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Health, Environment and Economic Growth: Theoretical Study on China

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Contents

1 Abstract

This dissertation consists of four related essays on health policy analysis. More precisely, this dissertation focuses on three most striking health related issues in China: health care system reform, pollution-induced health degradation, and culture effect on the evaluation of health policy.

The first essay gives a qualitative study on the evolution of China's health care system with highlight on the reform policies. We provide policy implications by statistical analysis to various Chinese health data on mortality rate, life expectancy, health care expenditure and health care providers. Policy insights for the further health care reform are to expand the health insurance coverage, lower copay or deductible, and particularly, integrate diverse medical insurance systems into a unified and standardized system nationwide. This essay highlights the need for diminishing the urban-rural health care inequalities, promoting diverse medical care providers (e.g. private hospital) and providing basic medical care assistance for extreme poor people without insurance. In addition, we discuss Traditional Chinese Medicine (TCM) and its role in China's health care system.

The second essay presents a theoretical framework to study economic policy subject to health and production fluctuations. The proposed model has the advantage of being analytically tractable with closed-form solutions for the optimal abatement policy and economic growth rate. It also demonstrates that the relationship between mitigation policy and economic growth rate is inverted-U shaped. Our numerical study shows that the optimal abatement policy reacts sensitively to the health parameter and uncertainty parameters. We find that the abatement policy should be 0.46%, indicating 33 U.S. dollar per ton coal, or 0.69%, indicating 50 U.S. dollar per ton coal, if the abatement technology improvement is viewed in a less optimistic way. Both numbers are comparable but higher than existing literature. Thus, we suggest tight environmental policy when pollution induced uncertainty is considered.

The third essay aims to extend the stochastic health demand model by introducing two kinds of catastrophic shock: nature disaster and epidemic. The closed-from solution for abatement policy and economic growth are derived. In addition, we provide the necessary and sufficient condition for the existence and uniqueness of the equilibrium. The innovative message from our quantitative analysis is that optimal abatement policy reacts sensitively to the parameters of health and catastrophe intensity. Our calibration suggests higher carbon tax and more stringent climate policy: a taxation of 103 U.S. dollar per ton coal or 56 U.S. dollar per ton coal when the development of the abatement technology is viewed in an optimistic way. Indeed, the emission-induced extreme events are underestimated when the social cost of carbon is calculated in conventional approach.

The fourth essay demonstrates that, in an one-period two-stage model, the relationship between medical demand of TCM and WM depends on both health policy and culture effect. We develop a theoretical health demand model following expected utility framework to illustrate culture effect in individual's health decision, and the impact of TCM in China's health care system. We demonstrate that the marginal effect of copay rate and insurance policy are invert related. Moreover, the relationship between copay rate and individual welfare is inverted-U shaped, and hence a smaller copay rate may enhance medical demand while reducing steady-state individual welfare. Finally, we generalize the benchmark model to study how the age effect influence individual's medical demand between TCM and WM.

2 Motivation and Research Background

Health is "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmit"(WHO, 1964)[1]. Health to everyone is the most basic and essential asset, which entails individual to develop to their potentials for a life in dignity. Good health is a critical element of individual and societal well-being, in light of the fact that achieving the highest attainable standard of health requests for a set of social health arrangements which is conducive to the health of all people. This implies that health services, goods and facilities should be available in sufficient quantity, physically and economically accessible, medically and culturally acceptable, and provided in good quality and without any discrimination. Moreover, as a fundamental part of human rights, good health is closely related to the accomplishment of other human rights, including safe food and water, adequate housing and sanitation, healthy working and environmental conditions, and health-related education and information (United Nations, 2008). Taking the angle of health, this dissertation is motivated from three striking phenomena in China: health inequality, rapid population ageing and severe detrimental impact of environmental pollution on health.

Health enhancement is usually associated with the economic growth. Empirical studies suggest a strong relationship between health and economic growth (Fogel, 1994; Barro, 1998; Bloom, Canning, and Sevilla, 2004). Indeed, China has been successful in improving population health as well as increasing per capita income (World Bank, 2013). Nevertheless, despite the unprecedented economic growth, remarkable progress in health status and life expectancy gained over the past decades, there remain significant inequalities across population groups with different socioeconomic status between urban and rural areas, and different regions in China. Facing public discontent, Chinese government has launched several rounds of health care reforms since 1980 in the purpose to provide universal health coverage

[1]Defined in 1946 Constitution of World Health Organization.

nationwide. Being a self-proclaimed socialist country, why China's health care system become one of the least "socialist" worldwide? What causes the disparities in health provision across the nation? Is China on the path of achieving the goal of universal health coverage? The first essay qualitatively discusses the evolution of China's health care system, with emphasis on reform policy strategies to address the issue of inequality.

Rapid economic growth, however, generates adverse effect to environment, such as pollution, CO_2 emissions and intensified severity of catastrophes. Air pollution (e.g. haze) is probably a very serious concern in most emerging economies, like China. World Health Organization (2016) reports that outdoor air pollution causes more than 1 million death in China in 2012, accounting for one third of total global deaths. The environmental degradation leads to significant health and economic losses and the change of individual consumption and saving decisions, which, in turn, affects economic growth. Hence, it ranks in the top agenda of policy maker to appropriately balance the production, consumption (on health) and reduction of emissions to maximize the society well-being. How to determine the optimal abatement and mitigation policy and growth rate, given the uncertainty of the detrimental impact of pollutants and emissions on health? Is it worth to implement tight environmental policy that is harmful to economic growth but beneficial to a healthy environment? The second essay gives a quantitative analysis on these questions. The third essay extends the model by further considering two kinds of catastrophic shocks on health: nature disaster and epidemic.

Alongside the drastic economic growth is the dramatic demographic change. China is rapidly ageing due to precipitous decline in fertility as well as longer life expectancy. Until the end of 2015, the amount of people aged 60 or over in China accounted for 24.64% of total world ageing population (United Nations, 2015). The changes in total population and age structure, accompanied by the prevalence of chronic diseases, significantly diversify the individual preferences and demands on medical and health care services, specifically, between Traditional Chinese Medicine (TCM) and Western Medicine (WM). In addition, TCM has been increasingly under the spotlight in recent years, since President Xi Jinping has highly complimented TCM on many important occasions since 2012. To promote TCM consumption in health care services, official documents are issued to request for expanding the reimbursement scope, and increasing the reimbursement rate of TCM related drugs and non-drug therapies compared with that of WM. Thus, how would the Chinese culture based on TCM influence individual medical decision? And how the diversified copay rate as well as the deductibles affect consumer's medical demand? We address these appealing questions in the fourth essay.

3 Evolution of China's Health Care System From Policy Perspective: Efforts Toward Equality

3.1 Introduction

Over the past five decades, China's health care system has undergone a roller-coaster ride. In the Alma-Ata meeting in 1978, WHO acknowledged the health achievements gained in China, especially in vast rural areas with the model of Rural Cooperative Medical Scheme and the work of village doctors (known as "barefoot doctors"), which inspired the health care design in third-world countries (WHO, 2008). Ironically, it was in the same year that the government started to abandon the rural medical care system. Being a self-proclaimed socialist country, why China's health care system become one of the least "socialist" worldwide? What caused the disparities in health care across the nation? Chinese government has launched several rounds of health care system reforms in recent 30 years in facing the public discontent stemming from the growing inequality among population groups with different socioeconomic status across different regions, and between urban and rural areas. Is China on the path of achieving the goal of universal health coverage? What are the policy strategies and priorities of these reforms in order to sustain the achievements in the next decades? This section provides a background investigation of the evolution of China's health care system, with emphasis on reform policies and strategies to address issue of inequality.

3.2 Found of National Health Care System (1949-1979)

China's national health care system has been established up since the found of People's Republic of China in 1949. The design of national health care system is mainly embodied in three sub-systems of health insurance.

First, Labor Insurance System. It came to existence in 1951 under the issue of the *Labor Insurance Regulation of People's Republic of China* by State Council, and further developed according with the *Amendment on Rules of Implementation of Labor Insurance Regulation* by Ministry of Labor in 1953. It was a work-unit based health insurance system, covering people who worked in state-owned enterprises and collectively-owned enterprises, as well as their immediate family members (parents and children), and the retirees. These workers were entitled with almost free medical service in designated medical institutions, while their family members had to pay half of the medical expense. The funding was extracted from the net income of the enterprise with a certain ratio of the total wages of workers[1].

Second, Government Insurance System. It was implemented in 1952 based on the *Instruction on Implementation of Government Insurance System in Governments at All Levels, Parties, Organizations and Affiliated Institutions* issued by State Council. It covered staffs in all levels of government, parties, public organizations and the army, and later expanded to the cadres in rural villages and towns, staffs in education institutions (also including college students), and retirees of these institutions. The fund came from the fiscal budget of central and local governments, and was managed by Commission of Government Insurance System in locality. People who were under coverage enjoyed full reimbursement of expenses in designated medical institutions[2].

Third, Rural Cooperative Medical Scheme. It was targeted to people living in rural areas, which accounted for 87% of total population in 1953[3]. From

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[1] Based on source: Labor Insurance Regulation of People's Republic of China. February 26, 1951. Amendment on Rules of Implementation of Labor Insurance Regulation. January 26, 1953.

[2] Based on source: Instruction on Implementation of Government Insurance System in Governments at All Levels, Parties, Organizations and Affiliated Institutions. June 27, 1952.

[3] Basic Information of Give National Population Census. China Statistical Yearbook 2001.

1950s it was launched as a pilot program in some provinces[4], and gradually spread nationwide from 1965 with the release of *Report on Focusing Health Service in Rural Areas* by Ministry of Health[5]. It was organized on the principle of mutual aids of participants, collectively financed and managed by local agricultural communes (Wu, 1997). The cooperative medical fund mainly came from the public welfare fund set aside by local agricultural communes (called as People's Communes), others from the health care fee paid yearly by local residents. Local residents enjoyed almost free medical diagnosis and treatment, but only for minor diseases. In this case, Chinese herbals and self-made patent medicine were encouraged to widely use because of their low expenses, convenience and effectiveness. The local medical service provider, or the village doctors, were selected and supported by their villages, and paid in the form of "work point" (Gong Fen, in Chinese)[6]. These village doctors, well known as "barefoot doctors", were not professionals, but usually had middle school education and only a few months training on medicine (Eggleston, 2012; Yip, 2010). They could only provide preventive and primary medical care, such as immunizations.

We can easily detect two main characteristics of the health care system: centralization and urban-rural dual structure. First, at the time of Cold War, being self-proclaimed as a socialist country in the camp of Soviet Union, China followed the Soviet-type economic planning for national development. It was a form of economic planning that characterized with highly centralized investment decisions, state ownership of means of production, administrative allocation of available inputs and targeted outputs. The entire course was guided by a series of so-called Five-Year Plans. This setting was naturally reflected on the structure of national health care system.

Another unique feature that even different with other socialist countries was the urban-rural dual social structure artificially created by Chinese government. This design was companied with government ambition in transforming China from a rural economy into an industrial giant under

[4]Based on source: National Conference on Rural Health. November, 1959.

[5]Report on Focusing Health Service in Rural Areas, Ministry of Health. September 21, 1965.

[6]Gong Fen: a unit of measurement of payment at that specific time, not real currency, like a check or credentials. Under this workday payment system, Gong Fen was recorded as one person worked per day. At the end of the year, collective incomes were divided to every person according to the work points they earned.

the planned economics. In order to speed up the industrialization, national policy priority were given to industrial development, which in turn limited and even sacrificed agricultural development as well as rural welfare. It is worth to note here that the urban-rural dual social structure is not marked by whether a person is living in city or countryside, or doing farming or non-farming work, but by her officially registered permanent residential status (Hu Kou, in Chinese). If one is registered officially as a rural resident, she is recognized as a farmer, no matter in fact what she does and where she live. This system severely restricts population mobility nationwide, especially from rural to urban areas. Moreover, this urban-rural dual structure has significant impact on individual's entire livelihood, because urban and rural residents are provided different packages of social welfare by government, such as grain, government-assigned jobs, housing, education, medical care, pensions, and so on. Compared with urban residents, rural residents have very limited social welfare guaranteed by governmen, hence they have to mainly rely on themselves and the families.

Overall, national health care is provided at three tiers. Primary care is delivered by barefoot doctors and workplace clinics, secondary care by rural township and urban district hospitals, and tertiary care by county and city hospitals (Barber and Yao, 2010). Hospitals, all public, charge for medical care and drugs, but the price is kept below the costs under government price control. Meanwhile, they receive financial subsidies from government, amounting to 50% to 60% of total costs (Yip, 2010). Thereby, urban population is largely covered by the work-unit based Labor Insurance System and Government Insurance System, with some differences in the level of benefits among different types of work units. The vast rural population has access to basic medical services through Rural Cooperative Medical Scheme that covering 90% of administrative villages in 1978.

During this period, the government has achieved its aim of building up universal health care by providing basic public medical service with emphasis on preventive and primary care. Population health has been remarkably improved with large expansion of health insurance and accessibility of basic health services, as well as the widespread of public health interventions, despite the very limited amount of technical and financial resources (Hsiao, 1995; Eggleston, 2012). According to statistics, at the end of 1949, the total population was 541.67 million. The birth rate was 36 ‰, and the mortality rate was 20 ‰. Until 1979, birth rate and mortality rate decreased to 17.52 ‰and 6.21 ‰respectively, while total population increased to 975.42

million[7]. Figure 3.1 shows the change of mortality rate from 1949-1979[8]. Meanwhile, life expectancy at birth increased from 43.39 to 65.19 between 1950 to 1980 (Figure 3.2).

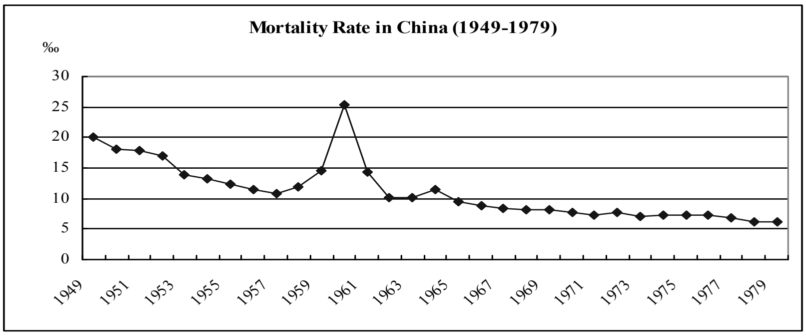

Figure 3.1 – Mortality Rate in China (1949-1979)[9].

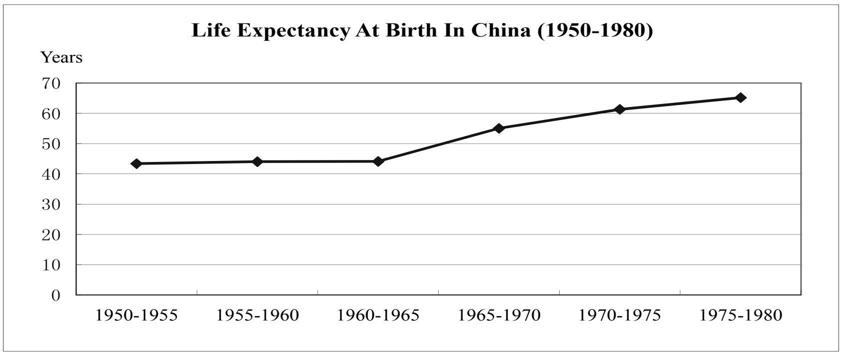

Figure 3.2 – Life expectancy at birth in China (1950-1980)[10].

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[7] China Compendium of Statistics 1949-2008. Ed. National Bureau of Statistics of China. China Statistics Publishing House (January 1, 2010).

[8] The sharp increase of mortality rate between 1959 and 1961 is due to the widespread famine, term as Three Years of Great Chinese Famine. There are a lot of studies on the cause and result (especially the number of death). It is generally considered that among the various causes, government strategy (Great Leap Forward) dominates others, and the death population is underestimated by government.

[9] Source: Database of National Bureau of Statistics of China.

[10] Source: 2015 Revision of World Population Prospects. United Nations. Life expectancy at birth is 43.19 in 1950-1955, and 65.19 in 1975-1980

3.3 Dilemma and Preliminary Reforms (1980-2009)

3.3.1 Socioeconomic Background

The central planning system has gained certain economic and social achievements. For example, annual gross domestic product (GDP) has increased from 30.55 billion U.S. dollar to 174.94 billion U.S. dollar from 1952 to 1976[11]. However, the national economic development was halted from late 1960s. The Cultural Revolution[12] dominated the primary objective of the country, which led to poor economic performance and social disorder. After Mao's death in 1977, Deng Xiaoping, who believed in the need of socioeconomic reforms in China but was excluded by Mao, decided to abandon the planning system and turn to market-oriented reforms in order to salvage the failing economy, which gained widespread support among the party and the public.

The Third Plenary Session of the Eleventh Central Committee of the CPC in 1978 promulgated the national strategic policy as Reform and Open-up: an internal reform of economic system, and an opening up to the outside world, while emphasized with "Socialism with Chinese characteristics". A number of important measures were implemented, including the decollectivization of agriculture, dismantling of Soviet-type central planning in industry, opening up to foreign investment and international trade, permission for entrepreneurs to start businesses, privatization and contracting out of many state-owned enterprises (especially small and medium sized ones), and decontrol of price system.

These reforms incurred a more rapid economic growth and market-based economy, which further had a significant impact on social welfare system. Chinese annual GDP increased from 184.52 billion U.S. dollar to 4,521.83 billion U.S. dollar between 1980 and 2008, with a 10.04% average annual growth rate of real GDP, while the corresponding growth rate for the world as a whole was 3.1%[13]. As a consequence, population's living conditions was greatly improved with rapidly increasing income level. Between 1978 and 2008, both urban and rural income increased more than seven-fold

[11] Database of National Bureau of Statistics of China.

[12] Cultural Revolution: formally the Great Proletarian Cultural Revolution, a sociopolitical movement engineered by Mao Zedong, chairman of the Community Party of China, lasted from 1966-1976.

[13] Based on Database of World Bank and National Bureau of Statistics of China.

even after adjustment for inflation (see Table 3.1). This indicated a shift of households spending from a focus on basic needs, such as food and clothing, to more diverse consumption for a quality life, including education, health, housing, and so on.

Year	Per capita disposable income of urban households (RMB)	Per capita net income of rural households (RMB)	Consumption price index (1978=100)		Engel's coefficient (%)	
			Urban households	Rural households	Urban households	Rural households
1978	343.4	133.6	100	100	57.5	67.7
1980	477.6	191.3	127	139	56.9	61.8
1985	739.1	397.6	160.4	268.9	53.3	57.8
1990	1510.2	686.3	198.1	311.2	54.2	58.8
1995	4283	1577.3	290.3	383.6	50.1	58.6
2000	6280	2253.4	383.7	483.4	39.4	49.1
2005	10493	3254.9	607.4	624.5	36.7	45.5
2008	15780.5	4760.6	815.7	793.2	37.9	43.7

TABLE 3.1 – *People's Living Standards (1978-2008)*[14].

3.3.2 Emerging Problems on Health Care

Besides the rapid economic growth, the amount of population has grown quickly. Total population in China mainland increased 73% from 1953 to 1982, from 583 million to more than 1 billion, and further reached to over 1.3 billion in 2010[15]. Moreover, with the agricultural and industrial reforms, and the course of urbanization, rural surplus laborers transferred from the farmland to urban areas. The International Labor Organization reports that the internal rural-urban migration in China is the most extensive in the world[16]. The volume of the "floating population", i.e. migrants without local household registration status, arrived at 211 million till 2009,

[14] Source: China Statistical Yearbook 2012.

[15] Chinese Population Census in 1953, 1982 and 2010. National Bureau of Statistics of China.

[16] Labor migration in China and Mongolia. International Labor Organization. Available
online: http://www.ilo.int/beijing/areas-of-work/labour-migration/lang–en/index.htm

78.7% of which were registered as rural household[17]. These dramatic demographic changes exposed the health care system into big challenges.

First, in urban areas, with the fast rising urban population, from 77.26 million in 1953, 191.40 million in 1980, to 624.03 million in 2008[18], on one hand, Labor Insurance System and Government Insurance System already suffered heavy financial burden to fulfill their commitments. On the other hand, the two systems could barely satisfy the growing public demands, since they only covered a limited amount of people. They provided no coverage for employees that not worked in government and public organizations, state-owned and collectively-owned enterprises, and those who were self-employed, or currently not employed. Moreover, state-owned and collectively-owned enterprises were restructured to downsized, financially independent and/or privatization under economic reforms, which further weakened their ability to finance health care service. Therefore, employees were unable to have their medical expenses reimbursed, and was practically uninsured (Liu et al., 2007; Yip, 2010).

Meanwhile, in rural areas, collectively-financed and organized village health care service under Rural Cooperative Medical Scheme collapsed following with the disintegration of agricultural communes. The collective farming was replaced by individual household responsibility system from early 1980s, which was the first step of agricultural reform (Audibert et al., 2013; Hsiao, 1995). This new system undermined the economic foundation of all kinds of cooperative services, including health care, and consequently resulted in a sharp decline in health care coverage from 90% to only 4.8% (Wang, 2003). Most barefoot doctors abandoned medical work and returned to farming. However, the government did not take any remedial action, but left it to the market with a laissez-faire policy by default, which led to the virtually privatization of rural health care provision as most of the village clinical service were then offered by fee-for-service private practitioners (Hsiao, 1995; Liu et al., 2007). As a consequent, rural residents must pay directly out of pocket for all health services.

Furthermore, public hospitals, as well as other health care organizations,

[17]Report on China's Migrant Population Development 2010. Ed. National Health and Family Planning Commission of China. China Population Publishing House. June, 2010.

[18]Chinese Population Census in 1953, 1982 and 2010. National Bureau of Statistics of the People's Republic of China.

received decreasing government subsidies, falling to a mere 10% of the organizations' total revenues by the early 1990s (Yip and Hsiao, 2008). Because, though marked with an unprecedented economic growth during that transition period, the government experienced a drastic reduction in its revenue which crippled its capacity to fund health care. Under this situation, while a strict price control on delivering basic health care below cost still existed, hospitals were permitted to charge a price above the cost for the new and high-tech diagnostic services, and make a 15% profit margin on drug selling, in order to be financially survival. However, these measures generated adverse incentives, turning these organizations into profit-oriented entities, since they must generate another 90% of their revenue from sales of medicines and offering medical services. This gave rise to the over-prescription of pharmaceutical drugs and medical tests by doctors, and engined the hospital races on more expensive medicines, high-tech medical equipments and infrastructure (Eggleston and Yip, 2004; Blumenthal and Hsiao, 2005). Such irrational and inefficient behaviors further caused the rapid rising of health care cost. For instance, total health care spending was 18.73 billion RMB in 1978, and reached to 359.39 billion RMB in 2008 (see Figure 3.3). The average annual growth rate of total health care spending was 17.92%, which was 7.88% faster than the growth of GDP at the same period[19]. At the meantime, when the out-of-pocket payment increased quickly each year, individuals had to shoulder the lion's share of medical expenses (see Figure 3.4). This led to reduced medical accessibility and increased medical impoverishment.

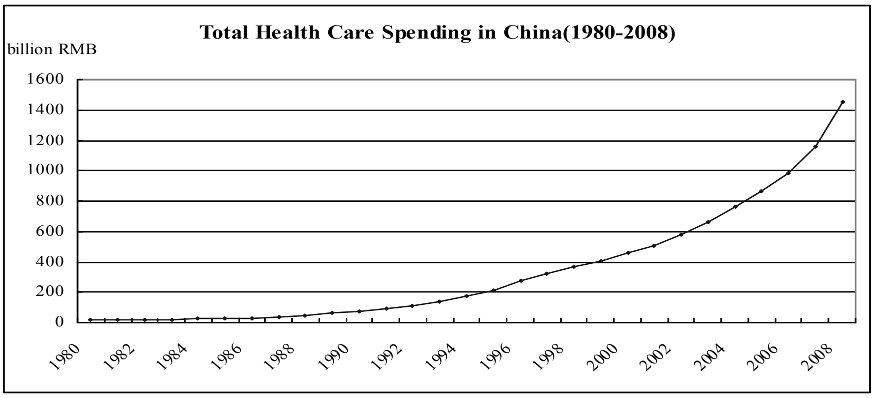


Figure 3.3 – Total Health Care Spending in China(1980-2008)[20].

[19] Based on source: China Health Statistical Yearbook 2013.

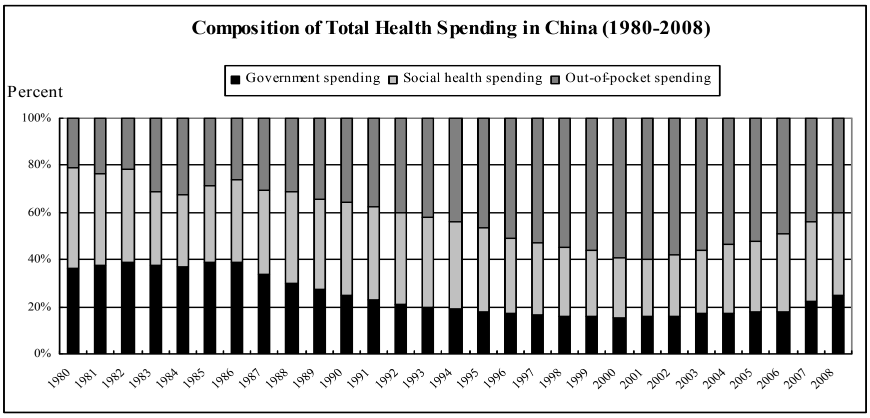


Figure 3.4 – Composition of Total Health Spending in China (1980-2008)[21].

3.3.3 Policy Design of Health Care Reform

Facing the emerging problems, the government implemented a series of health care reforms with a variety of experimentation since 1980s. The reforms mainly involved four aspects: health care financing, health care delivery, hospital reforms and drug supply, in which the first two aspects are focused in this part. Overall, the government attempted to find an integrative way for health care system reform: a clearly integrated system of public and private financing, provision and administration of health care (Hsiao, 1995). The progress could be divided into two main phases.

First phase, the exploration and experiment phase (1980-1997). In this period, the government was exploring and experimenting various solutions in order to control medical costs, such as co-payment, price control on reimbursable medical services, and pharmaceutical products. Important policy engines, including regulations, decisions and opinions for health care reform issued by central government are listed in Table 3.2.

The year 1985 was considered as the starting year of the official imple-

[20]Source: China Health Statistical Yearbook 2013.
[21]Source: China Health Statistical Yearbook 2013.

Year	Regulation, decisions and opinions
1984	Notice on Further Strengthening the Administration of Government Insurance System
1985	Report on Several Policy Issues Connected with Heath Services Reforms
1988	Considerations on the Reform of the Employee Health Insurance System (Draft)
1989	Notice on the Administration of Government Insurance System
1989	The Notification of Key Points of 1989 Economic Reform
1989	Measures for the Hierarchical Administration of Hospital (for Trial Implementation)
1992	Some Opinions on Deepening the Health Care System Reform
1994	Opinions on the Trial of Employee Heath Care System Reform
1996	Opinions on Expanding the Number of Pilot Cities for Employee Health Insurance System
1997	Decision of the Central Committee of CPC and the State Council Concerning Health Reform and Development
1997	Some Opinions on Developing and Improving Rural Cooperative Medical Scheme

TABLE 3.2 – *Regulation, Decisions and Opinions Related to Health Care Reform 1980-1997*

mentation of heath care reform in China. Some local cities and enterprises had spontaneously begun the experiment on employee medical insurance before that year. They were only officially encouraged to raise the charges or formulate charging standards for different medical services until the issue of *Report on Several Policy Issues Connected with Heath Services Reforms* in 1985. The purpose of reformulating the charging system was to cut down medical expenditure by reducing consumer moral hazard in health care decision. Because consumers, being fully insured, were inclined to over-utilize health care services, which resulted in a great deal of waste of health care resources. Nevertheless, they would become more cost-conscious if they had to pay part of their medical expenses. In 1988, central government special work team, Research Group on Health Care Reform, was formed in the purpose to investigate the issues related to health care reform, especially on Labor Insurance System and Government Insurance System. The group drafted the *Considerations on the Reform of the Employee Health Insurance System*, highlighting that the medical costs should be borne jointly by individuals, enterprises, and government. Pilot programs were started in four cities, Dangong, Siping, Huangshi and Zhuzhou, in March 1989.

From early 1990s, the focus of reform had gradually shifted to the (increase of) level of socialization, or social risk pooling scheme. A major breakthrough took place in late 1994 with the famous pilot program in two cities, Jiu Jiang and Zhen Jiang, called as "Two Jiang Trial". This "Two Jiang Model" created a fund with combination of individual medical savings accounts and social risk pooling accounts to finance medical expenditures. Individual must first use her own account for medical payment. In case the account was finished, individual had to pay by out-of-pocket, equal to 5% of her annual income (i.e. annual deductible). Then she could have access to the social risk pooling accounts, with a certain copay rate[22]. The goals of the measurements were: first, to improve the individual cost-consciousness when consuming medical services. Second, to strengthen social protection with city-wide risk pooling for catastrophic medical expenses.

In January 1997, the *Decision Concerning Health Reform and Development* clearly put forward the overall guidelines, goals and requirements of health care reform. However, we can observe that, while underlining the goal as creating a universal health care system, the document practically acknowledges the innegligible fact of growing inequalities of health care between urban and rural areas, and different regions in setting different level of indicators of health for economically developed and less developed regions.

Second phase, the implementation and extension phase (1998-2008). The year 1998 was the landmark of comprehensive implementation of health care reform, with the release of *The Decision of the State Council on Establishing the Urban Employee Basic Medical Insurance System*. Important engines, including regulations, decisions and opinions relating to health care reform are listed in Table 3.3.

The new Urban Employee Basic Medical Insurance System (UEBMI) was launched in 1999 based on "Two Jiang Trial", which was co-financed by premium contributions from individual employees and their employers. Individual paid 2% of her wage as insurance fee, while employer provided 6% of its total employee wages. Similarly, the fund was divided into individual medical savings accounts and social risk pooling accounts. Individual insurance fee, and 30% of the employer contributions went to individual

[22] Based on source: Opinions on the Trial of Employee Heath Care System Reform. April 14, 1994.

Year	Regulation, decisions and opinions
1998	The Decision of the State Council on Establishing the Urban Employee Basic Medical Insurance System
2000	Guiding Opinions on Urban Medial and Health Care System Reform
2000	National Basic Medial Insurance Drug Catalogue
2002	Notice on Strengthening the Management of Individual Medical Savings Account of the Urban Employee Basic Medical Insurance System
2002	Decision on Further Strengthening the Rural Health Work
2003	Opinions on Establishing the New Rural Cooperative Medical Scheme
2003	Guiding Opinions on the Participation of Urban Workers in Flexible Employment in Health Insurance
2005	Opinions on Establishing Pilot Program of Urban Medical Financial Assistance System
2006	Notice on Accelerating the Pilot Program of the New Rural Cooperative Medical
2006	Notice on Carrying out a Special Campaign Concerning the Participation of Migrant Workers in Health Insurance
2007	Guiding Opinions of the State Council on Piloting the Urban Resident Basic Medical Insurance System
2008	Guiding Opinions of the General Office of the State Council on Including University Students in the Pilot of Urban Resident Basic Medical Insurance
2008	Opinions of the CPC Central Committee and the State Council on Deepening the Reform of the Medical and Health Care System (Consultation Paper)

TABLE 3.3 – *Regulation, Decisions and Opinions Related to Health Care Reform 1998-2008*

accounts, and the remain 70% entered to social accounts[23]. UEBMI aimed to cover all urban workers, including employees of government, public organizations, state-owned and private enterprises, but their dependants and migrant workers were excluded. By 2000, it covered 37.87 million urban employers. The amount further increased to 199.96 million in 2008[24].

We can observe from Table 3.2 and 3.3. that rural health care reform was lagged behind urban reform. There had been several policy documents, researches and pilot programs since mid-1980s, but all were experimental programs in limited places, thus achieved no significant change across the country. Only 6.57% of rural residents were covered by health care in 1998,

[23]Based on source: The Decision of the State Council on Establishing the Urban Employee Basic Medical Insurance System. December 14, 1998.

[24]China Health Statistical Yearbook 2009.

while the majority (87.44%) were left uninsured[25]. This further widened urban and rural gap on health care provision.

It was not until 2003 a nationwide rural health care reform had implemented, with the goal to achieve coverage for almost all rural residents by year of 2010, declared in the *Opinions on Establishing the New Rural Cooperative Scheme*, A primary objective of New Rural Cooperative Medical Scheme (NRCMS) was to protect rural residents against catastrophic health expenses and impoverishment by disease (Yip and Hsiao, 2008). NRCMS was co-financed from local governments and rural residents, with each party contributed no less than 10 RMB per year. The central government would subsidy 10 RMB per capita per year in central and western regions. NRCMS fund was mainly supposed to compensate for inpatient expenses and large amount expenses. Besides, the participation was voluntary. Enrollment expanded quickly from 80 million to 815 million people between 2004 and 2008, which covered 91.53% of rural residents. In addition, per capita premium increased from 50.36 to 96.30 RMB during the same period[26].

In 2007, Urban Resident Basic Medical Insurance System (URBMI) came to being as pilot programs, and then promoted across the country. The URBMI targeted to urban residents in flexible type of employment, including the minors and students, the elder and disabled, and those currently not employed. Participation was voluntary. The source of fund mainly came from individual charge, and subsidies from central and local governments (no less than 40 RMB, variable according to regional and local circumstances). The fund mainly aimed to compensate for inpatient expenses and large amount expenses[27]. 118.26 million urban residents participated in URBMI by the end of 2008[28].

In addition, medical financial assistance system and supplementary medical insurance system begun to develop in this phase. Marked by the *Opinions on Conducting the Pilot Program of Urban Medical Assistance System*, a unified and standardized Urban Medical Financial Assistance System (UMFAS) initialized nationwide from 2005, which aimed to cover catastrophic

[25] National Health Service Survey 1998. Ministry of Health of China. July, 1999.

[26] Source: China Health Statistical Yearbook 2009.

[27] Based on source: Guiding Opinions of the State Council on Piloting the Urban Resident Basic Medical Insurance System. July 10, 2007.

[28] Source: China Health Statistical Yearbook 2009.

health expenses for the very poor. Supplementary medical insurance system was supported in four dimensions. First, government supplementary insurance specialized to its employees. Second, enterprise supplementary insurance, provided by employers to employees. Third, social insurance bureaus, and last, commercial insurance companies, insurance services provided to any group and individual (Liu, 2002).

Based on above observation, we can find that, on one hand, health insurance coverage is largely expanded through the country, which implying the great enhancement of population health. On the other hand, the problems relating to equality between urban and rural areas, and different regions still exist, and even exacerbate due to the different level of benefit package. Insurance premium, deductible, copay rate and reimbursement scope were different in above three insurance systems, which results in urban-rural, and urban-urban disparity. Besides, since the insurance systems were carried out at city and county level, population in different regions enjoyed diverse packages. Under socioeconomic transition, the basic characteristic of health care reform is the growing market-orientation on health care provision with less government interventions and controls. Market-orientation and commercialization stimulates the expansion of health care service, but also intensifies negative consequences, such as roaring medical service price, decreasing medical affordability and increasing impoverishment, which wreck the equality of health care. Therefore, the reform is "basically unsuccessful", as evaluated in a 2005 report conducted by WHO and Chinese government[29]. This negative assessment evokes widespread public debate and thus another round of health care reform, marked by the publish of *Opinions of the CPC Central Committee and the State Council on Deepening the Reform of the Medical and Health Care System (Consultation Paper)* in 2008.

3.3.4 Health Care Reform From 2009

The *Opinions of the CPC Central Committee and the State Council on Deepening the Reform of the Medical and Health Care System* in March 2009 marked a new round of health care system reform. It proposed to

[29] Analysis on Chinese Health Care System Reform. October 27, 2005. World Health Organization, Development Research Center of the State Council. Available online: http://www.drc.gov.cn/zjsd/20051027/4-4-2869110.htm

building up a health care system that integrated with public health services, medical services, medical insurance, and pharmaceutical supply which covering both urban and rural residents. Followed in April was the release of the *Implementation Plan of Recent Priorities in Carrying out the Reform of Health Care System (2009-2011).* The fundamental goal was to guarantee all citizens have comprehensive universal basic health care by the year 2020, which included five key priorities in this plan.

- Accelerating the expansion of the basic health care system.
- Establishing a national essential drug list system.
- Improving primary health care services.
- Promoting the equalization of basic public health services.
- Facilitating pilot reform programs in public hospitals.

The government committed 850 billion RMB (about 124.26 billion U.S. dollar) over three years, about 40% of which came from the central government, while the remainder from the local government. Besides, an estimated 46% of the fund was dedicated as insurance subsidies to the rural and urban residents' insurance programs (Barber and Yao, 2010). The above five goals were basically fulfilled at the end of 2011, especially the first goal.

The Twelfth Five-Year Plan for Development of Health Care (2011-2015) in 2011 further extended the major policy blueprint of the health care system reform as a medium and long-term plan. It was elaborated by the *Outline and the Implementation Plan for Deepening the Medical and Health Care System Reform During the Twelfth Five-Year Plan* in 2012 with six main goals.

- Strengthen public health care infrastructure
- Strengthen health care service network
- Develop a comprehensive medical insurance system
- Improve drug supply system
- Reform the public hospital system
- Support the development of Chinese Medicine

Under these policy frameworks, health care coverage is further expanded. Over 95% of the population has been covered by public medical insurance system. Especially, primary care is increasingly delivered across the country under the support of grass root providers. Nevertheless, the depth of coverage is yet limited (Eggleston, 2012).

3.4 Contemporary Setting of Health Care System

3.4.1 Government and Administration

The regulation of health care system is under several ministries and departments. Table 3.4 outlines the major stakeholders and their functions and responsibilities[30].

3.4.2 Health Insurance System

China has established a multi-level health care insurance system combined with safety net, basic medical insurance system, and supplementary systems (see Figre 3.5)[31]. Among the multiply forms of insurance, the most important part is the second level, including Urban Employee Basic Medical Insurance (UEBMI), Urban Resident Basic Medical Insurance (URBMI), and New Rural Cooperative Medical Scheme (NRCMS). We have combed their histories in previous part, and here we focus on their composition and development.

Urban Employee Basic Medical Insurance (UEBMI)

Enforced in 1998 and reformed in 2009, UEBMI is mandatory for all types of enterprises, government sectors, social organizations, and other employees. UEBMI provides medical insurance to all urban employees through the funding combined with both social pooling collective fund and individual

[30] Source: China's Health care System-Overview and Quality Improvements. Swedish Agency for Growth Policy Analysis (SAGPA), 2013.03.

[31] Source: China's Health care System-Overview and Quality Improvements. Swedish Agency for Growth Policy Analysis (SAGPA), 2013.03.

Stakeholder	Function and responsibility
NDRC: National Development and Reform Commission inc. Price Bureau	Monitoring and evaluation of health care system reform; setting the price of drugs and medical services.
MOF: Ministry of Finance	Financial support and investment in health care as well as subsidies for health insurance and to ensure zero mark-ups for essential medicines.
NHFPC: National Health and Family Planning Commission inc. State Food and Drug Administration, and Bureau of Chinese Traditional Medicine	Operation of rural medical cooperatives; public hospital reforms; essential medicine policy; bidding and procurement of drugs and medical equipment; rational use of medicine; public health service; supervision of food and drug safety/quality.
MOHRSS: Ministry of Human Resources and Social Security	Management of medical insurance for urban employees and residents; reform of drug reimbursement and payment systems.
MOC: Ministry of Civil Service	Poverty alleviation; medical aid for the poor.
MOC: Ministry of Commence	Drug wholesale and retail; pharmacy administration; distribution of medicines and medical equipment.

Table 3.4 – *Stakeholders for governing health care system*

medical savings account. The major components and processes of UEBMI can be seen in Figure 3.6[32].

Urban Resident Basic Medical Insurance (URBMI)

URBMI is complementary to UEBMI for urban residents, with target to the non-working urban residents (mainly adolescents, students, retirees, the elder, disabled and poor citizens), and the self-employed who are not accessible to UEBMI. The policy framework of URBMI is similar to UEBMI in terms of administration, social pooling and payment. The main difference lies in that URBMI is voluntary, less benefit, and with only a social pooling account. The benefit coverage of URBMI is mainly on inpatient

[32]Source: China's 12th Five-Year Plan: Health Care Sector. KPMG China, May 2011.

