of including these fractions occurs during the Malthusian phase when the subsistence constraint binds, but even there, the relative dynamics between genotypes remain largely unchanged.

More critically, the incorporation of participation fractions introduces a problematic computational circularity that Collins et al. (2014) do not address in their article. The calculation of f_t^i depends on potential income z_t^i, which in turn depends on the wage rate w_t as $z_t^i = w_t h_t^i$. However, the wage rate is determined by output per efficiency unit of labour $x_t = A_t \times X / H_t$, which itself requires knowledge of H_t. This creates a fixed-point problem: to calculate H_t, we need the participation fractions, but to calculate the participation fractions, we need to know H_t. Collins et al. provide no discussion of how they resolve this circularity in their implementation, leaving a methodological gap in their presentation.

The system dynamics approach employed here avoids this computational complexity while preserving the essential dynamics of the model. By excluding the participation fractions, the model maintains tractability without sacrificing the core evolutionary mechanism: quality-preferring genotypes still gain a fitness advantage during the Malthusian era through higher human capital and income, while quantity-preferring genotypes achieve higher fitness during the modern growth era due to lower educational investments. The transition dynamics from Malthusian stagnation to sustained growth, driven by the changing composition of genotypes and their educational choices, remain intact.

3.3 Agent-Based Modelling Extension

The next step was to extend the system dynamics framework with an agent-based modelling (ABM) layer that introduces heterogeneity within each genotype population. While the original Collins et al. (2014) model treats each genotype as homogeneous, real populations exhibit considerable variation even among individuals with identical genetic preferences. This extension captures this within-genotype heterogeneity while maintaining consistency with the macro-level dynamics.

Individual agents within each genotype are assigned human capital values drawn from a log-normal distribution with mean h_t^i (the genotype's average human capital from the system dynamics model) and standard deviation of 0.05. The log-normal distribution for human capital is well-established in the labour economics literature, reflecting several empirical regularities. Mincer (1974) and subsequent studies have shown that earnings distributions, which directly correlate with human capital, follow approximately log-normal patterns. This distributional form emerges naturally from multiplicative processes in human capital accumulation, where returns to education, ability and experience compound over time (Battistin, Blundell, and Lewbel (2009)). The standard deviation $\sigma = 0.05$ represents moderate heterogeneity, implying a coefficient of variation of approximately 5% for small σ, which aligns with calibrated innovations in human capital models and focuses variability on inter-genotype differences without introducing excessive outliers that could destabilize aggregates (Vejlin and Veramendi (2023)).

Each agent j of genotype i receives an individual human capital $h_{j,t}^i$ drawn from a log-normal distribution $h^i_{j,t} \sim \log\mathcal{N}(\mu^i_t, \sigma^2)$, where the mean $\mu^i_t = h^i_t$ (the genotype-specific average from the prior period) and standard deviation $\sigma = 0.05$. This parametrization ensures the expected value equals h^i_t. Agents then calculate their individual potential income $z^i_{j,t} = w_t \times h^i_{j,t}$, where w_t is the economy-wide wage per efficiency unit determined at the macro level. Individual fertility decisions follow the same optimization framework as the aggregate model, but based on each agent's specific potential income. This creates a distribution of fertility outcomes within each genotype, rather than a single representative value.

Beyond human capital heterogeneity, the model introduces stochasticity in educational investment decisions. Each agent's education choice is drawn from a log-normal distribution centred on their genotype's optimal education level:

$$e^i_{j,t+1} \sim \log\mathcal{N}\left(\mu^i_{e,t}, \sigma^2_e\right),$$

where $\mu^i_{e,t} = e^i_{t+1}$ represents the genotype's baseline education choice and $\sigma_e = 0.01$. This smaller variance for education reflects the notion that educational decisions, while subject to individual variation through factors like access to schooling, family circumstances and personal aptitude, are more tightly constrained by genetic preferences than the accumulated human capital outcomes. The educational heterogeneity captures realistic within-group variation in schooling investments while preserving the distinct behavioural patterns between genotypes that drive the evolutionary dynamics.

Individual fertility decisions follow the same optimization framework as the aggregate model, but based on each agent's specific potential income and education costs. This dual source of heterogeneity (in both human capital endowments and educational choices) creates realistic distributions of fertility outcomes within each genotype, rather than single representative values, while maintaining the evolutionary selection pressures that operate on genotype averages.

Incorporating stochastic heterogeneity at the individual level provides several modelling advantages (Epstein and Axtell (1996); Tesfatsion (2006)):

1. The stochastic approach generates more realistic demographic patterns, avoiding the artificial synchronization that occurs when all members of a genotype make identical fertility choices. This produces smoother population transitions and more plausible age structures.

2. Individual heterogeneity tests whether the evolutionary dynamics are robust to within-group variation or depend critically on the unrealistic assumption of perfect homogeneity. The persistence of selection pressures despite individual variation strengthens confidence in

the model's core mechanisms.

3. The model naturally generates income and fertility inequality within genotypes, allowing examination of how evolutionary selection operates on distributions rather than just means. This provides insights into whether selection acts primarily on average traits or is sensitive to distributional tails.

4. Individual randomness can enhance numerical stability by preventing discontinuous jumps that occur when entire genotype populations simultaneously cross income thresholds for behavioural changes.

This ABM framework emphasizes micro-macro links in population forecasting, where micro-level fertility choices aggregate to macro-level demographic forecasts, such as total fertility rates (TFR) and population growth trajectories (Billari and Prskawetz (2003); Silverman, Bijak, Hilton, Cao, and Noble (2013)). By simulating bottom-up emergence, the model bridges agent heterogeneity to system-wide outcomes, improving predictive accuracy for scenarios like fertility declines compared to deterministic aggregates.

3.4 Extension with a Third Genotype

Building upon the two-genotype framework, this research extends the model by introducing a third, strongly quantity-preferring genotype (c) to examine the stability and robustness of the evolutionary growth dynamics. This extension follows the approach outlined in Collins et al. (2014), but implements it within the system dynamics and agent-based modelling framework described earlier.

The introduction of a strongly quantity-preferring genotype addresses several methodological and theoretical considerations in evolutionary growth modelling. From a methodological perspective, testing model behaviour with expanded parameter spaces reveals whether the two-genotype results represent a special case or a robust general pattern. The demographic literature suggests substantial heterogeneity in fertility preferences across populations (Caldwell and Caldwell (1987); Lesthaeghe (2010)), making a three-genotype specification more representative of real-world diversity.

Additionally, genotype c can be interpreted as immigrant populations with higher fertility preferences. As D. Coleman (2006) notes, "immigrants from higher-fertility countries often maintain fertility rates substantially above the receiving country average for one or two generations." Similarly, Sobotka (2008) documents that "migrant fertility often remains elevated relative to natives even after controlling for socioeconomic characteristics, suggesting persistent cultural or preference-based differences." Recent data from European countries exemplify these patterns. Kulu et al. (2017) find that "first-generation immigrants from high-fertility origin countries in Europe show total fertility rates 0.5-1.0 children higher than natives, with convergence occurring slowly across generations."

The extended model incorporates three genotypes with preference parameters:

- Genotype a (quality-preferring): $\beta^a = 1.0$

- Genotype b (moderate): $\beta^b = 0.9$

- Genotype c (strongly quantity-preferring/immigrant): $\beta^c \in [0.6, 0.85]$

The parameter range for β^c reflects empirical observations about immigrant fertility preferences. The upper bound of 0.85 represents partial assimilation, while the lower bound of 0.6 captures populations from the highest-fertility regions.

The methodology incorporates comprehensive sensitivity analysis along three dimensions particularly relevant to migration dynamics:

1. Preference Parameter Variation:

The analysis systematically varies β^c from 0.6 to 0.85 in increments of 0.05. This range corresponds to different origin regions as documented by of Economic and Affairs (2024): Sub-Saharan Africa (TFR: 4.6), Middle East/North Africa (TFR: 2.8), and South Asia (TFR: 2.4), compared to developed country averages (TFR: 1.6).