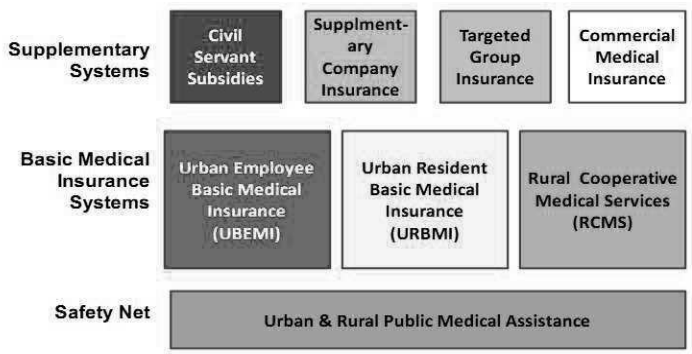


Figure 3.5 – Composition of Health Care Insurance System

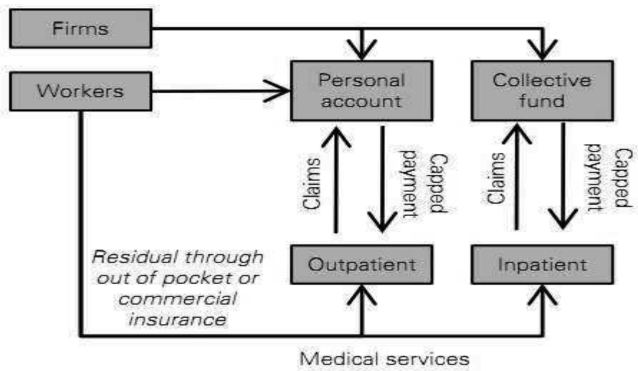


Figure 3.6 – Major Components and Processes of UEBMI

and catastrophic outpatient expenses. Since both URBMI and UEBMI are provided at city level, it is not surprisingly to observe disparities from city to city, considering the fact of regional imbalance in economic development (SAGPA, 2013). The major components and processes of UEBMI are shown in Figure 3.7[33]. In addition, we summarize the progress of UEBMI and URBMI in terms of amount of enrolment and fund from 2005 to 2014 in Table 3.5.

[33]Source: China's 12th Five-Year Plan: Health Care Sector. KPMG China, May 2011

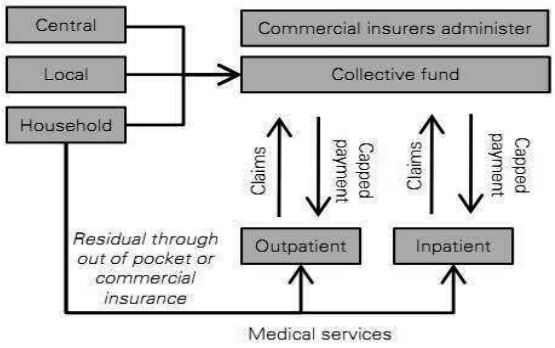


Figure 3.7 – Major Components and Processes of URBMI

New Rural Cooperative Medical Scheme (NRCMS)

NRCMS brings protection to rural residents as well as the migrant rural workers in urban areas[35]. Enrolment of NRCMS is voluntary, and enrollment unit is household. The funding is raised from government fiscal subsides (central and local government) and contribution of households. Similar to URBMI, there is only one account which is mainly supposed to cover inpatient and catastrophic outpatient expenses. The major components and process of NRCMS are presented in Figure 3.8[36]. Besides, we presents the progress of NRCMS in terms of amount of enrolment and fund from 2005 to 2014 in Table 3.6.

Through a variety of reform strategies, we find that China has been achieving wide health insurance coverage, covering almost all population. However, while the fund is increasing each year, the protection is yet considered to be shallow (Eggleston, 2012). Recalling the fact of inequality between urban and rural areas, and different regions, the government highlights on creating an integrated system of basic medical insurance for both urban and rural residents nationwide. In March 2015, the *Outline for the*

[34]Source: China Health Statistical Yearbook 2015, and database of National Bureau of Statistics. Note: URBMI started from 2007.

[35]Source: China's 12th Five-Year Plan: Health care sector. KPMG China, May 2011.

[36]Source: China's Health care System-Overview and Quality Improvements. Swedish Agency for Growth Policy Analysis, 2013.03.

[37]Source: China Health Statistical Yearbook 2015, and database of National Bureau of Statistics. Note: URBMI started from 2007.

Year	Numbers of enrollees (million)			Fund raised (billion RMB)		
	Total	UEBMI	URBMI	Total	URBMI	URBMI
2005		137.83	--		696.9	--
2006		157.32	--		174.71	--
2007	223.11	180.2	42.91	225.72	221.42	4.3
2008	318.22	199.96	118.26	304.04	288.55	15.49
2009	401.47	219.37	182.1	367.19	342.03	25.16
2010	432.63	237.35	195.28	430.89	395.54	35.35
2011	473.43	252.27	221.16	553.92	494.5	59.42
2012	535.89	264.67	271.22	693.87	606.16	87.68
2013	570.73	274.43	296.29	824.83	706.16	118.67
2014	597.74	283.25	314.49	968.72	803.79	164.93

TABLE 3.5 – *Progress of UEBMI and URBMI 2005-2014*[34].

Year	Numbers of enrollees (millions)	Percentage of enrolled (%)	Per capita premium (RMB)	Fund raised (billion RMB)
2005	179	75.66	42.10	7.53
2006	410	80.66	52.10	21.36
2007	726	86.20	58.90	42.80
2008	815	91.53	96.30	78.46
2009	833	94.19	113.36	94.43
2010	836	96.00	156.57	130.83
2011	832	97.48	246.21	204.76
2012	805	98.26	308.50	248.47
2013	802	99.00	370.59	297.25
2014	736	98.90	410.89	302.53

TABLE 3.6 – *Progress of NRCMS 2005-2014*[37].

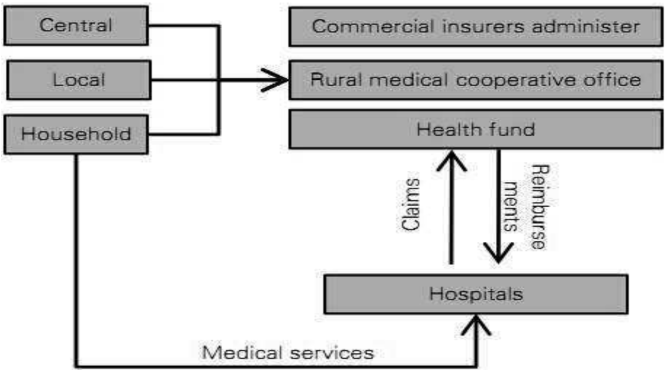


Figure 3.8 – Major Components and Processes of NRCMS

Planning of the National Medical and Health Services System (2016-2020) put forward the goal of establishing comprehensive universal basic health care system by the year of 2020. In the beginning of 2016, a guideline document, *Opinions on the Integration of Basic Medical Insurance for Urban and Rural Residents*, prioritized the combination of URBMI and NRCMS into one system, where insured person will enjoy the same payment standards and scope of subsidies. A unified and standardized insurance practice is expected to ensure equal medical treatments and health care for those who are insured. It is reported that 20 provinces have finished or on the process of the integration[38].

3.4.3 Organization of Health Care Delivery

Hospital matters significantly in providing medical health care service, as discussed in previous part. Health care delivery system in China is mainly composed with three parties. The principal one is the hospital at different levels. The second is the grassroots medical and health institution, such as village clinics, township health service, and community health service. The last is the specialized public health organization, such as Chinese Center for Disease Control and Prevention[39]. Among which, hospital bears the most important responsibility in delivering medical service including out-

[38] Source: Press conference of Ministry of Human Resource and Social Security on October 25, 2016. Available online: http://www.gov.cn/xinwen/2016-10/25/content-5123989.htm

[39] China Health Statistical Yearbook 2015.

patient and inpatient, which absorbing 2.9% of GDP[40]. Hospitals can be divided as public and private hospitals considering the ownership. From the type of the medical service provided, there are general hospital (Western Medicine style), Traditional Chinese Medicine hospital, and specialty hospital. What's more important, based on the comprehensive medical service quality, combining with the level of service provision, size, medical equipment and technology, medical education and research, etc, hospitals are divided into three grades, primary, secondary and tertiary. Each grade is further subdivided into three classes, A, B and C (Jia, Yi, and Bing, in Chinese). Therefore, totally there are nine levels for hospital ranking in China. For example, the highest level is labeled as 3A. The hierarchy system leads to imbalance distribution of medical resource and inefficient utilization.

Public hospital

Public hospital has dominated the medical and health service delivery, since China is characterized with socialism. Agglomerated with majority of well-trained doctors and government funding, public hospital plays a critical role in health service provision. Unfortunately, the folk slogan "access to health care is expensive and difficult" (Kan Bing Nan, Kan Bing Gui, in Chinese) captures the great public concern(Eggleston, 2012). Unlike many EU countries, there is no gate keeping system in China. Patients are normally free to choose any service provider. Hence, a large number of primary level patients directly visit the secondary and tertiary hospitals in believing that the higher ranking hospitals offer diagnosis and treatment in a much better and effective way. Not surprisingly, the large and prestigious 3A hospitals are always busy for visit, while some small hospitals are left in idle.

The discussion on hospital reform has started from early 1990s, and broken out in early 2000s, evolving with the market-oriented economic reform. The focus of the debate has been on the primary goal of hospital: profit-oriented or welfare-oriented? After the *Decision of the Central Committee of CPC and the State Council Concerning Health Reform and Development* in 1997, and the *Guiding Opinions on Urban Medial and Health Care Sys-*

[40]Source: China National Health Account Report. China National Health Development Research Center. Beijing, China, 2011.

tem Reform in 2000, 13 supporting policies were implemented successively for health institution and drug system. Pilot reforms of public hospitals were undertook in 17 state-designated cities and 37 province-level districts, under the instruction of *Guiding Opinions on Public Hospital Reform Pilot* in 2010. Further pilots were conducted at 600 county-level public hospitals in 18 provinces during the Twelfth Five-Year Plan (2011-2015) (SAGPA, 2013). The reform mainly covered the following important points[41]:

- Adjustment of hospital reimbursement, especially the heath service price.
- Promote grassroots providers and eliminating drug markups.
- Transition from quantity to quality of the providers.
- Establish hospital alliance, and form a multi-hospital system.

Private hospital

Private hospital came into market from 1980s as a result of economic reform, and has developed from 2001 with the opening up of medical and health market. Private hospital is composed with specialty hospital, Traditional Chinese Medicine hospital, and minority hospital.

Privatization of medical and health institution is essentially important with a substantial increase in health demand. The rapid economic growth in recent 30 years has created a growing number of middle-income class. Besides, the total population is ageing fast. An increasing and diversified demand for medical and health both quantity and quality could hardly be satisfied merely through public health care system. Consequently, delivery privatization is encouraged by the government. *The Opinions on Further Encouraging and Guiding the Establishment of Medical Institutions by Social Capital* in 2010 enhanced the accessibility for social capital investing in health institutions. The *Outline and the Implementation Plan for Deepening the Medical and Health Care System Reform During the Twelfth Five-Year Plan* in 2012 further eased the access standard of social capital. It proposed a target of 20% share in total amount of beds and medical service offered private hospitals and institutions. In 2013, *Several Opinions of the*

[41] Source: Twelfth Five-Year Plan for Health Care Development (2011-2015). October 8, 2012.

State Council on Promoting the Development of Health Service Industry put forward the reform of taxation policy on private medical hospital and institutions.

Although public hospital still dominates the medical provision, and there are important issues to be addressed, such as the accreditation of private hospital and professional staff, accessibility of patient with basic medical insurance, the impact of private hospitals could not be ignored with the growing amount, especially after health care reform in 2009 (SAGPA, 2013). In fact, the amount of private hospitals is almost catching the public ones. Figure 2.9 shows the growth of private hospital compared with public hospital between 2005 and 2014.

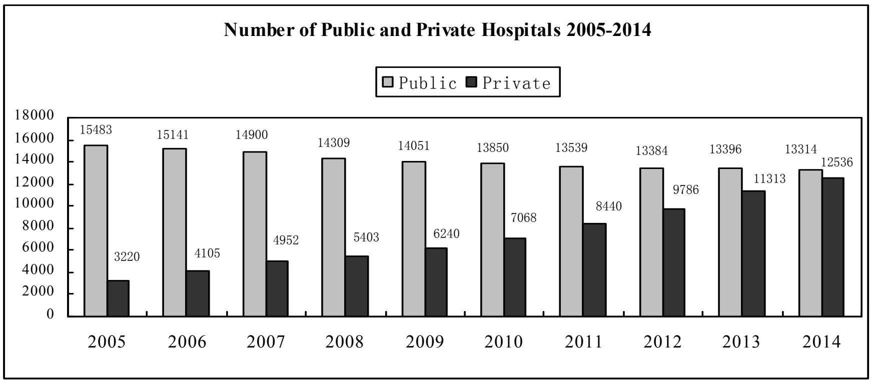


Figure 3.9 – Number of Public and Private Hospitals 2005-2014[42].

3.5 The Role and Application of Traditional Chinese Medicine in China's Health Care System

Traditional Chinese Medicine (TCM) is deeply embedded in Chinese culture with thousands of years of history behind it, influenced by the philosophy of Confucianism and Taoism particularly. It has been widely used in China and other East Asian countries, and is an established part in China's

[42]Source: China Health Statistical Yearbook 2015, and database of National Bureau of Statistics.

health care system. Moreover, TCM is further promoted by Chinese government in recent years. President Xi Jingping has addressed the significance of TCM to traditional cultural renaissance in several importance occasions. This section gives an overview on TCM philosophy, practice, development and its role in health care system, which also entails better understanding of chapter 6.

3.5.1 Philosophy and Treatment of TCM

TCM is different to Western Medicine (WM) in theory and practice. TCM concerns on the holistic interrelationship and balance of nature and human. Each individual is a part of a bigger complex, the universe, where there are laws to regulate the nature and mankind. The human body is an organic part of the nature and health depending on the balanced and harmonic inner and outer environment. Healing is a natural process that can be promoted by appropriate nutrition and lifestyle. TCM purposes to restore and harmonize normal body function through strengthening the body's own resistance of neutralizing or minimizing any toxicity of the individual constituents (Bensky and Barolet, 1990; Bensky and Gamble, 1993).

Assessment of TCM is on the basis of a range of unique diagnostic and treatment methods, including pulse taking, facial and tongue diagnosis. They are derived from two fundamental theories, Yin Yang, and Wu Xing (or Five Elements): metal, wood, water, fire and earth, which are believed by ancient Chinese people to explain all changes and natural phenomena in the universe, as well as the human being (Li and Cheng, 1987). Yin Yang theory holds that the universe is a whole with a composition of two opposites, Yin and Yang. They are interdependent, and can transform into each other. Their equilibrium ensures the harmony of physical world, as well as the human body (Lao, 1999). Wu Xing theory, or Five Elements theory, believes that the universe consists of five basic elements that are ecologically related with each other. It aims to describe the philosophical relationships between the human body and the external environment, the physiological and pathological interactions among the internal organs within a human body (Lao et al., 2012). Based on the principles, TCM regards the human physiological functions are maintained by Qi, Zang Fu (or internal organs), blood, bodily fluids and Jing Luo (or meridians and collaterals). Qi denotes the vital energy, which is an essential substance in maintaining the activities of life. (Lao et al., 2012). If the normal flow of energy, i.e. Qi, through a meridian is obstructed, symptoms occur.

When illness occurs, a TCM practitioner analyzes the symptoms by using four diagnostic methods of TCM: inspection, auscultation, or listening, inquiring, and palpation. As for therapy, TCM involves a wide range of modalities and techniques. The most well-known practices probably are Chinese herbal medicine and acupuncture. Chinese herbal medicine includes plants, minerals, and animal parts, categorized by nature, flavor, and function, which can be used internal and external. There are approximately 6,000 products available as specified in the Pharmacopoeia. Acupuncture involves the use of needles inserting at specific acupoints on the body in order to manipulate the vital energy or Qi. Other therapies are like Chinese massage (Tui Na), moxibustion, auriculotherapy, cupping, Gua Sha (scrapping), Die-da (bone-setting), Qigong and Tai Chi, food therapy, to only name a few.

3.5.2 Historical Development of TCM

TCM has evolved over thousand of years with a huge amount of historical literature elaborating its theories. The earliest records can be traced to the Ancient or Legendary Period (2697-1122 B.C.), which were largely mythological and full of legends concerning the founders of Chinese medicine. Among which, the most venerated was Shen Nong, The Father of Medicine. These legends developed into more reliable history considered as the second great phase, the Historical or Golden Period (1122 B.C.-960 A.D.). During this period, literature, philosophy and art of TCM flourished into a state of civilization (Wong and Wu, 1932).

The Yellow Emperor's Inner Canon (Huang Di Nei Jing, in Chinese), compiled between 300-100 B.C., was the most important and influential treatise, which was regarded as the fundamental doctrinal source of TCM theory. The multi-volume treatise presented a holistic view of human life under the interrelated balance of human body and physical world. Yellow Emperor also is the symbol of the vital spirit of Chinese civilization.

The Treatise on Cold Damage Disorders (Shang Han Lun, in Chinese), collated by Zhang Zhongjing, was published around 220 A.D. in Han dynasty. It was the first known treatise on drug and herbal medicine, and the first medical work to combine theory of Yin Yang and Wu Xing with drug therapy. This formulary was the earliest public Chinese medical text to group symptoms into clinically useful "patterns" (Zheng, in Chinese) that could serve as targets for therapy (Unschuld, 1985). It was circulated and edited into two separate books in 11th century, under Song dynasty: *Treatise on Cold Damage Disorders* and *Essential Prescriptions of the Golden Casket* (Jin Gui Yao Lue, in Chinese) (Goldschmidt, 2009).

The Compendium of Materia Medica (Ben Cao Gang Mu, in Chinese) was the most complete and comprehensive work on herbs and drugs Mediaeval Period (961-1800 A.D.). It was written by Li Shizhen in the middle of Ming Dynasty (1368-1644). The treatise shows the state of Chinese medical theory before the introduction of Western Medicine in 1800s.

TCM has closely related with health care in ancient times. First of all, ancient Chinese health care was based on medical aid, featured as unilateral and gratis. It reflected the ancient morality on social fraternity, philanthropy and mutual aids, which was in consistence with ethical concepts of TCM of saving life. Moreover, health care offered by government was delivered through the means of TCM treatment. Usually there were three ways: sent special doctors for medical ward inspection, distributed free medicines, and set medical institutions offering medical service. It also involved in the care of the elderly and the vulnerable, and disaster relief (Weng and Zhang, 2006).

Evolved into the Modern or Transitional Period (1801-1932 A.D.), however, TCM faced the challenge of survival. With western doctors coming to Qing Empire (1644-1911), many scholars started to study Western Medicine (WM) and became suspicious on TCM theory. After the fall of Qing Dynasty, some political leaders wanted to rid China of ancient medical ideas. For instance, Dr. San Yat-sen strongly advocated WM as himself was a western-trained medical doctor. Later, the Kuomintang of China (KMT) had twice tried to abolish TCM in 1913 and 1929, but failed to executed due to fierce public opposition. After the found of China in 1949, some officials again proposed to get rid of TCM in considering it as superstitious and non-scientific (Li, 2015). The voice was diminished with Chairman Mao Zedong's speech in support of TCM, as well as the integration of TCM and WM in 1950. However, practically, TCM has not received sufficient support compared with that of WM in China, evidenced by the dominant position of WM in medical service and health care.

3.5.3 TCM's Role and Application in Health Care in China

TCM has played an important role in delivering basic and primary medical services, especially in rural areas where lived majority of population. Due to the very limited amount of technical and financial resources, the primary method of treatment of rural service provider, known as the "barefoot doctors", was typically "a needle with a bundle of herbs". Local health centers of the agricultural communes strongly encouraged traditional medicine treatments and self-meditation, as well as promoted herb planting and homemade medicine. With various folk treatments that are effective, convenient and cheap, health status in rural areas has been greatly improved (Du et al., 2005).

TCM has been an indispensable part of the efforts in health care reforms. In 1982, the government wrote "developing Traditional Chinese Medicine" into the national Constitution, which identified the legal status of TCM[43]. Specific office of State Administration of Traditional Chinese Medicine under Ministry of Health was established in 1986, who took charge for the provision of guidelines, policies and laws on the development of TCM and its integrated delivery.

The *Implementation Plan of Recent Priorities in Carrying out the Reform of Health Care System (2009-2011)* and *The Twelfth Five-Year Plan for Development of Health Care (2011-2015)* in 2011 both addressed that health care system should be established in consistence with national characteristics and conditions, where TCM could play a full role in disease prevention and control, public health emergency service, and primary medical service[44]. The 2012 *Outline and Implementation Plan for Deepening the Medical and Health Care System Reform During the Twelfth Five-Year Plan* further promoted the use of TCM in the aim to improve the quality of primary health care. Community health service centres were growing, where people are encouraged to visit Community health service centres for minor illness and preventive treatment with TCM, in order to ease economic

[43]Source: Constitution of People's Republic of China 1982. December 4, 1982.

[44]Source: Implementation Plan of Recent Priorities in Carrying Out the Reform of Health Care System 2009-2011. April 8, 2009.

burden of outpatients, and accelerate the formation of multiple-layer treatment system[45].

TCM works on multiple system complexity and new viral diseases in modern times. For instance, Epidemic encephalitis B broke out in several provinces of China in later 1950s. One TCM treatment, called *Bai Hu Tang*, was used, and reported to be positive in 90% cases. In 1960s, measles was popular among infants in Guangdong Province, and TCM therapy was used to clear heat for promoting eruption without sequel. In 1990, U.S. Center for Disease Control and Prevention compared the mortality rate as 1:234 on hepatitis B overlapped with hepatitis A by treatment of TCM in Shanghai, China and WM in U.S. from 1983 to 1988 (Jia et al., 2003).

TCM has contributed in combating SARS in China (WHO, 2004). Integrated treatment with TCM and WM was proved to be safe with many potential benefits. WHO (2004) reported that lower mortality rate were associated with patients involved in combined treatment with TCM and WM than that with WM alone. Total number of case worldwide was 8,422 until July 2003, among which 5,327 in China Mainland, and 1,775 in Hong Kong. Global average fatality rate was reported to be 9.5%, Hong Kong 17%, while in Mainland it was 6.5%(Jia et al., 2005). Besides, associated side-effects of SARS was reduced or alleviated due to less dosage of glucocorticoid and antiviral agents. Furthermore, the cost of TCM intervention was less than WM treatment alone. The case of highest cost was 5,000 RMB in TCM hospital in Guangzhou, compared to over 50,000 RMB of the average cost of WM treatment.

TCM has accumulated rich experience with systematic theoretical knowledge on treatments of chronic disease, including various non-drug therapies, like acupuncture or cupping. A large number of clinic practice studies, including randomized controlled and systematic reviews, have proved positive result of TCM treatment on chronic diseases (Wang, 2000; Covington, 2001; Normile, 2003; Lao et al., 2012; Wang, 2013). This is especially important for Chinese social and economic development in next decades, as China is rapidly ageing with prevalence of chronic disease. According to 2010 Population Census, people aged 60 or over occupied 13.26% of total

[45]Source: Outline and the Implementation Plan for Deepening the Medical and Health Care System Reform During the Twelfth Five-Year Plan. March 14, 2012

population, among which, people aged 65 or over accounted for 8.87%[46]. The figures reached to 16.1% and 10.5% respectively in 2015[47]. This implies that chronic diseases, or formally non-communicable diseases (NCDs), such as hypertension, diabetes, cardiovascular disease, cancer Alzheimer's disease and so on, have become principal public health killers, and lead to the increase in burden of disease in terms of human suffering, health care system, and socioeconomic growth (Suhrcke et al., 2006). World Bank (2011) reports that NCDs contributed to 68.6% of the total disease burden of China, and NCD-related morbidity accounts for more than 90% of the total NCDs burden. In contrast, reducing the CVD mortality, say, by 1% per year over a 30-year period (2010–2040) is estimated to generate an economic value equivalent to 68% of its real GDP in 2010, more than 10.7 trillion PPP U.S. dollar.

3.5.4 TCM's Potential Application Worldwide

WHO claimed that non-communicable diseases (NCDs) have become a global threat and the main cause of death of adults worldwide. All age groups in all regions are affected by NCDs, which causes an unprecedented public health crisis and medical crisis that damage the developed and developing countries likewise (Chen, 2013).

WHO (2014) demonstrated that 38 million deaths of a total of 56 million deaths were due to NCDs worldwide in 2012. Among them, approximately 42% (16 million) of all NCDs deaths occurred before the age of 70 years, which is considered as premature death. Besides, the number of new cases is increasing. For example, annual cancer cases are expected to rise from 14 million in 2012 to 22 million over the next two decades[48]. Individual and national costs of addressing NCDs, together with the loss of workforce productivity due to workdays lost and premature death, not only result in cumulative economic losses, but also jeopardize sustainable growth. The accumulative losses are higher in larger countries, such as China, Russian and India. Between 2005 and 2015, an estimated accumulative loss of 558

[46]Chinese Population Census 2010. National Bureau of Statistics of China.

[47]Statistical Communiqué of the People's Republic of China on the 2015 National Economic and Social Development. National Bureau of Statistics of China. February 29, 2016.

[48]World Cancer Report 2014. World Health Organization.

billion U.S. dollar occurred in China, 303 billion U.S. dollar in Russia, and 236 billion U.S. dollar in India (Armenio et al., 2013).

Continually rising medical expenditure has triggered medical crisis worldwide. For instance, in 2014 the U.S. government has spent nearly 3 trillion U.S. dollar, 17.1% of its GDP, on medical and health care services, where chronic ailments explaining for 86% of total expenditures. Nevertheless, 11.7% of U.S. population (33 million) have not yet covered by any health insurance.[49]. The U.S. is not the single case. Evidence shows that health expenditure has kept growing around the world in recent years. Table 3.7 and 3.8 give a glimpse on the trend between 2005 and 2014 in taking nine big countries as example. We can find that national health expenditure has kept growing either in absolute amount or relative value in ten years.

Country	Total expenditure % of GDP (billion U.S. dollar current year)	Public % of total expenditure	Out of pocket % of total expenditure	Per capita (PPP U.S. dollar)	Physicians per 1,000 people	Hospital beds per 1,000 people
China	4.7 (107)	38.8	52.2	235.0	1.6	2.5
France	10.6 (234)	78.0	7.1	3241.0	3.4	7.3
Germany	10.5 (300)	76.1	14.0	3384.0	3.4	8.4
Italy	8.7 (161)	76.3	20.7	2587.0	3.7	4.0
India	4.3 (36)	26.5	65.9	122.0	0.6	0.9
Japan	8.2 (375)	81.4	15.5	2491.0	2.4	14.1
Russian	5.2 (40)	62.0	31.3	616.0	4.0	9.7
U.K.	8.2 (198)	80.9	9.5	2746.0	2.8	3.4
U.S.	15.2 (1,990)	44.4	13.3	6741.0	2.4	3.2

Table 3.7 – *Main health expenditure indicators in nine countries 2005*[50].

WHO indicates the root of global public health crisis lies in the purpose of medicine. Early in 1996, WHO reported that the current medicine was creating a global atmosphere of injustice and unaffordability, where a lot

[49]Source: 2015 Current Population Survey (CPS). United States Census Bureau.
[50]Source: World Development Indicators. World Bank Data.
[51]Source: World Development Indicators. World Bank Data.

Country	Total expenditure % of GDP (billion U.S. dollar current year)	Public % of total expenditure	Out of pocket % of total expenditure	Per capita (PPP U.S. dollar)	Physicians per 1,000 people	Hospital beds per 1,000 people
China	5.5 (569)	55.8	32.0	731	1.9	3.8
France	11.5 (325)	78.2	6.3	4,508	3.2	6.4
Germany	11.3 (437)	77.0	13.2	5,182	3.9	8.2
Italy	9.2 (197)	75.6	21.2	3,239	3.8	3.4
India	4.7 (96)	30.0	62.4	267	0.7	0.7
Japan	10.2 (469)	83.6	13.9	3,727	2.3	13.7
Russian	7.1 (144)	52.2	18.9	1,836	4.3	unavailable
U.K.	9.1 (272)	83.1	9.7	3,377	2.8	2.9
U.S.	17.1 (2,967)	48.3	11.0	9,403	2.5	2.9

TABLE 3.8 – *Main health expenditure indicators in nine countries 2014*[51].

of countries have been pushed to its limit. An important way to eliminate inequality is to encourage the rapid diffusion of successful innovations (Deaton, 2013). However, innovation cost is expensive. A 2014 report shows that the average cost of a new drug that approved to public use is about 2.56 billion U.S. dollar, including direct investment of 1.40 billion U.S. dollar, and indirect investment of 1.16 billion U.S. dollar. Compared to the amount of 0.8 billion U.S. dollar in 2003, it has increased by 145% in ten years[52].

TCM provides the possible source of innovation. An important case is the discovery of artemisinin(Qing Hao Su, in Chinese), which is awarded of 2015 Nobel Prize in Physiology or Medicine. The winner Tu Youyou was inspired from an ancient TCM recipe in *Handbook of Prescriptions for Emergency Treatments* (Zhou Hou Bei Ji Fang, in Chinese), written by Ge Hong in 340 A.D. Artemisinin is the pure substance extracted from the plant Artemisia annua (Qing Hao, in Chinese), which is a typical and cheap herbal medicine used TCM therapy. Artemisinin-based medicines

[52]Source: Tufts Center for the Study of Drug Development (CSDD). Available online http://csdd.tufts.edu/reports

are proved to be highly effective against malaria, and recommended as standard treatment in WHO Model List of Essential Medicines[53]. It has profoundly cut down the incident and mortality of malaria worldwide, especially the most vulnerable citizens in tropical developing countries in sub-Saharan Africa, South America and South Asia, which representes a great improvement of global health and welfare (Andersson, Forssberg and Zierath, 2015).

3.6 Conclusion

In this essay we make a qualitative study on the evolution of China's health care system with highlight on the reform policies and strategies. Specifically, we emphasize the issue of the inequality in rural and urban health care system. We investigate the causes of inequality, and provide insights as well as associated policy implications for further reform. The main causes of the inequality are twofold: historical aspect and economic aspect. Historically, the health care disparities are endowed from the found of health care system in 1951. Economically, health care providers are mainly funded by regional government, and hence imbalanced economic growth across regions worsen this inequality.

We provide some policy implications by statistically analysis to various Chinese health care data on mortality rate, life expectancy, health care expenditure and health care providers. Policy insights for further health care reform are to expand the health insurance coverage, lower copay or deductible, and particularly, integrate diverse medical insurance systems into a unified and standardized system nationwide. This essay highlights the need for diminishing the urban-rural health care inequalities, promoting diverse medical care providers (e.g private hospital) and basic medical care assistance for extreme poor people without insurance.

This essay not only concludes the achievement and drawback of China's health care system, but also highlights the contemporary striking problem, such as population ageing and environmental degradation. Finally, we discuss Traditional Chinese Medicine (TCM) and its application in China's health care system. Given its advantages, we consider that TCM will play

[53] WHO Model List of Essential Medicines, 14th edition, March, 2005.

a more active role in further health care reform, which we will discuss in later chapter.

4 Environment Degradation, Health Shocks, and Sustainable Economic Growth

4.1 Introduction

4.1.1 Purpose and Stylized Facts

The detrimental impact of production-induced environmental degradation, such as pollution, CO_2 emissions and intensified severity of catastrophes, leads significant health and economic losses that changes population's consumption and saving decisions, and as a consequence, economic growth. First of all, a growing number of empirical evidence shows that the influence of environmental pollution, like air pollution (Haze), water pollution, and food contamination entails severe human health degradation, for instance, the increasing morbidity of chronic diseases and the associated mortality rate. Specially, pollution-induced disease has a major detrimental impact in working-age population, and hence, reduces economic activity in terms of lacking labour productivity. The World Health Organization (WHO, 2004) reports that 56% population suffering from chronic diseases are aged between 15 to 59 in high-income countries. Moreover, an overall 3 million deaths are caused by outdoor air pollution in global cities and rural in 2014, and the vast majority of those form of deaths (70%) occurs in low- and middle-income countries.[1] The associated economic losses are striking. In U.S., an amount of 277 billion U.S. dollar annual expenditure is spent on treatment to seven most common chronic diseases, and the productivity loss is equal to 1.1 trillion U.S. dollar per year (Devol and Bedroussian, 2007). In Europe, air pollution causes approximate 6 million premature deaths, and the associated economic loss is no less than 1.6 trillion U.S. dollar a year (WHO and OECD 2015). The situation is even worse in

[1]WHO news, March, 25, 2014. Available online: http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/

emerging economies. Taking China as an example, World Bank (2007) estimates that the health costs due to air and water pollution is equal to 4.3% of its annual GDP.

Consequently, reducing production emissions has become an urgent and primary issue of environmental and health policies worldwide. This goal can be achieved by tightening mitigation policy and enlarging investment in abatement technologies, such as, low carbon transport system and renewable fuels. From economic point of view, we motivate our analysis with a number of stylized facts of pollution-induced health degradation, matched by the corresponding properties of our theoretical model, as follows:

(i) The pollution-induced health degradation is caused by negative externalities of production. As a consequence, the conversational free market optimal allocations are no longer efficient without consideration of environmental policies.

(ii) As a fundamental component of labour productivity, the population's health status thus constitutes an imperative part of sustainable economic growth.

(iii) The detrimental impact of pollutants and emissions on human health is uncertain both at the individual level and the aggregate level, yet proportional to the level of economic growth.

Given the uncertain nature of the detrimental impact of pollutants and emissions on human health, how should an economy appropriately balance its production, consumption, investment, and reduction of emissions? How to determine the optimal mitigation policy and growth rate in such an uncertain environment? Is it worth to implement tight environmental policy, harmful to economic growth for compensating a healthy environment? And how do these key variables respond to the fluctuations of capital accumulation, health degradation, and individual risk preferences?

The aim of this essay is to study the production induced environment degradation and its detrimental impact on health. Specifically, our model enables policy maker to maximize the society well-being while optimally preparing the economy growth under both capital accumulation and health regeneration uncertainties. In this essay, we consider a modified version of stochastic dynamic model illustrated in Bretschger and Vinogradova

(2016). This model is composed by a dynamical system of deterministic capital accumulation and health uncertainty. Specially, we contribute to the literature by introducing a two dimensional stochastic endogenous growth model composed of stochastic capital accumulation and health regeneration. Indeed, our model can also be viewed as an extension of Steger's one dimensional stochastic growth model(2005) where health dynamics is absent. The benchmark of capital and health uncertainties are driven by two correlated Winer processes. Roughly speaking, the proposed dynamic constraint can be interpreted as the multi-factor Geometric Brownian motion. We provide close-form solutions of the optimal mitigation policy and expected growth rate. The impact of parameters on economic variables are detailedly discussed with clear-cut implication for environmental policy.

4.1.2 Literature Review

There is a growing number of theoretical models that highlight the detrimental impact of environmental externalities on human health and economic growth. The aim is to analyse the linkages between the production, pollutants, health degradation, the role of mitigation policy and public investment. There exist several overlapping generations (OLG) models, which have addressed these questions with individual's living for two periods like Gutiérrez (2008), Balestra and Dottori (2012), and Wang et al. (2015). In these models, the young generation is never sick while the old generation faces the risk of mortality or unhealthy state, depending on the probability affected by pollutants. A common feature in those models is that health status does not enter the utility function. Specially, Gutiérrez (2008) finds that pollution raises health costs, as a consequence, fosters precautionary savings and capital accumulation, which stimulates growth. However, most of papers find welfare and growth losses. Overcoming the dynamic inefficiency in OLG framework á la Diamond (1965), many papers, including Davide and Dottori (2012) and Wang et al. (2015), discuss the second-best equilibrium using health insurance as an instrument. In particular, Wang et al. (2015) highlight that precautionary saving acts as a substitute for lacking health insurance. A three period OLG model can be found in Mariani et al. (2010), where agents may invest in environmental care, which affects their life expectancy. An interesting scenario of multiple equilibria is discussed. This illustrates the so-called low-life-expectancy/low-environmental-quality trap caught by some developing countries. In Mariani et al. model, the survival probability depends on the inherited environmental quality and is assumed to constant in equilibrium states. While Davide and Dottori (2012) assume that the life expectancy in second period depends on the current environmental conditions. Hence, young generation can invest in environmental quality and benefit when they are old. Political effect of population ageing is discussed as well. However, above mentioned models do not explicitly introduce human health into the utility function. By considering the health status in the welfare function á la Grossman (1972a), Pautrel (2012) extends the OLG model by taking into account of the impact of pollution as endogenous depreciation on health dynamics. In Pautrel model, working-age agents make trade-off between consumption and investment in health enhancing activities in order to maximize their welfare. Pautrel shows the relationship between environmental taxation and economic activities is inverted-U shaped, which also holds between environmental taxation and lifetime welfare.

Following the central topics in health economics and the canonical model of the demand for health à la Grossman (1972a), we include human health in welfare function. Theoretical extensions and some competing economic models can be found in Grossman (1972b, 2000), Wagstaff (1987), Zweifel and Breyer (1997), and Galama (2011), where health is viewed as a capital stock depreciating overtime but can be enhanced by investment in medical care to produce healthy time that benefiting individual welfare and promoting labour productivity. Some empirical studies on the model of demand for health can be found in Wagstaff (1986) who estimates Grossman model (1972a) using 1976 Danish Welfare Survey. Van Doorslaer (1987) and Wagstaff (1993) extend the empirical study using longitudinal data. Uncertainty effect is introduced in the model of demand for health by a number of papers. Cropper (1977) assumes that illness will occur once the stock of health falling below a critical sickness level, which is random. This model indicates that an agent with higher income or wealth level will maintain higher stock of health than a poorer agent. Selden (1993) and Chang (1996) show that risk averse people enlarge their investments in health due to the effect of uncertainty. Compared to the model with perfect certainty, the expected value of the stock of health, the optimal investment and health inputs are all larger when the effect of uncertainty is taken into account. Laporte and Ferguso (2007) extend Grossman model by considering of health as a stochastic variable in order to characterize the case of permanent reduction in individual's stock of health when a serious illness happens.

Furthermore, increasing amount of theoretical models highlight the role of environmental uncertainty on economic growth. Weitzman and Läfgren (1997) show the effect of environmental catastrophe on economic growth using national accounting and welfare measures, where the probability of catastrophe occurrence is driven by anthropogenic activities. Tsur and Withagen (2011) study a dynamic model on abrupt climate change, where a certain kind of capital is used to adapt the catastrophe. The catastrophe is caused by climate change, and the occurrence date is stochastic, whose distribution depends on atmospheric GHGs concentration. Bretschger and Vinogradova (2014) present a stochastic model of a growing economy where natural disasters random occur, and the damages are caused by polluting activity. Besides climate catastrophe, Martin and Pindyck (2015) analyse different types of catastrophes. They focus on the social cost of each catastrophe and develop a rule to determine which kind of catastrophe should be averted. While health and environment literature are explicit about health production by households and production induced environmental degradation respectively, the correlation between health and environment are largely disregarded.

4.1.3 Outline of the Results

Our objective is to propose a dynamic system that allows social planner to make decisions by considering economic growth, GHGs emissions and pollutants as well as their detrimental impact on human health. In this regard, we extend a benchmark model for intertemporal decision making à la Ramsey with uncertainty, where the optimal environmental policy and economic growth rate are optimally computed. In contrast to the vast majority of empirical estimations and complex numerical simulations, we derive clear-cut analytic solutions with implications for the optimal environmental policy. The policy maker has to decide optimal policy to mitigate pollutants and emissions for the purpose of enhancing health, while preventing dramatic damage to economic activity, depending on a couple economic parameters, such as the sensitivity of health to pollutant, efficiency of abatement technology, polluting intensity of output.

The particularity of our model is the introduction of correlations between uncertainties in capital and health dynamics. Inspired by Martin and

Pindyck (2015), our model considers an endogenous growing economy where the associated uncertainties are dependent and not necessarily caused by global warming. Our model can be seen as a generalized version of Bretschger and Vinogradova (2016), in which the uncertainty only exists in health regeneration dynamic. They assume the dynamic of health regeneration follows a Geometric Brownian Motion (GBM), whose diffusion coefficient (or percentage volatility) only depends on mitigation policy. Therefore, given a fixed mitigation policy, capital accumulation and health degradation are independent processes. In this scenario, individual can always be better off by enlarging production without affecting health. However, more production indicates more pollutants which degrades labour's health. That is why they can not be studied in isolation. In AK economy where population size is unitized to one, health status does not enter directly into the production function. The introduction of correlation between two dynamics entails the (indirect) effect of labours' health fluctuation on production.

It is worth to note the sign of correlation coefficient can be either positive or negative. For instance, a positive fluctuation on health may accelerate growth in terms of labour productivity (i.e. positive correlation). While a positive fluctuation on production may generate pollutants which harm health (i.e. negative correlation). Therefore, health may positively or negatively correlated with economic activity, denoted "productivity effect" and "environment effect", receptively. In clean economy with updating and less pollutant industry, "productivity effect" dominates "environment effect", and we observe positive correlation between production and health. While in many developing countries, production is associated with more pollutant. The "productivity effect" is very likely to be dominated by "environment effect", and we can observe negative correlation. Moreover, in case of negative correlation, individual can not always be better off by producing (i.e. more consumption) while lacking health. The results of the numerical application show the importance of introducing capital uncertainty.

Nevertheless, we privilege the mitigation policy, defined as a fraction of output for abating emission, to underline its role in economic production and social welfare. We find that the economic growth rate is negatively affected by health fluctuation. In addition, we demonstrate that the associated correlation between capital and health uncertainty may strengthen or offset this detrimental effect, depending on the sign of correlation coefficient.

Another contribution is to find that the relationship between mitigation policy and economic growth rate is inverted-U shaped when both capital and health uncertainties are considered. Specially, we show that the greater the relative risk aversion, the more likely that the environmental policy will stimulate economic growth. Furthermore, we provide the necessary and sufficient condition for the existence and uniqueness of equilibrium emission concentration.

Finally, using numerical calibration, we show that the optimal abatement policy reacts sensitively not only to the variations in conventional economic parameters, like emission intensity, efficiency of abatement technology, and TFP, but also to the health parameter (the relative important of health respect to consumption) and uncertainty parameters, such as the sensitivities of health to fluctuation and damage intensity. The abatement policy is also sensitive to the sign of correlation coefficient. An intensified sensitivity is observed when the measure of relative risk averse decreases. Specifically, we find that the mitigation policy should be 0.46%, indicating 33 U.S. dollar per ton coal in the benchmark model setting, and 0.69%, implying a relatively higher carbon price equal to 50 U.S. dollar per ton coal, when the development of abatement technology is viewed in a less optimistic way. The former number is higher but comparable to 0.42% which is found in Nordhause (2008). Our calculation suggests a higher carbon tax when the interdependent uncertainties in health and capital are taken into account.

The rest of the essay is organized as follows. Section 2 introduces the benchmark model. Section 3 presents analytical treatment and derives closed-form optimal solutions. Section 4 is an analytical discussion of appealing economic properties. Section 5 presents the numerical calibration to show the effects of model parameters on mitigation policy and growth rate. Section 6 is the conclusion.

4.2 Economic Growth with Health and Environment Uncertainties

The Model

Let us consider the frequently occurred small-scale fluctuations, which might be environmental pollution, global warming damage, or something else. The economic dynamic system proposed here is inspired by Bretschger and Vinogradova (2016) model. Firms produce a composite consumption good using broadly defined capital stock, denoted K_t as input. We assume the production function is constant returns to scale, i.e. $Y = A_t\, K_t$, where total factor productivity A_t is assumed to be constant for simplicity: $A_t \equiv A$. It is worth to remark that, as a broadly accepted model in endogenous growth literature, the input K_t in AK model is interpreted as a broad measure of capital in the economy, such as physical capital, human capital, knowledge, etc. The stock of pollution is due to production that releasing detrimental emissions to the atmosphere, measured by ϕ units of emissions per unit of production. Following Grossman (1972a, 1972b) and Cropper (1981), we consider that a variety of pollution degrades health status. Yet, the exact negative impact of pollution on health is non-deterministic, and therefore is assumed to be driven by a stochastic process: $R(q_t)h_t dZ_{h,t}$, where $Z_{h,t}$ is the standard Wiener process, and q_t is the emission concentration per unit of capital. The relationship between pollution and health status is defined as:

$$dh_t = R(q_t)h_t dZ_{h,t}\,, \quad t\,, q_t \geq 0\,, R(q_t) \leq 0\,. \tag{4.1}$$

$R(q_t)$ is a decreasing function of emissions concentrations. For simplicity, we assume a linear relationship: $R(q) = \delta\, q_t$, where $\delta \geq 0$ denotes the sensitivity of the health status to pollution. Moreover, we model productivity fluctuation by another stochastic process $\sigma K_t dZ_{k,t}$, where $Z_{k,t}$ is the standard Wiener process, and is assumed to be correlated with health shock $Z_{h,t}$ according to

$$\mathrm{E}(dZ_{k,t}\, dZ_{h,t}) = \rho_{k,h}\, dt\,, \quad \rho_{k,h} \in [-1, 1]\,, \, t \geq 0\,. \tag{4.2}$$

where $\mathrm{E}(\cdot)$ denotes expected values of $(\cdot)$ and $\rho_{k,h}$ is correlation coefficient, indicating the mutual influence between health and productivity fluctuations. Parameter $\sigma \geq 0$ measures the amplitude of randomness caused by pollution shock entering the process of capital accumulation. The aggregate form of mitigation (or abatement) M_t is provided to mitigate the emissions, financed by a fraction of output, denoted by m_t. The remaining share of output $1 - m_t$ is divided between consumption and capital accumulation. Obviously, the total mitigation is an increasing function of the abatement spendings, which is simplified as the following linear relationship: $M_t = \mu m_t Y_t$, where $\mu \geq 0$ is so-called the efficiency of mitigation and abatement. The law of motion of the stock of aggregate emission is thus

$$Q_t = (\phi - \mu m_t) Y_t \,, \quad \phi \,, \mu \,, t \geq 0 \,. \tag{4.3}$$

where parameter $\phi \geq 0$ represents the emission intensity of output. It is worth nothing that the total emission needs to be non-negative: $Q_t \geq 0$. Hence, the efficient mitigation of output (i.e. μm_t) needs to be bounded from above: $\phi \geq \mu m_t$, given that the fraction of output for mitigation and abatement $m_t \in (0, 1)$. In addition, we define the emission concentrations per unit of capital $q_t = Q_t / K_t$ as follows.

$$q_t = (\phi - \mu m_t) A \,, \quad \phi \,, \mu \,, t \geq 0 \,. \tag{4.4}$$

The social planner's objective is to maximize the overall expected discounted welfare over an infinite horizon. On a given date, welfare depends on the amount of consumption, denoted c_t, and health status h_t, and is measured by a standard utility function $U(\cdot)$, which is positive, increasing and concave. For instance, we use a standard constant relative risk aversion (CRRA) utility function

$$U(c_t, h_t) = \frac{c^{1-\epsilon}}{1 - \epsilon} h^{\beta} \tag{4.5}$$

where the constant parameters $\epsilon \,, 1 - \beta \in (0, 1)$ represent Arrow-Pratt measure of relative risk aversion and the elasticity of marginal utility to consumption and health respectively[2]. Population is constant and unitized to 1. As compared to the capital dynamic in a deterministic Keynes-Ramsey model, we assume that production is subject to random shocks which may due to population's health shock. More precisely, inspired by the stochastic economic growth model of Steger (2005), we define the law of motion of capital accumulation as follows:

$$dK_t = \big[(1 - m_t) Y_t - c_t\big] dt + \sigma K_t dZ_{k,t} \,, \quad K_t \,, c_t \,, t \geq 0 \,, \; K(0) = K_0 \text{ given} \tag{4.6}$$

[2] In order to guarantee concavity of $U(\cdot)$ i.e. $U'_h(\cdot) > 0$, we require that $\epsilon \in (0, 1)$. It is worth nothing that when $\epsilon = 1$, using L'hospital's rule, we have the logarithm utility function: $U(c_t, h_t) = \ln(c) \, h^{\beta}$.

where $Z_{k,t}$ is a Wiener process or Brownian motion, and $\sigma \geq 0$ reflects the sensitivity of the capital to fluctuations. Furthermore, it is worth to remark that in AK economy, consumption is proportional to capital stock, denoted $c = xk$, with x constant. Therefore, Eq.(4.6) can be expressed as following:

$$dK_t = \big[(1-m)A - x\big]K dt + \sigma K_t dZ_{k,t}\,, \quad K_t\,,\, t \geq 0\,,\; K(0) = K_0 \text{ given} \tag{4.7}$$

Hence, the stochastic process K_t follows a geometric Brownian motion (GBM), with drift parameter $(1-m)A - x$ and volatility parameter σ. Moreover, combing Eqs.(4.1), (4.2) and (4.6), we define our Pontryagin problem composed by two correlated stochastic processes: capital and health as follows:

$$\max_{c,m} \mathrm{E}_0 \left\{ \int_0^\infty U(c_t, h_t)\, e^{-\rho\, t}\, dt \right\} \tag{4.8}$$

subject to

$$\begin{aligned} &dK_t = \big[(1-m_t)Y_t - c_t\big]dt + \sigma K_t dZ_{k,t}\,, \quad K_t\,,\, c_t\,,\, t \geq 0\,,\; K(0) = K_0 \text{ given}\,,\\ &dh_t = R(q_t)h_t dZ_{h,t}\,, \qquad q_t\,,\, h_t\,,\, t \geq 0\,,\\ &E(dZ_{k,t}dZ_{h,t}) = \rho_{k,h}dt\,, \qquad \rho_{k,h} \in [0,1]\,,\, t \geq 0\,. \end{aligned}$$

It is worth to remark that we consider the AK-type growth model with constant population size unitized to 1 for simplicity. Hence, capital per labour and output per labour are identical to overall capital and output respectively, i.e.

$$Y_t = AK_t\,, \quad L_t = 1 \quad \Rightarrow k_t \equiv \frac{K_t}{L_t} = K(t)\,, \quad y_t \equiv \frac{Y_t}{L_t} = Y_t \tag{4.9}$$

4.2.1 Analytical Treatment

Following the approach of Dixit and Pindyck, (1994), Steger (2005), we write down the Hamilton-Jacobi-Bellman (HJB) equation for Eqs.(4.2) to (4.8) as follows:

$$\rho V(k,h) = \max_{c,m} \left\{ U(c,h) + \frac{1}{dt}\mathrm{E}\big[dV(k,h)\big] \right\} \tag{4.10}$$

where $V(k,h)$ is the value function associated with the optimal control problem. In Appendix A, applying Ito's lemma, we obtain HJB in the following expression:

$$\rho V(k,h) = \max_{c,m} \Big\{ U(c,h) + V_k(k,h)\big[(1-m)y - c\big] + \frac{1}{2}\big[V_{kk}(k,h)\sigma^2 k^2 + V_{hh}(k,h)R^2(q)h^2 + 2\rho_{k,h}V_{kh}(k,h)\sigma k R(q)h\big]\Big\} \tag{4.11}$$

For convenience, we omit the time subscripts and denote $V_k(k,h) \equiv \partial V(k,h)/\partial k$, $V_h(k,h) \equiv \partial V(k,h)/\partial h$, $V_{kk}(k,h) \equiv \partial V^2(k,h)/\partial k^2$, $V_{hh}(k,h) \equiv \partial V^2(k,h)/\partial h^2$, and $V_{kh}(k,h) \equiv \partial V^2(k,h)/\partial k \partial h$. The first-order conditions (FOCs) of control and state variables are derived as follows:
For consumption c:

$$U_c = V_k \tag{4.12}$$

For abatement fraction m:

$$V_k\, y_t = (-\mu y_k')\Big(V_{hh}R(q)R'(q)h^2 + V_{kh}\sigma R'(q)\rho_{kh}kh\Big) \tag{4.13}$$

For capital stock k:

$$\rho V_k = V_{kk}[(1-m)y - c] + V_k(1-m)A + \frac{1}{2}\Big[V_{kkk}\sigma^2 k^2 + 2\sigma^2 V_{kk}k + V_{hhk}R^2(q)h^2 + 2\rho_{kh}\sigma V_{khk}R(q)hk + 2\sigma\rho_{kh}V_{kh}R(q)h\Big] \tag{4.14}$$

For health status h :

$$\rho V_h = U_h + V_{kh}[(1-m)y - c] + \frac{1}{2}\Big[V_{kkh}\sigma^2 k^2 + V_{hhh}R^2(q)h^2 + 2V_{hh}R^2(q) + 2\sigma\rho_{kh}V_{khh}R(q)kh + 2\sigma\rho_{kh}V_{kh}R(q)k\Big] \tag{4.15}$$

Applying Ito's lemma and substituting Eq.(4.14) into Eq.(4.12), we obtain the following key analytical results for optimal growth rate of consumption, where the detailed analytical treatment can be found in Appendix A.

$$dV_k = V_k\Big\{\rho - (1-m)A - \Big[\sigma^2\frac{V_{kk}}{V_k}k + \sigma\rho_{kh}\frac{V_{kh}}{V_k}R(q)h\Big]\Big\}dt + \sigma V_{kk}k dZ_k + V_{kh}R(q)hdZ_h\,. \tag{4.16}$$

It is worth nothing that consumption can be expressed as an inverse function of the marginal utility defined in Eq.(4.5) as follows:

$$c = (U_c\, h^{\beta})^{-\frac{1}{\epsilon}} = U_c^{-\frac{1}{\epsilon}} h^{\frac{\beta}{\epsilon}} := f^c(U_c, h) \tag{4.17}$$

Applying Ito's lemma and Ito's multiplication rules to Eq.(4.17), we have the expected growth rate of consumption i.e. $\mathrm{E}\big(\dot{c}/c\big)$ with $\dot{c} = dc/dt$ taking the following form:

$$\mathrm{E}\left(\frac{\dot{c}}{c}\right) = \frac{1}{\epsilon}\left\{(1-m)A - \rho - \frac{1}{2}\beta(1-\beta)(\delta q)^2 - \frac{1}{2}\sigma^2\epsilon(1-\epsilon) + \rho_{kh}\big(1-\epsilon\big)\beta\sigma\delta q\right\} \quad (4.18)$$

Substituting Eq.(4.4) into Eq.(4.18), we obtain the expected growth rate of consumption, denoted g, as follows:

$$g = \mathrm{E}\left(\frac{\dot{c}}{c}\right) = \frac{1}{\epsilon}\left\{(1-m)A - \rho + \Delta\right\}, \quad (4.19)$$

where the last item of RHS of Eq.(4.19), denoted Δ, represents the effect of uncertainty on the expected growth rate of consumption. Let us focus on Δ, which can be decomposed into the following three items: $\Delta = \Delta_h + \Delta_k + \Delta_\rho$, with

$$\Delta_h = -\frac{1}{2}\beta(1-\beta)(\delta A)^2(\phi - \mu m)^2 \leq 0\,, \quad (4.20)$$

$$\Delta_k = -\frac{1}{2}\sigma^2\epsilon(1-\epsilon) \leq 0\,, \quad (4.21)$$

$$\Delta_\rho = \rho_{kh}(1-\epsilon)\beta\sigma\delta A(\phi - \mu m)\,. \quad (4.22)$$

where $\Delta_h\,,\Delta_k\,,\Delta_\rho$ represent uncertainty effect due to health, capital and their correlation respectively. It is worth nothing that $\Delta_h\,,\Delta_k$ are negative. Therefore, there are two scenarios about Δ, depending on the sign of correlation parameter $\rho_{k,h}$. Specifically, $\rho_{k,h} < 0$ leads to $\Delta_\rho < 0$. Hence Δ is negative, implying the effect of uncertainty plays a negative impact on the expected growth rate, compared to the case with perfect certainty.

Indeed, the expected growth rate of consumption is the drift term of the stochastic process, which represents the "trend" of the consumption growth path when the detrimental impact of pollution shocks the economy. The trend depends negatively on mitigation and emission concentration. Eq.(4.4) tells us that the mitigation and emission concentration are inversely related. As a consequence, using a larger portion of output m_t as abatement may reduce pollution concentration, thus enhance economic growth. Besides, a larger m_t implies smaller $1 - m_t$ i.e. smaller proportion for production and consumption, and hence slows down the growth. In particular, we have the following property.

Proposition 4.2.1. *When endogenous fractions of output for mitigation and abatement (or mitigation fraction in short), and the stochastic detrimental impact of pollution on health are taken into account, we have three following properties:*

(i) Each uncertainty of capital and health dynamics in isolation has a negative impact on expected growth rate, compared to the case with perfect certainty.

(ii) Correlation structure between different uncertainties can worsen (or offset) the uncertainty-induced negative impact on expected growth rate, if $\rho_{k,h} < 0\,(or\,\rho_{k,h} > 0)$.

(iii) The relationship between the expected growth rate and mitigation fraction has an inverted-U shape. Specifically, $m_g^* = \dfrac{\phi}{\mu} - \dfrac{1+(1-\epsilon)\beta\rho_{kh}\mu\sigma\delta}{A\beta(1-\beta)(\mu\delta)^2}$, with $\delta \geq 0\,,\ \beta\,,\epsilon \in (0,1]\,,\sigma\,,\delta \in [0,1]\,,\rho_{k,h} \in [-1,1]$. When $m < m_g^*$ (or $m > m_g^*$), a greater mitigation fraction will raise (or lower) the expected growth rate.

Proof. The property (i) can be proved straightforward from Eqs.(4.20) and (4.21), where negative impact on expected growth rate due to fluctuation Δ increases when either Δ_h or Δ_k increases. It is worth nothing that $\partial\Delta_h/\partial\delta = -\beta(1-\beta)\delta q^2 \leq 0$ and $\partial\Delta_k/\partial\sigma = -\sigma\epsilon(1-\epsilon) \leq 0$. Especially, the above equalities hold when $\delta = \sigma = 0$, which indicates an extreme case that the negative impact due to uncertainty vanishes in the previous model (i.e. $\Delta = 0$). The property (ii) can be proved from Eq.(4.22) that $\partial\Delta/\partial\rho_{h,k} = \partial\Delta_\rho/\partial\rho_{h,k} = (1-\epsilon)\beta\sigma\delta q \geq 0$. Hence, when $\rho_{h,k} < 0$, the uncertainty impact on growth rate, denoted Δ, decreases as the negative correlation strengthens i.e. $\rho_{h,k} \to -1$. In the case of $\rho_{h,k} > 0$, Δ increases as $\rho_{h,k}$ increases. The equality holds when $\rho_{h,k} = 0$, implying that the shocks on health and capital are independent. The influence of mitigation fraction on the expected growth rate of consumption is positive if $\dfrac{\partial g}{\partial m} > 0$ implying:

$$m < \underbrace{\frac{\phi}{\mu} - \frac{1+(1-\epsilon)\beta\rho_{kh}\mu\sigma\delta}{A\beta(1-\beta)(\mu\delta)^2}}_{:=m_g^*} = \frac{\phi}{\mu} - \frac{(1-\epsilon)\big[1+\beta\rho_{kh}\mu\sigma\delta\big]+\epsilon}{A\beta(1-\beta)(\mu\delta)^2}\,, \quad (4.23)$$

$$\delta \geq 0\,,\ \beta\,,\epsilon \in (0,1]\,,\sigma\,,\delta \in [0,1]\,,\rho_{k,h} \in [-1,1].$$

Vice verse , $m > m_g^*$ implies $\dfrac{\partial g}{\partial m} < 0$. □

In Eq.(4.18), the first term in the RHS of the trend represents the negative impact i.e. the slow-down effect of the mitigation fraction on the growth rate of consumption, which is positively affected by the fluctuation term Δ i.e. the uncertainty effect. When the mitigation fraction $m = m_g^*$, the slow-down effect and the uncertainty effect exactly offset each other.

The basic mechanism underlying Proposition (4.2.1) is that, mitigation policy influences the expected growth rate through two channels. Firstly, mitigation policy, occupying a share of output as abatement, reduces consumption and saving. In other words, the proportion $1 - m_t$ indicates a negative impact of m_t on economic growth. Secondly, mitigation can dampen fluctuations, hence reducing risk premium and stimulating economic growth. For simplicity, let us denote them "slow-down" effect and "uncertainty" effect respectively. Indeed, mitigation represents a transmission between capital and health, fluctuations and production activities, which affects the consumption sector as well.

Production-induced pollution increases the fluctuation of health regeneration. Recalling that in Eq.(4.1), $R(q)$ is proportional to emission concentration. Consequently, the mitigation fraction reduces the stock of emissions, and thus diminishes the uncertainty in health regeneration, implying individuals are better off. Given the assumption of positive correlation ($\rho_{kh} > 0$) between health and capital fluctuations, the uncertainty effect on capital accumulation diminishes as well, indicating a positive impact on economic growth. For a risk-averse representative agent with measure of CRRA between 0 and 1 ($\epsilon \in (0, 1)$) defined in Eq.(4.5), the impact of uncertainty reduces the expected economic growth rate at a deterministic level. The economic implication can be illustrated by employing the well-known concept of certainty equivalent return on saving (Weil, 1990). Specially, when $\epsilon = 1$, the stochastic impact of capital accumulation on growth rate disappears. In addition, we have a higher threshold value of mitigation fraction (i.e. m_g^* increases), and hence the domain of mitigation fraction to promote economic activity enlarges. When the uncertainty correlation coefficient is negative, i.e. $\rho_{kh} < 0$, the fluctuations of health and capital offset each other. A positive shock on capital generates a negative shock on health. The economic implication is: a boom in production will enhance emission, and thus degrade health. It is worth to note that, when $\rho_{h,k} = 0$, stochasticity of health status and capital are independent. Consequently, the pollution induced fluctuation of health does not transit into fluctuation on capital, and vice versa. Hence, superposition effect of uncertainty disappear, and steady state growth rate is higher. For an extreme case: $\sigma\,, \delta = 0$, health and capital accumulation are independent of detrimental emission. Thus, the uncertainty effect vanishes, and only the "slow-down" effect remains where we have deterministic growth rate. In such a case, the optimal mitigation fraction goes to zero, and there is no difference between the deterministic and the stochastic growth rate. Nevertheless, environmental uncertainties are interdependent in reality and should not be considered in isolation (Martin and Pindyck, 2015).

An appealing policy implication of this inverted-U shape is: when mitigation fraction is relatively small and satisfying $m < m_g^*$, the "slow-down" effect is dominated by "uncertainty" effect. In this way, a tighter mitigation policy reduces the economic uncertainty, leading a higher growth rate. In this scenario, the environmental policy promotes economic activity. This scenario particularly provides insights to some emerging economies where we observe serious pollutions but less efficient mitigation policies. In addition, it is worth to note that a larger measure of relative of risk aversion, ϵ, will decrease (or increase) m_g^* when $\rho_{k,h}$ is negative (or positive) i.e.

$$\frac{\partial m_g^*}{\partial \epsilon} = \frac{\beta \rho_{kh} \mu \sigma \delta}{A\beta(1-\beta)(\mu\delta)^2} \begin{cases} < 0 & \text{when } \rho_{k,h} < 0 \\ > 0 & \text{when } \rho_{k,h} > 0 \end{cases} \tag{4.24}$$

This indicates, once an agent becomes more risk averse, m_g^* decreases, and hence the domain of $\partial g / \partial m > 0$ shrinks, indicating the "slow-down" effect is less likely to be offset by "uncertainty" effect when $\rho_{kh} < 0$. Similarly, we can obtain the contrary conclusion in the case of $\rho_{kh} > 0$.

Based on our CRRA utility function defined in Eq.(4.5), the value function can be derived explicitly in the following form:

$$V(k,h) = \frac{(x\,k)^{1-\epsilon}}{1-\epsilon} h^{\beta}\,, \quad \epsilon\,, \beta \in (0,1)\,. \tag{4.25}$$

As we remark before, in AK model, consumption is proportional to capital stock i.e. $c = x\,k$, where x is a proportional coefficient, whose close-form solution is derived as follows (See detail treatment in Eqs.(7.29), (7.30), and (7.31) in Appendix A):

$$x = \frac{1}{\epsilon}\Big\{\rho - (1-\epsilon)(1-m)A + I_x\Big\}\,, \qquad \rho\,, \epsilon \in (0,1)\,. \tag{4.26}$$

$$\text{where} \quad I_x = \underbrace{\frac{1}{2}\beta(1-\beta)\delta^2\big[(\phi-\mu\, m)A\big]^2}_{I_{x_h}} + \underbrace{(1-\epsilon)\beta\sigma(-\rho_{kh})\delta\big[(\phi-\mu m)A\big]}_{I_{x_{h,k}}}$$
$$+\underbrace{\frac{1}{2}\epsilon(1-\epsilon)\sigma^2}_{I_{x_k}}$$

with $\phi-\mu m \geq 0\,, A\,,\delta\,,\sigma \geq 0\,,\epsilon\,,\beta \in (0,1)\,,\rho_{kh} \in [-1,1]\,,m \in [0,1)$

$I_x \geq 0$ represents the effect of environmental uncertainty. Especially, it is composed by single effect on health, single effect on capital and the joint effect on both, denoted by $I_{x_h} \geq 0$, $I_{x_k} \geq 0$ and $I_{x_\rho} \gtreqless 0 \Leftrightarrow \rho_{kh} \gtreqless 0$ respectively. Substituting Eqs.(4.25) and (4.26) into Eq.(4.13), we derive the optimal fraction of output for mitigation as follows:

$$m^* = \frac{\phi}{\mu} - \frac{(1-\epsilon)\big[1+\beta\rho_{kh}\mu\sigma\delta\big]}{A\beta(1-\beta)(\mu\delta)^2}\,, \tag{4.27}$$
$$\text{with } A\,,\delta\,,\sigma\,,\rho\,,\mu \geq 0\,,\epsilon\,,\beta \in (0,1)\,,\rho_{kh} \in [-1,1].$$

In order to ensure $m^* \in [0,1)$, the parameters should satisfy the following inequality: $\dfrac{\phi}{\mu} - 1 < \dfrac{(1-\epsilon)\big[1+\beta\rho_{kh}\mu\sigma\delta\big]}{A\beta(1-\beta)(\mu\delta)^2} \leq \dfrac{\phi}{\mu}$. Therefore, using the relationship between m_t and q_t in Eq.(4.4), we obtain the optimal emission concentration straightforward:

$$q^* = \frac{(1-\epsilon)\big[1+\beta\sigma\mu\rho_{kh}\delta\big]}{\beta(1-\beta)\mu\delta^2}\,, \tag{4.28}$$
$$\text{with} \quad A\,,\delta\,,\sigma\,,\rho\,,\mu \geq 0\,,\epsilon\,,\beta \in (0,1)\,,\rho_{kh} \in [-1,1].$$

We require $-1 \leq \beta\rho_{kh}\sigma\mu\delta \leq 0$ to ensure $q^* \geq 0$. In practice, this condition holds since $\beta\,,\mu\,,\delta\,,\sigma \in (0,1)$ and $\rho_{kh} \in [-1,1]$. Substituting optimal mitigation fraction m^* and emission concentration q^* in Eqs.(4.27) and (4.28) into Eq.(4.18), we obtain expected optimal growth rate g^* expressed in following form:

$$g^* = \mathrm{E}\Big(\frac{\dot{c}}{c}\Big) = \frac{1}{\epsilon}\Big\{\Big(1-\frac{\phi}{\mu}\Big)A - \rho + I_g\Big\} \tag{4.29}$$

where I_g represents uncertainty effect on optimal growth rate of consumption which could be decomposed into health shock $I_{g,h}$ and capital shock $I_{g,k}$ respectively. $I_g = \dfrac{\big[(1-\epsilon)(1+\beta\sigma\delta\mu\rho_{kh})+\epsilon\big]^2-\epsilon^2}{2\beta(1-\beta)(\mu\delta)^2} - \dfrac{1}{2}\epsilon(1-\epsilon)\sigma^2$, and the parameters are defined before. The growth rate in Eq.(4.29) can be decomposed as follows:

$$g^* = \mathrm{E}\Big(\frac{\dot{c}}{c}\Big) = \frac{A-\rho}{\epsilon} - \frac{1}{\epsilon}\Big(\frac{\phi}{\mu}A - I_g\Big) \tag{4.30}$$

The first term in Eq.(4.30) reflects the standard Keynes-Ramsey rule of optimal consumption, which states that the difference between the risk-free interest rate (equals to marginal product of capital (MPK) i.e. $r = A$) less the preference rate, divided by the constant measure of relative risk aversion, ϵ. The last term implies the implicit risk premium, adjusted by the elasticity of intertemporal substitution for consumption, à la Dorfman (1969). Hence, in our model, the real interest rate is composed by risk-free rate less the risk premium. It represents one of the main channels through which uncertainty affects economic growth (De Hek, 1999). Specifically, this can be illustrated by environmental mitigation effect and uncertainty effect. The mitigation effect is defined by the ratio of the emission intensity of output to the abatement efficiency, i.e ϕ/μ. In particular, mitigation effect has a negative impact on the real interest rate because production-induced pollutants and emissions have an unambiguously negative effect on MPK, which can be dampened by either reducing the pollution intensity or improving the mitigation and abatement efficiency. The overall uncertainty effect, represented by I_g in Eq(4.29), can be decomposed into fluctuations of heath, denoted $I_{g,h}$, capital, denoted $I_{g,k}$ and their correlation, denoted $I_{g,\rho}$ as follows:

$$I_g = \underbrace{\frac{\big[1+(1-\epsilon)\beta\sigma\delta\mu\rho_{kh}\big]^2}{2\beta(1-\beta)(\mu\delta)^2}}_{I_{g,\rho}} - \underbrace{\frac{\epsilon^2}{2\beta(1-\beta)(\mu\delta)^2}}_{I_{g,h}} - \underbrace{\frac{1}{2}\epsilon(1-\epsilon)\sigma^2}_{I_{g,k}} \tag{4.31}$$

This uncertainty effect could stimulate or slow down the economic growth depending on the sign of I_g. The economic reason is best described by employing the concept of certainty equivalent return on saving (see Weil 1990 and Steger 2005). On one hand, the intertemporal income effect can depress contemporaneous consumption, which in turn induces more savings and faster growth. The logic is analogous to the literature on economy's propensity to save (PTS) under uncertainty which can be found in Wälde (1999), Toche (2001), Steger (2005), Bretschger and Vinogradova (2014). The peculiarity of the current setting is that the gross savings are endogenously split between two purposes: capital accumulation and emission abatement, both of which serve to protect the economy and individual from fluctuations in capital stock and health status respectively. Obviously, abatement reduces pollutants and emissions, which dampens the fluctuations of both capital accumulation and individual's health regeneration. More capital implies more output, and hence more pollutants harmful to health, indicating a negative correlation between capital and health fluctuations i.e. $\rho_{kh} < 0$. This is consistent to the result in Gutierrez (2008), who shows that an intensified positive link between pollution and economic growth can be found when health effect is included. Because more pollutants lead to the fluctuation of health regeneration, and hence motive precautionary savings and capital accumulation.

On the other hand, the intertemporal substitution effect may dominate income effect, implying a rise in contemporaneous consumption, and in turn, fosters precautionary dissaving, and consequently slower growth. Similar analysis can be found in Müller-Fürstenberger and Schumacher (2015), Bretschger and Vinogradova (2016). Moreover in our model, this scenario implies $\rho_{kh} > 0$, which indicates a positive link between pollution and economic growth.

In this section, our model presents the dynamic of the economy activity with interdependent uncertainties, and the optimal economic growth rate decreases when the number of the uncertainty increases and their interdependence may amplify or offset this uncertainty impact. A detail illustration of some attractive properties can be found in the following subsection.

4.2.2 An analytical illustration

In this subsection, we illustrate detailedly the effects of the model parameters on the optimal mitigation policy and the economic growth rate. Let us firstly focus on the optimal mitigation policy as follows:

Proposition 4.2.2. *When the dynamics of the economy's capital stock and health are affected by pollution-induced uncertainties (via a Wiener process), the optimal mitigation policy (a fraction of output for abatement, denoted by m^*), is constant over time, and is a function of model's parameters with following properties:*

(i) m^* increases when either the function of the total factor productivity (TPF) increases, or pollution intensity of output increases, or the

sensitivity of the health to pollution increases.

(ii) When multiple uncertainties are taken into account, the optimal policy may tighten or loose, depending on the sign of correlation coefficient.

(iii) The correlation coefficient between different uncertainties has negative impact on the mitigation policy.

(iv) m^* *either decreases or increases when the abatement efficiency improves, depending on the threshold level of abatement technology.*

(v) m^* *either decreases or increases when the the elasticity of marginal utility of health improves, depending on the threshold value of health parameter.*

(vi) m^* *is an increasing function of the elasticity of marginal utility to consumption.*

Proof. Given the optimal policy m^* in Eq.(4.27), the above properties can be derived straightforward through partial derivatives respect to the related parameters in Eqs.(4.32) to (4.41). In particular, Eqs.(4.32) to (4.34) are the proof of property (i), and Eqs.(4.35) to (4.39) are corresponding proof of properties (ii) to (vi) given the threshold values of abatement efficiency and health preference in Eqs.(4.40) and (4.41) respectively.

$$\frac{\partial m^*}{\partial A} = \frac{(1-\epsilon)(1+\beta\sigma\delta\mu\rho_{kh})}{A^2\beta(1-\beta)(\mu\delta)^2} > 0\,, \tag{4.32}$$

$$\frac{\partial m^*}{\partial \phi} = \frac{1}{\mu} > 0\,, \tag{4.33}$$

$$\frac{\partial m^*}{\partial \delta} = \frac{2(1-\epsilon)\left(1+\frac{1}{2}\rho_{kh}\beta\mu\sigma\delta\right)}{A\beta(1-\beta)\mu^2\delta^3} > 0\,, \tag{4.34}$$

$$\frac{\partial m^*}{\partial \sigma} = -\frac{(1-\epsilon)\big(\rho_{kh}\beta\mu\delta\big)}{A\beta(1-\beta)(\mu\delta)^2}\begin{cases}\geq 0 & \text{when } \rho_{kh}\leq 0\,,\\ < 0 & \text{when } \rho_{kh} > 0\,.\end{cases} \tag{4.35}$$

$$\frac{\partial m^*}{\partial \rho_{k,h}} = -\frac{(1-\epsilon)\big(\sigma\beta\mu\delta\big)}{A\beta(1-\beta)(\mu\delta)^2} < 0 \tag{4.36}$$

$$\frac{\partial m^*}{\partial \mu}\begin{cases}\geq 0 & \text{when } 0<\mu\leq\mu^*\,,\\ <0 & \text{when } \mu>\mu^*\,.\end{cases} \tag{4.37}$$

$$\frac{\partial m^*}{\partial \beta}\begin{cases}\geq 0 & \text{when } 0<\beta\leq\beta^*\,,\\ <0 & \text{when } \beta^*<\beta<1\,.\end{cases} \tag{4.38}$$

$$\frac{\partial m^*}{\partial \epsilon}=\frac{1+\beta\sigma\delta\mu\rho_{kh}}{A\beta(1-\beta)(\mu\delta)^2}>0\,, \tag{4.39}$$

$$\text{with } \mu^*=\frac{2(1-\epsilon)}{\phi A\beta(1-\beta)\delta^2-(1-\epsilon)\rho_{kh}\beta\sigma\delta}\,,\ \text{when } \phi>\frac{(1-\epsilon)\rho_{kh}\sigma}{A(1-\beta)\delta}\,, \tag{4.40}$$

$$\text{and } \beta^*=\frac{1}{1+\sqrt{1-a}}\,,\ \text{when } a:=-\rho_{kh}\mu\sigma\delta\in(-\infty,1)\,. \tag{4.41}$$

It is worth to note that when $\phi\leq\dfrac{(1-\epsilon)\rho_{kh}\sigma}{A(1-\beta)\delta}\Leftrightarrow\mu^*\leq 0$, hence only the second case of Eq.(4.37) holds, i.e. $\dfrac{\partial m^*}{\partial\mu}<0$. Moreover, when $a\geq 1$, the first case of Eq.(4.38) holds, i.e. $\dfrac{\partial m^*}{\partial\beta}\geq 0$. □

The economic implications behind property (i) are straightforward. A higher level of TPF implies more production, thus more emissions and pollutants. Therefore, both a higher level of TPF and emission intensity of output worsen the detrimental impact of production-induced emission on health, which requires tighten mitigation policy to offset the deteriorating effect. Intuitively, a greater sensitivity of health to pollutants implies a higher environmental impact on health, thus larger abatement is needed to hedge this risk. Properties (ii) and (iii) reveal that the sign of the correlation may amplify or offset the detrimental impact. Specifically, a negative correlation means that an increasing positive fluctuation on capital leads more production and emission, thus accelerates health degradation, which requires more abatement(i.e. "production" effect). In case of positive correlation, we observe that labours' health degradation reduces labour productivity, and hence slows down production (i.e. "health" effect). Whether it is a negative or positive correlation depends on the trade-off between precautionary saving and consumption under uncertainty, which is explained detailedly in previous subsection. Property (iv) reveals the ambiguous relationship between abatement faction and the related efficiency. The first term of m^*, defined in Eq.(4.27), tends to decrease when abatement efficiency increases, implying a negative effect of abatement efficiency on mitigation policy. Meanwhile, the second term will decrease as well, because of an increased abatement efficiency offsetting detrimental impact of fluctuation on health. Our calibration in next subsection shows that the decrease in first term dominates the second except when the technology is relatively slow. An alternative illustration could be straightforward but more intuitive: when efficiency of abatement technology is low, both abatement efficiency and abatement policy need to be strengthened in order to dampen health degradation until a certain level of abatement efficiency is reached. Afterwards, less abatement fraction is possible when the efficiency of abatement technology further improves. Property (v) shows two opposite effects of health parameter β on the optimal abatement policy. Indeed, based on individual's welfare function defined in Eq.(4.5), a larger health parameter β indicates a larger weight of health relative to consumption in utility function (i.e. "weight" effect). Hence, a larger abatement fraction is preferred to offset health fluctuation. Meanwhile, $1-\beta$, indicating measurement of risk aversion with respect to health, will decrease when β increases (i.e. "risk effect"). Therefore, individual becomes less risk aversion towards health, implying less sensitive to health fluctuation, and thus requires smaller abatement fraction. There is a trade-off between these two effects. Specifically, the "weight effect" will dominate (or dominated by) the "risk effect" when β is small (or larger, respectively). Property (vi) is quite intuitive: a larger measure of risk aversion will lead a tight mitigation policy. Furthermore, let us show the effects of parameters on optimal economic growth rate in **Proposition 4.2.3**.

Proposition 4.2.3. *When the evolution of the economy's capital stock and health are affected by pollution-induced uncertainties (via a Wiener process), the optimal economic growth rate, denoted by g^*, is constant over time, and is a function of model's parameters with following properties:*

(i) g^* increases when either the function of the total factor productivity (TPF) increases, or pollution intensity of output decreases, or the sensitivity of the health to pollution decreases.

(ii) When multiple fluctuations are considered, the optimal mitigation policy may tighten or loose, depending on negative or positive correlation.

(iii) The correlation coefficient between different fluctuations has negative impact on the mitigation policy.

(iv) g^* either decreases or increases when the abatement efficiency improves, depending on the threshold level of abatement technology.

(v) *g^* either decreases or increases when the the elasticity of marginal utility of health improves, depending on the threshold value of health parameter.*

Proof. Given the optimal economic growth rate g^* in Eq.(4.29), the above properties can be derived straightforward through partial derivatives respect to the related parameters as follows:

$$\frac{\partial g^*}{\partial A} = \frac{1}{\epsilon}\Big(1 - \frac{\phi}{\mu}\Big) > 0\,, \tag{4.42}$$

$$\frac{\partial g^*}{\partial \phi} = -\frac{1}{\epsilon}\frac{A}{\mu} < 0\,, \tag{4.43}$$

$$\frac{\partial g^*}{\partial \delta} = -\frac{(1-\epsilon)\big(1+\beta\rho_{kh}\mu\delta\sigma\big)+\epsilon(1-\epsilon)}{\epsilon\beta(1-\beta)\mu^2\delta^3} < 0\,, \tag{4.44}$$

$$\frac{\partial g^*}{\partial \sigma}\begin{cases} < 0 & \text{if} \begin{cases} -1 \le \rho_{kh} \le 0 \\ \{0 \le \rho_{kh} < \rho^*_{kh}\} \cap \{\sigma > \sigma^*\} \end{cases} \\ = 0 & \text{if} \quad \{0 \le \rho_{kh} < \rho^*_{kh}\} \cap \{\sigma = \sigma^*\} \\ > 0 & \text{if} \begin{cases} \{\rho^*_{kh} \le \rho_{kh} \le 1\} \cap \{0 \le \rho^*_{kh} < 1\} \\ \{0 \le \rho_{kh} < \rho^*_{kh}\} \cap \{\sigma < \sigma^*\} \end{cases} \end{cases} \tag{4.45}$$

$$\frac{\partial g^*}{\partial \rho_{k,h}} = \frac{(1-\epsilon)\sigma\big[(1-\epsilon)\big(1+\beta\rho_{kh}\mu\delta\sigma\big)+\epsilon\big]}{\epsilon(1-\beta)\delta} > 0\,, \tag{4.46}$$

$$\text{with } \rho^*_{kh} = \sqrt{\frac{(1-\beta)\epsilon}{\beta(1-\epsilon)}}\,,\ \sigma^* = \frac{\rho_{kh}/\big(\epsilon(1-\beta)\mu\delta\big)}{1-\big(\rho_{kh}/\rho^*_{kh}\big)^2} \tag{4.47}$$

$$\frac{\partial g^*}{\partial \mu}\begin{cases} > 0 & \text{when } \mu > \mu^* \\ \le 0 & \text{when } \mu \le \mu^* \end{cases} \tag{4.48}$$

$$\text{with } \mu^* = \frac{1-\epsilon^2}{A\phi\beta(1-\beta)\eta^2 - (1-\epsilon)\beta\rho_{kh}\delta\sigma}\,, \tag{4.49}$$

$$\frac{\partial g^*}{\partial \beta}\begin{cases} \le 0 & \text{if} \begin{cases} 0 \le \rho_{kh} \le 1 \\ \{-1 \le \rho_{kh} < 0\} \cap \{0 < \beta < \beta^*\} \end{cases} \\ > 0 & \text{if} \quad \{-1 \le \rho_{kh} < 0\} \cap \{\beta^* < \beta < 1\} \end{cases} \tag{4.50}$$

with

$$\beta^* = \begin{cases} 1/\Bigg(1+\sqrt{\dfrac{2(1+\rho_{kh}\mu\delta\sigma)(2+\rho_{kh}\mu\delta\sigma)}{1-\epsilon^2}}\Bigg) & \text{if}\,\{-1 \le \rho_{kh} < \frac{-2}{-\mu\delta\sigma}\} \cup \{\frac{-1}{\mu\delta\sigma} < \rho_{kh} < 0\} \\ 1 & \text{if}\,\{\frac{-2}{-\mu\delta\sigma} \le \rho_{kh} \le \frac{-1}{-\mu\delta\sigma}\}\,. \end{cases}$$

Eqs.(4.42) to (4.44) are the proofs of property (i). It can be illustrated by the first term of the expected growth rate in Eq.(4.29), where uncertainty effect is not considered. Obviously, a higher level of TFP implies more production, thus promotes growth. Higher emission intensity and greater sensitivity of health to pollutants imply tight abatement fraction, thus slows down economic growth. Eqs.(4.45) to (4.50) are corresponding proofs to properties (ii) to (v). The associated arguments are similar to **Proposition 4.2.2**, but with contrary conclusions because we have $m^* > m_g^*$, thus $\partial g^*/\partial m^* < 0$ (see in **Proposition 4.2.1**). □

4.2.3 Numerical Analysis of the Economy under Health and Environmental Shocks

In our benchmark calibration, we choose the total factor productivity (TFP), denoted A, emission intensity, denoted ϕ, and abatement efficiency, denoted σ, equal to 5%, 0.4‰ and 8% respectively[3]. It is worth to remark that $\phi = 0.4‰$ stands for a CO_2 emission of 0.4‰ tons (0.4 kg) per unit of GDP in U.S. dollar for the world average during 2011-2015. $\mu = 8\%$ corresponds to 12.5 U.S. dollar per ton coal burned (or CO_2 emission). For comparative study, we also set both a larger TFP (e.g. $A = 7\%$) from an optimistic point of view, and a smaller TFP ($A = 2.1\%$) for some relatively slower growth economy. We adopt a higher emission intensity, $\phi = 2.1‰$ for high CO_2 emission countries, e.g. China. Also, $\mu = 5\%$ is considered in case of the technology development slows down. We set the value of health parameter $\beta = 0.5$, according to Pautrel (2012) for the benchmark calibration, and study the sensitivity of the change of health parameter on mitigation policy and economic growth rate. In order to guarantee the concavity of utility to health, we require the elasticity of marginal utility to consumption ϵ within 0 and 1, and choose benchmark value of $\epsilon = 0.9$ (e.g. India), and $\epsilon = 0.44$ (e.g. Japan) as comparative analysis, according to Gandelman and Hernández-Murillo (2014). In addition, we choose time discount rate equal to 1.5% per year according to Nordhaus (2008). Parameters σ, δ and ρ_{kh} , measuring the sensitivity of the capital and health to fluctuations, and their correlation, are crucial in determining uncertainty effect on mitigation policy and economic growth rate. We investigate their impacts on economic activity for calibration in both table and graphical presenting. The benchmark values of the parameters are summarized in

[3]based on the World Bank series 2016 "CO_2 emissions per GDP" and empirical studies by Hood (2011), McKinsey (2009), and Bretschger and Vinogradova (2014).