2. Initial Migration Proportion:

The model tests initial proportions of genotype c ranging from 0.001 to 0.10 of the total population, reflecting realistic migration scenarios:

- Trace amounts: $q_0^c = 0.001$

- Small minority: $q_0^c \in [0.005, 0.01]$

- Substantial minority: $q_0^c \in [0.05, 0.10]$

3. Introduction Timing:

To simulate different migration waves, the methodology includes delayed introduction of genotype c:

- Pre-industrial introduction (generation 1-31): Historical migration patterns

- Transition-period introduction (generation 41-51): Industrial era labour migration

- Post-transition introduction (generation 61+): Modern economic migration

These scenarios reflect historical migration patterns (Hatton and Williamson (1998)).

See variables description and their simulation values in Appendix A and simulation pseudocode in Appendix B.

Chapter 4

Results

All simulation scenarios were run for 200 generations. Baseline scenario included only 2 genotypes: a and b. A third genotype c was added in immigration scenarios. These scenarios vary by genotype c preference parameter, initial migration proportion and introduction timing.

4.1 Baseline Dynamics Without Migration

As shown in Figures 4.1, 4.2 and 4.3, the baseline scenario (only 2 initial genotypes) demonstrates the transition from Malthusian stagnation to modern economic growth. During the initial phase (generations 0-40), population education level remain near zero (only genotype a invests in education), technological progress is minimal (below 1%) and fertility rates grow over replacement level (1.0 in the model). Income growth is almost non-existent. The take-off phase begins around generation 40, marked by a sharp rise in education levels, accompanied by technological progress acceleration above 5%. This triggers the characteristic fertility drop. The next growth phase emerges by generation 45-50, where education stabilizes at high levels, technological progress maintains steady rates and fertility undergoes demographic transition, declining to around replacement level.

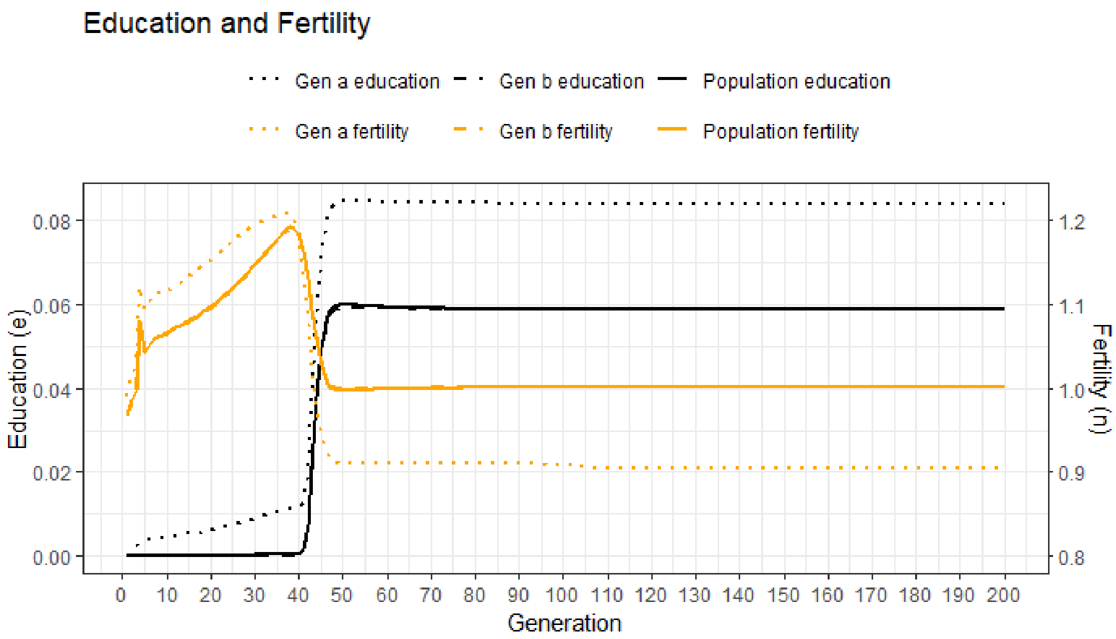

Figure 4.1: Baseline - Education and Fertility

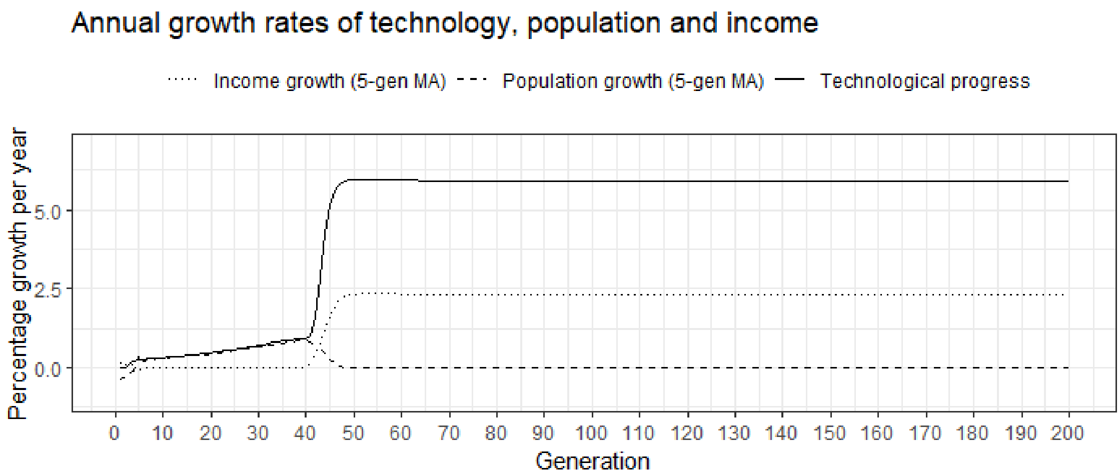

Figure 4.2: Baseline - Annual growth rates of technology, population and income

4.2 Impact of Migration

4.2.1 Education

Figure 4.4 shows that education levels reveal the most dramatic divergence from baseline trajectories. The baseline scenario exhibits a sharp transition around generation 40-50, rising from zero to 0.06 and maintaining this plateau indefinitely. Introduction of genotype c fundamentally alters this pattern in predictable ways. Education collapses after initial achievement of high levels. For $\beta^c <= 0.8$ the timing of collapse can only be postponed depending

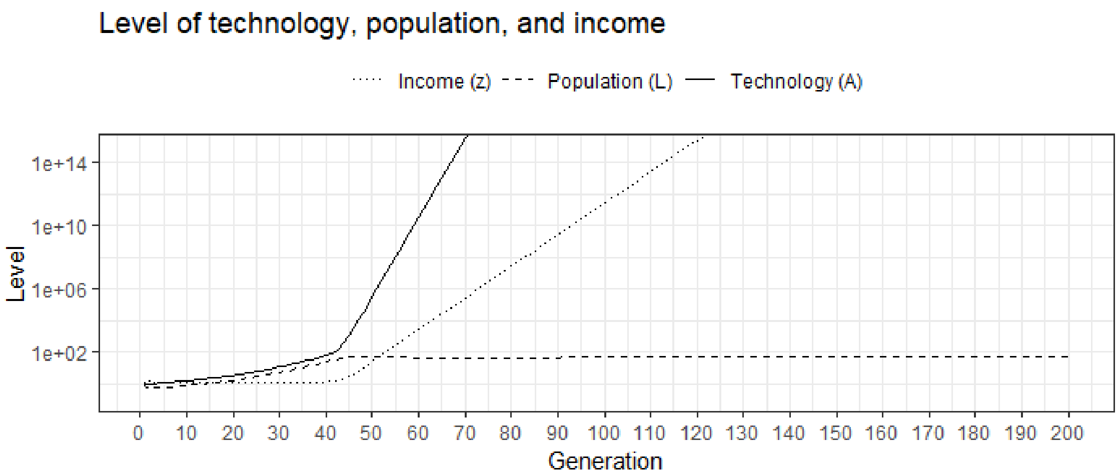

Figure 4.3: Baseline - Level of technology, population and income

on introduction time and initial proportion of genotype c. Only scenarios with $\beta^c = 0.8$ maintain education levels above 0.04 till generation 200.