Table 4.1:

A	the total factor productivity	5%
ϕ	output emission intensity	0.04%
μ	abatement efficiency	0.08
ρ	time discount rate	0.015
δ	health sensitivity to fluctuation	$1.7 \cdot 10^3$
σ	capital sensitivity to fluctuation	0.001
β	health parameter	0.5
ϵ	elasticity of marginal utility	0.9

Table 4.1 – *Parameters values for the numerical example*

Under the benchmark calibration described above, we obtain the optimal share of output for abatement m^* equal to 0.4582%, and the economic growth rate equal to 3.86333%. Our value of m^* is slightly higher than 0.42% in Nordhaus (2008), who calculated the carbon tax as 30 U.S.dollar per ton coal at a yearly global output of 70 trillion U.S.dollar in 2010. The difference is due to the factor of health fluctuation.

The emission concentration per unit of capital q_t is defined in Eq.(4.4), implying $0 \leq q_t \leq \phi A = 0.4 \cdot 10^{-3} \times 0.05 = 2 \cdot 10^{-5}$. Given the parameter defined in Table 4.1, we present the relationship between Arrow-Pett measure of relative risk aversion and the optimal emission concentration per unit of capital q^*, given in in Table 4.2.

CRRA parameter ϵ	Optimal Emissions q^* (10^{-5})	Optimal abatement m^* (10^{-3})
1	0	5
0.9	0.167	4.582
0.5	0.836	2.911
0.1	1.504	1.240

Table 4.2 – *The effect of CRRA measurement ϵ on optimal emission concentration per unit of capital q^* and fraction of output for abatment m^*.*

Table 4.3 and Table 4.4 show the influences of model parameters on mitigation policy and economic growth rate for a benchmark measure of relative risk aversion $\epsilon = 0.9$. In addition, we consider various values of correlation coefficient. The dynamics of the parameters are shown in the following figures. We find empirical evidence to Propositions (2.2) and (2.3) where parameters of diffusion terms significantly impact both mitigation policy and economic growth.

Parameters	Optimal Mitigation Policy and Growth Rate		
	$q^*(10^{-6})$	$m^*(‰)$	$g^*(\%)$
$A^H = 7\%$	1.671	4.702	6.0744
$A^L = 5\%$	1.671	4.582	3.8633
$\phi^H = 2.1‰$	1.671	25.832	3.7453
$\phi^L = 0.4‰$	1.671	4.582	3.8633
$\delta^H = 1.7 \cdot 10^4$	0.0114	4.997	3.8611
$\delta^L = 1.7 \cdot 10^3$	1.671	4.582	3.8633
$\sigma^H = 1\%$	1.142	4.715	3.8621
$\sigma^L = 0.1\%$	1.671	4.582	3.8633
$\rho_{kh}^H = 1$	1.848	4.538	3.8636
$\rho_{kh}^{NH} = 0.5$	1.789	4.553	3.8635
$\rho_{kh}^{NH} = 0$	1.730	4.567	3.8634
$\rho_{kh}^L = -0.5$	1.671	4.582	3.8633
$\rho_{kh}^{NL} = -1$	1.612	4.597	3.8632
$\beta^H = 0.9$	4.512	3.872	3.8679
$\beta^M = 0.5$	1.671	4.582	3.8635
$\beta^L = 0.1$	4.773	3.807	3.8675
$\mu^H = 0.08$	1.671	4.582	3.8633
$\mu^L = 0.05$	2.709	6.916	3.8502

TABLE 4.3 – *The optimal emission concentration, mitigation fraction, and grwoth rate when* $\epsilon = 0.9\,, \rho_{kh} < 0$.

Table 4.5 presents a specific case when the measure of relative risk aversion is relatively small, $\epsilon = 0.44$ (e.g. Japan). In this scenario, we observe that policy and economic activity are more sensitive to the parameters of diffusion terms who characterize uncertainty effect. Our calibration highlights that the interdependent uncertainty effects in both health and capital dy-

Parameters	Optimal Mitigation Policy and Growth Rate		
	$q^*(10^{-6})$	$m^*‰$	$g^*\%$
$A^H = 7\%$	1.789	4.768	6.0746
$A^L = 5\%$	1.789	4.553	3.8635
$\phi^H = 2.1‰$	1.789	25.925	3.7454
$\phi^L = 0.4‰$	1.789	4.553	3.8635
$\delta^H = 2.0 \cdot 10^3$	1.30	4.675	3.8628
$\delta^L = 1.7 \cdot 10^3$	1.789	4.553	3.8635
$\sigma^H = 1\%$	2.31	4.420	3.8637
$\sigma^L = 0.1\%$	1.789	4.553	3.8635
$\rho_{kh}^H = 1$	1.848	4.538	3.8636
$\rho_{kh}^L = 0.5$	1.789	4.553	3.8635
$\rho_{kh}^{NH} = 0$	1.730	4.567	3.8634
$\rho_{kh}^{NH} = -0.5$	1.671	4.582	3.8633
$\rho_{kh}^{NL} = -1$	1.612	4.597	3.8632
$\beta^H = 0.9$	4.02	3.725	3.8679
$\beta^M = 0.5$	1.848	4.553	3.8635
$\beta^L = 0.1$	2.90	3.790	3.8675
$\mu^H = 0.08$	1.848	4.553	3.8635
$\mu^L = 0.05$	2.827	6.869	3.8504

Table 4.4 – *The optimal emission concentration, mitigation fraction, and grwoth rate when* $\epsilon = 0.9\,, \rho_{kh} > 0$.

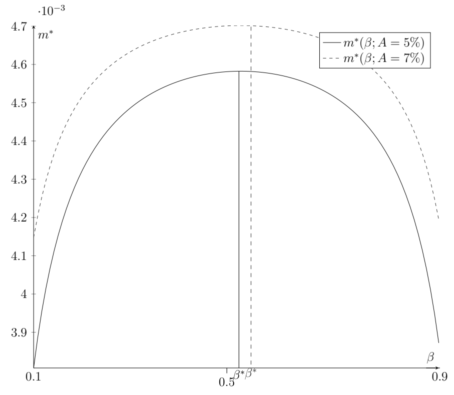
namics should be taken into consideration for policy maker. Moreover, our numerical results on emission mitigation and abatement policy is comparable to the empirical study of ENERDATA (2014). ENERDATA reports that, to maintain the global temperature rising below 2°C, a GHGs target of 50% domestic reduction in CO_2 emission by 2030 costs EU at 0.6% of GDP in 2030. Furthermore, it is worth to highlight that the GHGs emissions reduction target will reduce reliance on imported energy sources (e.g. fossil fuels) which could cut down EU health costs on respiratory illness by an average of 0.1% of GDP in 2030 under the mean value of health impacts. The average world GDP growth rate in last 50 years (1961-2015) is 3.8% [4].

We graphically present the effect of model's parameter on the optimal mitigation policy and growth rate in Fig.(4.1) and Fig.(4.2).

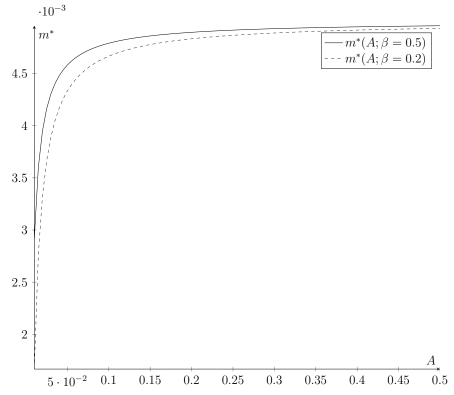
Parameters	Optimal Mitigation Policy and Growth Rate		
	$q^*(10^{-5})$	m^*‰	g^*%
$\delta^H = 1.7 \cdot 10^4$	0.0102	5.016	1.33986
$\delta^L = 1.7 \cdot 10^3$	1.517	4.343	1.35864
$\sigma^H = 1\%$	1.023	4.551	1.34832
$\sigma^L = 0.1\%$	1.497	4.343	1.35864
$\rho_{kh}^H = 1$	1.656	4.274	1.36147
$\rho_{kh}^{NH} = 0.5$	1.603	4.297	1.36051
$\rho_{kh}^{NH} = 0$	1.550	4.567	1.35959
$\rho_{kh}^L = -0.5$	1.497	4.343	1.35864
$\rho_{kh}^{NL} = -1$	1.445	4.367	1.35773
$\beta^H = 0.9$	4.043	3.228	1.39019
$\beta^M = 0.5$	1.497	4.343	1.35864
$\beta^L = 0.1$	4.277	3.125	1.39427

TABLE 4.5 – *The optimal emission concentration, mitigation fraction, and grwoth rate in some developped countries (e.g. Japan), when* $\epsilon = 0.44, A = 2.1\%, \phi = 0.04\%, \delta = 1700, \mu = 0.08, \delta = 0.001, \rho_{kh} = -0.5$.

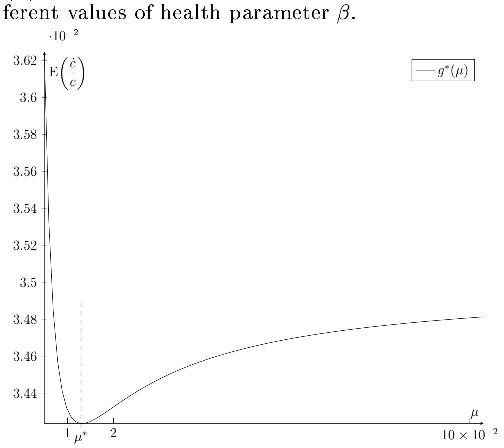
[4]Based on Source: Global Growth Tracker The World Economy: 50 Years of Near Continuous Growth, editor: Dariana Tani, March 2016.



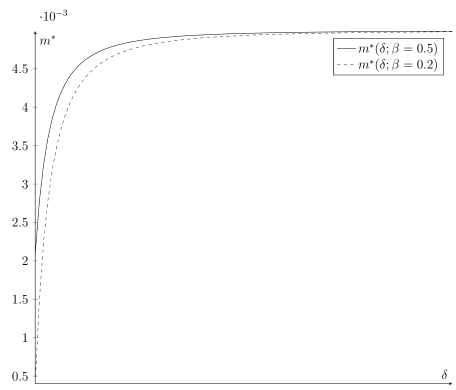
(a) The optimal mitigation policy m^* for different values of health parameter β.



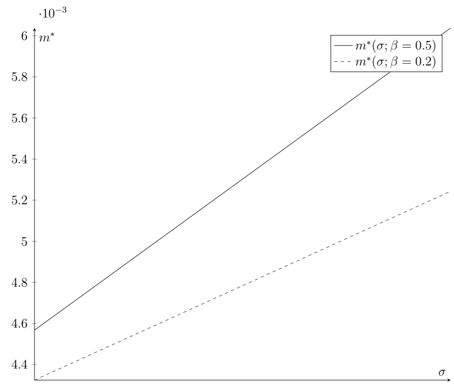
(b) The optimal mitigation policy m^* for different values of TFP, A.



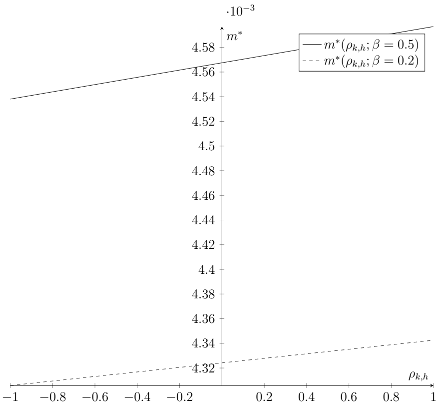
(c) The optimal growth rate g^* for different values of the efficiency of abatement μ.



(d) The optimal mitigation policy m^* for different values of the sensitivity of the health status to pollution δ.

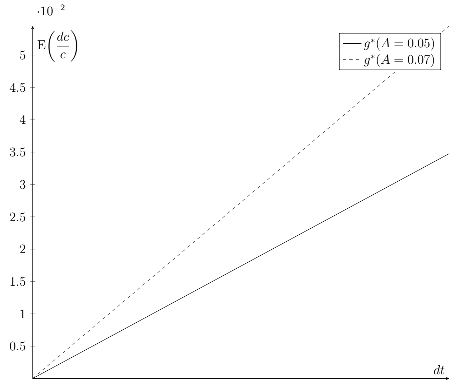


(e) The optimal mitigation policy m^* for different values of the (percentage) voatility parameter of captial σ.

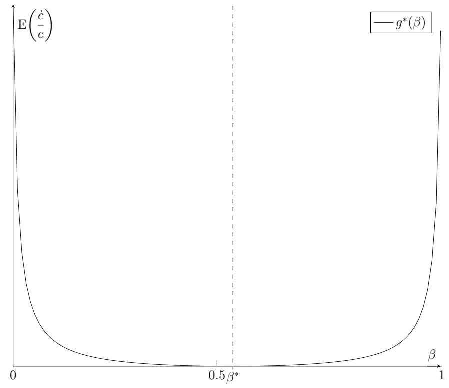


(f) The optimal mitigation policy m^* for different values of the correlation coefficient ρ_{kh}.

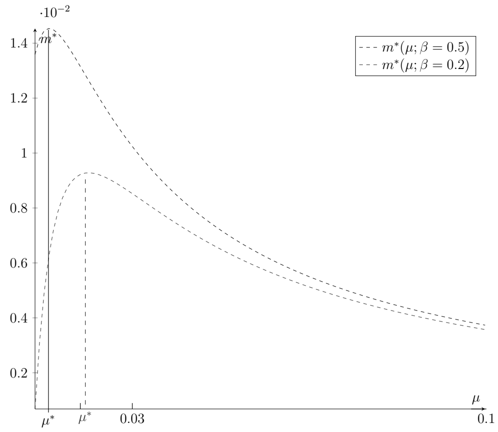
Figure 4.1 – The effect of model's parameters on the optimal mitigation policy m^*.



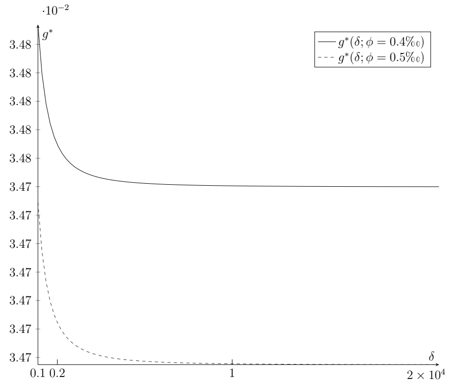
(a) The optimal growth rate g^* for different values of TFP, A over time.



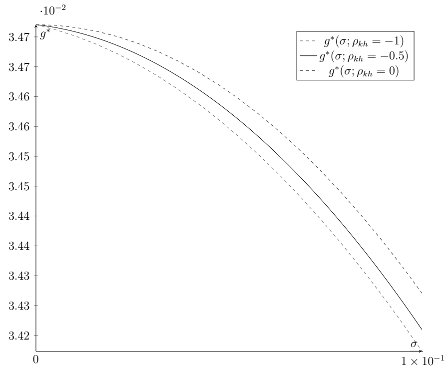
(b) The optimal growth rate g^* for different values of health parameter β.



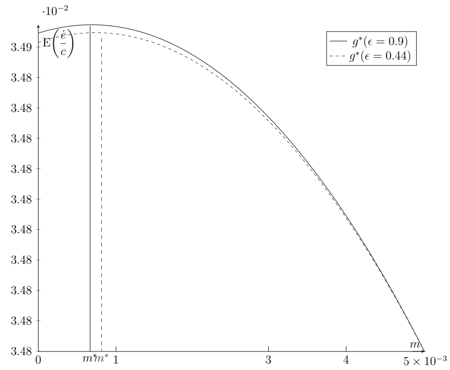
(c) The optimal mitigation policy m^* for different values of the efficiency of abatement μ.



(d) The optimal growth rate g^* for different values of the sensitivity parameter of health stautus to pollution δ.



(e) The optimal growth rate g^* for different values of the volatility parameter of captial σ and correlation coefficient ρ_{kh}.



(f) The optimal growth rate g^* for different values of the mitigation policy m.

Figure 4.2 – The effect of model parameters on economic growth rate g^*.

4.3 Conclusion

This essay investigates a sustainable endogenous growth economy, where the detrimental impact of pollutant on health is taken into account, and the policy maker has to decide optimal policy to mitigate pollutants and emissions from health enhancing perspective. Our objective is to propose a dynamic system to allow policy maker to take into account of economic growth, GHGs emissions, pollutants, and their detrimental impact on human health. We present the endogenous growth model under Wiener uncertainty. This model can be seen as a generalized model of Bretschger and Vinogradova (2016), and the benchmark model for intertemporal decision making à la Ramsey, where uncertainty exists not only in human health but also capital stock. The model is analytically tractable. We provide clear-cut closed-form solutions of optimal growth rate and the appealing first-best policy. We particularly focus on the environmental policy which, acting as a powerful tool, benefits individuals health status while eliminates negative externalities of economic growth. It demonstrates that the relationship between mitigation policy and economic growth rate is inverted-U shaped. The fact that using a share of output to mitigate environmental degradation decreases both consumption and capital accumulation. Thus mitigation policy has a so-called "slow-down effect" on economy activity. Meanwhile, reducing the stock of emission, the mitigation policy benefits individuals' health and welfare by eliminating the fluctuation on health regeneration (i.e."uncertainty effect"). Thus, a tighter mitigation policy is more likely to stimulate economic growth when health is highly pollution-sensitive, and the efficiency of abatement technology is high. Moreover, when the correlations between different stochastic diffusions in both capital and health dynamics are considered, the optimal fraction of output for abatement may increase or decrease, depending on the sign of correlation coefficients. This essay also demonstrates the striking effects of health and environmental parameters on mitigation policy and economic growth, which are detailedly discussed in Propositions (2.2) and (2.3).

We conduct a numerical analysis of four different scenarios based on different measures of relative risk aversion, the direction of correlation between fluctuations, and various scales of uncertainty. In fact, our calibration provides empirical insights that the introduction of both health and capital uncertainties is indeed important. Specifically, the correlation coefficient between two stochastic processes in capital and health dynamics entails the indirect effect of labours' health degradation on production. Recalling in AK economy where population size is unitized to one, health status does not enter directly into the production function. Moreover, we find that, in case of small fluctuation, the associated correlation between capital and health uncertainty may strengthen or offset this detrimental effect, depending on the sign of correlation coefficient.

Our numerical calibration shows some quantitative implications to the recent data on global CO_2 emission per GDP, total factor of productivity, subjective discounting rate, price of carbon taxation, and the associated damages. Some parameters concerning pollutant-induced health fluctuation and capital sensitivity to uncertainty are chosen intuitively inspired from various strands of literature. In order to explore the influence of key parameters on policy and economic activity, we study several scenarios associated to various representative values of parameters. In addition, we plot the dynamic of the policy and economic growth as the parameters varying. We find that the mitigation policy (or the fraction of output as abatement) should be 0.46%, indicating 33 U.S.dollar per ton coal when elasticity of marginal utility is 0.9. This number is slightly higher but comparable to 0.42% in Nordhause (2008). The difference is due to the effect of health fluctuation. The emission defined in our model includes not only the GHGs, but also other pollutants harmful to human health. The detrimental impact of emission on health will lead tighten emission policy and thus higher abatement technology cost. Also, according to ENERDATA (2014), nearly 0.5% of GDP will be used to reach the target of keeping the global temperature below 2°C. It is worth to note that the abatement cost is very sensitive to fuel efficiency (Ekins et al., 2011), when we set a less optimistic value of abatement technology improvement, $\mu = 0.05$. The optimal abatement fraction dramatically increases to 0.69%, implying a relatively higher carbon price equal to 50 U.S.dollar per ton coal, which is close to 56 U.S.dollar per ton coal calculated by Golosov et al. (2014) using a DSGE framework.

5 Health Shock and Stochastic Growth Under the Threat of Catastrophe

5.1 Introduction

Production-induced CO_2 and other greenhouse gases (GHGs) emissions entail unfavourable climate change worldwide: global warming, higher sea level, and intensified occurrence frequency of nature disasters, which significantly harms human life and causes tremendous economic losses. On 26 December, 2004, Indian Ocean earthquake and tsunami affected 10 countries, resulting in more than 2.2 million deaths and enormous economic losses. Take Indonesia for example, economic losses account 4,451 million U.S. dollar[1], which equals to 1.73% of its overall annual GDP and 30.35% of GDP growth rate. For Thailand, economic losses account 2,198 million U.S. dollar[2], which equals to 1.36% of its overall annual GDP and 29.56% GDP growth rate. On 27 February, 2010, the Chile earthquake affected 82% of the country's population. A preliminary report[3] estimates the value of total infrastructure losses at 30 billion U.S. dollar. Based on our observations of numerous destructive earthquakes, we estimate that losses may double once the building contents, commercial and industrial business interruptions are taken into account.[4] The Global Catastrophe Recap (2015) reports that the expected economic losses in 2015 Nepal earthquake reaches and pos-

[1] Asian Disaster Preparedness Center 2004. Available online: http://cmsdata.iucn.org/downloads/social_and_economic_impact_of_december_2004_tsunami_apdc.pdf

[2] Asian Disaster Preparedness Center 2004. Available online: http://cmsdata.iucn.org/downloads/social_and_economic_impact_of_december_2004_tsunami_apdc.pdf

[3] Based on the MercoPress, 18 March 2010. Retrieved from http://en.mercopress.com/2010/03/18/chile-s-quake-death-toll-700-and-economic-damage-18-of-gdp

[4] Based on the World Bank report, 27 February 2010. Retrieved from http:// documents.worldbank.org/curated/en750511468217448787/pdf/701380ESW0P12100WB0Report0final01EN.pdf

sibly exceeds 5 billion U.S. dollar[5], which is a quarter of the country's GDP.

In this essay, we consider a generalized version of stochastic dynamic model illustrated in previous chapter. This model is composed by a two dimensional stochastic processes: capital accumulation and health regeneration, explained by two types of randomness i.e. small-scale continuous fluctuations occurring more frequently, and large-scale catastrophic shocks less frequently. The small-scale capital and health diffusions are driven by two correlated Winer processes. While the catastrophic shock are driven by Poisson process. Here we extend our model by analysing the expected growth rate under catastrophic shocks. We provide close-form solutions of the optimal mitigation policy and expected growth rate. The impact of parameters on economic variables are detailedly discussed with clear-cut implication for environmental policy.

5.1.1 Outline of the Results

Our objective is to propose a dynamic system that allows social planner to make decisions by considering economic growth, pollutants, GHGs emissions, extreme events and their detrimental impact on human health. The particularity of our model is the introduction of correlations between uncertainties in capital and health dynamics. The economy is affected by two types of uncertainties: small fluctuation and catastrophic shocks which are assumes to follow Wiener and Poisson processes, respectively. We provide clear-cut analytically tractable solution of optimal growth rate and the appealing first-best mitigation policy.

In numerical experiment, we show that the optimal abatement policy reacts sensitively not only to the variations in conventional economic parameters, like emission intensity, efficiency of abatement technology, and TFP, but also to the health parameter and uncertainty parameters. When catastrophic shock is taken into account, the optimal abatement fraction will increase, i.e. $m^* = 1.4\%$, indicating a carbon taxation of 103 U.S. dollar per ton coal in benchmark model, and $m^* = 0.8\%$ if the development of the abatement technology is viewed in an optimistic way. The latter number is identical to Golosov et al. (2014). Our calculation suggests a higher carbon tax when the catastrophic shocks in health and capital are taken

[5] Aon Benfield Analytics - Impact Forecasting, April 2015. Retrieved from http://thoughtleadership.aonbenfield.com/Documents/20150507-if-april-global-recap.pdf

into account.

The rest of the essay is organized as follows. Section 2 introduces the model. Section 3 presents analytical treatment and derives closed-form optimal solutions. Section 4 is an analytical discussion of appealing economic properties. Section 5 presents the numerical calibration to show the effects of model parameters on mitigation policy and growth rate. Section 6 is the conclusion.

5.2 Health Shock and Stochastic Growth Under the Threat of Catastrophe

5.2.1 The Model

Besides pollution, production emissions cause deterioration of the natural environment and severe global warming, leading to a random occurrence of catastrophic disaster. In this section, we extend the model of previous chapter to include the possibility of two kinds of sudden shocks to the health and capital. The first shock is nature catastrophe, such as hurricane, earthquake and nuclear leak, which seriously hit both production and human health. The second shock is epidemic due to negative production externalities, which impacts only in the health regeneration process.

Let us assume that nature catastrophe and epidemic follow two independent Poisson processes, with increment $dN_{c,t}$ and $dN_{e,t}$, and with intensity λ_c and λ_e respectively. Catastrophe shock causes damages both to production level ξ percent and health level $D_c(q_t)$ percent. Epidemic shock causes damage to health level $D_e(q_t)$ percent. The stochastic process for production and health then becomes the following:

$$dk_t = \big[(1-m_t)y_t - c_t\big]dt + \sigma k_t dZ_{k,t} - \xi K dN_{c,t}\,,\ K(0) = K_0 \text{ given.} \quad (5.1)$$

$$dh(t) = R(q_t)h_t dZ_{h,t} - D_c(q_t)h_t dN_{c,t} - D_e(q_t)h_t dN_{e,t}\,, \qquad \alpha = \frac{1}{2}, 1 \quad (5.2)$$

$$E(dN_{c,t}dN_{e,t}) = 0\,. \quad (5.3)$$

where $dZ_{k,t}$ and $dZ_{h,t}$ are correlated standard Wiener processes defined in previous chapter. $dN_{c,t}$ and $dN_{e,t}$ are independent Poisson processes with

$$dN_{i,t} = \begin{cases} 1: & \text{probability}\lambda_i dt \\ 0: & \text{probability}1-\lambda_i dt \end{cases}, \quad i = \{c, e\}$$

Therefore, we have two following remarkable results: $\mathrm{E}\left(dN_{c,t}\right)=\lambda_c dt$ and $\mathrm{E}\left(dN_{e,t}\right)=\lambda_e dt$. D_c and D_e represent capital destruction and health damage (or morality rate) during catastrophic shocks, where the subscript "c" and "e" stand for "nature disaster" and "epidemic" respectively.

5.2.2 The Dynamics of the Economy

We define $V(k,h)$ as the value function associated with the optimal control problem in Eq.(4.8) and Eqs.(5.1) to (5.3). Applying Ito's lemma with Jumps, we obtain the Hamilton-Jacobi-Bellman (HJB) equation as follows:

$$\rho V(k,h)=\max_{c,m}\Big\{U(c,h)+V_k\big[(1-m)y-c\big]+\frac{1}{2}\Big[V_{kk}\sigma^2k^2+V_{hh}R^2(q)h^2+ 2\rho_{k,h}V_{kh}\sigma kR(q)h\Big]+\lambda_c\Big[\Big(V^{\tilde{k}}-V\Big)+\Big(V^{\tilde{h}}-V\Big)\Big]+\lambda_e\Big(V^{\tilde{\tilde{h}}}-V\Big)\Big\}. \tag{5.4}$$

For detailed analytical treatment, please refer to Appendix B. Let us simplify the following notations: $V^{\tilde{k}}=V(\tilde{k},h)$, $V^{\tilde{h}}=V(k,\tilde{h})$ and $V^{\tilde{\tilde{h}}}=V(k,\tilde{\tilde{h}})$, where $\tilde{k}=k(1-\xi)$, $\tilde{h}=h\big[1-D_c(q)\big]$ and $\tilde{\tilde{h}}=h\big[1-D_e(q)\big]$. Hereby, we focus on the first order conditions (FOCs) as follows.

For consumption c :

$$\frac{\partial U(c,h)}{\partial c}-V_k(k,h)=0\,,\quad \text{i.e.}\, U_c=V_k \tag{5.5}$$

For mitigation and abatement policy m :

$$\frac{1}{\mu A}V_k\,y_t=-V_{hh}R(q)R'(q)h^2-V_{kh}\sigma R'(q)kh\rho_{kh} +\Big(\lambda_c\,V^{\tilde{h}}_{\tilde{h}}D'_c(q)+\lambda_e V^{\tilde{\tilde{h}}}_{\tilde{\tilde{h}}}D'_e(q)\Big)h \tag{5.6}$$

where $V^{\tilde{h}}_{\tilde{h}}:=\dfrac{\partial V^{\tilde{h}}}{\partial\tilde{h}}=\dfrac{\partial V(k,\tilde{h})}{\partial\tilde{h}}=V_h(k,h)\mid_{h=\tilde{h}}$

and $\tilde{V}^{\tilde{\tilde{h}}}_{\tilde{\tilde{h}}}:=\dfrac{\partial V(k,\tilde{\tilde{h}})}{\partial\tilde{\tilde{h}}}=V_h(k,h)\mid_{h=\tilde{\tilde{h}}}$.

For capital stock k :

$$\rho V_k=V_{kk}\big[(1-m)y-c\big]+V_k(1-m)A+\frac{1}{2}\Big[V_{kkk}\sigma^2k^2+2\sigma^2V_{kk}k+V_{hhk}R^2(q)h^2 +2\rho_{kh}\sigma V_{khk}R(q)hk+2\sigma\rho_{kh}V_{kh}R(q)h\Big]+\lambda_c\Big[\big(V^{\tilde{k}}_k-V_k\big)+\big(V^{\tilde{h}}_k-V_k\big)\Big]+\lambda_e\big(V^{\tilde{\tilde{h}}}_k-V_k\big) \tag{5.7}$$

For health status h :

$$\rho V_h = U_h + V_{kh}[(1-m)y - c] + \frac{1}{2}\Big[V_{kkh}\sigma^2 k^2 + V_{hhh}R^2(q)h^{2\alpha} + 2V_{hh}R^2(q)h^2$$
$$+2\sigma V_{khh}R(q)kh\rho_{kh} + 2\sigma V_{kh}R(q)k\rho_{kh}\Big] + \lambda_c\Big[\big(V_h^{\tilde{k}} - V_h\big) + \big(V_h^{\tilde{h}} - V_h\big)\Big] + \lambda_e\big(V_h^{\tilde{\tilde{h}}} - V_h\big) \quad (5.8)$$

Considering that fact that epidemic, caused by contagious diseases, lowers an average health status $\bar{h}$ of all individuals, we adopt the utility function in Bretschger and Vinogradova (2016) and generalize the previously defined utility with an average health term as follows:

$$U(c, h, h_a) = \frac{c^{1-\epsilon}}{1-\epsilon} h^{\beta}\bar{h}^{\gamma}\,, \quad \beta\,, \gamma\,, \epsilon \in [0, 1]\,. \quad (5.9)$$

Let us now consider an average health status $\bar{h}$ is proportional to h (i.e. $\bar{h} \sim h$), based on the fact that rising h of the representative household will increase $\bar{h}$ proportionally, and vice versa. Without loss of generality, we consider the utility function in the following form:

$$U(c, h) = \frac{c^{1-\epsilon}}{1-\epsilon} h^{\tilde{\beta}}\,, \quad \tilde{\beta} = \beta + \gamma\,, \quad \beta\,, \gamma\,, \epsilon \in [0, 1]. \quad (5.10)$$

The above utility function is designed under the inspiration of Lucas (1988). The associated properties of utility are similar to ones we discussed in previous chapter. From Eq.(5.5), we have:

$$U_c = V_k \Rightarrow c^* = c(k) = \tilde{x}\,k \quad (5.11)$$

where $\tilde{x}$ is constant function of the model's parameters. Therefore, we can show that the value function takes the following form:

$$V(k, h) = \frac{\big(\tilde{x}\,k\big)^{1-\epsilon}}{1-\epsilon} h^{\beta'} \quad (5.12)$$

Furthermore, substituting Eq.(5.12) into Eq.(5.6), we obtain an implicit solution for optimal emission concentration. In particular, we have the following property:

Proposition 5.2.1. *Assuming* $D_c(q) = \eta_c q_t$ *and* $D_e(q) = \eta_e q_t$*, where* $\eta_c\,, \eta_e > 0$ *and* $q \in [0, +\infty)$*. The implicit solution for the equilibrium emission concentration* $\tilde{q}^*$ *satisfies the following equation:*

$$\big(1-\epsilon\big)\big(1 + \tilde{\beta}\mu\sigma\delta\rho_{k\,h}\big) = \tilde{\beta}\mu\bigg\{\Big[\lambda_c\eta_c\big(1 - \eta_c\tilde{q}^*\big)^{\tilde{\beta}-1} + \lambda_e\eta_e\big(1 - \eta_e\tilde{q}^*\big)^{\tilde{\beta}-1}\Big]$$
$$+\big(1-\tilde{\beta}\big)\delta^2\tilde{q}^*\bigg\}. \quad (5.13)$$

Moreover, Eq.(5.13) exists unique solution $\tilde{q}^*$ if and only if

$$\big(1-\epsilon\big)\big(1+\tilde{\beta}\mu\sigma\delta\rho_{k\,h}\big)-\tilde{\beta}\mu\big(\lambda_c\eta_c+\lambda_e\eta_e\big)\geq 0 \tag{5.14}$$

Proof. Substituting Eq.(5.12) into optimality condition of mitigation policy in Eq.(5.6), we obtain Eq.(5.13).

- Existence
  Let us focus on the right-hand side (RHS) of Eq.(5.13), and define $F(\tilde{q}^*)=\tilde{\beta}\mu\Big\{\Big[\lambda_c\eta_c\big(1-\eta_c\tilde{q}^*\big)^{\tilde{\beta}-1}+\lambda_e\eta_e\big(1-\eta_e\tilde{q}^*\big)^{\tilde{\beta}-1}\Big]+\big(1-\tilde{\beta}\big)\delta^2\tilde{q}^*\Big\}$.
  Obviously, $F(\tilde{q}^*)$ is monotonically increasing with $\tilde{q}^*$, i.e. $\dfrac{\partial F(\tilde{q}^*)}{\partial\tilde{q}^*}>0$. Therefore, we have $F(\tilde{q}^*)\geq F(0)=\tilde{\beta}\mu\big(\lambda_c\eta_c+\lambda_e\eta_e\big)$, implying LHS=RHS in Eq.(5.13). Hence $\big(1-\epsilon\big)\big(1+\tilde{\beta}\mu\sigma\delta\rho_{k\,h}\big)\geq\tilde{\beta}\mu\big(\lambda_c\eta_c+\lambda_e\eta_e\big)$.

- Uniqueness
  For $\tilde{\beta}$, $\mu\neq 0$, let us re-order Eq.(5.13) as follows:

$$\frac{\big(1-\epsilon\big)\big(1+\tilde{\beta}\mu\sigma\delta\rho_{k\,h}\big)}{\tilde{\beta}\mu}-\big(1-\tilde{\beta}\big)\delta^2\tilde{q}^* =\lambda_c\eta_c\big(1-\eta_c\tilde{q}^*\big)^{\tilde{\beta}-1}+\lambda_e\eta_e\big(1-\eta_e\tilde{q}^*\big)^{\tilde{\beta}-1} \tag{5.15}$$

  Let us define LHS and RHS of Eq.(5.15) as

$$L(\tilde{q}^*)=\frac{\big(1-\epsilon\big)\big(1+\tilde{\beta}\mu\sigma\delta\rho_{k\,h}\big)}{\tilde{\beta}\mu}-\big(1-\tilde{\beta}\big)\delta^2\tilde{q}^*$$

  and

$$R(\tilde{q}^*)=\lambda_c\eta_c\big(1-\eta_c\tilde{q}^*\big)^{\tilde{\beta}-1}+\lambda_e\eta_e\big(1-\eta_e\tilde{q}^*\big)^{\tilde{\beta}-1}$$

  In order to avoid cumbersome algebra proof, we use a geometrical illustration instead:

Obviously, $L(\tilde{q}^*)$ is a linear monotonic decreasing function of $\tilde{q}^*$, and $R(\tilde{q}^*)$ is a power monotonic increasing function of $\tilde{q}^*$. The monotonicity guarantees the uniqueness once $L(\tilde{q}^*)\geq L(\tilde{q}^*)^{Min}$, which implies Eq.(5.14) holds. □

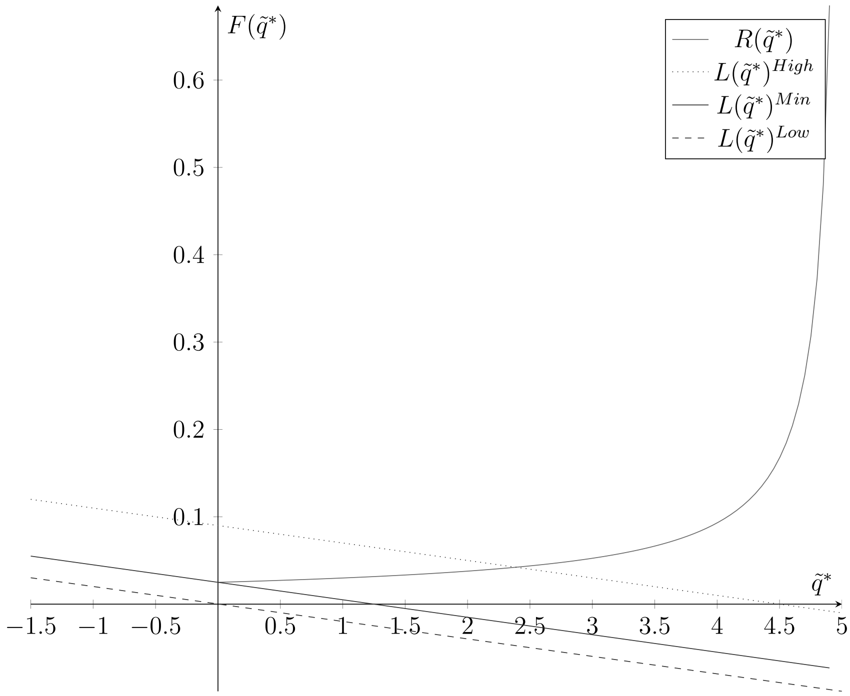


Figure 5.1 – The condition for solution existence and uniqueness

Although we prove the existence of the optimal emission concentration $\tilde{q}^*$, the closed-form solution of Eq.(5.13) is not obvious. We overcome this difficulty by linearising $\tilde{q}^*$ around original points using Taylor expansion. Therefore, for both nature catastrophe and epidemic shocks, we approximate $(1-\eta\,\tilde{q}^*)^{\tilde{\beta}-1}$, $\eta=\{\eta_c\,,\eta_e\}$ as follows:

$$\begin{aligned}(1-\eta\,\tilde{q}^*)^{\tilde{\beta}-1} &= 1+(-\eta)(\tilde{\beta}-1)(1-\eta\,\tilde{q}^*)^{\tilde{\beta}-1}\,|_{\tilde{q}^*=0}\,+o(\tilde{q}^*)\\ &\doteq 1+\eta(1-\tilde{\beta})\tilde{q}^*\,,\quad \eta=\{\eta_c\,,\eta_e\}\,. \end{aligned} \tag{5.16}$$

Substituting Eq.(5.16) into (5.13), we obtain optimal emission concentration:

$$\tilde{q}^* = \frac{\big(1-\epsilon\big)\big(1+\tilde{\beta}\mu\sigma\delta\rho_{k\,h}\big)-\tilde{\beta}\mu\big(\lambda_c\eta_c+\lambda_e\eta_e\big)}{\tilde{\beta}(1-\tilde{\beta})\mu\Big[\delta^2+\big(\lambda_c\eta_c+\lambda_e\eta_e\big)\Big]} \tag{5.17}$$

It is worth to highlight that $\tilde{q}^*<q^*$, since the denominator and nominator of $\tilde{q}^*$ in Eq.(5.17) are respectively larger and smaller than q^* in Eq.(4.28). This implies a lower optimal emission concentration rate when our model takes into account of catastrophic environmental shocks i.e. nature disaster

and epidemic. Substituting Eq.(5.17) into Eq.(4.4), we obtain the optimal abatement share as follows:

$$\tilde{m}^* = \frac{\phi}{\mu} - \frac{\tilde{q}^*}{\mu A} = \frac{\phi}{\mu} - \frac{\big(1-\epsilon\big)\big(1+\tilde{\beta}\mu\sigma\delta\rho_{kh}\big) - \tilde{\beta}\mu\big(\lambda_c\eta_c + \lambda_e\eta_e\big)}{\tilde{\beta}(1-\tilde{\beta})\mu^2 A\Big[\delta^2 + \big(\lambda_c\eta_c + \lambda_e\eta_e\big)\Big]} \tag{5.18}$$

Proposition 5.2.2. *The optimal abatement share $\tilde{m}^*$ is positively correlated with both the frequencies and the intensities of catastrophe i.e.* $\frac{\partial \tilde{m}^*}{\partial \lambda_c} > 0\,,\ \frac{\partial \tilde{m}^*}{\partial \eta_c} > 0\,,\ \frac{\partial \tilde{m}^*}{\partial \lambda_e} > 0\,,\ \frac{\partial \tilde{m}^*}{\partial \eta_e} > 0.$

Proof. The analytical calculation of derivatives is straightforward, however, we hereby consider an alternative convenient proof. From Eq.(5.17), we can easily observe that $\tilde{q}^*$ decreases as z increases, since an incremental of z leads an larger denominator and smaller nominator of $\tilde{q}^*$, where $z = \{\lambda_c\,, \eta_c\,, \lambda_e\,, \eta_e\}$. It implies $\frac{\partial \tilde{q}^*}{\partial z} < 0$. Therefore, $\frac{\partial \tilde{m}^*}{\partial z} > 0$ based on $\tilde{m^*} \sim \big(-\tilde{q}^*\big)$ in Eq.(5.18), where mathematical operation "$\sim$" stands for proportion. □

5.2.3 Optimal Growth Path

In this section, we focus on the optimal growth rate. Combining capital and health dynamics in Eqs.(5.1) and (5.2), and applying Ito's Lemma with jump to V_k, the optimality conditions of consumption defined in Eq.(4.16), we obtain the stochastic process of dV_k as follows:

$$\begin{aligned}\frac{dV_k}{V_k} &= \Bigg\{\rho - (1-m)A - \Big[\sigma^2\frac{V_{kk}}{V_k}k + \sigma\rho_{kh}\frac{V_{kh}}{V_k}R(q)h\Big] - \lambda_c\Bigg[\Bigg(\frac{V_k^{\tilde{k}}}{V_k} - 1\Bigg) + \Bigg(\frac{V_k^{\tilde{h}}}{V_k} - 1\Bigg)\Bigg] \\ &-\lambda_e\Bigg(\frac{V_k^{\tilde{\tilde{h}}}}{V_k} - 1\Bigg)\Bigg\}dt + \frac{V_{kk}}{V_k}\sigma k dZ_k + \frac{V_{kh}}{V_k}R(q)hdZ_h + \Bigg[\Bigg(\frac{V_k^{\tilde{k}}}{V_k} - 1\Bigg) + \Bigg(\frac{V_k^{\tilde{h}}}{V_k} - 1\Bigg)\Bigg]dN_{c,t} \\ &+\Bigg(\frac{V_k^{\tilde{\tilde{h}}}}{V_k} - 1\Bigg)dN_{e,t}\end{aligned} \tag{5.19}$$

Rewriting Eq.(5.10), we obtain $U_c(c,h) = c^{-\epsilon}h^{\tilde{\beta}}$. In other words, $c(U_c,h) = U_c^{-\frac{1}{\epsilon}}h^{\frac{\tilde{\beta}}{\epsilon}}$. From optimality consumption in Eq.(5.5), we have $c(U_c,h) = c(V_k,h) = V_k^{-\frac{1}{\epsilon}}h^{\frac{\tilde{\beta}}{\epsilon}}$. Applying Ito's lemma with Possion jump to $c(U_c,h)$, we obtain the expected optimal growth path of consumption as follows:

$$\tilde{g}^* := \mathrm{E}\Big(\frac{\dot{c}}{c}\Big) = \underbrace{\frac{1}{\epsilon}\Big\{\Big(1-\frac{\phi}{\mu}\Big)A - \rho + I_g}_{g^*} + \Gamma\Big\} \tag{5.20}$$

where g^* and I_g are defined in Eq.(4.29), which represent stochastic growth rate and uncertainty effect driven by the Wiener process respectively. $\Gamma = \lambda_c\Gamma_c(q) + \lambda_e\Gamma_e(q)$ represents the effect of catastrophic shocks by nature disaster and epidemic , driven by two independent Poisson processes. Specifically, we have:

$$\begin{aligned}\Gamma_c(q) = {} & \Big(\Big[\big(1-\xi\big)^{1-\epsilon} - 1\Big] + \Big[\big(1-D_c(q)\big)^{\tilde{\beta}} - 1\Big]\Big) + \epsilon\Big[\Big(1 + \Big[\big(1-\xi\big)^{-\epsilon} - 1\Big] + \\ & \Big[\big(1-D_c(q)\big)^{\tilde{\beta}} - 1\Big]\Big)^{-\frac{1}{\epsilon}} - 1\Big] + \epsilon\Big[\big(1-D_c(q)\big)^{\frac{\tilde{\beta}}{\epsilon}} - 1\Big] \end{aligned} \tag{5.21}$$

$$\Gamma_e(q) = \Big[\big(1-D_e(q)\big)^{\tilde{\beta}} - 1\Big] + \epsilon\Big[\big(1-D_e(q)\big)^{-\frac{\tilde{\beta}}{\epsilon}} - 1 + \big(1-D_e(q)\big)^{\frac{\tilde{\beta}}{\epsilon}} - 1\Big] \tag{5.22}$$

We are interested in the sign of Eqs.(5.21) and (5.22), specially for a small $q \ll 1$. We have when negative $\Gamma_e(q)$ when $q \ll 1$ (see detailed illustration in Appendix B). Therefore both the frequencies of nature disaster λ_c and epidemic λ_e place a direct negative effect on the growth rate $\tilde{g}^*$, since from Eq.(5.5) we have $\Gamma_c = \dfrac{\partial\tilde{g}^*}{\partial\lambda_c}$, $\Gamma_e = \dfrac{\partial\tilde{g}^*}{\partial\lambda_e}$.

In addition, a more convenient approach to illustrate our previous arguments and derive an analytical solution can be approximated through linearisation. Indeed, we can approximate Γ_c and Γ_e using a first-order Taylor expansion around $q = 0$ and $\xi = 0$ as follows:

$$\big(1-D_c(q)\big)^{\tilde{\beta}} \doteq 1 - \tilde{\beta}\eta_c q\,, \quad \text{where } D_c(q) = \eta_c q \tag{5.23}$$

$$\big(1-D_e(q)\big)^{\tilde{\beta}} \doteq 1 - \tilde{\beta}\eta_e q\,, \quad \text{where } D_e(q) = \eta_e q\,. \tag{5.24}$$

$$\big(1-\xi\big)^{1-\epsilon} \doteq 1 - (1-\epsilon)\xi\,. \tag{5.25}$$

Substituting Eqs.(5.23)-(5.25) into Eqs.(5.21) and (5.22) , we obtain analytically the following:

$$\Gamma_c(q) = -\xi - \tilde{\beta}\eta_c q < 0 \tag{5.26}$$

$$\Gamma_e(q) = -\tilde{\beta}\eta_e q < 0 \tag{5.27}$$

Thus we have overall catastrophic shock effect expressed as follows:

$$\begin{aligned}\Gamma &= \lambda_c \Gamma_c(q) + \lambda_e(q)\Gamma_e \\ &= -\xi\lambda_c - \big(\lambda_c\eta_c + \lambda_e\eta_e\big)\tilde{\beta} q \end{aligned} \tag{5.28}$$

Substituting Eqs.(5.17) and (5.28) into (5.20), we obtain constant catastrophe effect and growth rate in steady state:

$$\tilde{g}^* = g^* + \frac{1}{\epsilon}\Gamma\,, \tag{5.29}$$

$$\Gamma = -\xi\lambda_c - \big(\lambda_c\eta_c + \lambda_e\eta_e\big)\frac{(1-\epsilon)\big(1+\tilde{\beta}\mu\sigma\delta\rho_{kh}\big) - \tilde{\beta}\mu\big(\lambda_c\eta_c + \lambda_e\eta_e\big)}{(1-\tilde{\beta})\mu\Big[\delta^2 + \big(\lambda_c\eta_c + \lambda_e\eta_e\big)\Big]} \tag{5.30}$$

where g^*, defined in Eq.(4.29), stands for the optimal growth rate without catastrophic shock. Furthermore, the effects of the key parameters characterizing capital and health shocks are discussed below.

Proposition 5.2.3. *The catastrophic shock slows down the expected economic growth rate, i.e. $\tilde{g}^* < g^*$. Moreover, both the intensity and severity of catastrophic shocks on capital and health may have negative impact on economic growth (i.e. $\tilde{g}^* < g^*$ and $\frac{\partial \tilde{g}^*}{\partial \lambda_c} < 0\,,\ \frac{\partial \tilde{g}^*}{\partial \lambda_e} < 0\,,\ \frac{\partial \tilde{g}^*}{\partial \eta_c} < 0\,,\ \frac{\partial \tilde{g}^*}{\partial \eta_e} < 0$). Also, economic growth rate may recover or accelerate under certain conditions detailedly described as follows:*

$$\frac{\partial \tilde{g}^*}{\partial \lambda_c}\begin{cases} < 0 & \textit{when} \begin{cases} z \geq 0 & \textit{if } 0 < \tilde{\beta} \leq \xi/(\xi+\eta_c)\,, \\ 0 \leq z < \tilde{z}^* & \textit{if } \xi/(\xi+\eta_c) < \tilde{\beta} < 1 \end{cases}, \\ \geq 0 & \textit{when } z \geq \tilde{z}^*\,, \textit{if } \xi/(\xi+\eta_c) < \tilde{\beta} < 1\,. \end{cases} \tag{5.31}$$

$$\frac{\partial \tilde{g}^*}{\partial \eta_c}\begin{cases} < 0 & \textit{when } 0 \leq z < z^*\,, \\ \geq 0 & \textit{when } z \geq z^*\,. \end{cases} \tag{5.32}$$

$$\frac{\partial \tilde{g}^*}{\partial \lambda_e}\begin{cases} < 0 & \textit{when } 0 \leq z < z^*\,, \\ \geq 0 & \textit{when } z \geq z^*\,. \end{cases} \tag{5.33}$$

$$\frac{\partial \tilde{g}^*}{\partial \eta_e}\begin{cases} < 0 & \textit{when } 0 \leq z < z^*\,, \\ \geq 0 & \textit{when } z \geq z^*\,. \end{cases} \tag{5.34}$$

$$\textit{with } z^* = \left(\sqrt{1 + (1-\epsilon)(1+\tilde{\beta}\mu\sigma\delta\rho_{kh})/(\tilde{\beta}\mu\delta^2)} - 1\right)\delta^2 \tag{5.35}$$

$$\textit{and } \tilde{z}^* = \left(\sqrt{\frac{1 + (1-\epsilon)(1+\tilde{\beta}\mu\sigma\delta\rho_{kh})/(\tilde{\beta}\mu\delta^2)}{1 - \xi(1-\tilde{\beta})/(\eta_c\tilde{\beta})}} - 1\right)\delta^2 \tag{5.36}$$

Proof. For convenience, let us firstly separate Eq.(5.30) into two items:

$$\Gamma = -\big(\mathrm{I} + \mathrm{II}\big)\,, \tag{5.37}$$

$$\mathrm{I} = \xi \lambda_c\,, \tag{5.38}$$

$$\mathrm{II} = \big(\lambda_c\eta_c + \lambda_e\eta_e\big)\frac{(1-\epsilon)\big(1+\tilde{\beta}\mu\sigma\delta\rho_{k\,h}\big) - \tilde{\beta}\mu\big(\lambda_c\eta_c + \lambda_e\eta_e\big)}{(1-\tilde{\beta})\mu\Big[\delta^2 + \big(\lambda_c\eta_c + \lambda_e\eta_e\big)\Big]}\,. \tag{5.39}$$

Let us define $z = \lambda_c\eta_c + \lambda_e\eta_e \geq 0$, and $\Omega = (1-\epsilon)(1+\tilde{\beta}\mu\sigma\delta\rho_{kh}) \geq 0$ for further convenience. Then, Eq.(5.38) can be written as

$$\mathrm{II} = \frac{\Omega\, z - \tilde{\beta}\mu\, z^2}{(1-\tilde{\beta})\mu\big(\delta^2 + z\big)} \tag{5.40}$$

We are interested in the associated derivatives of Eqs.(5.29) and (5.30) respect to catastrophe parameters as follows:

$$\frac{\partial \tilde{g}^*}{\partial \lambda_c} = \frac{\partial \Gamma}{\partial \lambda_c} = -\frac{\partial \mathrm{I}}{\partial \lambda_c} - \frac{\partial \mathrm{II}}{\partial z}\frac{\partial z}{\partial \lambda_c} = -\xi - \eta_c\frac{\partial \mathrm{II}}{\partial z} = -\eta_c\left(\frac{\xi}{\eta_c} + \frac{\partial \mathrm{II}}{\partial z}\right), \tag{5.41}$$

$$\frac{\partial \tilde{g}^*}{\partial \eta_c} = \frac{\partial \Gamma}{\partial \eta_c} = -\lambda_c\frac{\partial \mathrm{II}}{\partial z}\,, \tag{5.42}$$

$$\frac{\partial \tilde{g}^*}{\partial \lambda_e} = \frac{\partial \Gamma}{\partial \lambda_e} = -\eta_e\frac{\partial \mathrm{II}}{\partial z}\,, \tag{5.43}$$

$$\frac{\partial \tilde{g}^*}{\partial \eta_e} = \frac{\partial \Gamma}{\partial \eta_e} = -\lambda_e\frac{\partial \mathrm{II}}{\partial z}\,, \tag{5.44}$$

The above four derivatives contain one common item, $\partial\mathrm{II}/\partial z$, which directly determines the sign of Eqs.(5.42) to (5.44), and needs particular treatment as follows:

$$\frac{\partial \mathrm{II}}{\partial z} = \frac{1}{(1-\tilde{\beta})\mu(\delta^2+z)^2}\Big[(\Omega - 2\tilde{\beta}\mu z)\delta^2 - \tilde{\beta}\mu z^2\Big]\,, \tag{5.45}$$

$$= \underbrace{\frac{\tilde{\beta}}{(1-\tilde{\beta})(\delta^2+z)^2}}_{>0}\left[\left(1+\frac{\Omega}{\tilde{\beta}\mu\delta^2}\right)\delta^4 - \big(z+\delta^2\big)^2\right] \tag{5.46}$$

Hence,

$$\frac{\partial \mathrm{II}}{\partial z} \geq 0 \quad \Leftrightarrow \quad \left(1+\frac{\Omega}{\tilde{\beta}\mu\delta^2}\right)\delta^4 - \big(z+\delta^2\big)^2 \geq 0\,, \tag{5.47}$$

$$\Leftrightarrow \quad 0 \leq z \leq \underbrace{\left(\sqrt{1+\frac{\Omega}{\tilde{\beta}\mu\delta^2}} - 1\right)\delta^2}_{z^*} \tag{5.48}$$

Hereby, a necessary and sufficient condition for $\partial \Pi/\partial z \geq 0$ is $0 \leq z \leq z^*$, with $z^* = \left(\sqrt{1 + \frac{(1-\epsilon)(1+\tilde{\beta}\mu\sigma\delta\rho_{kh})}{\tilde{\beta}\mu\delta^2}} - 1\right)\delta^2$. In addition, the sign of Eq.(5.41) is determined by

$$\frac{\xi}{\eta_c} + \frac{\partial \Pi}{\partial z} = \underbrace{\frac{\tilde{\beta}}{(1-\tilde{\beta})(\delta^2+z)^2}}_{>0} \left[\left(1 + \frac{\Omega}{\tilde{\beta}\mu\delta^2}\right)\delta^4 - \left(1 - \frac{\xi}{\eta_c}\frac{1-\tilde{\beta}}{\tilde{\beta}}\right)\left(z+\delta^2\right)^2\right] \quad (5.49)$$

and

$$\frac{\xi}{\eta_c} + \frac{\partial \Pi}{\partial z} \geq 0 \quad \Leftrightarrow \quad \left(1 + \frac{\Omega}{\tilde{\beta}\mu\delta^2}\right)\delta^4 - \left(1 - \frac{\xi}{\eta_c}\frac{1-\tilde{\beta}}{\tilde{\beta}}\right)\left(z+\delta^2\right)^2 \geq 0 \quad (5.50)$$

Therefore, we have the following two scenarios:

(i) when $0 < \tilde{\beta} \leq \xi/(\xi+\eta_c)$ ($\Leftrightarrow 1 - \frac{\xi}{\eta_c}\frac{1-\tilde{\beta}}{\tilde{\beta}} \leq 0$), Eq.(5.50) obviously holds.

(ii) when $\xi/(\xi+\eta_c) < \tilde{\beta} < 1$ ($\Leftrightarrow 1 - \frac{\xi}{\eta_c}\frac{1-\tilde{\beta}}{\tilde{\beta}} > 0$), we require $0 \leq z \leq \tilde{z}^*$, where $\tilde{z}^* = \left(\sqrt{\frac{1+\Omega/\tilde{\beta}\mu\delta^2}{1-\xi(1-\tilde{\beta})/(\eta_c\tilde{\beta})}} - 1\right)\delta^2$. Obviously, $0 < 1 - \underbrace{\xi(1-\tilde{\beta})/(\eta_c\tilde{\beta})}_{\geq 0} \leq 1$, and thus, we have $\tilde{z}^* \geq z^*$.

In summary, we conclude the above mentioned results as follows:

$$\frac{\partial \tilde{g}^*}{\partial \lambda_c} \begin{cases} < 0 & \text{when} \begin{cases} z \geq 0 & \text{if } 0 < \tilde{\beta} \leq \xi/(\xi+\eta_c)\,, \\ 0 \leq z < \tilde{z}^* & \text{if } \xi/(\xi+\eta_c) < \tilde{\beta} < 1 \end{cases}, \\ \geq 0 & \text{when } z \geq \tilde{z}^*\,, \text{if } \xi/(\xi+\eta_c) < \tilde{\beta} < 1\,. \end{cases} \quad (5.51)$$

$$\frac{\partial \tilde{g}^*}{\partial \eta_c} \begin{cases} < 0 & \text{when } 0 \leq z < z^*\,, \\ \geq 0 & \text{when } z \geq z^*\,. \end{cases} \quad (5.52)$$

$$\frac{\partial \tilde{g}^*}{\partial \lambda_e} \begin{cases} < 0 & \text{when } 0 \leq z < z^*\,, \\ \geq 0 & \text{when } z \geq z^*\,. \end{cases} \quad (5.53)$$

$$\frac{\partial \tilde{g}^*}{\partial \eta_e} \begin{cases} < 0 & \text{when } 0 \leq z < z^*\,, \\ \geq 0 & \text{when } z \geq z^*\,. \end{cases} \quad (5.54)$$

$$\text{with } z^* = \left(\sqrt{1 + (1-\epsilon)(1 + \tilde{\beta}\mu\sigma\delta\rho_{kh})/(\tilde{\beta}\mu\delta^2)} - 1\right)\delta^2 \tag{5.55}$$

$$\text{and } \tilde{z}^* = \left(\sqrt{\frac{1 + (1-\epsilon)(1 + \tilde{\beta}\mu\sigma\delta\rho_{kh})/(\tilde{\beta}\mu\delta^2)}{1 - \xi(1-\tilde{\beta})/(\eta_c\tilde{\beta})}} - 1\right)\delta^2 \tag{5.56}$$

□

It is worth to note that a larger measure of relative risk aversion ϵ will decrease (or increase) m_g^* when $\rho_{k,h}$ is negative (or positive), i.e.

$$\frac{\partial m_g^*}{\partial \epsilon} = \frac{\beta\rho_{kh}\mu\sigma\delta}{A\beta(1-\beta)(\mu\delta)^2} \begin{cases} < 0 & \text{when } \rho_{k,h} < 0 \\ > 0 & \text{when } \rho_{k,h} > 0 \end{cases} \tag{5.57}$$

This indicates that, once an agent becomes more risk averse, m_g^* decreases, hence the domain of $\partial g/\partial m > 0$ shrinks, indicating "slow-down" effect is less likely to be offset by "uncertainty" effect when $\rho_{kh} < 0$. Similarly, we obtain the contrary result in the case of $\rho_{kh} > 0$.

The expression of expected growth rate of consumption gives a similar Keynes-Ramsey rule (KRR) albeit the uncertainty effect in the last three items of the equation, driven by Wiener process and Poisson process respectively. KRR states that the growth rate equals to the real interest rate less time preference, divided by the elasticity of intertemporal substitution. Specifically, the conventional KRR in isoelastic utility (or CRRA utility) function has the following form:

$$\frac{\dot{c}}{c} = \frac{r_t - \rho}{\epsilon}, \qquad \text{with } \epsilon = -\frac{c\,U_c''}{U_c'} \text{ constant.} \tag{5.58}$$

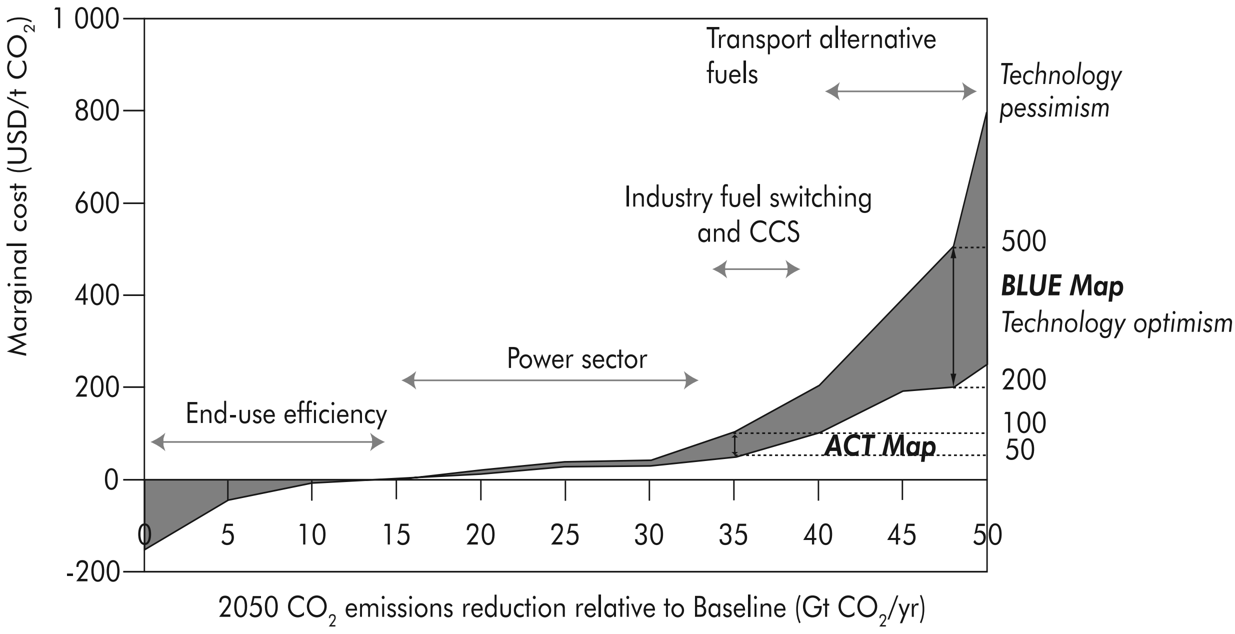
The first item in the RHS of Eq.(5.20) shows that out model's real interest rate, calculated by the marginal product of capital adjusted by the ratio of emission intensity of production to the efficiency of mitigation, i.e. $r_t = A\big(1 - \frac{\phi}{\mu}\big)$, is smaller than the conventional marginal product of capital in Keynes-Ramsey form. This is due to the fact that negative impact of detrimental emission reduces the real interest rate, and this can be dampened by a greater efficiency of mitigation or/and a smaller emission intensity (i.e. a smaller value of ϕ/μ).

Furthermore, the last item Γ on RHS of Eq.(5.20) accounts for the effect of catastrophic shock including nature disaster and epidemic, driven by two independent Poisson distributions. We are particularly interested in the sign of this item. When Γ is negative i.e. $0 \leq q \leq \bar{q}$, with $\bar{q} = \min\left\{\frac{1}{\eta_c}\left[1-\left(2-\left(1-\xi\right)^{-\epsilon}\right)^{\frac{1}{\beta}}\right], \frac{1}{\eta_e}\left[1-\left(1+\frac{1}{\epsilon}\right)^{-\frac{\epsilon}{\beta}}\right]\right\}$. The risky shock decelerates the economic growth. The presence of risky environment leads to a certainty equivalent return on saving which is smaller than the expected rate of return (Steger, 2005). In other words, the economic implication can be described as a precautionary dissaving motive (Muller-Furstenberger and Schumacher 2015, Bretschger and Vinogradova, 2016). Note that Γ is composed of two kinds of catastrophic shocks: nature disaster, $\Gamma_c(q)$, and epidemic $\Gamma_e(q)$, which represent the change of the post-shock capital and health to the pre-shock capital and health when nature disaster and epidemic happen respectively i.e. $d\tilde{k}/dk$, $d\tilde{h}/dh$ and $d\tilde{\tilde{h}}/dh$. It is worth to note that the shocks on consumption include a direct effect on both capital and health, $\tilde{k}$, $\tilde{h}$, and $\tilde{\tilde{h}}$ respectively, and an indirect effect due to shock reaction on marginal utility to a jump in capital and health, $dV_{\tilde{k}}^{\tilde{k}}/dV_k$, $dV_{\tilde{k}}^{\tilde{h}}/dV_k$ and $dV_{\tilde{k}}^{\tilde{\tilde{h}}}/dV_k$ respectively, given a multiplier ϵ. Whether the direct effect dominates the indirect effect depends on the magnitude of ϵ. In this context, it is also equal to the Arrow-Pratt measure of relative risk aversion and the elasticity of marginal utility to consumption, which is required to be strictly larger than zero and smaller than one. Empirical literature suggests $q^* \ll 1$ (i.e. a small number close to zero). The indirect effect is unambiguously dominated by the direct effect. The intuition here is obvious. Since the overall effect of catastrophic shocks on capital accumulation and health dynamics is negative, the optimal growth rate of the economy decreases as well.

5.3 Calibration

First, let us focus on the abatement efficiency μ. Energy Technology Perspectives (2008)[8] reports that the ACT and BLUE scenarios in Figure.(5.2) represent a set of optimal pathways to reduce energy-related GHGs emissions. The family of ACT and BLUE scenarios describe least-cost pathways to return CO_2 emissions back to 2005 level by 2050, and reduce 50% of emission to the level of 2005 by 2050, respectively. The ACT scenario requires options with a marginal cost up to 50 U.S. dollar per ton CO_2

[7]Based on Source: Energy Technology Perspectives (ETP) of IEA, June, 2008.
[8]ETP, publication of The International Energy Agency (IEA).



Marginal costs increase significantly between ACT Map and BLUE Map, and the cost uncertainty increases.

Figure 5.2 – Marginal emissions reduction costs for the global energy system, 2050[7]

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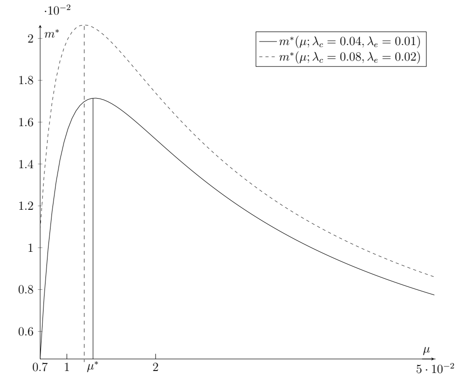
emission, while BLUE scenario needs 200 U.S. dollars per ton CO_2 emission, when significant technology cost reductions is viewed in an optimistic way. Under pessimistic assumption about abatement technology development, the associated two scenarios will require 100 U.S. dollar and 500 U.S. dollar per ton respectively. The difference is due to the cost uncertainty for the abatement technology improvement. Nevertheless, technology improvement is observed by time. In IEA 2011, Hood summaries that significant level of emissions abatement could be achieved with existing technology, at carbon price less than 50 U.S. dollar per ton of CO_2 emission. However, further emission reduction for achieving a 2°C target will require new technology which associates with higher and more uncertain cost, such as carbon capture and storage (CCS) in industry, and alternative transport fuels. According to ETP (2010), up to 175 U.S. dollar per ton of CO_2

emission is needed to achieve the BLUE Map scenario.

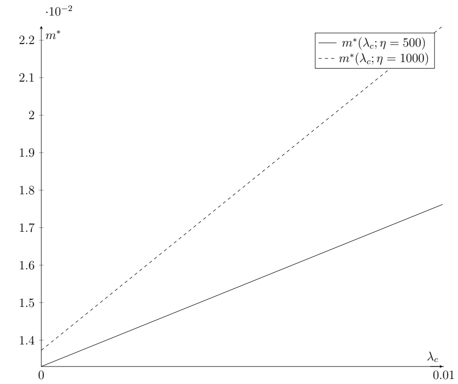
The emission defined in our model includes not only the GHGs but also other pollutants harmful to human health. The detrimental impact of emission on health will lead tight mitigation policy, and thus higher abatement technology cost. In addition, uncertain effect of CO_2 emission is underestimated. Ekins et al. (2011) argue that the abatement cost is very sensitive to many factors, like discounting rate, variations in investment cost and fuel efficiency, etc. Hereby, we compare various abatement measures and aim to include potential abatement technology development as well as uncertainty cost by setting emission price at 50 U.S. dollar per ton coal (implying abatement efficiency $\mu = 0.02$) as benchmark scenario, and 20 U.S. dollar per ton coal (implying $\mu = 0.05$), and 100 U.S. dollar per ton coal (implying $\mu = 0.01$) respectively, for both optimistic and pessimistic assumptions of technology development.

Our calibration highlights that the share of abatement dramatically increases when a greater uncertainty is taken into account, i.e. the economy is under the threat of catastrophes. Moreover, the quantitative implications of our numerical simulation on the abatement fraction is comparable to the recent findings in Golosov et al. (2014), who use a dynamic stochastic general-equilibrium (DSGE) model to calculate the total tax amount to 0.8% of world output (with the tax of 56.9 U.S. dollar per ton coal) when they adopt the subjective discount 1.5% per year (the same with Nordhaus (2008)), when the total world emissions is about 9.7 billion tons of carbon in 2010. Calibrating the model under the benchmark parameters described above, we obtain the optimal abatement fraction $m^* = 1.4\%$, indicating carbon taxation up to 103 U.S. dollar per ton coal, and $m^* = 0.8\%$, indicating 56.9 U.S. dollar per ton coal, when abatement technology development is viewed in an optimistic way. Our calculation suggests a higher carbon tax when the catastrophic shocks in health and capital are both considered. Of course, in case of catastrophic shock, the abatement efficiency is viewed less optimistic than that in the case of small-scale fluctuation. The economic implication is that the real social cost of carbon could be higher because the extreme events (or so-called "fat tail" are neglected in conventional approaches (Weitzman 2011, 2014).

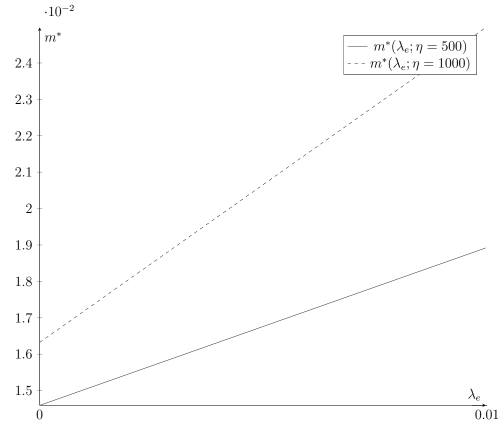
Hereby, we graphically present the effect of parameters on the economic policy and growth rate respectively.



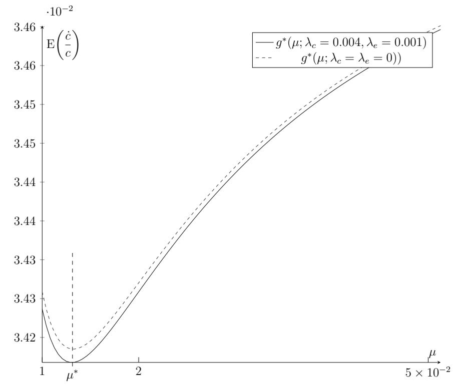
(a) The optimal mitigation policy m^* for different values of the efficiency of abatement μ.



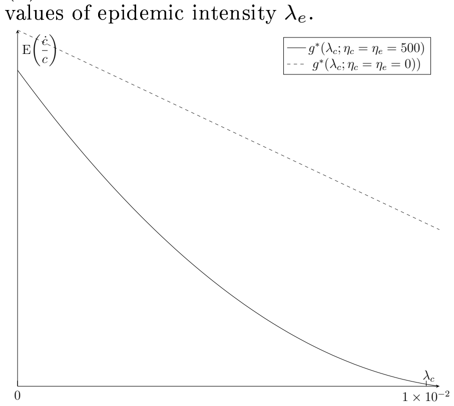
(b) The optimal mitigation policy m^* for different values of catastrophe intensity λ_c.



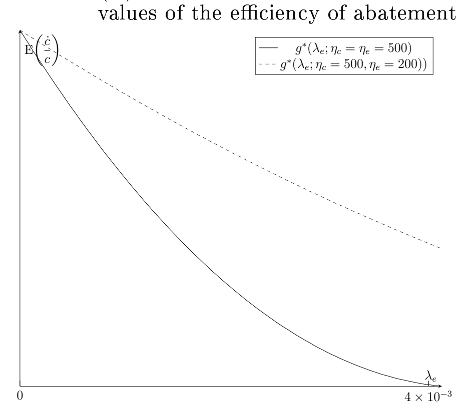
(c) The optimal mitigation policy m^* for different values of epidemic intensity λ_e.



(d) The optimal growth rate g^* for different values of the efficiency of abatement μ.



(e) The optimal growth rate g^* for different values of nature disaster intensity λ_c.



(f) The optimal growth rate g^* for different values of epidemic intensity λ_e.

Figure 5.3 – The effect of model's parameters on the optimal mitigation policy m^* and growth rate g^* under the treat of catastrophes

λ_c	natural catastrophe intensity	0.004
ξ	capital destruction during a natural disaster	0.001
λ_e	epidemic intensity	0.004
η_c	health sensitivity to nature disaster shock	500
η_e	health sensitivity to epidemic shock	500

Table 5.1 – *Parameters values for the numerical example in chatastrophic shock*

5.4 Conclusion

In the last section, we extend the stochastic growth model by introducing two kinds of catastrophic shocks: nature disaster and epidemic. The closed-from solutions for abatement policy and economic growth are derived, and the differences of economic growth under Wiener and Poisson uncertainties are discussed. Moreover, we provide the necessary and sufficient condition for the existence and uniqueness of the equilibrium emission concentration.

Furthermore, despite of the discussion on conventional economic parameters, such as emission intensity, efficiency of abatement technology, and TFP, the innovative message from our quantitative analysis is that optimal abatement policy reacts sensitively to relatively small variations in health parameter (the relative importance of health respect to consumption), and both small and large scale uncertainty parameters, including health and capital sensitivities to fluctuation, health sensitivity to catastrophic shock, and catastrophe intensity. The abatement policy is also sensitive to the sign of correlation coefficient, and this sensitivity will become intensified for some countries with less CRRA measurement.

Finally, the main policy implication of our finding suggests a more stringent climate policy should be implemented, since the emission-induced extreme events are ignored when the social cost of carbon is calculated by conventional approach. In other words, the uncertainty effect due to CO_2 emission is underestimated. Our model calibration highlights the share of abatement dramatically increases when the economy is under the threat of catastrophe. Calibrating the model under the benchmark parameters described above, we obtain the optimal abatement fraction $m^* = 1.4\%$, indicating 103 U.S. dollar per ton coal taxation and $m^* = 0.8\%$, indicating 56.9 U.S. dollar per ton coal respectively, if the abatement technology development is viewed

Parameters	Optimal Mitigation Policy and Growth Rate		
	$q^*(10^{-6})$	$m^*\%$	$g^*\%$
$\lambda_c = 0, \lambda_e = 0$	1.497	1.185	3.8155
$\mu = 0.01$	12.181	1.564	3.8157
$\mu = 0.02$	4.973	1.432	3.8142
$\mu = 0.05$	0.647	0.774	3.8494
$\eta^H = 1 \cdot 10^3$	2.810	1.679	3.8140
$\eta^L = 5 \cdot 10^2$	4.973	1.432	3.8142
$\lambda_c^H = 0.01$	2.377	1.728	3.8135
$\lambda_c^L = 0.004$	4.973	1.432	3.8142
$\lambda_e^H = 0.004$	3.675	1.58	3.8140
$\lambda_e^L = 0.001$	4.973	1.432	3.8142

TABLE 5.2 – *The optimal emission concentration, mitigation fraction and grwoth rate in banchmark setting when catastrophie happens,* $\epsilon = 0.9, A = 5\%, \phi = 0.04\%, \delta = 1700, \mu = 0.08, \delta = 0.001, \rho_{kh} = -0.5.$

in an optimistic way. Our calculation suggests a higher carbon tax when the interdependent continuous fluctuations and discontinuous catastrophic shocks are taken into account. Apparently in face of catastrophic shock, it is reasonable to have less optimistic view on the abatement efficiency than that in the case of only small-scale fluctuation. Indeed, the real social cost of carbon could be higher because the extreme events (or so called "fat tail" are neglected in conventional approaches (Weitzman 2011, 2014).

6 Cultural Factors in Health Care Consumption: Theoretical Study On The Role of Chinese Traditional Medicine

6.1 Introduction

6.1.1 Motivation and Research Background

Chinese society is ageing rapidly. Until the end of 2015, the amount of people aged 60 or over accounted for 16.1% of total population (about 222 million)[1]. The number has increased 2.83% from 2010 to 2015, and is 3.8% higher than world average ageing population in 2015[2]. Homing to nearly one quarter of the world's ageing population, however, the pace of population ageing in China is accelerating. The number of population aged 60 or over in China is projected to grow by 71 % between 2015 and 2030 (United Nations, 2015). Population ageing has profound implications in many facets of individual life and society, which requires social planner to equip with right set of polices to address the challenge and reap the benefits. Elder people are generally subject to more uncertainty on health degradation and higher health care expenditure, thus more likely to have diverse health preferences compared to young people (Bolhaar, Lindeboom and Klaauw, 2008). In China, empirical studies show that middle-aged and older population are more likely to choose Traditional Chinese Medicine (TCM) treatment, or TCM combined with Western Medicine (WM) treatment when making decision on medical care service (Chung et al., 2009; Jin, 2010; Liu et al., 2015).

[1]Based on source: Statistical Communiqué of the People's Republic of China on the 2015 National Economic and Social Development.

[2]Based on source: Chinese Population Census 2010. National Bureau of Statistics of China, February 29, 2016.

The growth in the number of older population also influences the pace of change of chronic disease, and related mortality and morbidity (United Nations, 2015). The 2015 Report on Chinese Nutrition and Chronic Disease[3] finds, firstly, the number of people suffering from chronic diseases was continually rising during the period of 2002-2012. Secondly, although death caused by chronic diseases in 2012 accounted for 86.6% of all deaths, there was yet a down-trend in mortality rate for most types of chronic diseases. An increase in the prevalence of chronic diseases, together with a decrease in mortality suggest a longer survival period of patients with chronic diseases.