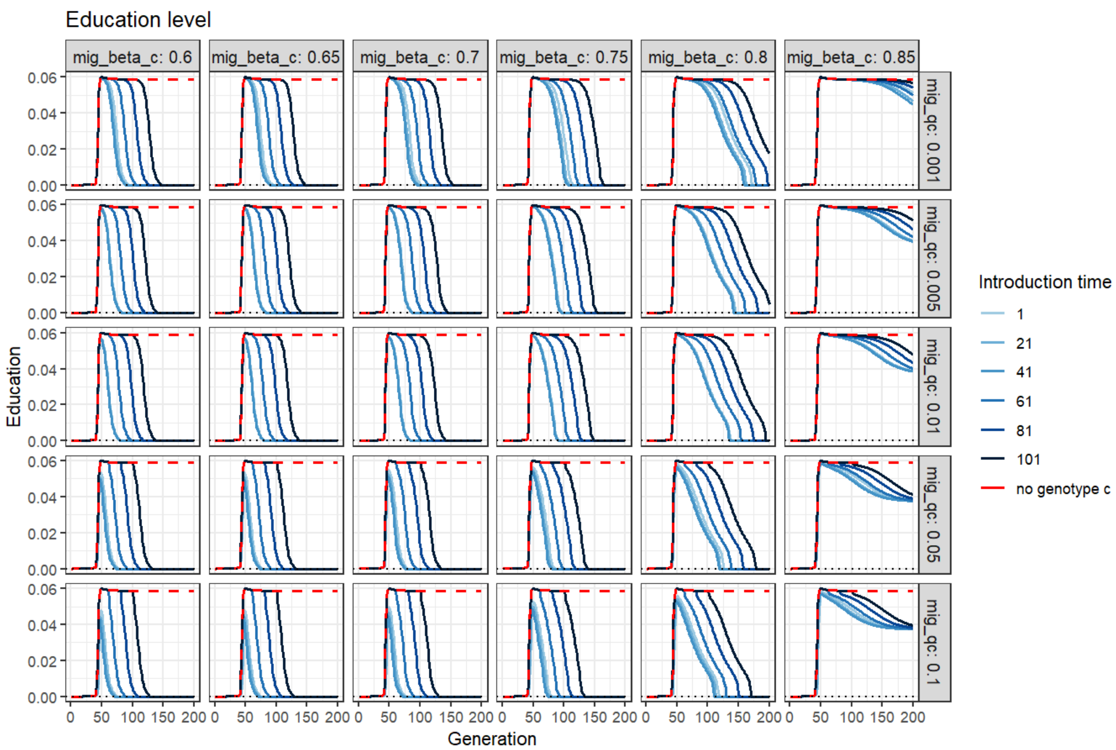

Figure 4.4: Education by Migration Scenario

4.2.2 Technological Progress

Technological progress follows education patterns, as can be seen in Figure 4.5. Only scenarios with $\beta^c = 0.8$ maintain technological growth above 0.05 till generation 200. All other scenarios show collapse of technological growth that follows the collapse of education. Technology levels plateau once genotype c predominates, as near-zero educational investment eliminates the human capital accumulation driving innovation. Scenarios with later introduction and lower genotype c initial proportion still can reach substantial technology level, see Figure 4.6. Accumulated technology remains but without continued innovation, population growth dilutes per capita resources until Malthusian conditions return.

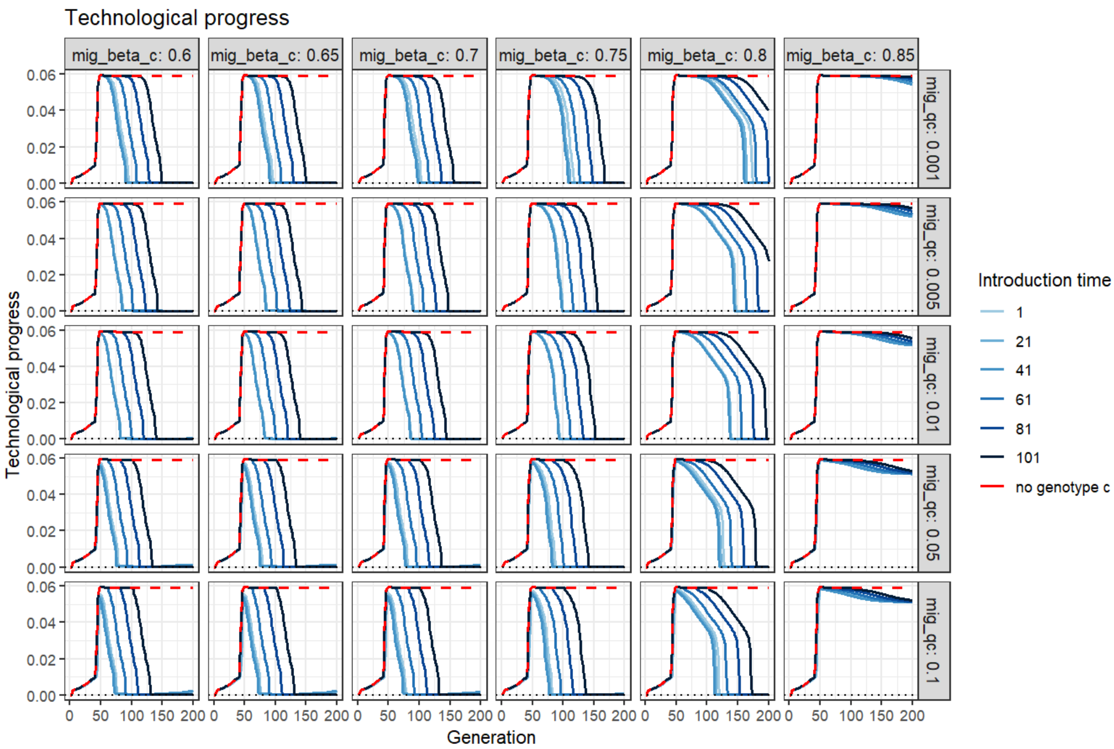

Figure 4.5: Technological Growth by Migration Scenario

4.2.3 Income

As income growth depends on education level and technological growth through human capital, similar patterns as above can be observed (see Figure 4.7). While baseline scenario shows stable income growth after generations 40-50, migration scenarios with $\beta^c \geq 0.8$ show income decline (negative income growth) after initial growth. Only $\beta^c = 0.85$ scenarios maintain positive growth rates above 1.5% for 200 generations. Figure 4.8) shows overall income