Either being old or young, patients suffering from chronic illness that conventional treatment (WM) is not effective tend to seek alternative solutions, like TCM (Ruggie, 2004). An increasing amount of literature suggests that chronic disease is associated with higher possibility of TCM intervention due to its positive effects and lower costs in terms to both individual expenditure and national health care system. A large-scale survey conducted by Liao et al. (2013) concludes that TCM is more cost-efficient than WM in treating lung cancer. First, the overall medical expenditures of WM users are higher than those of TCM users, no matter whether they undergo surgery. Meanwhile, the mortality rate of WM users is higher than that of TCM users in no surgery treatment. The morality rate has no statistical difference between WM and TCM users who had surgery. Similar results are obtained through TCM intervention on diseases like migraine (Vickers et al., 2004), female infertility (Ried and Stuart, 2011), liver cancer (Liao et al., 2013), and uterine fibroids (Su, Muo, and Morisky, 2015).

TCM has been increasingly under the spotlight in recent years. President Xi Jingping highly praised TCM on many occasions since he came to power in 2012. Xi indicated that the strength of a country and a people is underpinned by a vigorous culture, while Traditional Chinese Medicine is the key to the treasure of Chinese culture, since TCM embodies the profound traditional Chinese philosophical wisdom on human, society and universe besides the health concept and practical experience. Xi also stated that TCM should be center in medical service provision and reform priorities in health care system. In 2013, President Xi proposed the strategy of "One Belt, One Road" (OBOR): the land and maritime Silk Road linking East

[3]Released by National Health and Family Planning Commission of China on June 30, 2015.

Asia to Western Europe. This intercontinental trade and infrastructure project seeks for not only the economic benefits, rather, culture works as an important pillar within this strategy to secure global influence. TCM is being promoted in this initiative since it embodies the profound Chinese culture and generate abundant economic opportunities. For instance, the amount of export of Chinese herbal medicine is 56.4 billion U.S. dollar in 2015, 2.7% larger than that in 2014[4].

Given this background, TCM is gaining more policy support as an established component of health care system. The *Implementation Plan of Project on Enhancing Basic-Level Traditional Chinese Medicine Service* issued in 2012 sets it clearly to expand the reimbursement scope, and increase the reimbursement rate of TCM related drugs and non-drug therapies, in order to promote TCM consumption and its advantages in health care system, especially in primary and preventing care at basic level. Several provinces have proposed the plan to increase the reimbursement rate of TCM i.e to decrease the individual copay rate. For example, Hunan province has announced to increase TCM reimbursement rate of NRCMS by 5%[5]. Hainan and Sichuan province propose to increase TCM reimbursement rate by 5% - 10% to all individuals that are covered by three basic insurance systems[6]. In Heze, Shandong province, the reimbursement rate of TCM treatment has increased by 10% for NRCMS participants, and at least by 5% for urban residents covered by UEBMI and URBMI[7].

Considering the increasing consumer demand for diverse medical care service (TCM and WM) in an ageing society, how does the culture effect influence individual decisions on medial treatment? How does the health insurance policy affect individual medical decisions? Specially, how individuals, both urban and rural, determine their optimal demand for medical care? Besides, what is the effect of copay rate on optimal consumption of diverse medical care? In this essay, we address these questions using theoretical models. Our aim is to insight on the impact of culture and civilization on consumer's medical decision, and to propose a modelling strategy that enables policy makers to maximize social welfare.

[4] China Chamber of Commerce for Import and Export of Medicines and Health Products. Available online: http://www.cccmhpie.org.cn/Pub/3317_List.shtml

[5] News online: http://www.hunan.gov.cn/zw/hnyw/zwdt/201305/t20130525_1333092.html

[6] News online: http://news.xinhuanet.com/health/2013-05/21/c_124741170.htm; http://www.sc.gov.cn/10462/10464/10797/2012/11/27/10237257.shtml

[7] News online: http://news.sina.com.cn/o/2013-05-03/121927016257.shtml

6.1.2 Literature review and contribution

There is a growing number of literature addressing the cultural influence on individual decision to health, where most are explanatory from the social or medical point of view. Inglehart and Baker (2000) indicate that, despite the process of modernization and urbanization, cultural heritage generates significant imprints on social values which influence population's economic decision and behaviour. Economic development is usually associated with cultural changes, however, we can never ignore the impact of traditional values acting as an alternative driven force. For example, in China, although there are more numbers of practitioners and organizations of WM, patients' medical care decisions show a balanced preference between WM and TCM (Scheid, 2002). The embedded cultural belief system with regard to health, disease and healing greatly contributes to how individuals understand the causality of illness, experience an illness and expect the medical care to be delivered. Hence culture belief significantly motivates individual's medical consumption towards traditional therapy like TCM (Simpson, 2003; Hildreth and Elman, 2007; Vaughn, Jacquez and Baker, 2009). Xu et al. (2006) highlight that patients, with preference to TCM, believe that the therapy of TCM is a self-help process, grounded by the traditional values on nature and human life. They also believe that an individualized and tailored prescription is more effective than WM therapy.

We adopt the standard assumption in health insurance literature that decision making in purchasing insurance and the associated benefits are uncertain. The uncertainty arises from the fact that agents never know their lifetime health status before signing the insurance contract, apart from the moral hazard. Thus, the expected utility theory is employed here, and individual's risk preference becomes a key parameter in her health decision. For instance, a risk-averse agent demands more risk-bearing goods to offset the possible detrimental impact due to health degradation and accidental injury. Arrow (1963) has observed that the demands for health care and health insurance are intimately related. Given health as a specific good in consumer utility function, medical care needs to be purchased for hedging the risk in both the incidence of disease and the efficacy of therapy, which are two main features distinguishing the demand for health care from other goods and service. Grossman (1972a) indicates that health is a choice variable because it is a source of utility. Based on Grossman's (1972a) pure consumption model, Dardanoni and Wagstaff (1990) as well as Picone et al. (1998) suggest that greater uncertainty leads to an increase in the demand for health care. Selden (1993) and Chang (1996) suggest that a risk-averse agent tends to enlarge the investments in health due to the effect of uncertainty. Moreover, it is worth to remark that the issue of moral hazard enlarges the effect of uncertainty in decision making in the health care industry.

Apparently, health insurance plays an important role in health care system both at micro- and macro-level. Cameron et al. (1988) illustrate the interaction between decisions for health insurance and health care with a two-period utility function under uncertainty, where individual chooses between a discrete number of mutually exclusive health insurance policies. With empirical analysis, they conclude that health status matters more in consumer decision on health care service than on health insurance, while income level affects more in health insurance than in health care service. Following the model of Cameron et al. (1988), Cutler and Zeckhauser (2000), Koc (2004) uses an one-period and two-stage model to highlight the interdependence between health care and insurance demand decision, where two types of uncertainty faced by individuals are examined: uncertainty in consumer's pretreatment health, and in the productivity of health care, i.e. the treatment outcome. Wang et al. (2010) develop an expected utility function to examine the consumer demand of medical services and health insurance in a two-stage decision model under uncertainty. Especially, the model is applied to China's health insurance system for urban and rural residents in respectively. Empirical evidence shows Chinese health insurance reform in 2003 has significant impact on urban residents but not on rural residents.

There is also an increasing amount of studies discussing the income effect and price effect on health insurance. Cropper (1977) demonstrates that an agent with higher income or wealth level will maintain higher stocks of health than a poorer agent. Feenberg and Skinner (1994), Manning and Marquis (1996) have estimated the income elasticity of demand for medical care. Nyman (2002) argues that the primary impact of health insurance lies in an income effect rather than price effect, because health insurance to be purchased is viewed as an income transfer (to the time of illness), and it is not necessarily that a consumer is risk-averse.

6.1.3 Outline of the Results

Given the significances and the urgency of the rapidly ageing population in China, and the associated demand on health care system reform emerging from, it is quite surprising that the majority of literature evaluates policy only in cost-benefit terms, and the effect of culture has been largely ignored. To the best of our knowledge, our paper is the first to provide quantitative closed-form solutions on how the culture effect influences the consumer's medical demand between two types of therapy (i.e. TCM vs WM), when flexible health insurance policy is taken into consideration. Our contribution is threefold.

First, we derive closed-form analytical solutions for health demand following expected utility framework to illustrate culture effect on individual's health decisions, and the impact of TCM in China's health care system. Our model relates to various strands of literature. In the benchmark model, we extend the settings of Koc (2004) and Wang et al. (2010) by introducing two kinds of therapy in both budget constraint and individual welfare function. Our study shows the optimal demand of medical care for both urban and rural individuals, classified into four cohorts based on heterogeneous preferences and wealth.

Second, we demonstrate that the marginal effect of copay rate on optimal medical consumption and insurance policy are inverse related, with shape across the horizontal line. We also show that the relationship between copay rate and individual welfare is inverted-U shaped. A smaller copay rate has two opposite effects. On one hand, it saves individual's medical expenditure and promotes medical demand, so-called "medical effect". On the other hand, it increases the cost of health and hence reduces the individual income, so-called "income effect". Consequently, our results also highlight that the welfare implications of any health insurance policy should be carefully taken into account, in order to avoid the situation that copay rate negatively impact on welfare, while medical demand is increasing.

Third, we generalize the model with endogenous share parameter in CES utility function to investigate the ageing effect on the optimal medical care demand. We suggest to implement flexible health insurance policy and get ready for the coming ageing society. Adopting different copy rate to promote the TCM therapy is a possible candidate solution.

The remainder of the essay proceeds as follows. Section 2 presents our theoretical framework and the competitive equilibriums. Section 3 discusses the background of culture and the effect of deductibles on individual health care decisions. Section 4 extends the model to study the ageing effect. Finally, Section 5 concludes our findings.

6.2 The Model

In this section, we consider an one-period two-stage model with a constant elasticity of substitution (CES) preference á la Solow (1956), in the spirit of Koc (2004) and Wang et al. (2010). A representative agent lives for one period but two stages, and makes medical decision between Traditional Chinese Medicine (TCM) and Western Medicine (WM). At the first stage, she makes decision on purchasing health insurance when her health status is unrevealing. At the second stage, her health status is overt, and she makes medical care decisions between TCM and WM based on her preference. Population is constant and symmetric. Individual's decision on health insurance in the first stage and her medical care in the second stage are interdependent: the better she insures at the fist stage, the less she will pay for medical treatment in the second stage. The preference of an agent is represented by Cobb-Douglas type of health utility function as follows:

$$U(c,h;\gamma) = c^{\alpha}h^{1-\gamma}\,, \quad \alpha > 0\,, \gamma \in (0,1) \tag{6.1}$$

and

$$h = h(m,s) = m^{\beta}s^{1-\beta}\,, \quad \beta \in (0,1) \tag{6.2}$$

where c and h are respectively individual's consumption and health status. m and s are respectively medical care service and endowed health state. Parameter α indicates the individual's relative importance of consumption to her health level, which is assumed to be strictly positive. γ is the coefficient of relative risk aversion, which is assumed to be constant and between zero and one. β means the effectiveness of the medical care service relative to her health state. It is worth to note that $\beta(1-\gamma)$ indicates each individual's relative preference on health with respect to normal consumption goods. Thus, a higher β, or smaller γ, implies an individual attaches more importance to health level. Each individual is endowed with heath state s, which is unknown at the fist stage but revealed at the second stage. Besides the endowed health state, this health production function implies that individuals can always improve their health level by consuming medical care. Substituting Eq.(6.2) into Eq.(6.1), we obtain:

$$\tilde{U}(c, m, s; \gamma) = c^{\alpha} m^{\beta(1-\gamma)}\, s^{(1-\beta)(1-\gamma)} \tag{6.3}$$

The individual medical care spending m, which an agent spends in the second stage, includes both WM and TCM, denoted m_w and m_c receptively. In addition, $m = m(m_w, m_c)$, depends on individual preference. We use a standard CES medical care function, which implies constant elasticity of substitution between TCM and WM.

$$m(m_w, m_c) = \Big(\theta\, m_w^{\rho} + (1-\theta) m_c^{\rho}\Big)^{\frac{1}{\rho}} \tag{6.4}$$

Parameter ρ is constant, and the measure of elasticity of substitution is $\dfrac{1}{1-\rho}$. It is worth nothing that a perfect substitution preference (or linear function) or Cobb-Douglas preference are special cases of CES, when the parameter ρ is set to be equal to 1 or tend to 0 respectively. Share parameter $\theta \in [0, 1]$ indicates individual preference between TCM and WM. For instance, an agent who prefers TCM, i.e. $\theta \in (0, 1/2)$, intends to consume more in TCM than WM when total medical care spending m is fixed. Substitute Eq.(6.4) into Eq.(6.3), we obtain the following utility function:

$$\tilde{U}(c, m_w, m_c, s; \gamma) = c^{\alpha} \Big(\theta\, m_w^{\rho} + (1-\theta) m_c^{\rho}\Big)^{\frac{\beta(1-\gamma)}{\rho}} s^{(1-\beta)(1-\gamma)} \tag{6.5}$$

Moreover, $\tilde{U}$ is assumed to be quasi-concave in order to obtain an interior solution of c^*, m_c^* and m_w^*. At the first stage, the individual maximizes her expected utility and chooses the optimal health insurance.

$$\max_{c, m_w, m_c} E_0\, U\big(c, h(m_w, m_c, s); \gamma\big) = \max_{c, m_w, m_c} E_0\, \tilde{U}(c, m_w, m_c, s; \gamma) \tag{6.6}$$

subject to

$$y = \tilde{y} + a(b_c, b_w) \tag{6.7}$$

where b_c and b_w are the two co-pay rates of diverse health insurance policies, determined by TCM and WM therapy. $a(\cdot)$ is the insurance premium function, which is non-increasing in its arguments i.e. $a'_{b_c}(b_c, b_w) := \dfrac{\partial a(b_c, b_w)}{\partial b_c} \leq 0$, $a'_{b_w}(b_c, b_w) := \dfrac{\partial a(b_c, b_w)}{\partial b_w} \leq 0$. Moreover, $\tilde{y}$ represents the available income for the second stage, where the health status is revealed and individual's budget constraint is allocated between consumption and expected medical care spendings:

$$\max_{c,m_w,m_c} U(c, h(m_w, m_c, s); \gamma) = \max_{c,m_w,m_c} \tilde{U}(c, m_w, m_c, s; \gamma) \tag{6.8}$$

subject to

$$\tilde{y} = c + \mathrm{E}(M) \tag{6.9}$$

M is individual's overall medical spendings between two medical therapies, which is random and depends on her preference parameter θ. Specifically, individual's preference parameter determines the distribution of her medical spendings between TCM and WM. Without loss of generality, we assume M follows a Bernoulli (or two-point) distribution[8] as follows:

$$M = \begin{cases} b_w(p_w m_w - d) + d & \theta\,, \qquad \theta \in [0,1] \\ b_c(p_c m_c - d) + d & 1-\theta\,. \end{cases} \tag{6.10}$$

where p_w and p_c are the relative therapy prices of WM and TCM respect to consumption which is unitized to 1. d represents the deductible of the health insurance policy. Therefore, individual's expected medical care spending is:

$$\mathrm{E}(M) = \big[b_w(p_w m_w - d) + d\big]\theta + \big[b_c(p_c m_c - d) + d\big](1-\theta) \tag{6.11}$$

and the associated budget constraint in Eq.(6.9) has the following form:

$$\tilde{y} = c + \big[b_w(p_w m_w - d) + d\big]\theta + \big[b_c(p_c m_c - d) + d\big](1-\theta)\,,\ \theta \in [0,1] \tag{6.12}$$

It is worth to note that the minimum requirements to utilize deductible and copay rate are $m_w \geq d/p_w$ (or $p_w m_w \geq d$) and $m_c \geq d/p_c$. Especially, we have the following four types of individuals:
Type 1: General individual without extreme preference to TCM or WM utilizes deductibles and copay rates of both therapies. In this case, we have $m_w \geq d/p_w\,, m_c \geq d/p_c$ and $\theta \in [\underline{\theta}, \bar{\theta}]$, where $\underline{\theta}, \bar{\theta}$ are threshold values of

[8]Indeed, individual preference is a function of θ, denoted $\nu(\theta)$. For simplicity, we assume $\nu(\theta) = \theta$ in this section, however, this setting weakens the effect of preference (e.g. culture effect) on optimal solutions. This will be detailedly discussed in Section 3, where a more generalized model is presented.

preference parameters with $0 < \underline{\theta} < \bar{\theta} < 1$. The medical spending follows Bernoulli distribution:

$$M = \begin{cases} b_w(p_w m_w - d) + d\,, & m_w \geq d/p_w\,, \\ b_c(p_c m_c - d) + d\,, & m_c \geq d/p_c\,. \end{cases} \tag{6.13}$$

and have the expected value:

$$\mathrm{E}(M) = \big[b_w(p_w m_w - d) + d\big]\theta + \big[b_c(p_c m_c - d) + d\big](1-\theta)\,,\ \theta \in [\underline{\theta}, \bar{\theta}]. \tag{6.14}$$

Type 2: Individual with extreme preference to TCM utilizes only deductible and copay rate of TCM. In this case, we have $m_w \geq d/p_w\,, 0 \leq m_c/p_c \leq d$ and $\theta \in [0, \underline{\theta}]$. The medical spending follows Bernoulli distribution:

$$M = \begin{cases} b_w(p_w m_w - d) + d\,, & m_w \geq d/p_w\,, \\ p_c m_c\,, & 0 \leq m_c \leq d/p_c\,. \end{cases} \tag{6.15}$$

and have the expected value:

$$\mathrm{E}(M) = \big[b_w(p_w m_w - d) + d\big]\theta + (1-\theta)p_c m_c\,, \quad \theta \in [0, \underline{\theta}]. \tag{6.16}$$

Type 3: Individual with extreme preference to WM utilizes only deductible and copay rate of WM. In this case, we have $m_c \geq d/p_c\,, 0 \leq m_w \leq d/p_w$ and $\theta \in [\bar{\theta}, 1]$. The medical spending follows Bernoulli distribution:

$$M = \begin{cases} b_c(p_c m_c - d) + d\,, & m_c \geq d/p_c\,, \\ p_w m_w\,, & 0 \leq m_w \leq d/p_w\,. \end{cases} \tag{6.17}$$

and have the expected value:

$$\mathrm{E}(M) = \theta\, p_w m_w + \big[b_c(p_c m_c - d) + d\big](1-\theta)\,, \quad \theta \in [\bar{\theta}, 1]. \tag{6.18}$$

Type 4: Individual with no medical insurance or low income utilizes none deductible and copay rate of WM nor TCM. In this case, we have $0 \leq m_w \leq d/p_w\,, 0 \leq m_c \leq d/p_c$. The medical spending follows Bernoulli distribution:

$$M = \begin{cases} p_w m_w\,, & 0 \leq m_w \leq d/p_w\,, \\ p_c m_c\,, & 0 \leq m_c \leq d/p_c\,. \end{cases} \tag{6.19}$$

and have the expected value:

$$\mathrm{E}(M) = \theta\, p_w m_w + (1-\theta)p_c m_c\,, \quad \theta \in [0, 1]. \tag{6.20}$$

Technically, the four types of individuals can be presented in a compact form in Eq.(6.10), with $0 \leq b_c < 1\,, 0 \leq b_w < 1$ for type 1 individual, with $0 \leq b_c < 1\,, b_w = 1$ for type 2 individual, $b_c = 1\,, 0 \leq b_w < 1$ for type 3 individual and $b_c = 1\,, b_w = 1$ for type 4 individual, respectively. Here we maintain the four types of individuals in order to show different economic implications in the following subsection.

6.2.1 Competitive Equilibrium

The two stage optimization problem can be solved backwards, i.e. starting from the second stage, where the health state is revealed, to the first stage. It is worth to note that optimal arguments c^*, m_c^* and m_w^* in Eq.(6.67) are independent from health state s. Therefore, the health status only changes the value of utility, but not the shape of indifference cure. That is to say, no matter her health status, an individual always chooses the same level of consumption and medical care, given her income and insurance policy fixed. In spite of the occurrence of moral hazard, this fact can be explained by considering a general kind of health care which includes health enhancing activities, such as, healthy diet, nutritional supplements, physical exercise and preventive treatment. For instance, the rich individual can choose some costly preventive therapies to maintain or enhance their health status even when they are healthy while the poor can not. It is worth to highlight that preventive treatment is indeed a popular therapy of TCM.

Solving the optimization problem, we obtain the four cohorts of equilibrium states in the Table6.1, where $\chi = \dfrac{\beta(1-\gamma)}{\alpha+\beta(1-\gamma)} \in (0,1)\,, \tilde{\tilde{y}}_c = y - a(b_c) - (1-\theta)(1-b_c)d$ $\,, \tilde{\tilde{y}}_w = y - a(b_w) - \theta(1-b_w)d$, and $\tilde{\tilde{y}} = y - a(b_c, b_w) - [\theta(1-b_w) + (1-\theta)(1-b_c)]\, d$. Without loss of generality, let us focus on **Type 1** individual, and solve the optimal consumption and medical spending of TCM and WM (see Appendix C). For **Type 2**, **Type 3** and **Type 4** individual, the equilibriums can be solved similarly by setting $b_c = 1$ or/and $b_w = 1$ respectively. The outline of the results are as follows:

$$c^* = \frac{\alpha\,\tilde{\tilde{y}}}{\alpha+\beta(1-\gamma)}\,, \tag{6.21}$$

and

$$m_c^* = \left[\frac{\beta(1-\gamma)}{\alpha+\beta(1-\gamma)}\right]\frac{(1-\Theta_w^c)\,\tilde{\tilde{y}}}{(1-\theta)b_c p_c}\,,\ \ \beta\,,\gamma\,,\theta\,,b_c\,,\Theta_w^c \in [0,1]\,, \text{and}\ \alpha\,,p_c > 0 \tag{6.22}$$

Individual Types	c^*	m_c^*	m_w^*
Type 1	$(1-\chi)\tilde{\tilde{y}}$	$\dfrac{\chi(b_cp_c)^{\frac{-1}{1-\rho}}\tilde{\tilde{y}}}{\theta(b_wp_w)^{\frac{-\rho}{1-\rho}}+(1-\theta)(b_cp_c)^{\frac{-\rho}{1-\rho}}}$	$\dfrac{\chi(b_wp_w)^{\frac{-1}{1-\rho}}\tilde{\tilde{y}}}{(1-\theta)(b_cp_c)^{\frac{-\rho}{1-\rho}}+\theta(b_wp_w)^{\frac{-\rho}{1-\rho}}}$
Type 2	$(1-\chi)\tilde{\tilde{y}}_c$	$\dfrac{\chi(b_cp_c)^{\frac{-1}{1-\rho}}\tilde{\tilde{y}}_c}{\theta(p_w)^{\frac{-\rho}{1-\rho}}+(1-\theta)(b_cp_c)^{\frac{-\rho}{1-\rho}}}$	$\dfrac{\chi(p_w)^{\frac{-1}{1-\rho}}\tilde{\tilde{y}}_c}{(1-\theta)(b_cp_c)^{\frac{-\rho}{1-\rho}}+\theta(p_w)^{\frac{-\rho}{1-\rho}}}$
Type 3	$(1-\chi)\tilde{\tilde{y}}_w$	$\dfrac{\chi(p_c)^{\frac{-1}{1-\rho}}\tilde{\tilde{y}}_w}{\theta(b_wp_w)^{\frac{-\rho}{1-\rho}}+(1-\theta)(p_c)^{\frac{-\rho}{1-\rho}}}$	$\dfrac{\chi(b_wp_w)^{\frac{-1}{1-\rho}}\tilde{\tilde{y}}_w}{(1-\theta)(p_c)^{\frac{-\rho}{1-\rho}}+\theta(b_wp_w)^{\frac{-\rho}{1-\rho}}}$
Type 4	$(1-\chi)\,y$	$\dfrac{\chi\,p_c^{\frac{-1}{1-\rho}}\,y}{\theta p_w^{\frac{-\rho}{1-\rho}}+(1-\theta)p_c^{\frac{-\rho}{1-\rho}}}$	$\dfrac{\chi\,p_w^{\frac{-1}{1-\rho}}\,y}{(1-\theta)p_c^{\frac{-\rho}{1-\rho}}+\theta p_w^{\frac{\rho}{1-\rho}}}$

Table 6.1 – *Four cohorts of equilibriums depending on agent's type*

and

$$m_w^* = \left[\frac{\beta(1-\gamma)}{\alpha+\beta(1-\gamma)}\right]\frac{\Theta_w^c\tilde{\tilde{y}}}{\theta b_w p_w}\,,\ \ \beta\,,\gamma\,,\theta\,,b_w\,,\Theta_w^c\in[0,1]\,,\text{and}\,\alpha\,,p_w>0 \quad (6.23)$$

where $\tilde{\tilde{y}} = y - a(b_c,b_w) - [\theta(1-b_w)+(1-\theta)(1-b_c)]\,d$ and $\Theta_w^c(\theta,p_c,b_c,p_w,b_w) = \dfrac{\Phi_c}{\Phi_c+\Phi_w}$ with $\Phi_c(\theta,p_c,b_c) = \theta\,(b_cp_c)^{\frac{\rho}{1-\rho}}$ and $\Phi_w(\theta,p_w,b_w) = (1-\theta)(b_wp_w)^{\frac{\rho}{1-\rho}}$. Substituting Eqs.(6.21) (6.23) and (6.22) into utility function in Eq.(6.5), we obtain individual's welfare function as follows:

$$\tilde{U}(c,m_w,m_c,s;\gamma) = \Lambda\,\Psi^{\frac{\beta(1-\gamma)(1-\rho)}{\rho}}\,\tilde{\tilde{y}}^{\,\alpha+\beta(1-\gamma)}\,\mathrm{E}\big(s^{(1-\beta)(1-\gamma)}\big) \qquad (6.24)$$

with $\Lambda = \dfrac{\alpha^{\alpha}\big[\beta(1-\gamma)\big]^{\beta(1-\gamma)}}{\big[\alpha+\beta(1-r)\big]^{\alpha+\beta(1-\gamma)}}$ and $\Psi(\theta,p_c,b_c,p_w,b_w) = \theta(1-\theta)\big(\Phi_c^{-1}+\Phi_w^{-1}\big) = \theta(b_wp_w)^{\frac{-\rho}{1-\rho}}+(1-\theta)(b_cp_c)^{\frac{-\rho}{1-\rho}}$. The economic implications are discussed in the following proposition.

Proposition 6.2.1. *Individual's demand for TCM (or WM respectively) increases if:*

(i) income level y increases.

(ii) the relative price of TCM to WM, p_w/p_w (or p_w/p_c respectively) decreases.

(iii) preference to consumption relative to health decreases i.e. α decreases.

(iv) a lower deductible requirement d.

(v) health depends relatively larger on the medical care treatment rather than on endowed health state i.e. β increases.

(vi) a lower copay rate of TCM, b_c (or WM, b_w respectively) if the slop of the marginal insurance to copay rate is moderate. Specifically, we require $a'_{b_c}(b_c, b_w) \in (-\xi_c, 0]$ (or $a'_{b_w}(b_c, b_w) \in (-\xi_w, 0]$ respectively), where $\xi_c = y - [\theta(1-b_w) + (1-\theta))]\, d$ and $\xi_w = y - [\theta + (1-\theta)(1-b_c))]\, d$.

Proof. Here we only focus on the demand for TCM m_c^*, and the case of m_w^* can be obtained symmetrically. The influence of income level, preferences, deductible rate on the optimal level of TCM can be proved straightforward as follows.

$$\frac{\partial m_c^*}{\partial y} = \left(\frac{\beta(1-\gamma)}{\alpha+\beta(1-\gamma)}\right)\frac{(1-\Theta_w^c)}{(1-\theta)b_c p_c} > 0, \tag{6.25}$$

$$\frac{\partial m_c^*}{\partial \alpha} = -\frac{\beta(1-\gamma)}{\big[\alpha+\beta(1-\gamma)\big]^2}\frac{(1-\Theta_w^c)\,\tilde{\tilde{y}}}{(1-\theta)b_c p_c} < 0, \tag{6.26}$$

$$\frac{\partial m_c^*}{\partial d} = \left(\frac{\beta(1-\gamma)}{\alpha+\beta(1-\gamma)}\right)\frac{(1-\Theta_w^c)}{(1-\theta)b_c p_c}\Big[-\big(\theta(1-b_w)+(1-\theta)(1-b_c)\big)\Big] < 0, \tag{6.27}$$

$$\frac{\partial m_c^*}{\partial \beta} = \frac{\alpha(1-\gamma)}{\big[\alpha+\beta(1-\gamma)\big]^2}\frac{(1-\Theta_w^c)\,\tilde{\tilde{y}}}{(1-\theta)b_c p_c} > 0, \tag{6.28}$$

$$\text{with}\, \beta\,,\gamma\,,\theta\,,b_c\,,b_w\,,\Theta_w^c \in [0,1]\,, \text{and}\, \alpha\,,p_c\,,p_w > 0$$

The property (ii) is equivalent to say that individual demand for TCM increases if the price of TCM p_c decreases (denoted "$\uparrow$") or the price of WM p_w increases (denoted "$\downarrow$"). From the definition of equilibrium medical demand m_c^* in Eq.(6.22), we have $\Theta_w^c(\theta, b_c, p_c, b_w, p_w)$ "$\uparrow$" when the co-pay rate b_c and p_c of TCM $\uparrow$, or b_w and p_w "$\downarrow$". In other wards, we have the following results.

$$\frac{\partial \Theta_w^c(\theta, b_c, p_c, b_w, p_w)}{\partial b_c} > 0\,, \quad \frac{\partial \Theta_w^c(\theta, b_c, p_c, b_w, p_w)}{\partial p_c} > 0\,, \tag{6.29}$$

$$\frac{\partial \Theta_w^c(\theta, c, p_c, b_w, p_w)}{\partial b_w} < 0\,, \quad \frac{\partial \Theta_w^c(\theta, b_c, p_c, b_w, p_w)}{\partial p_w} < 0\,, \tag{6.30}$$

$$\frac{\partial \tilde{\tilde{y}}}{\partial b_c} = -a'_{b_c}(b_c, b_w) + 1 - \theta > 0\,, \quad \frac{\partial \tilde{\tilde{y}}}{\partial b_w} = -a'_{b_w}(b_c, b_w) + \theta > 0 \tag{6.31}$$

Therefore, we can prove property (ii) as follows:

$$\frac{\partial m_c^*}{\partial p_c} = \left(\frac{\beta(1-\gamma)}{\alpha+\beta(1-\gamma)}\right)\frac{\tilde{\tilde{y}}}{(1-\theta)b_c p_c}\left[(1-\Theta_w^c)(-1/p_c) + \left(-\frac{\partial \Theta_w^c}{\partial p_c}\right)\right] < 0, \tag{6.32}$$

$$\frac{\partial m_c^*}{\partial p_w} = \left(\frac{\beta(1-\gamma)}{\alpha+\beta(1-\gamma)}\right)\frac{\tilde{\tilde{y}}}{(1-\theta)b_c p_c}\left(-\frac{\partial \Theta_w^c}{\partial p_w}\right) > 0, \tag{6.33}$$

$$\tag{6.34}$$

Substituting Eqs.(6.29) and (6.31) into Eq.(6.23), we obtain the following monotonicity: $m_w^* \downarrow$ as $b_c \downarrow$.

$$m_w^* = \underbrace{\left[\frac{\beta(1-\gamma)}{\alpha+\beta(1-\gamma)}\right]\frac{1}{\theta b_w p_w}}_{\text{constant}} \underbrace{\Theta_w^c}_{\downarrow \text{as } b_c \downarrow} \underbrace{\tilde{\tilde{y}}}_{\downarrow \text{as } b_c \downarrow}, \tag{6.35}$$

$$\beta, \gamma, \theta, b_w, \Theta_w^c \in [0,1], \text{and } \alpha, p_w > 0$$

This implies $\frac{\partial m_w^*}{\partial b_c} > 0$. While the proof of the last property, i.e. $\frac{\partial m_c^*}{\partial b_c} \lesseqqgtr 0$, is not obvious since the copay rates play different roles which may offshore each other. Let us call them "medical effect" and "income effect" respectively. Taking b_c for example, "medical effect" means that a decreased copay rate b_c implies a higher reimbursement ratio, which benefits individual's medical demand, but meanwhile, individual suffers a so-called "income effect" because increased insurance premium $a(\cdot)$ leads decrease her second stage income $\tilde{y}$. In order to better explain the situation, we introduce the following corollary.

Corollary. *The relationship between the marginal effect of copay rate on optimal demand of medical care(e.g. $\partial m_c^*/\partial b_c$) and the marginal effect of copay rate on insurance policy (i.e. $a'_{b_c}(b_c, b_w)$) is inverse and across the horizontal line. Moreover, a sufficient condition for "the lower the copy rate, the higher the demand for medical care" is $a'_{b_c}(b_c, b_w) \in (-\xi, 0]$, with $\xi = y - [\theta(1-b_w) + (1-\theta))]\, d$.*

Proof. The equation above is remarkable for the proof.

$$\frac{\partial(\tilde{\tilde{y}}/b_c)}{\partial b_c} = \frac{\partial\left(\frac{y - a(b_c, b_w) - [\theta(1-b_w) + (1-\theta))]\, d}{b_c}\right)}{\partial b_c}$$

$$= (-1/b_c^2)\left[y - a(b_c, b_w) - [\theta(1-b_w) + (1-\theta))]\, d + b_c a'_{b_c}(b_c, b_w)\right] \tag{6.36}$$

Therefore $\dfrac{\partial(\tilde{\tilde{y}}/b_c)}{\partial b_c} \leq 0$ is equivalent to say :

$$\underbrace{y - a(b_c, b_w) - [\theta(1-b_w) + (1-\theta))]\, d}_{>0} + \underbrace{b_c a'_{b_c}(b_c, b_w)}_{<0} \geq 0\,, \tag{6.37}$$

Let us firstly consider a special case of Eq.(6.37), where the equality holds:

$$y - a(b_c, b_w) - [\theta(1-b_w) + (1-\theta))]\, d + b_c a'_{b_c}(b_c, b_w) = 0\,, \quad a(1, b_w) = 0^9 \tag{6.38}$$

Solving the above first order differential equation, we obtain $a(b_c, b_w) = \xi\,(1 - b_c)$, with $\xi = y - [\theta(1-b_w) + (1-\theta))]\, d$. Therefore, when $-\xi < a'_{b_c}(b_c, b_w) < 0$, we have inequality in Eq.(6.37)[10], which indicates $\dfrac{\partial(\tilde{\tilde{y}}/b_c)}{\partial b_c} < 0$. In other words, $\tilde{\tilde{y}}/b_c \uparrow$ as $b_c \downarrow$. Recalling that Eq.(6.29) tells us $\Theta^c_w(\theta, b_c, p_c, b_w, p_w) \uparrow$ as $b_c \downarrow$, and Eq.(6.22) can be written as follows:

$$m^*_c = \underbrace{\left[\frac{\beta(1-\gamma)}{\alpha + \beta(1-\gamma)} \frac{1}{(1-\theta)p_c}\right]}_{\text{constant parameters}} \underbrace{\frac{\tilde{\tilde{y}}}{b_c}}_{\uparrow \text{ as } b_c \downarrow} \underbrace{(1 - \Theta^c_w)}_{\uparrow \text{ as } b_c \downarrow} \tag{6.39}$$

Therefore, we obtain $m^*_c \uparrow$ as $b_c \downarrow$. In other words, $-\xi < a'_{b_c}(b_c, b_w) = -\tilde{\xi} < 0$ is a sufficient condition to guarantee $\dfrac{\partial m^*_c}{\partial b_c} < 0$. □

Figure 6.1 displays a graphical illustration of this reverse relationship. Let us now consider one special case as an appealing example, where the copay rate associated to various therapy is identical. From national point of view, we still adopt identical copay rate insurance policy in contemporary China's health care system, though diversifying health insurance is piloted in some specific regions of China.

Example 1. Let us consider a special case when the copay rate is identical between WM and TCM (i.e. $b_w = b_c = b$), and insurance premium

[9] Since we only focus on TCM in this proof, we ignor the effect of b_w on the insurance premium. Without loss of generality, we set initial condition when no insurance on TCM i.e. $b_w = 1$, the health insurance has no utility i.e. $a(1, b_w) = a(1, 1) = 0$.

[10] Indeed, if we consider $a(1, b_w) > 0$, the first order differential equation in Eq.(6.38) can be solved similarly with the solution $a(b_c, b_w) = \xi - \tilde{\xi}\, b_c$, with $\tilde{\xi} = y - [\theta(1-b_w) + (1-\theta))]\, d - a(1, b_w)$. Obviously, we have $-\xi < a'_{b_c}(b_c, b_w) = -\tilde{\xi} < 0$. Therefore, our conclusion on sufficient condition stays the same only by substituting ξ with $\tilde{\xi}$, and nothing substantially changes

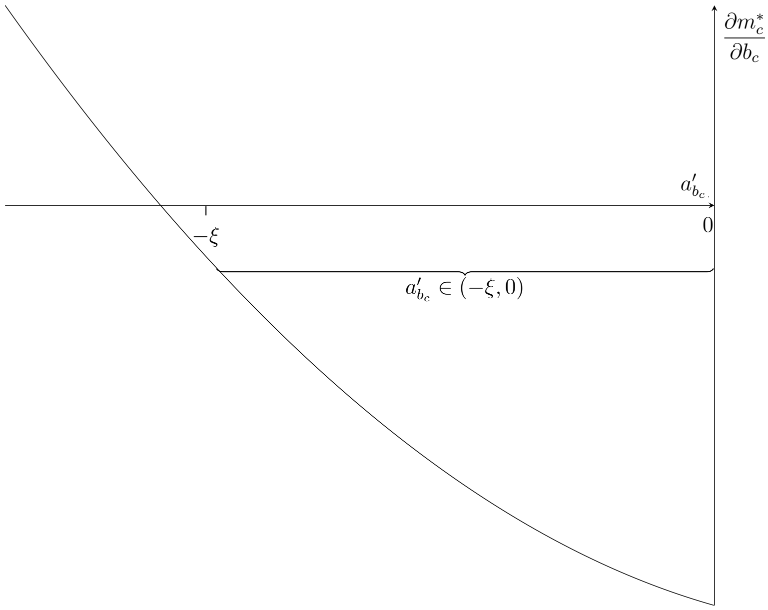


Figure 6.1 – Inverse relationship between the marginal effect of copay rate on TCM and on insurance policy

$a(b_c, b_w) = a$ is constant for public health insurance. We have the following remarkable results. For instance, the equilibrium demand of WM and TCM in Eqs.(7.89) and (7.90) are simplified as:

$$m_w^* = \frac{y - a(b) - (1-b)d}{b\,p_w\left[1 + \frac{\alpha}{\beta(1-r)}\right]\left[\theta + (1-\theta)\left[\frac{p_w}{p_c}\right]^{\frac{\rho}{1-\rho}}\right]} \tag{6.40}$$

and

$$m_c^* = \frac{y - a(b) - (1-b)d}{b\,p_c\left[1 + \frac{\alpha}{\beta(1-r)}\right]\left[(1-\theta) + \theta\left[\frac{p_c}{p_w}\right]^{\frac{\rho}{1-\rho}}\right]} \tag{6.41}$$

The last property holds if the income effect is dominated by the substitution effect, and thus we require:

$$\frac{\partial m_w^*}{\partial b} < 0 \Rightarrow \frac{\partial\left(\frac{y - a(b) - d}{b}\right)}{\partial b} < 0 \Rightarrow a'(b) := \frac{\partial a}{\partial b} < \frac{1}{b} \tag{6.42}$$

Similar condition can be derived from $\dfrac{\partial m_c^*}{\partial d} < 0$. Furthermore, constant insurance premium a simplifies Eqs.(7.89) and (7.90) as follows:

$$m_w^* = \frac{y - a - (1-b)d}{b\,p_w \left[1 + \dfrac{\alpha}{\beta(1-r)}\right] \left[\theta + (1-\theta)\left[\dfrac{p_w}{p_c}\right]^{\frac{\rho}{1-\rho}}\right]} \tag{6.43}$$

and

$$m_c^* = \frac{y - a - (1-b)d}{b\,p_c \left[1 + \dfrac{\alpha}{\beta(1-r)}\right] \left[(1-\theta) + \theta\left[\dfrac{p_c}{p_w}\right]^{\frac{\rho}{1-\rho}}\right]} \tag{6.44}$$

Apparently in this scenario, we have $a'(b) = 0$, and hence the last property holds for sure. □

6.2.2 Urban and Rural Difference: a Welfare Analysis

China's health medical insurance system involves three sub-systems, introduced in previous chapter. The Urban Resident Basic Medical Insurance (URBMI) and New Rural Cooperative Medical Scheme (NRCMS) tend to merge into one system. Hence, here we assume two constant insurance premium i.e. a_U and a_R to deduce the following proposition.

Proposition 6.2.2. *The necessary condition for the individual participating in medical care system is that the deductible below a threshold vale. Specifically, we require $d \in [0, \bar{d}]$ with the threshold value $\bar{d}$ satisfying:*

$$\bar{d} = \frac{y\left(1 - \left[\dfrac{\Phi_c^{-1}(\theta, p_c, 1) + \Phi_w^{-1}(\theta, p_w, b_w)}{\Phi_c^{-1}(\theta, p_c, b_c) + \Phi_w^{-1}(\theta, p_w, b_w)}\right]^{\frac{\beta(1-\gamma)(1-\rho)}{[\alpha+\beta(1-\gamma)]\rho}}\right) - a(b_c, b_w)}{\theta(1-b_w) + (1-\theta)(1-b_c)} \tag{6.45}$$

Proof. Apparently, any individual not participating in the medical care system can not be covered by public health insurance. In this scenario, we can simplify our model by setting $b_w = b_c = 1$ and $a(b_c, b_w) = 0$. Therefore, the expected medical care spending and the budget constraint $\tilde{\tilde{y}}$ take the following forms: $\mathrm{E}(M) = \theta p_w m_w + (1-\theta) p_c m_c$, and $\tilde{\tilde{y}} = y$. Individual has incentive to enrol in medical care system only when their welfare are better off, i.e. $\tilde{U}^b(c, m_w, m_c, s; \gamma) \geq \tilde{U}^1(c, m_w, m_c, s; \gamma) \geq 0$. In other words:

$$\frac{\tilde{U}^b(c, m_w, m_c, s; \gamma)}{\tilde{U}^1(c, m_w, m_c, s; \gamma)} \geq 1 \,, \quad \text{and } \tilde{U}^1(c, m_w, m_c, s; \gamma) > 0\,. \tag{6.46}$$

$$\Rightarrow \left[\frac{\Psi(\theta, p_c, b_c, p_w, b_w)}{\Psi(\theta, p_c, 1, p_w, 1)}\right]^{\frac{\beta(1-\gamma)(1-\rho)}{\rho}} \left(\frac{y - a(b_c, b_w) - [\theta(1-b_w) + (1-\theta)(1-b_c)]d}{y}\right)^{\alpha+\beta(1-\gamma)} \geq 1$$
$$\Rightarrow 0 \leq d \leq \bar{d} \tag{6.47}$$

with

$$\bar{d} = \frac{y\left(1 - \left[\frac{\Phi_c^{-1}(\theta, p_c, 1) + \Phi_w^{-1}(\theta, p_w, b_w)}{\Phi_c^{-1}(\theta, p_c, b_c) + \Phi_w^{-1}(\theta, p_w, b_w)}\right]^{\frac{\beta(1-\gamma)(1-\rho)}{[\alpha+\beta(1-\gamma)]\rho}}\right) - a(b_c, b_w)}{\theta(1-b_w) + (1-\theta)(1-b_c)}$$

where utility function for individual enrolling (i.e. $b \in (0,1)$) and not enrolling (i.e. $b = 1$) in health care system is defined as $\tilde{U}^b(c, m_w, m_c, s; \gamma)$ and $\tilde{U}^1(c, m_w, m_c, s; \gamma)$ respectively. For a special case when $b_c = b_w = b$, the deductible $\bar{d}$ in Eq.(6.47) is $\bar{d} = \dfrac{y\left(1 - b^{\frac{\beta(1-\gamma)}{\alpha+\beta(1-\gamma)}}\right) - a(b)}{1-b}$. This indicates that individual in urban and rural areas, whose income and preference parameters satisfying the condition $d > \bar{d}$, are worse off for enrolling in the medical care system. □

Proposition 6.2.3. *The role of copay rate has important property on medical care decision, and individual tends to choose lower copay rate insurance if:*

(i) income level y increases.

(ii) compared to health, other consumption is less preferred i.e. α decreases.

(iii) health care efficiency increases i.e. β increases.

(iv) risk aversion rate decreases i.e. $\gamma < 0$

Proof. The first order condition relative to copay rate b_c on the individual welfare function in Eq.(6.24) is:

$$\frac{\beta(1-\gamma)(1-\rho)}{\rho}\frac{\partial \Psi}{\partial b_c}\tilde{\tilde{y}} + \Psi[\alpha+\beta(1-\gamma)]\frac{\partial \tilde{\tilde{y}}}{\partial b_c} = 0 \tag{6.48}$$

Substituting $\tilde{\tilde{y}}$ in Eq.(6.23) and Ψ in Eq.(6.24), we obtain:

$$f(b_c, y, \alpha, \beta, \gamma, \theta, b_w) = \Big(\alpha(1-\theta)\,d - [\alpha+\beta(1-\gamma)]a'_{b_c}\Big)b_c + \frac{\theta}{1-\theta}\Big(\alpha+\beta(1-\gamma)\Big)(p_w b_w)^{\frac{-\rho}{1-\rho}}$$
$$p_c^{\frac{\rho}{1-\rho}}\Big((1-\theta)d - a'_{b_c}\Big)b_c^{\frac{1}{1-\rho}} - \beta(1-\gamma)\Big(y - a(b_c, b_w) - [\theta(1-b_w)+(1-\theta)]d\Big) = 0 \tag{6.49}$$

Corollary. *A necessary condition for the existence of interior solution in individual welfare function in Eq.(6.24) is the second order derivative of $a(b_c, b_w$ relative to b_c is strictly positive i.e.*

$$a''_{b_c}(b_c, b_w) > \frac{\big[(1-\theta)d - a'_{b_c}\big]\,\omega}{(1-\rho)b_c} \geq 0\,, \tag{6.50}$$
$$\theta\,, \rho\,, b_c\,, \omega \in (0,1)\,, d \geq 0\,, a'_{b_c} \leq 0$$

with

$$\omega = 1 - \left(1 - \frac{\alpha(1-\rho)}{\alpha+\beta(1-\gamma)}\right)\left[1 + \frac{\theta}{1-\theta}\left(\frac{p_c b_c}{p_w b_w}\right)^{\frac{\rho}{1-\rho}}\right]^{-1} \tag{6.51}$$

Proof. From individual welfare function in Eq.(6.24), we have

$$\tilde{U}(b_c\,,\cdot) \sim \frac{(X_1 - a(b_c\,\cdot) + b_c)^{\alpha+\beta(1\gamma)}}{(X_2+b_c)^{\beta(1-\gamma)}}\,, \quad b_c \in [0,1] \tag{6.52}$$

□

From Eq.(6.50) in above corollary, we have $f_{b_c}(\cdot) = \dfrac{\partial f(\cdot)}{\partial b_c} < 0$. Moreover, we have:

$$\frac{\partial f(\cdot)}{\partial y} = -\beta(1-\gamma) < 0\,, \tag{6.53}$$

$$\frac{\partial f(\cdot)}{\partial \alpha} = (1-\theta)d\, b_c - a'_{b_c} b_c + \theta\left(d - \frac{a'_{b_c}}{1-\theta}\right)\big(p_w b_w\big)^{\frac{-\rho}{1-\rho}} p_c^{\frac{\rho}{1-\rho}} b_c^{\frac{1}{1-\rho}} > 0, \tag{6.54}$$

$$\frac{\partial f(\cdot)}{\partial \beta} = -\frac{\alpha}{\beta}\Big((1-\theta)d - a'_{b_c}\Big)\left[b_c + \frac{\theta}{(1-\theta)}\big(p_w b_w\big)^{\frac{-\rho}{1-\rho}} p_c^{\frac{\rho}{1-\rho}} b_c^{\frac{1}{1-\rho}}\right] < 0\,, \tag{6.55}$$

$$\frac{\partial f(\cdot)}{\partial \gamma} = \frac{\alpha}{1-\gamma}\Big((1-\theta)d - a'_{b}\Big)\left[b_c + \frac{\theta}{(1-\theta)}\big(p_w b_w\big)^{\frac{-\rho}{1-\rho}} p_c^{\frac{\rho}{1-\rho}} b_c^{\frac{1}{1-\rho}}\right] > 0\,, \tag{6.56}$$

$$\begin{aligned}\frac{\partial f(\cdot)}{\partial b_w} = & -\frac{\rho}{1-\rho}\frac{\theta\big(\alpha+\beta(1-\gamma)\big)}{(1-\theta)}\big((1-\theta)d - a'_b\big) p_w^{\frac{-\rho}{1-\rho}} b_w^{\frac{-1}{1-\rho}} p_c^{\frac{\rho}{1-\rho}} b_c^{\frac{1}{1-\rho}} \\ & -\beta(1-\gamma)\big(\theta\, d - a'_{b_c}\big) < 0\,. \end{aligned} \tag{6.57}$$

Thanks to the rule of the derivative of implicit function, we have the following:

$$\frac{\partial b_c}{\partial y} = -\frac{\partial f(\cdot)/\partial y}{\partial f(\cdot)/\partial b_c} < 0\,, \tag{6.58}$$

$$\frac{\partial b_c}{\partial \alpha} = -\frac{\partial f(\cdot)/\partial \alpha}{\partial f(\cdot)/\partial b_c} > 0\,, \tag{6.59}$$

$$\frac{\partial b_c}{\partial \beta} = -\frac{\partial f(\cdot)/\partial \beta}{\partial f(\cdot)/\partial b_c} < 0\,, \tag{6.60}$$

$$\frac{\partial b_c}{\partial \gamma} = -\frac{\partial f(\cdot)/\partial \gamma}{\partial f(\cdot)/\partial b_c} > 0\,, \tag{6.61}$$

$$\frac{\partial b_c}{\partial b_w} = -\frac{\partial f(\cdot)/\partial b_w}{\partial f(\cdot)/\partial b_c} < 0\,. \tag{6.62}$$

□

The results in Proposition (6.2.3) are intuitive. A higher level of income raises demand for health. Thus lower copay rate insurance policy is preferred in order to enlarge insurance coverage and save health care spending. Similarly, a smaller α or a larger $\beta(1-\gamma)$ indicates a larger weight of health in the utility function. Therefore, she needs better health care service and thus larger insurance coverage with lower copay rate. In addition, we illustrate the effect of the copay rate on insurance policy and individual welfare function graphically.

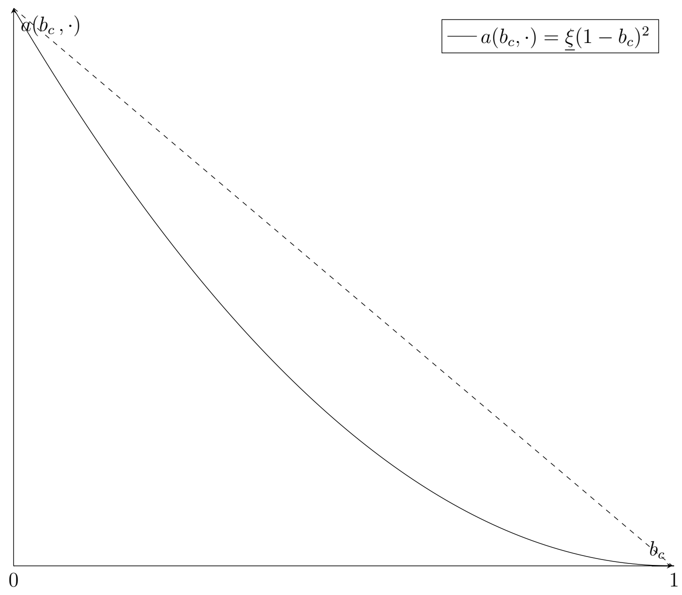


Figure 6.2 – Relationship between $a(b_c\, b_w)$ and b_c, when the interior solution is considered i.e. $a'_{b_c} < 0$ and $a''_{b_c} > 0$

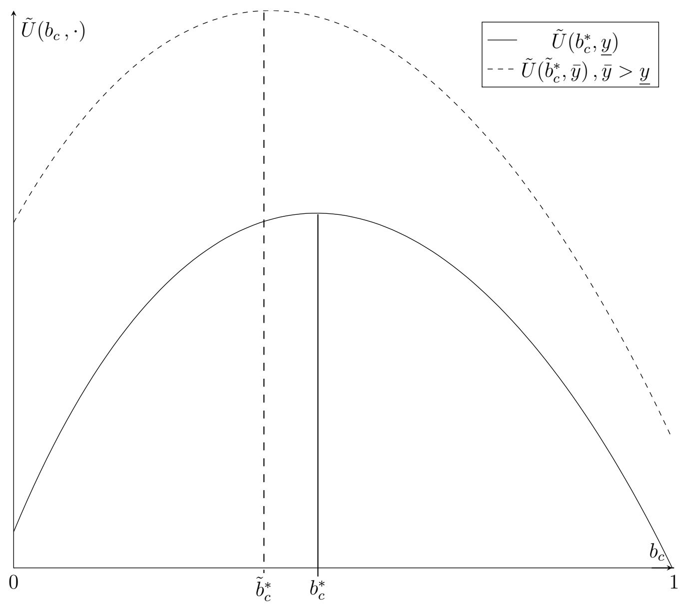


Figure 6.3 – Maximum utility relative to b_c when income is samll (solid line) and large (dashed line) in case of interor solution.

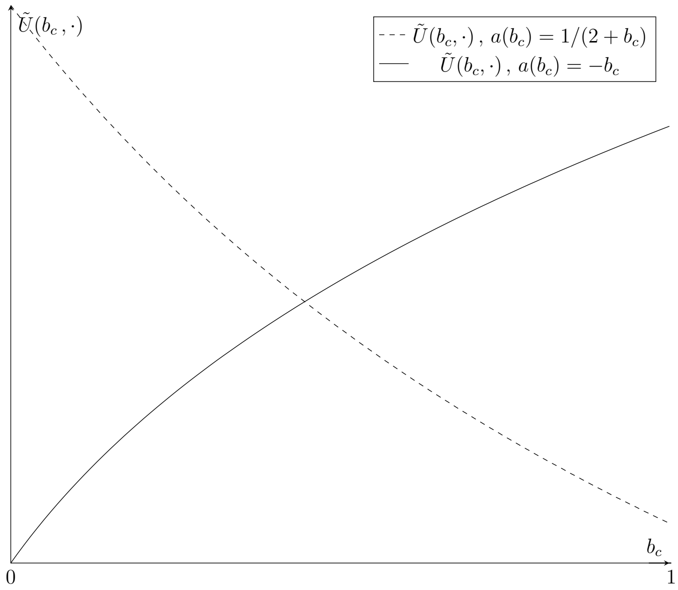


Figure 6.4 – Corner solution based on different function of a_c .

6.3 Culture Factors in Chinese Medical System

6.3.1 Model Generalization

In this section, the extension of the previous model is twofold. First, we investigate the impact of culture on individual's health decision in an ageing society. Second, we extend the model defined in section 2 with the extra impact of diverse deductibles of TCM and WM on health insurance policy, to investigate how the four types of individuals are affected. Let us define $\theta = \theta(\tau)$, where τ indicates age effect in individual's medical spending on TCM and WM, and $\dfrac{\partial\theta(\tau)}{\partial\tau} < 0$, implying older generation shows stronger preference to TCM than young generation. Moreover, we consider two different deductible requirements of insurance for TCM and WM respectively. Similar to Eq.(6.10) in Section 2, we define medical care spending M as follows:

$$M = \begin{cases} b_w(p_w m_w - d_w) + d_w & \theta(\tau) \in (0,1) \\ b_c(p_c m_c - d_c) + d_c & 1 - \theta(\tau) \end{cases} \tag{6.63}$$

p_c and p_w are the relative prices for TCM and WM therapies respect to consumption. d_w and d_c are two deductible requirements of the insurance for

WM and TCM. b_w and b_c are two copay rates determined by the insurance policy. Thus, the expected medical care expenditure takes the following form:

$$\mathrm{E}(M) = \big[b_w(p_w m_w - d_w) + d_w\big]\theta(\tau) + \big[b_c(p_c m_c - d_c) + d_c\big](1 - \theta(\tau)) \quad (6.64)$$

and the budget constraint in Eq.(6.9) has the following form:

$$\tilde{y} = c + \big[b_w(p_w m_w - d_w) + d_w\big]\theta(\tau) + \big[b_c(p_c m_c - d_c) + d_c\big](1 - \theta(\tau)), \quad (6.65)$$
$$\theta(\tau) \in [0, 1]$$

For simplicity, we denote θ instead of $\theta(\tau)$ from now on. As we have noted in Section 2, preference parameter and the associated share of medical spending are positively correlated, but not necessarily the same. We generalize preference parameter in CES medical demand function in Eq.(6.4) with $\nu(\theta)$ as follows:

$$m(m_w, m_c) = \Big(\nu(\theta)\, m_w^{\rho} + (1 - \nu(\theta)) m_c^{\rho}\Big)^{\frac{1}{\rho}} \quad (6.66)$$

Adapting to the fast ageing population is China's urgent challenge. This generalization captures the fact that the age induced culture effect plays different roles in preference and medical spending. Preference parameter $\nu(\theta)$ and $1 - \nu(\theta)$ indicate the preferences to WM and TCM respectively. In addition, we have the following proposition:

Proposition 6.3.1. *Preference parameter $\nu(\theta) \in [0, 1]$ is a monotonic function of θ, and satisfies the following conditions:*

(i) $\theta = 0 \Rightarrow \nu = 0$,

(ii) $\theta = 1 \Rightarrow \nu = 1$,

(iii) $\theta \uparrow \Rightarrow \nu(\theta) \uparrow$ *i.e.* $\nu(\theta)$ *(monotonic) increases, when* θ *increases.*

Substituting Eq.(6.66) into Eq.(6.3), we obtain the following utility function:

$$\tilde{U}^{\nu}(c, m_w, m_c, s; \gamma) = c^{\alpha}\Big(\nu\, m_w^{\rho} + (1 - \nu) m_c^{\rho}\Big)^{\frac{\beta(1-\gamma)}{\rho}} s^{(1-\beta)(1-\gamma)} \quad (6.67)$$

Solving the optimization problem detailedly in Appendix D, we obtain the optimal consumption and medical care spendings of TCM and WM as follows:

$$c^* = \frac{\alpha\, \tilde{\tilde{y}}_{\nu}}{\alpha + \beta(1 - r)}, \quad (6.68)$$

and

$$m_c^* = \left[\frac{\beta(1-\gamma)}{\alpha+\beta(1-\gamma)}\right]\frac{(1-\Theta^\nu)\,\tilde{\tilde{y}}_\nu}{(1-\theta)b_c p_c}\,, \qquad (6.69)$$
$$\text{with} \quad \beta\,,\gamma\,,\theta\,,b_c\,,\Theta^\nu_{c,w} \in [0,1]\,, \text{and}\; \alpha\,,p_c > 0$$

and

$$m_w^* = \left[\frac{\beta(1-\gamma)}{\alpha+\beta(1-\gamma)}\right]\frac{\Theta^\nu\tilde{\tilde{y}}_\nu}{\theta b_w p_w}\,, \qquad (6.70)$$
$$\text{with} \quad \beta\,,\gamma\,,\theta\,,b_w\,,\Theta^\nu_{c,w} \in [0,1]\,, \text{and}\; \alpha\,,p_w > 0$$

where $\tilde{\tilde{y}}_\nu = y - a(b_c, b_w) - [\theta(1-b_w)d_w + (1-\theta)(1-b_c)d_c]$ and $\Theta^\nu(\theta, p_c, b_c, p_w, b_w) = \dfrac{\Phi_c^\nu}{\Phi_c^\nu + \Phi_w^\nu}$ with $\Phi_c^\nu(\theta, p_c, b_c) = \theta^{\frac{q-\rho}{1-\rho}}(b_c p_c)^{\frac{\rho}{1-\rho}}$ and $\Phi_w^\nu(\theta, p_w, b_w) = (1-\theta)^{\frac{q-\rho}{1-\rho}}(b_w p_w)^{\frac{\rho}{1-\rho}}$, $q > 1$. Substituting Eqs.(6.68) (6.70) and (6.69) into utility function in Eq.(6.67), we obtain individual's welfare function as follows:

$$\tilde{U}(c, m_w, m_c, s; \gamma) = \Lambda\,\Psi_\nu^{\frac{\beta(1-\gamma)(1-\rho)}{\rho}}\;\tilde{\tilde{y}}_\nu^{\alpha+\beta(1-\gamma)}\,\mathrm{E}\big(s^{(1-\beta)(1-\gamma)}\big) \qquad (6.71)$$

with $\Lambda = \dfrac{\alpha^\alpha\big[\beta(1-\gamma)\big]^{\beta(1-\gamma)}}{\big[\alpha+\beta(1-r)\big]^{\alpha+\beta(1-\gamma)}}$ and $\Psi_\nu(\theta, p_c, b_c, p_w, b_w) = \left(\frac{[\theta(1-\theta)]^{q-\rho}}{\theta^q+(1-\theta)^q}\right)^{\frac{1}{1-\rho}}\Big(\big(\Phi_c^\nu\big)^{-1} + \big(\Phi_w^\nu\big)^{-1}\Big) = \left(\frac{\theta^{q-\rho}}{\theta^q+(1-\theta)^q}\right)^{\frac{1}{1-\rho}}(b_w p_w)^{\frac{-\rho}{1-\rho}} + \left(\frac{(1-\theta)^{q-\rho}}{\theta^q+(1-\theta)^q}\right)^{\frac{1}{1-\rho}}(b_c p_c)^{\frac{-\rho}{1-\rho}}$. Let us discuss the economic implications from equilibrium states in the following proposition.

Proposition 6.3.2. *Individual's demand for TCM relative to WM increases if:*

(i) the price of TCM relative to WM decreases.

(ii) individual preference to TCM relative to WM increases.

Proof. The two properties can be proved straightforward from a transforming version of Eq.(7.98) as follows:

$$\frac{m_c^*}{m_w^*} = \left[\frac{b_w p_w}{b_c p_c}\left(\frac{1-\theta}{\theta}\right)^{q-1}\right]^{\frac{1}{1-\rho}}\,, \quad q > 1\,,\ \rho\,,\theta \in (0,1). \qquad (6.72)$$

A higher price ratio of WM to TCM, i.e. p_w/p_c "↑ ", and enhanced preference to TCM relative to WM, i.e. $1 - \theta/\theta$ "↑ " , will increase the relative ratio between m_c^*/m_w^*. This implies individual's demand for TCM relative to WM increases. We graphically present the effect of model parameters on the associated therapies and their ratio in Figure 6.5. □

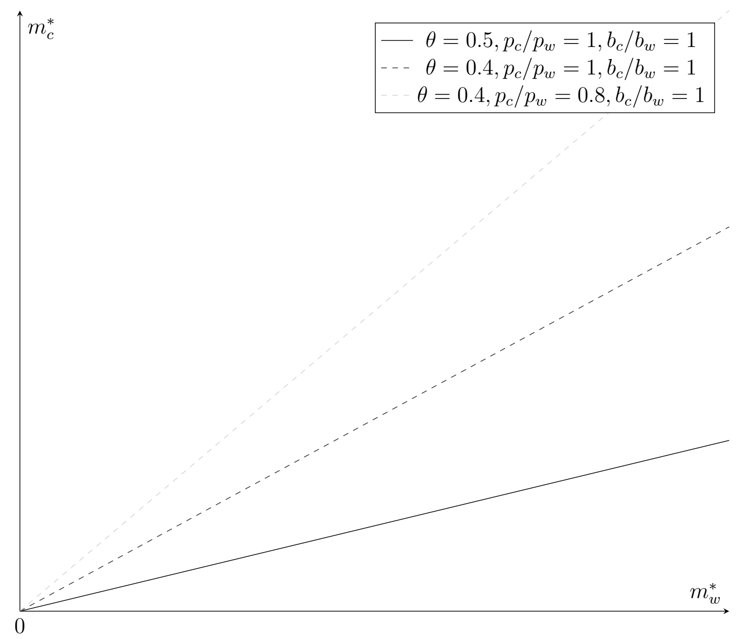


Figure 6.5 – The relationship between m_c^* relative to m_w^* when $q = 2\,, \rho = 0.5$.

6.3.2 The Effect of Deductibles

As emphasized in previous section, deductible affects the medical spending through a lower entrance requirement in participation in medical care system. As a result, a lower deductible of TCM relative to WM on health insurance policy will make **Type 2** and **Type 4** individuals better off, and transfer **Type 3** and **Type 4** individuals into **Type 1** and **Type 2** individuals by reducing the threshold value d_c/p_c.

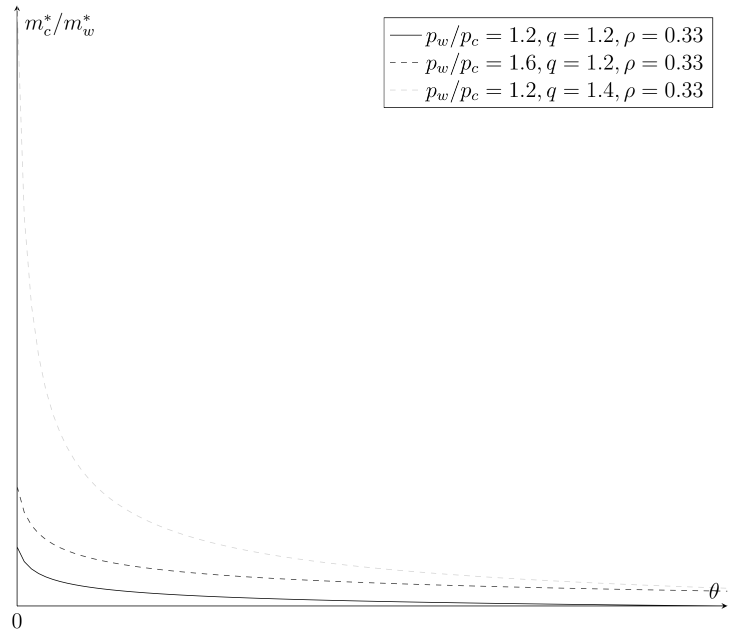


Figure 6.6 – The dynamic of m_c^*/m_w^* as θ changes.

6.4 Conclusion

This essay provides insights to one of the most spotlight issues in China: health care reform, while considering fast ageing population. A policy in health care insurance market is usually evaluated in cost-benefit terms, and the effect of culture is ignored. The present essay fills a gap in the literature by providing theoretical foundations on how the culture effect influence the consumer's medical demand between TCM and WM, when the flexible health insurance policy is taken into account.

This essay demonstrates that, in an one-period two-stage model, the relationship between consumer demand of diverse medical therapies depends on health policy and culture effect. We develop a theoretical model of health demand following expected utility framework, in order to illustrate culture effect in individual's health decisions, and the impact of TCM in China's health care system. Our study shows the optimal demand of medical care for both rural and urban individuals, who are classified into four cohorts based on preferences and wealth. Moreover, we demonstrate that the marginal effect of copay rate on optimal demand of medical care and insurance policy is invert related and across the horizontal line. In addition, we also show that the relationship between copay rate and individual welfare is inverted-U shaped, and hence a smaller copay rate may enlarge medical demand while reducing individual welfare.

Moreover, we find that it is not an optimal solution for all types of rural and urban individuals participating in public medical insurance system. Considering individual's diverse income level and different preference towards TCM and WM, policy maker should improve the existing medical system by providing more flexible insurance policies, like diverse copay rates, to make more individuals better off and increase overall social welfare.

Furthermore, individual's preference can vary over time, and it also depends on other externalities, such as environmental pollution. Pollution has caused severe health degradation, which increases the demand for efficient therapy like TCM. Consequently, we investigate the age effect on optimal medical demand. We generalize the share parameter in CES utility function, and study the determinants of relative demand between TCM and WM in optimal states.

The main policy implication of our results is to implement flexible health insurance policy and get ready for the fast ageing society. On one hand, adopting different copy rates to promote TCM is a candidate solution. It is particularly urgent in the north and west part of China, where the income level is low and population is predicted to be ageing quickly. On the other hand, the growing number of middle class promotes the demand of commercial insurance with higher coverage. Nevertheless, our results also highlight that the implementation of any health insurance policy should be considered with caution, in order to avoid welfare losses.

7 Appendix

7.1 Appendix A: The Analytical Treatment on the Benchmark Model under Wiener Uncertainty

Applying Ito's formula, we have:

$$dV(k,h) = \frac{\partial V(k,h)}{\partial k}dk + \frac{\partial V(k,h)}{\partial h}dh + \frac{1}{2}\Big\{\frac{\partial^2 V(k,h)}{\partial k^2}(dk)^2 + \frac{\partial^2 V(k,h)}{\partial h^2}(dh)^2 + 2\frac{\partial^2 V(k,h)}{\partial k \partial h}dkdh\Big\} \tag{7.1}$$

$$= \frac{\partial V(k,h)}{\partial k}\Big\{\big[(1-m)y - c\big]dt + \sigma k^{\alpha} dZ_{k,t}\Big\} + \frac{\partial V(k,h)}{\partial h}R(q)hdZ_{h,t} + \frac{1}{2}\Big\{ \frac{\partial^2 V(k,h)}{\partial k^2}\sigma^2 k^{2\alpha}dt + \frac{\partial^2 V(k,h)}{dh^2}R^2(q)h^{2\alpha}dt + 2\frac{\partial^2 V(k,h)}{\partial k \partial h}\sigma k^{\alpha} R(q) h^{\alpha}\rho_{k,h}dt\Big\} \tag{7.2}$$

Therefore, we have:

$$\frac{1}{dt}\mathrm{E}\big[V(k,h)\big] = V_k(k,h)\big[(1-m)y - c\big] + \frac{1}{2}\big[V_{kk}(k,h)\sigma^2 k^{2\alpha} + V_{hh}(k,h)R^2(q)h^{2\alpha} + 2V_{kh}(k,h)\sigma k^{\alpha} R(q)h^{\alpha}\rho_{k,h}\big] \tag{7.3}$$

Substituting Eq.(7.3) into Eq.(4.10), we obtain:

$$\rho V(k,h) = \max_{c,m}\Big\{U(c,h) + V_k(k,h)\big[(1-m)y - c\big] + \frac{1}{2}\big[V_{kk}(k,h)\sigma^2 k^{2\alpha} + V_{hh}(k,h)R^2(q)h^{2\alpha} + 2V_{kh}(k,h)\sigma k^{\alpha} R(q)h^{\alpha}\rho_{k,h}\big]\Big\} \tag{7.4}$$

F.O.C. conditions:
For c:

$$\frac{\partial U(c,h)}{\partial c} - V_k(k,h) = 0\,, \quad \text{i.e.}\, U_c = V_k \tag{7.5}$$

For m:

$$V_k\, y_t = V_{hh}R(q)R'(q)[-\mu A]h^{2\alpha} + V_{kh}\sigma R'(q)[-\mu A]k^{\alpha}h^{\alpha}\rho_{kh} \tag{7.6}$$

For k:

$$\rho V_k = V_{kk}[(1-m)y - c] + V_k(1-m)A + \frac{1}{2}\Big[V_{kkk}\sigma^2 k^{2\alpha} + 2\alpha\sigma^2 V_{kk}k^{2\alpha-1} + V_{hhk}R^2(q)h^{2\alpha} + 2\rho_{kh}\sigma V_{khk}R(q)h^\alpha k^\alpha + 2\sigma\rho_{kh}\alpha V_{kh}R(q)k^{\alpha-1}h^\alpha\Big] \quad (7.7)$$

For h :

$$\rho V_h = U_h + V_{kh}[(1-m)y - c] + \frac{1}{2}\Big[V_{kkh}\sigma^2 k^{2\alpha} + V_{hhh}R^2(q)h^{2\alpha} + 2\alpha V_{hh}R^2(q)h^{2\alpha-1} + 2\sigma V_{khh}R(q)k^\alpha h^\alpha\rho_{kh} + 2\alpha\sigma V_{kh}R(q)k^\alpha h^{\alpha-1}\rho_{kh}\Big] \quad (7.8)$$

From Eq.(7.5), we obtain:

$$U_c = V_k \Rightarrow c^* = c(k)\,,\text{and}\, V_k = \frac{\partial V}{\partial k}(k,h) := f(k,h) \quad (7.9)$$

Applying Ito's lemma to Eq.(4.16), we obtain:

$$dV_k = f_k dk + f_h dh + \frac{1}{2}\Big[f_{kk}(dk)^2 + f_{hh}(dh)^2 + 2f_{kh}dkdh\Big] \quad (7.10)$$

Substituting Eqs.(4.6) and (4.1), we obtain:

$$dV_k = \Big\{V_{kk}[(1-m)y - c] + \frac{1}{2}\Big[V_{kkk}\sigma^2 k^{2\alpha} + V_{khh}R^2(q)h^{2\alpha} + 2\sigma\rho_{kh}V_{kkh}R(q)k^\alpha h^\alpha\Big]\Big\}dt + V_{kk}\sigma k^\alpha dZ_{k,t} + V_{kh}R(q)h^\alpha dZ_{h,t} \quad (7.11)$$

Eq.(7.11)-(7.7)$\cdot dt$, we obtain:

$$dV_k = V_k\Big\{\rho - (1-m)A - \Big[\alpha\sigma^2\frac{V_{kk}}{V_k}k^{2\alpha-1} + \alpha\sigma\rho_{kh}\frac{V_{kh}}{V_k}R(q)k^{\alpha-1}h^\alpha\Big]\Big\}dt + \sigma V_{kk}k^\alpha dZ_k + V_{kh}R(q)h^\alpha dZ_h \quad (7.12)$$

Following Bretschger and Vinogradova 2016, and

$$U(c,h) = \frac{c^{1-\epsilon}}{1-\epsilon}h^\beta \quad \beta \in [0,1]\,, \epsilon \in [0,1]. \quad (7.13)$$

and $R(q) = \delta\, q$. It is worth nothing that from Eq.(7.13), we obtain $U_c(c,h) = c^{-\epsilon}h^\beta$. Therefore

$$c = (U_c\, h^\beta)^{-\frac{1}{\epsilon}} = U_c^{-\frac{1}{\epsilon}} h^{\frac{\beta}{\epsilon}} := f^c(U_c, h) \quad (7.14)$$

Applying Ito's lemma, we obtain:

$$dc = \frac{\partial f^c}{\partial U_c} dU_c + \frac{\partial f^c}{\partial h} dh + \frac{1}{2}\left\{ \frac{\partial^2 f^c}{\partial U_c^2}(dU_c)^2 + \frac{\partial^2 f^c}{\partial h^2}(dh)^2 + 2\frac{\partial^2 f^c}{\partial U_c \partial h} dU_c dh \right\} \quad (7.15)$$

It is worth to remark the following equalities:

$$(dU_c)^2 = (dV_k)^2 = \Big[\sigma^2 V_{kk}^2 k^{2\alpha} + V_{kh}^2 R^2(q) h^{2\alpha} + 2\sigma V_{kk} V_{kh} R(q) k^\alpha h^\alpha \rho_{kh}\Big] dt \quad (7.16)$$

$$(dh)^2 = R^2(q) h^{2\alpha} dt \quad (7.17)$$

$$dU_c dh = \Big[\sigma \rho_{kh} V_{kk} k^\alpha R(q) h^\alpha + V_{kh} R^2(q) h^{2\alpha}\Big] dt \quad (7.18)$$

$$\frac{\partial f^c}{\partial U_c} = -\frac{1}{\epsilon} c^{1+\epsilon} h^{-\beta}\,, \quad (7.19)$$

$$\frac{\partial f^c}{\partial h} = \frac{\beta}{\epsilon} c\, h^{-1}\,, \quad (7.20)$$

$$\frac{\partial^2 f^c}{\partial U_c^2} = \frac{1}{\epsilon}\left(1 + \frac{1}{\epsilon}\right) c^{1+2\epsilon} h^{-2\beta}\,, \quad (7.21)$$

$$\frac{\partial^2 f^c}{\partial h^2} = \frac{\beta}{\epsilon}\left(\frac{\beta}{\epsilon} - 1\right) c\, h^{-2}\,, \quad (7.22)$$

$$\frac{\partial^2 f^c}{\partial U_c \partial h} = -\frac{\beta}{\epsilon^2} c^{1+\epsilon} h^{-\beta-1}\,, \quad (7.23)$$

$$V_k = U_c = c^{-\epsilon} h^\beta\,, \quad (7.24)$$

$$V_{kh} = \beta c^{-\epsilon} h^{\beta-1}\,, \quad (7.25)$$

$$V_{kk} = -\epsilon c^{-\epsilon-1} h^\beta c_k\,, \quad \text{where } c_k = \frac{dc}{dk}\,. \quad (7.26)$$

Substituting Eqs.(7.5), (4.16) and (4.1) into (7.15), we obtain:

$$dc = \frac{\partial f^c}{\partial U_c} V_k \left\{ \rho - (1-m)A - \Big[\alpha\sigma^2 \frac{V_{kk}}{V_k} k^{2\alpha-1} + \alpha\sigma\rho_{kh} \frac{V_{kh}}{V_k} R(q) k^{\alpha-1} h^\alpha\Big] \right\} dt + \frac{1}{2}\left\{ \frac{\partial^2 f^c}{\partial U_c^2} \Big(\sigma^2 V_{kk}^2 k^{2\alpha} + V_{kh}^2 R^2(q) h^{2\alpha} + 2\sigma\rho_{kh} V_{kk} V_{kh} R(q) k^\alpha h^\alpha\Big) + \frac{\partial^2 f^c}{\partial h^2} R^2(q) h^{2\alpha} + 2\frac{\partial^2 f^c}{\partial U_c \partial h}\Big(\sigma\rho_{kh} V_{kk} R(q) k^\alpha h^\alpha + V_{kh} R^2(q) h^{2\alpha}\Big) \right\} dt + \frac{\partial f^c}{\partial U_c} \sigma V_{kk} k^\alpha dZ_k + \left[\frac{\partial f^c}{\partial U_c} V_{kh} + \frac{\partial f^c}{\partial h}\right] R(q) h^\alpha dZ_h \quad (7.27)$$

Therefore, the expectation of dc has the following form:

$$E\big(dc\big) = -\frac{c\,dt}{\epsilon}\Big\{\rho-(1-m)A-\alpha\sigma\Big[-\epsilon\sigma\frac{c_k}{c}k^{2\alpha-1}+\rho_{kh}\beta R(q)k^{\alpha-1}h^{\alpha-1}\Big]\Big\}+\frac{dt}{2}\Big\{$$
$$\frac{1}{\epsilon}(1+\frac{1}{\epsilon})\Big[\sigma^2\epsilon^2\frac{c_k^2}{c}k^{2\alpha}+\beta^2cR^2(q)h^{2\alpha-2}-2\epsilon\sigma\rho_{kh}\beta c_kR(q)k^{\alpha}h^{\alpha-1}\Big]+\frac{\beta}{\epsilon}\Big(\frac{\beta}{\epsilon}-1\Big)c\,R^2(q)h^{2\alpha-2}$$
$$-2\frac{\beta}{\epsilon^2}\Big[-\epsilon\sigma\rho_{kh}c_kk^{\alpha}R(q)h^{\alpha-1}+\beta cR^2(q)h^{2\alpha-2}\Big]\Big\} \tag{7.28}$$

It is worth to remark that in 'AK' model, consumption is linear with capital, i.e. $c = x\,k$, where x is linear factor. Therefore, we can derive $c_k = x$, $\frac{c}{k} = x$, and $\frac{c_k}{c} = k^{-1}$. It is worth to remark that

$$\frac{E\big(dc\big)}{c\,dt} = \frac{E\big(dk\big)}{dt}\frac{1}{k} = \frac{(1-m)y-c}{k} = (1-m)A - x \tag{7.29}$$

Moreover, choosing $\alpha = 1$, and substituting into Eq.(7.28), we obtain the following:

$$\frac{E\big(dc\big)}{c\,dt} = \frac{1}{\epsilon}\Big\{(1-m)A+\frac{1}{2}\beta(\beta-1)(\delta q)^2-\rho-\frac{1}{2}\sigma^2\epsilon(1-\epsilon)+\big[1-\epsilon\beta\big]\sigma\rho_{kh}(\delta q)\Big\} \tag{7.30}$$

Substituting Eq.(7.29) into Eq.(7.30), we obtain x_t as follows.

$$x_t = \frac{1}{\epsilon}\Big\{\rho-(1-\epsilon)(1-m)A-\frac{1}{2}\beta(\beta-1)\delta^2\big[(\phi-\mu\,m)A\big]^2$$
$$+\frac{1}{2}\epsilon(1-\epsilon)\sigma^2-(1-\epsilon\beta)\sigma\rho_{kh}\delta\big[(\phi-\mu m)A\big]\Big\} \tag{7.31}$$
$$:= \frac{1}{\epsilon}\Big\{\rho-(1-\epsilon)(1-m)A-\frac{1}{2}\beta(\beta-1)\delta^2\big[(\phi-\mu\,m)A\big]^2+\mathrm{Sx}\Big\} \tag{7.32}$$

where $\mathrm{Sx} = \frac{1}{2}\epsilon(1-\epsilon)\sigma^2-(1-\epsilon\beta)\sigma\rho_{kh}\delta\big[(\phi-\mu m)A\big]$ stands for shock effect on x_t. Recalling $V(k,h) = \frac{(x\,k)^{1-\epsilon}}{1-\epsilon}h^{\beta}$ and substituting into Eq.(7.6), we obtain the following equalities.

$$0 = -1+\frac{\rho(\beta-1)}{1-\epsilon}\delta^2(\phi-\mu m)A(-\mu)+\beta\sigma\delta(-\mu)\rho_{kh} \tag{7.33}$$

Therefore, we have the optimal m as follows:

$$m^* = \underbrace{\frac{\phi}{\mu}-\frac{1-\epsilon}{A\beta(1-\beta)(\mu\delta)^2}}_{\text{mitigation overall}}-\underbrace{\frac{(1-\epsilon)\beta\sigma\delta\mu\rho_{kh}}{A\beta(1-\beta)(\mu\delta)^2}}_{\text{``shock'' as mitigation}} \tag{7.34}$$

Moreover, subsisting Eq.(7.34) into Eq.(4.3) we obtain optimal q as follows:

$$q^* = \frac{(1-\epsilon)(1+\beta\sigma\delta\mu\rho_{kh})}{\beta(1-\beta)\mu\delta^2} \tag{7.35}$$

Substituting Eqs.(7.34) and (7.35) into Eq.(7.31), we obtain the optimal x as follows:

$$\begin{aligned} x^* &= \frac{1}{\epsilon}\Big\{\rho - (1-\epsilon)(1-m^*)A - \frac{1}{2}\beta(\beta-1)(\delta q^*)^2 + \frac{1}{2}\epsilon(1-\epsilon)\sigma^2 - (1-\epsilon\beta)\sigma\rho_{kh}\delta q^*\Big\} \\ &= \frac{1}{\epsilon}\Big\{\rho - (1-\epsilon)(1-\frac{\phi}{\mu})A - \frac{(1-\epsilon)(1+\beta\sigma\delta\mu\rho_{kh})}{\beta(1-\beta)(\mu\delta)^2}\Big[\frac{1}{2}(1-\epsilon) \\ &\quad +\Big(1-\frac{1}{2}(1+\epsilon)\beta\Big)\sigma\delta\mu\rho_{kh}\Big] + \frac{1}{2}\epsilon(1-\epsilon)\sigma^2\Big\} \end{aligned} \tag{7.36}$$

Substituting Eqs.(7.34) and (7.35) into Eq.(7.30), we obtain dynamics of optimal consumption as follows:

$$\begin{aligned} g^* = \frac{E\big(dc\big)}{c\,dt} &= \frac{1}{\epsilon}\Big\{\Big(1-\frac{\phi}{\mu}\Big)A + \frac{(1-\epsilon)(1+\beta\sigma\delta\mu\rho_{kh})}{\beta(1-\beta)(\mu\delta)^2}\Big[\frac{1}{2}(1+\epsilon) \\ &\quad +\Big(1-\frac{1}{2}(1+\epsilon)\beta\Big)\sigma\delta\mu\rho_{kh}\Big] - \rho - \frac{1}{2}\epsilon(1-\epsilon)\sigma^2\Big\} \end{aligned} \tag{7.37}$$

7.2 Appendix B: The Analytical Treatment on Extended Model under Poisson Uncertainty

Applying Ito's lemma with Jumps for $V(k,h)$, we obtain the following equation:

$$dV(k,h) = \big[(1-m_t)y - c\big]\frac{\partial V(k,h)}{\partial k}dt + \sigma k\frac{\partial V(k,h)}{\partial k}dZ_{k,t} + R(q_t)h_t\frac{\partial V(k,h)}{\partial h}dZ_{h,t}$$
$$+\frac{1}{2}\left\{\frac{\partial^2 V(k,h)}{\partial k^2}(\sigma k)^2 + \frac{\partial^2 V(k,h)}{\partial h^2}(R(q)h)^2 + 2\frac{\partial^2 V(k,h)}{\partial k\partial h}\sigma k R(q)h\right\}dt$$
$$+\Big[V(\tilde{k},h) - V(k,h)\Big]dN_{c,t} + \Big[V(k,\tilde{h}) - V(k,h)\Big]dN_{c,t} + \Big[V(k,\tilde{\tilde{h}}) - V(k,h)\Big]dN_{e,t} \quad (7.38)$$

where $\tilde{k} = k(1-\xi)$, $\tilde{h} = h\big[1-D_c(q)\big]$ and $\tilde{\tilde{h}} = h\big[1-D_e(q)\big]$. Calculating the expectation, we have:

$$\frac{1}{dt}\mathrm{E}\big[dV(k,h)\big] = V_k(k,h)\big[(1-m)y - c\big] + \frac{1}{2}\Big[V_{kk}(k,h)\sigma^2k^2 + V_{hh}(k,h)R^2(q)h^2$$
$$+2V_{kh}(k,h)\sigma k R(q)h\rho_{k,h}\Big] + \left\{\Big[V(\tilde{k},h) - V(k,h)\Big] + \Big[V(k,\tilde{h}) - V(k,h)\Big]\right\}\lambda_c$$
$$+\Big[V(k,\tilde{\tilde{h}}) - V(k,h)\Big]\lambda_e \quad (7.39)$$

For simplifying denotion, we define $V^{\tilde{k}} = V(\tilde{k},h)$, $V^{\tilde{h}} = V(k,\tilde{h})$ and $V^{\tilde{\tilde{h}}} = V(k,\tilde{\tilde{h}})$. Substituting Eq.(7.39) into Eq.(7.40), we obtain:

$$\rho V(k,h) = \max_{c,h}\Big\{U(c,h) + V_k\big[(1-m)y - c\big] + \frac{1}{2}\Big[V_{kk}\sigma^2k^2 + V_{hh}R^2(q)h^2 +$$
$$2V_{kh}\sigma k R(q)h\rho_{k,h}\Big] + \lambda_c\Big[\Big(V^{\tilde{k}} - V\Big) + \Big(V^{\tilde{h}} - V\Big)\Big] + \lambda_e\Big(V^{\tilde{\tilde{h}}} - V\Big)\Big\} \quad (7.40)$$

Hereby, we focus on the first order conditions (F.O.C.) as follows.