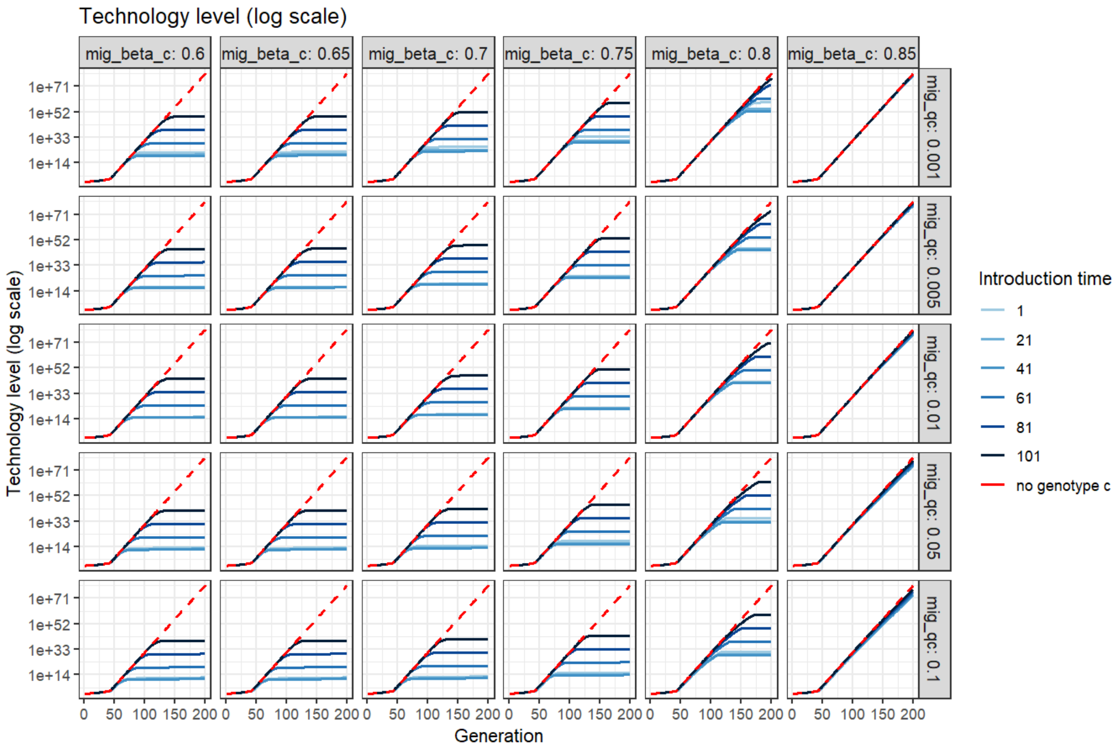

Figure 4.6: Technology Level by Migration Scenario

level. The economy maintains a larger absolute population 4.10) but at low per capita income, exemplifying a high-population, low-productivity equilibrium.

4.2.4 Fertility

Fertility dynamics exhibit three distinct regimes compared to baseline, as can be seen in Figure 4.9). The baseline shows the classic demographic transition: fertility near 1.0, a spike to 1.2 during take-off, then decline to around replacement level. With genotype c introduction, scenarios with $\beta^c \leq 0.8$ never complete the demographic transition - fertility rises during attempted take-off but stabilizes at 1.3 rather than declining. This persistent high fertility despite income growth indicates failure of the quality-quantity substitution mechanism. Sustainable scenarios with $\beta^c = 0.85$ show modified but successful demographic transitions, with fertility stabilizing around 1.1, suggesting incomplete convergence to modern fertility norms. Population levels for different scenarios can be observed in Figure 4.10).

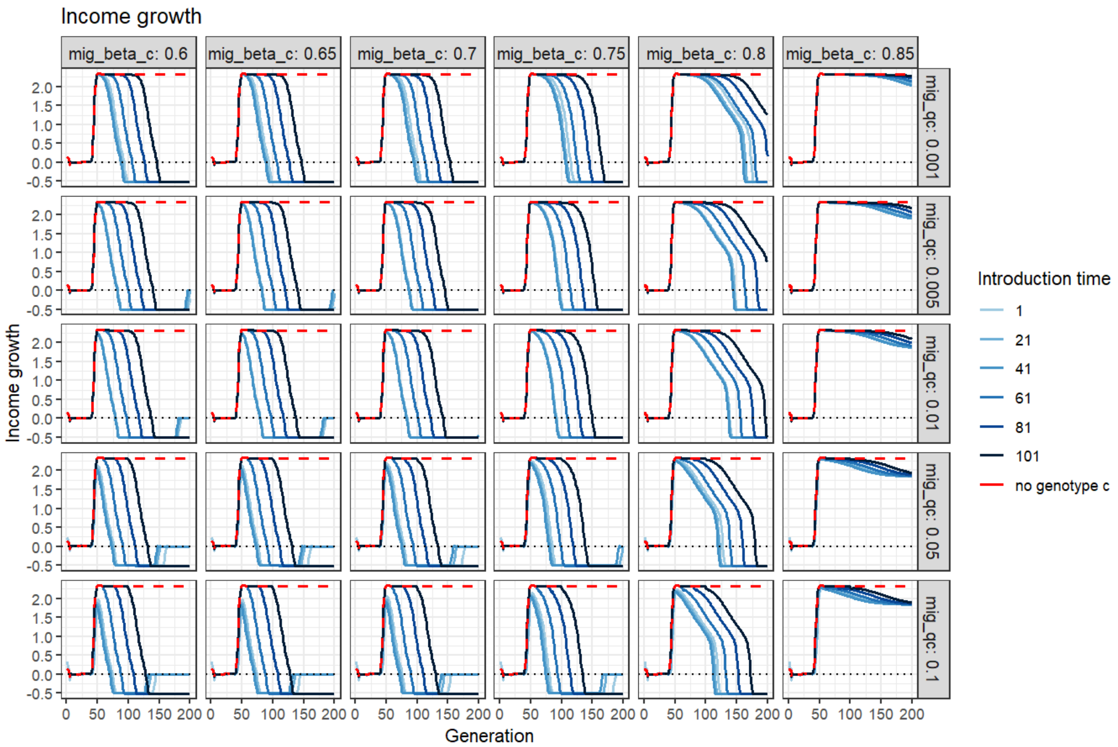

Figure 4.7: Income Growth by Migration Scenario

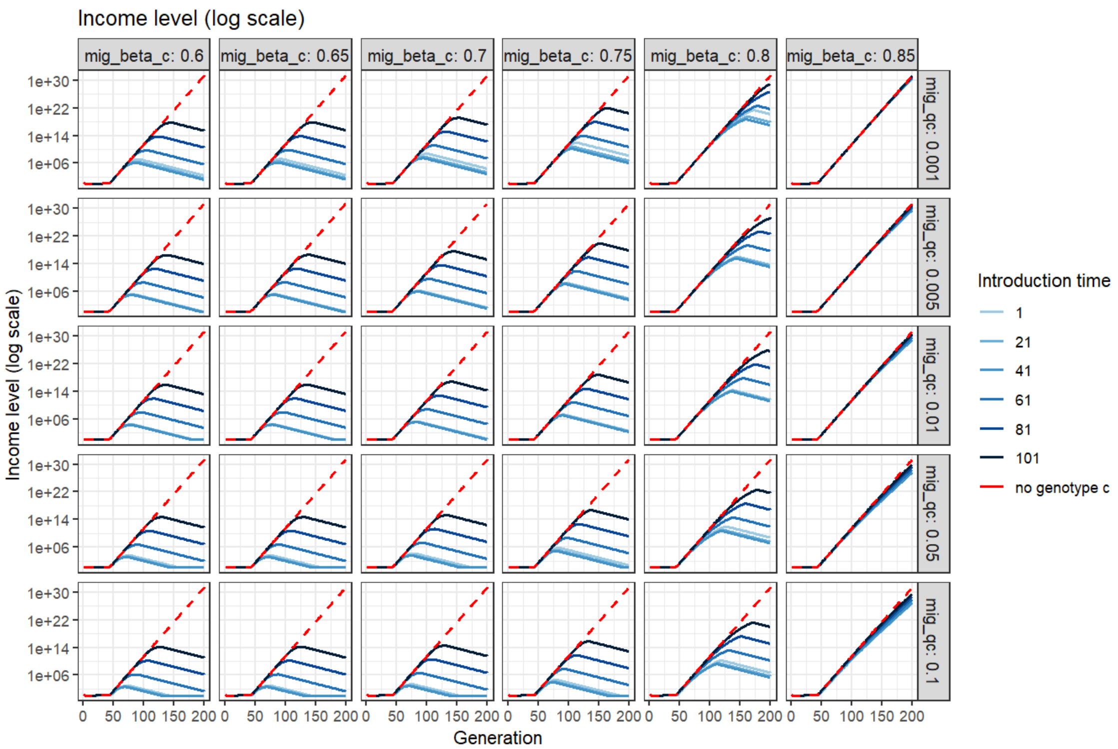

Figure 4.8: Income Level by Migration Scenario

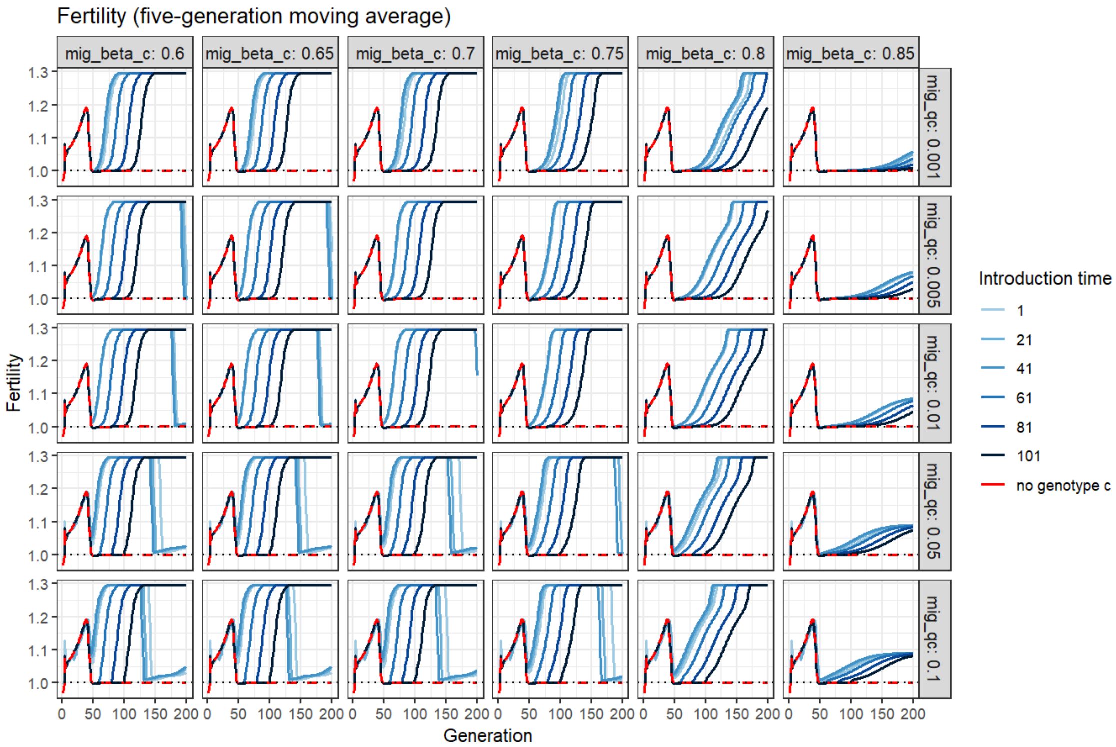

Figure 4.9: Fertility by Migration Scenario

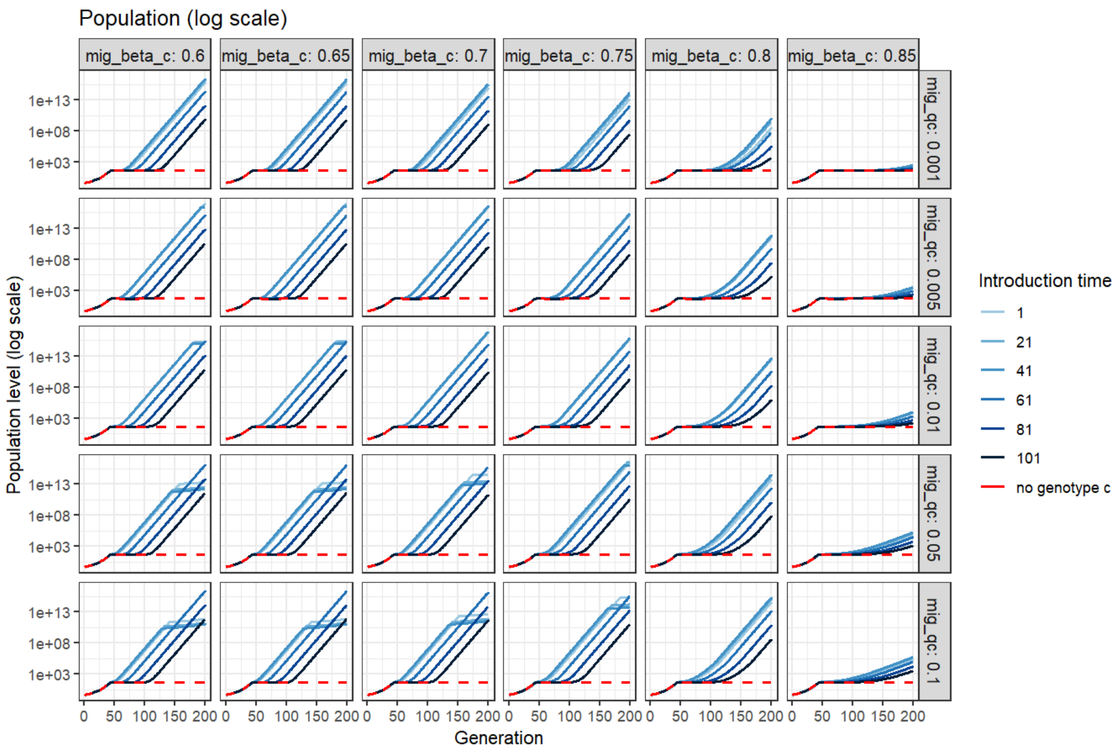

Figure 4.10: Population by Migration Scenario

4.2.5 Population Composition

The simulation results reveal a counter-intuitive dynamic in the evolutionary competition between native genotypes (a+b) and the immigrant genotype (c). Figure 4.11) shows how proportion of genotypes a+b changes over time for different migration scenario. When genotype c has moderate quantity preference ($\beta_c = 0.6 - 0.75$), native populations stabilize at approximately 20% of the total population across all introduction timing scenarios and initial proportions. This equilibrium emerges because genotype c's limited educational investment prevents complete dominance: while they have higher fertility, their lower human capital constrains their income and reproductive success during economic downturns.

Paradoxically, when genotype c has stronger preference for quality ($\beta_c = 0.8 - 0.85$), approaching the moderate genotype b's preferences, native populations face near-complete replacement. This occurs because genotype c with $\beta_c \geq 0.8$ invests sufficiently in education to maintain reasonable human capital while still retaining a fertility advantage over the native genotypes a and b. Genotype c occupies an optimal niche: educated enough to thrive economically but not so education-focused as to sacrifice fertility. This strategy proves evolutionarily superior to both the quality-preferring genotype a (who over-invests in education) and the moderate genotype b (who lacks genotype c's fertility).

The timing of introduction creates variation in the speed but not the endpoint of demographic transition. The consistent endpoints across different initial proportions suggest that these equilibria represent evolutionarily stable states determined primarily by the preference parameters rather than initial conditions.

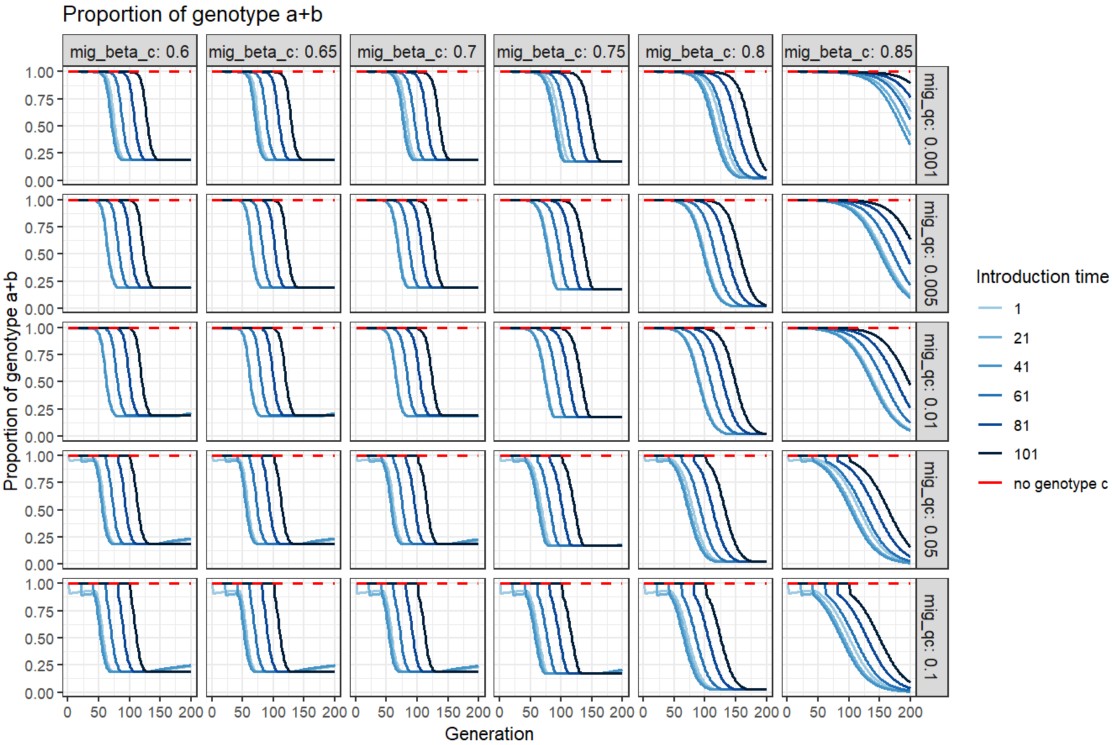

Figure 4.11: Genotypes a+b Proportions by Migration Scenario

Chapter 5

Discussion

The simulation results illustrate the profound impact of genotypic variations in fertility preferences on long-term economic and demographic trajectories, particularly under immigration scenarios introducing a third, strongly quantity-preferring genotype. In the baseline scenario (without immigration), a transition from Malthusian stagnation to sustained growth is characterized by declining fertility rates as education levels rise and technological progress accelerates. Fertility peaks during the initial phases before dropping around replacement levels in the modern regime, reflecting the quality-quantity trade-off where parents invest more in fewer offspring. However, introducing a genotype with higher quantity preference disrupts this pattern. Higher β_c values (indicating moderate quality preference in immigrants) allow for partial integration, with fertility trajectories showing temporary spikes before converging toward baseline declines. Conversely, lower β_c lead to persistent high fertility, suppressing education investments and halting technological progress, resulting in population explosion while income growth stagnates or reverses. These outcomes underscore how genotypes with elevated fertility preferences can delay or prevent fertility transitions.

5.1 Fertility Preferences

Central to this analysis is Galor's proposition that preferences for child quality over quantity are genetically determined, evolving through natural selection during the Malthusian era (Galor and Moav (2002)). In this framework, survival pressures favoured traits complementary to technological advancement, gradually increasing the prevalence of quality-biased genotypes and triggering the demographic transition. The simulations align with this by showing that introducing quantity-preferring genotypes mimics a reversal of evolutionary gains, where high-fertility traits outcompete others in the absence of strong selection for education. Empirical evidence from twin studies supports a genetic basis for fertility behaviours (Kohler, Rodgers, and Christensen (1999); Rodgers et al. (2001)). However, the extent to which immigrant fertility patterns reflect genetic persistence versus cultural adaptation remains debated.

Studies on immigrant fertility provide mixed insights into this genetic-cultural divide. First-generation immigrants often exhibit higher fertility rates than host populations, consistent with quantity preferences from origin countries, but convergence typically occurs across generations. For instance, in the United States, Hispanic immigrants show elevated initial fertility, but second- and third-generation descendants converge toward native white levels (Parrado and Morgan (2008)). Fernández and Fogli (2009) demonstrate that second-generation Americans' fertility correlates significantly with origin country fertility rates, even controlling for socioeconomic factors. Similarly, Blau, Kahn, Liu, and Papps (2013) find that immigrant women in the United States maintain fertility rates 0.5-1.0 children above natives, with only partial convergence by the third generation. Similarly, in Europe, descendants of high-fertility migrants from South Asia and Africa display fertility lower than their parents, approaching native averages by the second generation (Dubuc (2012); Kulu et al. (2017)). Milewski (2010) documents that Turkish immigrants to Germany maintain elevated fertility for two generations before converging, while Eastern European immigrants converge within one generation. Mussino and Strozza (2012) find that fertility convergence in Italy depends critically on labour market integration and educational opportunities. This assimilation supports cultural or environmental explanations, such as access to education and contraception in host countries, over purely genetic persistence. Yet, some persistence is observed; for example, Mexican-origin women in the U.S. maintain slightly higher fertility even in later generations, potentially indicating genetic components or incomplete cultural convergence (Bean and Stevens (2003)).

The model's prediction that strongly quantity-preferring types can prevent demographic transition completion finds empirical support in the persistent above-replacement fertility of certain immigrant groups in Europe, even after controlling for socioeconomic factors (D. A. Coleman and Dubuc (2010); Sobotka (2008)). The model's results also align with D. Coleman (2006) "third demographic transition" hypothesis, wherein sustained immigration from high-fertility regions could fundamentally alter receiving countries' demographic composition. The simulation shows this occurring most dramatically when $\beta_c \geq 0.8$, where native populations decline to near-extinction within 100-150 generations. This extreme outcome, while unlikely given observed convergence patterns, highlights the potential for demographic replacement under sustained fertility differentials.

The threshold effect at $\beta_c = 0.8$ implies that successful integration requires migrants whose fertility preferences are within approximately one standard deviation of the native population. Empirical studies support the existence of such thresholds: Goldscheider et al. (2016) found that fertility convergence occurs reliably only when the origin-destination fertility gap is less than 1.5 children per woman. Beyond this threshold, persistent fertility differentials can maintain distinct demographic subpopulations indefinitely, consistent with our model's prediction of stable high-fertility equilibria when quantity preferences are too strong.

The simulation results reveal fundamental tensions between fertility preferences and long-term economic sustainability in the evolutionary growth model. The introduction of a strongly quantity-preferring genotype (c) demonstrates that modern economic growth, rather than representing an irreversible transition, may constitute a fragile equilibrium vulnerable to demographic shifts. The outcomes depend critically on the precise calibration of fertility preferences, with a threshold effect around $\beta_c = 0.8$ determining whether the economy maintains growth or regresses to Malthusian conditions.

The threshold effect around $\beta_c = 0.8$ carries important implications. Small differences in immigrant fertility preferences determine whether immigration enhances or undermines long-term growth. The model suggests that immigration from moderately high-fertility regions ($\beta_c \geq 0.8$) may actually optimize growth by maintaining demographic dynamism without sacrificing human capital investment. This fertility level prevents both the demographic decline and the educational collapse threatening growth sustainability.

The high-fertility equilibrium observed in failed scenarios represents what demographers term a "low-education, high-fertility trap" (Lutz, Skirbekk, and Testa (2006)). Once average education falls below critical levels, the returns to human capital investment collapse, removing the primary mechanism for fertility reduction. The model's prediction that all genotypes converge to high fertility in failed scenarios demonstrates how institutional and economic environments shape reproductive behaviour more than individual characteristics.

5.2 Scale Effects and Model Robustness

A key feature of the model, inherited from Galor and Moav (2002), is the absence of a population scale effect in technological progress, where innovation depends solely on average education levels rather than population size: $g_{t+1} = \phi(\bar{e}_t)$. This contrasts with Galor and Weil (2000), which includes a scale effect: larger populations generate more ideas, accelerating technology via $g_{t+1} = \phi(L_t, \bar{e}_t)$, with positive elasticity to L_t. The omission in Galor and Moav shifts emphasis to human capital quality, avoiding empirical critiques of scale effects, such as the lack of correlation between post-1950 population growth and innovation rates in developed economies (Jones (1995)).

However, the empirical evidence on scale effects remains debatable. Supporting scale effects, Kremer (1993) documents correlation between world population and technological progress over millennia, while Boserup (1965) argues population pressure historically drove agricultural innovation. Urban agglomeration studies (Glaeser, 2011; Carlino et al., 2007) find innovation scales super-linearly with city size, suggesting positive externalities from population concentration. However, Jones (1995, 2022) presents compelling counter-evidence: despite number of researchers growing drastically since 1950, per capita growth rates remain stable, implying declining research productivity. Bloom, Jones, Van Reenen, and Webb (2020) document that maintaining constant innovation rates requires exponentially increasing research effort, contradicting simple scale effects. Cross-country comparisons show weak correlation between population size and growth rates once controlling for human capital (Mankiw, Romer, and Weil (1992)).

If scale effects existed, the model's dynamics would change dramatically. The population explosion following genotype c's dominance would generate innovation even with minimal education, potentially sustaining growth despite falling human capital investment. This highlights how assumptions about innovation mechanisms fundamentally determine conclusions about growth sustainability.

5.3 Model Limitations and Extensions

While the model provides valuable insights into the relationship between fertility preferences and long-run economic dynamics, several methodological and theoretical limitations warrant careful consideration when interpreting results.

The most fundamental limitation concerns the assumption of fixed, genetically determined fertility preferences. The model treats preference parameter as an immutable characteristic transmitted perfectly across generations, yet substantial empirical evidence documents preference adaptation through cultural transmission, education and policy interventions (Newson, Postmes, Lea, and Webley (2005); Colleran (2016)). Observed convergence in immigrant fertility (typically occurring within 2-3 generations) suggests that preferences respond to environmental incentives far more rapidly than genetic evolution would permit (Kulu and González-Ferrer (2014)). This limitation likely causes the model to overstate the persistence of fertility differentials and underestimate societies' adaptive capacity.

The assumption of asexual reproduction with perfect preference inheritance ignores the complexity of genetic transmission. Sexual reproduction with assortative or random mating would create preference distributions rather than discrete types, potentially smoothing evolutionary dynamics (Bisin and Verdier (2001)). Genetic recombination, mutation and epigenetic factors all generate variation that could prevent complete convergence to any single genotype, maintaining the diversity necessary for adaptive responses to environmental changes (Richerson and Boyd (2008)).

Spatial and network dimensions are entirely absent despite their documented importance in demographic processes. Real populations exhibit substantial geographic sorting by education and fertility, with high-education individuals concentrating in urban centres while high-fertility populations may cluster in peripheral regions (De La Croix and Doepke (2003)). This spatial heterogeneity creates local variation in evolutionary pressures and might allow high-education enclaves to sustain innovation even if broader populations shift toward quantity preferences (Desmet and Parente (2012)).

Future extensions should address these limitations through several methodological improvements. Incorporating cultural alongside genetic evolution would create a dual inheritance system better aligned with observed fertility transitions (Henrich, Boyd, and Richerson (2008)). Endogenizing institutional responses could identify policy mechanisms that maintain growth-supporting incentives (Cervellati and Sunde (2005)). Including scale effects would provide a more complete picture of how demographic composition affects economic dynamics (Ashraf and Galor (2011)). These extensions, while increasing model complexity, would enhance both realism and policy relevance.

Chapter 6

Conclusion

This study has demonstrated that the transition from Malthusian stagnation to modern economic growth may not represent an irreversible achievement of human civilization, but rather a potentially fragile equilibrium vulnerable to demographic shifts in fertility preferences. Through systematic replication and extension of the Galor and Moav (2002) evolutionary growth model using agent-based modelling, this research reveals critical thresholds in the quality-quantity trade-off that determine whether economies sustain growth or regress to subsistence conditions.

This dissertation makes several substantive contributions to unified growth theory, demographic economics and computational modelling of population dynamics. First, it provides the first systematic analysis of how migration-induced demographic shocks affect the stability of modern economic growth within an evolutionary framework. While Galor and Moav (2002) established the theoretical foundation for evolutionary selection in fertility preferences, their model assumed closed populations. This work demonstrates that the introduction of populations with divergent fertility preferences can fundamentally alter evolutionary trajectories, potentially reversing centuries of economic progress.

Second, the identification of a critical threshold for preference parameter represents a novel theoretical insight with practical implications. This finding suggests that successful economic integration requires immigrant fertility preferences within approximately 10-20% of native population norms - a surprisingly narrow band that helps explain both successful and failed integration experiences across different migration contexts.

Third, the agent-based modelling extension provides the first micro-founded approach to evolutionary growth theory. By introducing within-genotype heterogeneity in human capital and educational choices, this framework demonstrates how individual-level variation aggregates to population-level selection dynamics. This methodological contribution bridges the micro-macro gap that has long challenged demographic forecasting.

Fourth, the comprehensive sensitivity analysis across preference parameters, initial proportions and introduction timing provides a complete mapping of the model's state space - something absent from previous studies. This systematic exploration reveals multiple evolutionarily stable equilibria, path dependencies and regime-switching dynamics that were not apparent in earlier, more limited analyses. The finding that timing affects transition speed but not endpoints for most parameter values suggests that these equilibria represent fundamental attractors in the evolutionary landscape.

Finally, this work contributes to the broader literature on demographic transitions and fertility determinants by demonstrating how evolutionary models can inform contemporary policy debates. The model's prediction that maintaining modern growth requires careful balance between demographic openness and human capital investment speaks directly to current challenges facing ageing societies in Europe and East Asia.

These findings should be interpreted considering the model limitations discussed in Chapter 5, particularly the assumptions of fixed genetic preferences and absence of institutional adaptation mechanisms. While the model demonstrates potential vulnerabilities in modern economic growth, real societies possess cultural and institutional flexibility not captured in this framework. The rapid convergence of immigrant fertility observed empirically suggests that preferences adapt more quickly than pure genetic evolution would allow, and societies have historically developed educational and economic institutions that maintain human capital investment incentives even under demographic pressure. Nevertheless, the identification of critical thresholds and evolutionary dynamics provides valuable insights into the fundamental tensions between demographic change and economic sustainability that merit serious consideration in policy formulation.

The model's central insight that modern economic growth depends critically on maintaining populations whose fertility preferences support human capital investment carries profound implications for contemporary policy debates. The narrow threshold between sustainable and unsustainable migration scenarios suggests that demographic integration requires more than economic opportunity; it demands rapid cultural and educational assimilation to preserve growth-supporting preferences.

Ultimately, this research contributes to our understanding of how fertility choices at the individual level cascade through evolutionary and economic mechanisms to shape civilizational trajectories. The modern growth era, barely two centuries old, represents a brief departure from millennia of Malthusian stagnation. Whether this departure proves permanent or temporary may depend on humanity's ability to maintain the delicate balance between demographic vitality and human capital investment that the model identifies as crucial for sustained prosperity.

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Appendix A

Variables Description

Variable	Description	Value(s)
$\boldsymbol{1-\alpha}$	Output elasticity of labour	0.6
$\boldsymbol{\tau}$	Fixed time cost per child	0.20
$\boldsymbol{a}$	Portion of fixed cost time of raising child towards human capital, $a = 0.99 * \tau$	0.198
$\boldsymbol{m}$	Weighting of education in production of human capital	2
$\boldsymbol{X}$	Land (fixed resource)	1
$\boldsymbol{k}$	Scale parameter in growth function	8.88
$\boldsymbol{d}$	Curvature parameter in growth function	0.5
$\boldsymbol{r}$	Sensitivity of human capital to economic growth	0.108
γ	Weight on children in utility function	0.259
$\boldsymbol{\tilde{c}}$	Subsistence consumption threshold	1
$\boldsymbol{\tilde{z}}$	Income threshold for fertility cases, $\tilde{z} = \tilde{c}/(1-\gamma)$	≈ 1.35
$\boldsymbol{T}$	Simulation horizon (number of generations)	200
$\boldsymbol{N}$	Number of agents per generation	10,000
sd_h	Log-normal dispersion for h distribution for agents	0.05
sd_e	Log-normal dispersion for e distribution for agents	0.01
$\boldsymbol{\beta_a}$	Preference for child quality for genotype a	1

Variable	Description	Value(s)
$\boldsymbol{\beta_b}$	Preference for child quality for genotype b	0.9
$\boldsymbol{\beta_c}$	Preference for child quality for genotype c	$\{0.6, 0.65, 0.7, 0.75, 0.8, 0.85\}$
$\boldsymbol{T_c}$	Introduction generation for genotype c	$\{1, 21, 41, 61, 81, 101\}$
$\boldsymbol{L(1)}$	Initial total population	0.707
$\boldsymbol{q_a(1)}$	Initial population share of genotype a	0.01
$\boldsymbol{q_c(T_c)}$	Population share of genotype c at T_c	$\{0.001, 0.005, 0.01, 0.05, 0.10\}$
$\boldsymbol{e_i(1)}$	Initial education level of each genotype	0
$\boldsymbol{g(0)}$	Initial tech growth	0
$\boldsymbol{h_i(1)}$	Initial human capital of each genotype	0
$\boldsymbol{A(1)}$	Initial technology level	1

Appendix B

Simulation Pseudocode

1. Generational dynamics (for $t = 1, \ldots, T$)

   1.1. Case $t < T_c$ (before genotype c introduction)

   1.1.1. Create agent population of size $N = 10{,}000$ and split by generation:
   $N_a = round(N\ * q_a[t])$
   $N_b = N - N_a$

   1.1.2. For each agent set preference $\beta \in \{\beta_a, \beta_b\}$ based on their genotype

   1.1.3. For each agent draw their human capital h by genotype:
   $h \sim \log\mathcal{N}(\log h_i[t],\ sd_h)$

   1.1.4. Calculate aggregate labour H:
   $H[t] = L_a[t]h_a[t] + L_b[t]h_b[t]$

   1.1.5. Calculate population mean wage per efficiency unit w:
   $w[t] = \left(\frac{A[t]X}{H[t]}\right)^{\alpha}$

   1.1.6. For each agent calculate income z based on their human capital:
   $z = w[t] \cdot h$

   1.1.7. Compute genotype and population mean income $z_a[t], z_b[t], z[t]$

   1.1.8. Calculate tech growth g for the next generation based on education e of current generation:
   $g[t{+}1] = k\, e[t]^d$

   1.1.9. Calculate education choices e for each genotype, for $i \in \{a, b\}$:

   1.1.9.1. $term1_i = m(\beta_i - 1)(r\, g[t{+}1] + a) - a(\beta_i + 1)$

   1.1.9.2. $term2_i^2 = term1_i^2 + 4m((m\beta_i\tau - a)(r\, g[t{+}1] + a) - a\beta_i\tau)$

1.1.9.3. If $term2_i^2 \geq 0$ set $e_i[t{+}1] = \max\left\{0,\ \dfrac{term1_i + \sqrt{term2_i^2}}{2m}\right\}$, else set $e_i[t{+}1] = 0$

1.1.10. For each agent draw education choice e by genotype:
$e \sim \log\mathcal{N}(\log e_i[t{+}1],\ sd_e)$

1.1.11. Calculate population mean education for the next generation:
$e[t{+}1] = \text{mean}(e)$.

1.1.12. For each agent calculate agent fertility n based on their income z and education choice e:

1.1.12.1. If $z \geq \tilde{z}$, set $n = \dfrac{\gamma}{\tau + e}$

1.1.12.2. Else if $\tilde{c} \leq z < \tilde{z}$, set $n = \dfrac{1 - \tilde{c}/z}{\tau + e}$

1.1.12.3. Else set $n = 0$

1.1.13. Compute genotype and population mean fertility $n_a[t], n_b[t], n[t]$

1.1.14. Update the size of genotype population L for the next generation based on fertility n, for $i \in \{a, b\}$:
$L_i[t{+}1] = L_i[t] \cdot n_i[t]$

1.1.15. Update total population size L:
$L[t{+}1] = L_a[t{+}1] + L_b[t{+}1]$

1.1.16. Update genotype proportions for the next generation, for $i \in \{a, b\}$:
$q_i[t{+}1] = \dfrac{L_i[t{+}1]}{L[t{+}1]}$

1.1.17. Update technology level A for the next generation based on technological growth g:
$A[t{+}1] = A[t]\,(1 + g[t{+}1])$

1.1.18. Update human capital h for each genotype, for $i \in \{a, b\}$:
$h_i[t{+}1] = \dfrac{me_i[t{+}1] + a}{e_i[t{+}1] + r \cdot g[t{+}1] + a}$

1.2. Case $t \geq T_c$ (genotype c present)

1.2.1. If $t = T_c$, set $L_c[t] = L[t] \cdot q_c[t]$

1.2.2. Create agent population of size $N = 10{,}000$ and split by generation:
$N_a = round(N\ * q_a[t])$
$N_c = round(N\ * q_c[t])$
$N_b = N - N_a - N_c$

1.2.3. For each agent set preference $\beta \in \{\beta_a, \beta_b, \beta_c\}$ based on their genotype

1.2.4. For each agent draw their human capital h by genotype:
$h \sim \log\mathcal{N}(\log h_i[t],\ 0.05)$

1.2.5. Calculate aggregate labour H:

$H[t] = L_a[t]h_a[t] + L_b[t]h_b[t] + L_c[t]h_c[t]$

1.2.6. Calculate population mean wage per efficiency unit w:

$w[t] = \left(\frac{A[t]X}{H[t]}\right)^{\alpha}$

1.2.7. For each agent calculate income z based on their human capital:

$z = w[t] \cdot h$

1.2.8. Compute genotype and population mean income $z_a[t], z_b[t], z_c[t], z[t]$

1.2.9. Calculate tech growth g for the next generation based on education e of current generation:

$g[t+1] = k\, e[t]^d$

1.2.10. Calculate education choices e for each genotype, for $i \in \{a, b, c\}$:

1.2.10.1. $term1_i = m(\beta_i - 1)(r\, g[t+1] + a) - a(\beta_i + 1)$

1.2.10.2. $term2_i^2 = term1_i^2 + 4m((m\beta_i\tau - a)(r\, g[t+1] + a) - a\beta_i\tau)$

1.2.10.3. If $term2_i^2 \geq 0$ set $e_i[t+1] = \max\left\{0,\ \frac{term1_i + \sqrt{term2_i^2}}{2m}\right\}$, else set $e_i[t+1] = 0$

1.2.11. For each agent draw education choice e by genotype:

$e \sim \log\mathcal{N}(\log e_i[t+1],\ 0.01)$

1.2.12. Calculate population mean education for the next generation:

$e[t+1] = \text{mean}(e)$.

1.2.13. For each agent calculate agent fertility n based on their income z and education choice e:

1.2.13.1. If $z \geq \tilde{z}$, set $n = \frac{\gamma}{\tau + e}$

1.2.13.2. Else if $\tilde{c} \leq z < \tilde{z}$, set $n = \frac{1 - \tilde{c}/z}{\tau + e}$

1.2.13.3. Else set $n = 0$

1.2.14. Compute genotype and population mean fertility $n_a[t], n_b[t], n_c[t], n[t]$

1.2.15. Update the size of genotype population L for the next generation based on fertility n, for $i \in \{a, b, c\}$:

$L_i[t+1] = L_i[t] \cdot n_i[t]$

1.2.16. Update total population size L:

$L[t+1] = L_a[t+1] + L_b[t+1] + L_c[t+1]$

1.2.17. Update genotype proportions for the next generation, for $i \in \{a, b, c\}$:

$q_i[t+1] = \frac{L_i[t+1]}{L[t+1]}$

1.2.18. Update technology level A for the next generation based on technological growth g:

$A[t+1] = A[t]\,(1 + g[t+1])$

1.2.19. Update human capital h for each genotype, for $i \in \{a, b, c\}$:

$h_i[t+1] = \dfrac{me_i[t+1] + a}{e_i[t+1] + r \cdot g[t+1] + a}$