For consumption c :

$$\frac{\partial U(c,h)}{\partial c} - V_k(k,h) = 0\,, \quad \text{i.e.}\, U_c = V_k \quad (7.41)$$

For abatement policy m :

$$V_k\, y_t = V_{hh}R(q)R'(q)q'(m)h^2 + V_{kh}\sigma R'(q)q'(m)kh\rho_{kh} + \lambda_c\, V_{\tilde{h}}^{\tilde{h}}\frac{\partial\tilde{h}}{\partial m}$$
$$+\lambda_e V_{\tilde{\tilde{h}}}^{\tilde{\tilde{h}}}\frac{\partial\tilde{\tilde{h}}}{\partial m} \quad (7.42)$$

where $V_{\tilde{h}}^{\tilde{h}} := \dfrac{\partial V^{\tilde{h}}}{\partial \tilde{h}} = \dfrac{\partial V(k, \tilde{h})}{\partial \tilde{h}} = V_h(k, h) \mid_{h=\tilde{h}}$ and $\tilde{V}_{\tilde{\tilde{h}}}^{\tilde{\tilde{h}}} := \dfrac{\partial V(k, \tilde{\tilde{h}})}{\partial \tilde{\tilde{h}}} =$ $V_h(k, h) \mid_{h=\tilde{\tilde{h}}}$. Moreover, based on the definition of $\tilde{h}\,, \tilde{\tilde{h}}$ and $q'(m) = -\mu A$, we have:

$$\frac{\partial \tilde{h}}{\partial m} = h\big(- D_c'(q)\big) q'(m) = -\mu A\, D_c'(q)\, h \tag{7.43}$$

and

$$\frac{\partial \tilde{\tilde{h}}}{\partial m} = h\big(- D_e'(q)\big) q'(m) = -\mu A\, D_e'(q)\, h \tag{7.44}$$

Substituting Eqs.(7.43) and (7.44) into Eq(7.42), we obtain the following:

$$\begin{aligned} &\frac{1}{\mu A} V_k\, y_t \\ &= -V_{hh} R(q) R'(q) h^2 - V_{kh} \sigma R'(q) k h \rho_{kh} + \Big(\lambda_c\, V_{\tilde{h}}^{\tilde{h}} D_c'(q) + \lambda_e V_{\tilde{\tilde{h}}}^{\tilde{\tilde{h}}} D_e'(q)\Big) h \end{aligned} \tag{7.45}$$

For capital stock k :

$$\begin{aligned} \rho V_k &= V_{kk}\big[(1-m)y - c\big] + V_k(1-m)A + \frac{1}{2}\Big[V_{kkk}\sigma^2 k^2 + 2\sigma^2 V_{kk} k + V_{hhk} R^2(q) h^2 \\ &+ 2\rho_{kh}\sigma V_{khk} R(q) hk + 2\sigma \rho_{kh} V_{kh} R(q) h\Big] + \lambda_c\Big[\big(V_k^{\tilde{k}} - V_k\big) + \big(V_k^{\tilde{h}} - V_k\big)\Big] + \lambda_e\big(V_k^{\tilde{\tilde{h}}} - V_k\big) \end{aligned} \tag{7.46}$$

where

$$V_k^{\tilde{k}} := \frac{\partial V(\tilde{k}, h)}{\partial k} = \frac{\partial V(\tilde{k}, h)}{\partial \tilde{k}} \frac{\partial \tilde{k}}{\partial k} = V_{\tilde{k}}^{\tilde{k}}\,(1-\xi) \tag{7.47}$$

$$V_k^{\tilde{h}} := \frac{\partial V(k, \tilde{h})}{\partial k} = V_k(k, h) \mid_{h=\tilde{h}} \tag{7.48}$$

$$V_k^{\tilde{\tilde{h}}} := \frac{\partial V(k, \tilde{\tilde{h}})}{\partial k} = V_k(k, h) \mid_{h=\tilde{\tilde{h}}} \tag{7.49}$$

with $V_{\tilde{k}}^{\tilde{k}} = \dfrac{\partial V(\tilde{k}, h)}{\partial \tilde{k}} = V_k(k, h) \mid_{k=\tilde{k}}$ and $\dfrac{\partial \tilde{k}}{\partial k} = 1 - \xi\,.$

For health status h :

$$\begin{aligned} \rho V_h &= U_h + V_{kh}[(1-m)y - c] + \frac{1}{2}\Big[V_{kkh}\sigma^2 k^2 + V_{hhh} R^2(q) h^{2\alpha} + 2V_{hh} R^2(q) h^2 \\ &+ 2\sigma V_{khh} R(q) kh \rho_{kh} + 2\sigma V_{kh} R(q) k \rho_{kh}\Big] + \lambda_c\Big[\big(V_h^{\tilde{k}} - V_h\big) + \big(V_h^{\tilde{h}} - V_h\big)\Big] + \lambda_e\big(V_h^{\tilde{\tilde{h}}} - V_h\big) \end{aligned} \tag{7.50}$$

where

$$V_h^{\tilde{k}} := \frac{\partial V(\tilde{k}, h)}{\partial h} = V_h(k, h) \mid_{k=\tilde{k}} \tag{7.51}$$

$$V_h^{\tilde{h}} := \frac{\partial V(k, \tilde{h})}{\partial h} = \frac{\partial V(k, \tilde{h})}{\partial \tilde{h}} \frac{\partial \tilde{h}}{\partial h} = V_{\tilde{h}}^{\tilde{h}} (1 - D^c(q)) \tag{7.52}$$

$$V_h^{\tilde{\tilde{h}}} := \frac{\partial V(k, \tilde{\tilde{h}})}{\partial h} = \frac{\partial V(k, \tilde{\tilde{h}})}{\partial \tilde{\tilde{h}}} \frac{\partial \tilde{\tilde{h}}}{\partial h} = V_{\tilde{\tilde{h}}}^{\tilde{\tilde{h}}} (1 - D^e(q)) \tag{7.53}$$

with $V_{\tilde{h}}^{\tilde{h}} = \dfrac{\partial V(k, \tilde{h})}{\partial \tilde{h}} = V_h(k, h) \mid_{h=\tilde{h}}$, $\dfrac{\partial \tilde{h}}{\partial h} = 1 - D^c(q)$ and $V_{\tilde{\tilde{h}}}^{\tilde{\tilde{h}}} = \dfrac{\partial V(k, \tilde{\tilde{h}})}{\partial \tilde{\tilde{h}}} = V_h(k, h) \mid_{h=\tilde{\tilde{h}}}$, $\dfrac{\partial \tilde{\tilde{h}}}{\partial h} = 1 - D^e(q)$.

Analytical Treatment for Optimal Growth Path

In this section, we focus on the optimal growth rate of consumption. Combining capital stock and health dynamics in Eqs.(5.1) and (5.2), and applying the Ito's Lemma with jump to V_k, the optimality conditions of consumption defined in Eq.(4.16), we obtain the stochastic process of dV_k as follows:

$$dV_k = \left\{ V_{kk} \big[(1-m)y - c \big] + \frac{1}{2} \Big[V_{kkk} \sigma^2 k^2 + V_{khh} R^2(q) h^2 + 2\sigma \rho_{kh} V_{kkh} R(q) k\, h \Big] \right\} dt$$
$$+ V_{kk} \sigma k dZ_{k,t} + V_{kh} R(q) h dZ_{h,t} + \Big[\big(V_k \mid_{k=\tilde{k}} - V_k \big) + \big(V_k \mid_{h=\tilde{h}} - V_k \big) \Big] dN_{c,t} + \tag{7.54}$$

It is worth to remark that, based on our previous definition, $V_k \mid_{k=\tilde{k}} = V_{\tilde{k}}^{\tilde{k}}$, $V_k \mid_{h=\tilde{h}} = V_k^{\tilde{h}}$ and $V_k \mid_{h=\tilde{\tilde{h}}} = V_k^{\tilde{\tilde{h}}}$. Using Eq.(7.54)-(7.46)$\cdot dt$, we obtain:

$$\frac{d\,V_k}{V_k} = \left\{ \rho - (1-m)A - \left[\sigma^2 \frac{V_{kk}}{V_k} k + \sigma \rho_{kh} \frac{V_{kh}}{V_k} R(q) h \right] - \lambda_c \left[\left(\frac{V_k^{\tilde{k}}}{V_k} - 1 \right) + \left(\frac{V_k^{\tilde{h}}}{V_k} - 1 \right) \right] \right.$$
$$\left. - \lambda_e \left(\frac{V_k^{\tilde{\tilde{h}}}}{V_k} - 1 \right) \right\} dt + \frac{V_{kk}}{V_k} \sigma k dZ_k + \frac{V_{kh}}{V_k} R(q) h dZ_h + \left[\left(\frac{V_{\tilde{k}}^{\tilde{k}}}{V_k} - 1 \right) + \left(\frac{V_k^{\tilde{h}}}{V_k} - 1 \right) \right] dN_{c,t}$$
$$+ \left(\frac{V_k^{\tilde{\tilde{h}}}}{V_k} - 1 \right) dN_{e,t} \tag{7.55}$$

It is worth nothing that from Eq.(5.10), we obtain $U_c(c,h) = c^{-\epsilon}h^{\tilde{\beta}}$. In other words, $c(U_c,h) = U_c^{-\frac{1}{\epsilon}}h^{\frac{\tilde{\beta}}{\epsilon}}$. From optimality consumption in Eq.(5.5), we have $c(U_c,h) = c(V_k,h) = V_k^{-\frac{1}{\epsilon}}h^{\frac{\tilde{\beta}}{\epsilon}}$. Applying Ito's lemma with jump to $c(U_c,h)$, we obtain:

$$dc = \frac{\partial c}{\partial U_c}\Xi + \frac{\partial c}{\partial h}R(q)h_t dZ_{h,t} + \frac{1}{2}\Bigg\{\frac{\partial^2 c}{\partial U_c^2}\Big(V_{kk}^2\sigma^2k^2 + V_{kh}^2R^2(q)h^2 + 2V_{kk}V_{kh}\sigma R(q)kh\Big)$$
$$+\frac{\partial^2 c}{\partial h^2}R^2(q)h^2 + 2\frac{\partial^2 c}{\partial U_c \partial h}\Big(V_{kk}\sigma\rho_{kh}R(q)kh + V_{kk}R^2(q)h^2\Big)\Bigg\}dt + \Big[\Big(c^{\tilde{U}_c} - c\Big) + \Big(c^{\tilde{h}} - c\Big)$$
$$\Big]dN_{c,t} + \Big[\Big(c^{\tilde{\tilde{U}}_c} - c\Big) + \Big(c^{\tilde{\tilde{h}}} - c\Big)\Big]dN_{e,t} \tag{7.56}$$

where

$$\Xi = V_k\Bigg\{\rho - (1-m)A - \Big[\sigma^2\frac{V_{kk}}{V_k}k + \sigma\rho_{kh}\frac{V_{kh}}{V_k}R(q)h\Big] - \lambda_c\Big[\Big(\frac{V_k^{\tilde{k}}}{V_k} - 1\Big) + \Big(\frac{V_k^{\tilde{h}}}{V_k} - 1\Big)\Big]$$
$$-\lambda_e\Big(\frac{V_k^{\tilde{\tilde{h}}}}{V_k} - 1\Big)\Bigg\}dt \tag{7.57}$$

$$c^{\tilde{U}_c} = c(\tilde{U}_c, h) = c(\tilde{V}_k, h) = c(V_k + \varrho_c^{U_c}V_k, h)\,, \tag{7.58}$$
$$\text{with } \varrho_c^{U_c} = \Big(\frac{V_{\tilde{k}}^{\tilde{k}}}{V_k} - 1\Big) + \Big(\frac{V_k^{\tilde{h}}}{V_k} - 1\Big)$$
$$c^{\tilde{\tilde{U}}_c} = c(\tilde{\tilde{U}}_c, h) = c(\tilde{\tilde{V}}_k, h) = c(V_k + \varrho_e^{U_c}V_k, h)\,, \text{with } \varrho_e^{U_c} = \Big(\frac{V_k^{\tilde{\tilde{h}}}}{V_k} - 1\Big) \tag{7.59}$$
$$c^{\tilde{h}} = c(U_c, \tilde{h}) = c(V_k, \tilde{h}) = c(V_k, h + \varrho_c^h h)\,, \text{with } \varrho_c^h = -D_c(q) \tag{7.60}$$
$$c^{\tilde{\tilde{h}}} = c(U_c, \tilde{\tilde{h}}) = c(V_k, \tilde{\tilde{h}}) = c(V_k, h + \varrho_e^h h)\,, \text{with } \varrho_e^h = -D_e(q) \tag{7.61}$$

Based on the previous definitions, the following results are remarkable.

$$\frac{V_{\tilde{k}}^{\tilde{k}}}{V_k} = \Big(\frac{\tilde{k}}{k}\Big)^{-\epsilon} = \big(1 - \xi\big)^{-\epsilon} \tag{7.62}$$
$$\frac{V_k^{\tilde{h}}}{V_k} = \Big(\frac{\tilde{h}}{h}\Big)^{-\epsilon} = \Big(1 - D_c(q)\Big)^{\tilde{\beta}} \tag{7.63}$$
$$\frac{V_k^{\tilde{\tilde{h}}}}{V_k} = \Big(\frac{\tilde{\tilde{h}}}{h}\Big)^{-\epsilon} = \Big(1 - D_e(q)\Big)^{\tilde{\beta}} \tag{7.64}$$

Furthermore, we have

$$\frac{c^{\tilde{U}_c}}{c} = \left(\frac{\tilde{V}_k}{V_k}\right)^{-\frac{1}{\epsilon}} = \left[1 + \left(\left(1-\xi\right)^{-\epsilon} - 1\right) + \left(\left(1 - D_c(q)\right)^{\tilde{\beta}} - 1\right)\right]^{-\frac{1}{\epsilon}} \tag{7.65}$$

$$\frac{c^{\tilde{h}}}{c} = \left(\frac{\tilde{h}}{h}\right)^{\frac{\tilde{\beta}}{\epsilon}} = \left(1 - D_c(q)\right)^{\frac{\tilde{\beta}}{\epsilon}} \tag{7.66}$$

$$\frac{c_c^{\tilde{\tilde{U}}_c}}{c} = \left(\frac{\tilde{\tilde{V}}_k}{V_k}\right)^{-\frac{1}{\epsilon}} = \left(1 + \varrho_e^{U_c}\right)^{-\frac{1}{\epsilon}} = \left(1 - D_e(q)\right)^{-\frac{\tilde{\beta}}{\epsilon}} \tag{7.67}$$

$$\frac{c^{\tilde{\tilde{h}}}}{c} = \left(\frac{\tilde{\tilde{h}}}{h}\right)^{\frac{\tilde{\beta}}{\epsilon}} = \left(1 - D_e(q)\right)^{\frac{\tilde{\beta}}{\epsilon}} \tag{7.68}$$

Substituting Eqs.(7.65)-(7.68) into Eq.(7.56), we have the optimal growth path of consumption as follows:

$$\tilde{g}^* := \frac{E\big(dc\big)}{dc} = g^* + \lambda_c \Gamma_c(q) + \lambda_e \Gamma_e(q) \tag{7.69}$$

where g^* is defined in Eq.(4.29), and

$$\Gamma_c(q) = \frac{1}{\epsilon}\left(\left[\left(1-\xi\right)^{1-\epsilon} - 1\right] + \left[\left(1 - D_c(q)\right)^{\tilde{\beta}} - 1\right]\right) + \left(1 + \left[\left(1-\xi\right)^{-\epsilon} - 1\right]\right.$$
$$\left. + \left[\left(1 - D_c(q)\right)^{\tilde{\beta}} - 1\right]\right)^{-\frac{1}{\epsilon}} - 1 + \left[\left(1 - D_c(q)\right)^{\frac{\tilde{\beta}}{\epsilon}} - 1\right] \tag{7.70}$$

$$\Gamma_e(q) = \frac{1}{\epsilon}\left[\left(1 - D_c(q)\right)^{\tilde{\beta}} - 1\right] + \left(1 - D_e(q)\right)^{-\frac{\tilde{\beta}}{\epsilon}} - 1 + \left(1 - D_e(q)\right)^{\frac{\tilde{\beta}}{\epsilon}} - 1 \tag{7.71}$$

We are interested in the sign of Eqs.(5.21) and (5.22). Let us firstly check Eq.(5.21):

$$\Gamma_c(q) = \underbrace{\frac{1}{\epsilon}\left(\left[\left(1-\xi\right)^{1-\epsilon} - 1\right] + \left[\left(1 - D_c(q)\right)^{\tilde{\beta}} - 1\right]\right)}_{<0} + \underbrace{\left[\left(1 - D_c(q)\right)^{\frac{\tilde{\beta}}{\epsilon}} - 1\right]}_{<0}$$
$$+ \underbrace{\left(1 + \left[\left(1-\xi\right)^{-\epsilon} - 1\right] + \left[\left(1 - D_c(q)\right)^{\tilde{\beta}} - 1\right]\right)^{-\frac{1}{\epsilon}} - 1}_{\gtreqless 0} \tag{7.72}$$

Let us denote $\Delta_c = \left(1 + \underbrace{\left[\left(1-\xi\right)^{-\epsilon} - 1\right]}_{>0} + \underbrace{\left[\left(1 - D_c(q)\right)^{\tilde{\beta}} - 1\right]}_{<0}\right)^{-\frac{1}{\epsilon}} - 1$, and a sufficient condition for $\Delta_c \leq 0$ is $\left[\left(1-\xi\right)^{-\epsilon} - 1\right] + \left[\left(1 - D_c(q)\right)^{\tilde{\beta}} - 1\right] \geq 0$.

Hence, $0 \leq q \leq \frac{1}{\eta}\Big[1-\big(2-\big(1-\xi\big)^{-\epsilon}\big)^{\frac{1}{\tilde{\beta}}}\Big]$. The intuition behind this result is that for a small q e.g. around zero, Γ_c is negative. Rearranging the polynomials in Eq.(5.22), we have:

$$\Gamma_e(q) = \underbrace{\frac{1}{\epsilon}\Big[\big(1-D_c(q)\big)^{\tilde{\beta}}-1\Big]}_{<0} + \underbrace{\Big[\big(1-D_e(q)\big)^{-\frac{\tilde{\beta}}{\epsilon}}-1\Big]\Big[1-\big(1-D_e(q)\big)^{\frac{\tilde{\beta}}{\epsilon}}\Big]}_{>0} \tag{7.73}$$

Therefore

$$\begin{aligned}
&\underbrace{\frac{1}{\epsilon}\Big[\big(1-D_c(q)\big)^{\tilde{\beta}}-1\Big]}_{<0} + \underbrace{\Big[\big(1-D_e(q)\big)^{-\frac{\tilde{\beta}}{\epsilon}}-1\Big]}_{>0}\underbrace{\Big[1-\big(1-D_e(q)\big)^{\frac{\tilde{\beta}}{\epsilon}}\Big]}_{>0} < 0 \\
&\Leftrightarrow \Big[\big(1-D_e(q)\big)^{-\frac{\tilde{\beta}}{\epsilon}}-1\Big] \leq \frac{1}{\epsilon}\frac{\Big[1-\big(1-D_c(q)\big)^{\tilde{\beta}}\Big]}{\Big[1-\big(1-D_e(q)\big)^{\frac{\tilde{\beta}}{\epsilon}}\Big]}
\end{aligned} \tag{7.74}$$

where $\frac{\Big[1-\big(1-D_c(q)\big)^{\tilde{\beta}}\Big]}{\Big[1-\big(1-D_e(q)\big)^{\frac{\tilde{\beta}}{\epsilon}}\Big]} \leq 1$, hence a sufficient condition for $\Gamma_e(q) < 0$ is $0 \leq q \leq \frac{1}{\eta_e}\Big[1-\big(1+\frac{1}{\epsilon}\big)^{-\frac{\epsilon}{\tilde{\beta}}}\Big]$. This indicates that for a small q around origin leads a negative $\Gamma_e(q) < 0$. Hence both the frequencies of nature disaster λ_c and epidemic λ_e place a direct negative effect on the growth rate $\tilde{g}^*$, since from Eq.(5.5) we have $\Gamma_c = \frac{\partial \tilde{g}^*}{\partial \lambda_c}$, $\Gamma_e = \frac{\partial \tilde{g}^*}{\partial \lambda_e}$.
Moreover, a more convenient approach to illustrate our previous argument can be linearisation. Indeed, we can approximate Γ_c and Γ_e using a first-order Taylor expansion around $q = 0$ as follows:

$$\big(1-D_c(q)\big)^{\tilde{\beta}} \doteq 1-\tilde{\beta}\eta_c q\,, \quad \text{where}\, D_c(q) = \eta_c q \tag{7.75}$$

$$\big(1-D_e(q)\big)^{\tilde{\beta}} \doteq 1-\tilde{\beta}\eta_e q\,, \quad \text{where}\, D_e(q) = \eta_e q\,. \tag{7.76}$$

Thanks to Eqs.(7.75)-(7.76), we obtain the sign of Eqs.(5.21) and (5.22) around its origin :

$$\begin{aligned}\Gamma_c(q) &< \frac{1}{\epsilon}\Bigg(\Big[\big(1-\xi\big)^{1-\epsilon}-1\Big]+\Big[\big(1-D_c(q)\big)^{\tilde{\beta}}-1\Big]\Bigg)+\big(1-D_c(q)\big)^{-\frac{\tilde{\beta}}{\epsilon}}-1\\ &\quad+\Big[\big(1-D_c(q)\big)^{\frac{\tilde{\beta}}{\epsilon}}-1\Big]\\ &\doteq \frac{1}{\epsilon}\Bigg(\Big[\big(1-\xi\big)^{1-\epsilon}-1\Big]+\Big[\big(1-D_c(q)\big)^{\tilde{\beta}}-1\Big]\Bigg)<0 \qquad (7.77)\end{aligned}$$

$$\Gamma_e(q) \doteq \frac{1}{\epsilon}\big(1-D_e(q)\big)^{\tilde{\beta}}-1<0 \qquad (7.78)$$

7.3 Appendix C: Analytical Treatment on Benchmark Model Optimization-Exogenous Preference

Let us consider the following Lagrange function w.r.t Eqs.(6.5) and (6.12). Not surprisingly, maximization problem changes nothing if we apply log-transform to the objective function in Eq.(6.5).

$$\begin{aligned} L &= \ln\tilde{U}(c, m_w, m_c, s; \gamma) + \lambda\big(\tilde{y} - c - E(M)\big) \\ &= \Big\{\alpha \ln c + \frac{\beta(1-\gamma)}{\rho}\ln\Big(\theta\, m_w^{\rho} + (1-\theta)m_c^{\theta}\Big) + (1-\beta)(1-\gamma)\ln s\Big\} + \lambda\Big\{\tilde{y} - c \\ &\quad - \big[b_w(p_w m_w - d) + d\big]\theta - \big[b_c(p_c m_c - d) + d\big](1-\theta)\Big\} \quad \theta \in (0,1) \end{aligned} \tag{7.79}$$

First order condition (F.O.C) will gives us the following:

$$\frac{\partial L}{\partial c} = 0 \Rightarrow c = \frac{\alpha}{\lambda} \tag{7.80}$$

$$\frac{\partial L}{\partial m_w} = 0 \Rightarrow \frac{\beta(1-\gamma)}{\rho}\frac{\theta\rho m_w^{\rho-1}}{\theta m_w^{\rho} + (1-\theta)m_c^{\rho}} = \lambda b_w p_w \theta \tag{7.81}$$

$$\frac{\partial L}{\partial m_c} = 0 \Rightarrow \frac{\beta(1-\gamma)}{\rho}\frac{(1-\theta)\rho m_c^{\rho-1}}{\theta m_w^{\rho} + (1-\theta)m_c^{\rho}} = \lambda b_c p_c (1-\theta) \tag{7.82}$$

Substituting Eq.(7.82) into Eq.(7.81) and delete λ, we obtain the following:

$$\frac{m_w}{m_c} = \left[\frac{b_c p_c}{b_w p_w}\right]^{\frac{1}{1-\rho}} \tag{7.83}$$

Substituting Eq.(7.83)into Eqs.(7.81) and (7.82), we obtain the following:

$$b_w p_w m_w = \frac{1}{\lambda}\frac{\beta(1-r)}{\theta + (1-\theta)\left[\frac{b_c p_c}{b_w p_w}\right]^{\frac{\rho}{\rho-1}}} \tag{7.84}$$

and

$$b_c p_c m_c = \frac{1}{\lambda}\frac{\beta(1-r)}{(1-\theta) + \theta\left[\frac{b_w p_w}{b_c p_c}\right]^{\frac{\rho}{\rho-1}}} \tag{7.85}$$

Substituting Eqs.(7.80), (7.84) and (7.85) into (6.12), we obtain:

$$\frac{1}{\lambda} = \frac{\tilde{y} - [(1 - b_w d\theta + (1 - b_c)d(1 - \theta))]}{\alpha + \beta(1 - r)} \tag{7.86}$$

Substituting Eq.(7.86) into Eqs.(7.80) (7.84) and (7.85), we obtain:

$$c^* = \frac{\alpha \left\{\tilde{y} - [(1 - b_w)d\theta + (1 - b_c)d(1 - \theta)]\right\}}{\alpha + \beta(1 - r)} \tag{7.87}$$

For $\alpha \neq 0$ and $\theta \neq 0, 1$, we have:

$$c^* = \frac{\tilde{y} - [(1 - b_w)\theta + (1 - b_c)(1 - \theta)]\, d}{1 + \frac{\beta(1-r)}{\alpha}} \tag{7.88}$$

and

$$m_w^* = \frac{\tilde{y} - [(1 - b_w)\theta + (1 - b_c)(1 - \theta)]\, d}{b_w p_w \left[1 + \dfrac{\alpha}{\beta(1 - r)}\right] \left[\theta + (1 - \theta)\left[\dfrac{b_w p_w}{b_c p_c}\right]^{\frac{\rho}{1-\rho}}\right]} \tag{7.89}$$

and

$$m_c^* = \frac{\tilde{y} - [(1 - b_w)\theta + (1 - b_c)(1 - \theta)]\, d}{b_c p_c \left[1 + \dfrac{\alpha}{\beta(1 - r)}\right] \left[(1 - \theta) + \theta\left[\dfrac{b_c p_c}{b_w p_w}\right]^{\frac{\rho}{1-\rho}}\right]} \tag{7.90}$$

Substituting Eqs.(7.87) (7.89) and (7.90) into utility function in Eq.(6.5), we obtain individual's welfare function as follows.

$$\begin{aligned}\tilde{U}(c, m_w, m_c, s; \gamma) &= \Lambda \left[\frac{\left(\Psi_c + \Psi_w\right)^{\frac{1-\rho}{\rho}}}{b_w p_w b_c p_c}\right]^{\beta(1-\gamma)} s^{(1-\beta)(1-\gamma)}\, \tilde{\tilde{y}}^{\,\alpha+\beta(1-\gamma)} \\ &= \Lambda \left[\theta(b_w p_w)^{\frac{-\rho}{1-\rho}} + (1 - \theta)(b_c p_c)^{\frac{-\rho}{1-\rho}}\right]^{\beta(1-\gamma)} s^{(1-\beta)(1-\gamma)}\, \tilde{\tilde{y}}^{\,\alpha+\beta(1-\gamma)}\end{aligned} \tag{7.91}$$

where $\Lambda = \dfrac{\alpha^{\alpha}\left[\beta(1 - \gamma)\right]^{\beta(1-\gamma)}}{\left[\alpha + \beta(1 - r)\right]^{\alpha+\beta(1-\gamma)}}$

7.4 Appendix D: Analytical Treatment on the Generalized Optimization Problem-Endogenous Preference

Let us consider the following Lagrange function w.r.t Eqs.(6.67) and (6.65). Obviously, maximization problem changes nothing if we apply log-transform to the objective function in Eq.(6.67).

$$\mathcal{L}(c, m_w, m_c) = \ln\tilde{U}(c, m_w, m_c, s; \gamma) + \lambda\big(\tilde{y} - c - E(M)\big)$$
$$= \left\{\alpha \ln c + \frac{\beta(1-\gamma)}{\rho}\ln\Big(\nu(\theta)\, m_w^{\rho} + (1-\nu(\theta))m_c^{\theta}\Big) + (1-\beta)(1-\gamma)\ln s\right\} +$$
$$\lambda\left\{\tilde{y} - c - \big[b_w(p_w m_w - d_w) + d_w\big]\theta - \big[b_c(p_c m_c - d_c) + d_c\big](1-\theta)\right\} \quad \theta \in (0,1) \tag{7.92}$$

First order condition (F.O.C) will gives us the following optimal conditions:

$$\frac{\partial \mathcal{L}}{\partial c} = 0 \Rightarrow c = \frac{\alpha}{\lambda} \tag{7.93}$$

$$\frac{\partial \mathcal{L}}{\partial m_w} = 0 \Rightarrow \frac{\beta(1-\gamma)}{\rho}\frac{\nu(\theta)\rho m_w^{\rho-1}}{\nu(\theta)m_w^{\rho} + (1-\nu(\theta))m_c^{\rho}} = \lambda b_w p_w \theta \tag{7.94}$$

$$\frac{\partial \mathcal{L}}{\partial m_c} = 0 \Rightarrow \frac{\beta(1-\gamma)}{\rho}\frac{(1-\nu(\theta))\rho m_c^{\rho-1}}{\nu(\theta)m_w^{\rho} + (1-\nu(\theta))m_c^{\rho}} = \lambda b_c p_c(1-\theta) \tag{7.95}$$

Substituting Eq.(7.82) into Eq.(7.81) and delete λ, we obtain the following:

$$\frac{m_w}{m_c} = \left[\frac{b_c p_c}{b_w p_w}\frac{1-\theta}{\theta}\frac{\nu(\theta)}{1-\nu(\theta)}\right]^{\frac{1}{1-\rho}} \tag{7.96}$$

It is worth to remark the stylized fact that:
(1) $\frac{p_c}{p_w} \uparrow \Rightarrow \frac{m_w}{m_c} \uparrow$ which implies Chinese Medicine price $p_c \uparrow$(relative to WM) increase, Chinese Medicine demand $m_c \downarrow$ (relative to WM)decrease.
(2)$\theta \uparrow \Rightarrow m_w \uparrow$, preference determine medicine demand.
In order to satisfy property (2), let us assume $\frac{\nu(\theta)}{1-\nu(\theta)} = \left(\frac{\theta}{1-\theta}\right)^q$, $q > 1$. Therefore, $\nu(\theta)$ takes the following form:

$$\nu(\theta) = \frac{\theta^q}{\theta^q + (1-\theta)^q}\,, \; q > 1. \tag{7.97}$$

Obviously, $\nu(\theta)$ defined in Eq.(7.97) lies in $[0,1]$ and a monotonic function of θ. It is worth to remark that in this case, $\frac{1-\theta}{\theta}\frac{\nu(\theta)}{1-\nu(\theta)} = \left(\frac{\theta}{1-\theta}\right)^{q-1}$. In this case, property (2) holds, i.e. $\theta \uparrow \Rightarrow m_w \uparrow$. Therefore, substituting Eq.(7.97) into Eq.(7.96), we obtain

$$\frac{m_w}{m_c} = \left[\frac{b_c p_c}{b_w p_w}\left(\frac{\theta}{1-\theta}\right)^{q-1}\right]^{\frac{1}{1-\rho}} \tag{7.98}$$

Substituting Eq.(7.98)into Eqs.(7.94) and (7.95), we obtain the following:

$$b_w p_w m_w = \frac{1}{\lambda}\cdot\frac{\beta(1-r)}{\theta + \theta^{\frac{1-q}{1-\rho}}(1-\theta)^{\frac{q-\rho}{1-\rho}}\left[\frac{b_w p_w}{b_c p_c}\right]^{\frac{\rho}{1-\rho}}} \tag{7.99}$$

or in another form as follows:

$$b_w p_w m_w = \frac{1}{\lambda}\cdot\frac{\beta(1-r)\theta^{\frac{q-1}{1-\rho}}\big(b_c p_c\big)^{\frac{\rho}{1-\rho}}}{\theta^{\frac{q-\rho}{1-\rho}}\big(b_c p_c\big)^{\frac{\rho}{1-\rho}} + (1-\theta)^{\frac{q-\rho}{1-\rho}}\big(b_w p_w\big)^{\frac{\rho}{1-\rho}}} \tag{7.100}$$

and

$$b_c p_c m_c = \frac{1}{\lambda}\cdot\frac{\beta(1-r)(1-\theta)^{\frac{q-1}{1-\rho}}\big(b_w p_w\big)^{\frac{\rho}{1-\rho}}}{\theta^{\frac{q-\rho}{1-\rho}}\big(b_c p_c\big)^{\frac{\rho}{1-\rho}} + (1-\theta)^{\frac{q-\rho}{1-\rho}}\big(b_w p_w\big)^{\frac{\rho}{1-\rho}}} \tag{7.101}$$

Substituting Eqs.(7.93), (7.100) and (7.101) into (6.65), we obtain:

$$\frac{1}{\lambda} = \frac{y - a(b_w,b_c) - [\theta(1-b_w)d_w + (1-\theta)(1-b_c)d_c)]}{\alpha+\beta(1-r)} \tag{7.102}$$

Substituting Eq.(7.102) into Eqs.(7.93) (7.100) and (7.101), we obtain:

$$c^* = \left[\frac{\alpha}{\alpha+\beta(1-r)}\right]\hat{y} \tag{7.103}$$

where $\hat{y} = y - a(b_w,b_c) - [\theta(1-b_w)d_w + (1-\theta)(1-b_c)d_c)]$ and

$$m_w^* = \left[\frac{\beta(1-r)}{\alpha+\beta(1-r)}\right]\frac{\hat{y}}{\Psi}\hat{m}_w \tag{7.104}$$

where $\hat{m}_w = \theta^{\frac{q-1}{1-\rho}} \big(b_c p_c\big)^{\frac{\rho}{1-\rho}} \big(b_w p_w\big)^{-1}$ and $\Psi = \theta^{\frac{q-\rho}{1-\rho}} \big(b_c p_c\big)^{\frac{\rho}{1-\rho}} + (1-\theta)^{\frac{q-\rho}{1-\rho}} \big(b_w p_w\big)^{\frac{\rho}{1-\rho}}$. Moreover, let us de-composite study further on the above two definition.

$$\Psi(\theta, b_w, b_c, p_w, p_c) = \Psi_c(\theta, b_c, p_c) + \Psi_w(\theta, b_w, p_w)\,, \tag{7.105}$$

$$\text{where } \Psi_c(\theta, b_c, p_c) := \theta^{\frac{q-\rho}{1-\rho}} \big(b_c p_c\big)^{\frac{\rho}{1-\rho}}\,, \text{and } \Psi_w(\theta, b_w, p_w) = (1-\theta)^{\frac{q-\rho}{1-\rho}} \big(b_w p_w\big)^{\frac{\rho}{1-\rho}}\,,$$

$$\hat{m}_w = \Psi_c(\theta, b_c, p_c)(\theta b_w p_w)^{-1}\,. \tag{7.106}$$

Therefore, substituting Eqs.(7.105) and (7.106) into (7.107), we obtain the following form of m_w^*.

$$m_w^* = \left[\frac{\beta(1-r)}{\alpha + \beta(1-r)}\right] \frac{\hat{y} \cdot \Psi_c}{\Psi_c + \Psi_w} \big(\theta b_w p_w\big)^{-1} \tag{7.107}$$

Similarly, let us define $\hat{m}_c = (1-\theta)^{\frac{q-1}{1-\rho}} \big(b_w p_w\big)^{\frac{\rho}{1-\rho}} \big(b_c p_c\big)^{-1} := \Psi_w(\theta, b_w, p_w)(\theta b_c p_c)^{-1}$ and we obtain optimal m_c^* as follows.

$$m_c^* = \left[\frac{\beta(1-r)}{\alpha + \beta(1-r)}\right] \frac{\hat{y}}{\Psi} \hat{m}_c\,, \tag{7.108}$$

$$= \left[\frac{\beta(1-r)}{\alpha + \beta(1-r)}\right] \frac{\hat{y} \cdot \Psi_w}{\Psi_c + \Psi_w} \big(\theta b_c p_c\big)^{-1}\,. \tag{7.109}$$

Substituting Eqs.(7.103) (7.107) and (7.109) into utility function in Eq.(6.67), we obtain individual's welfare function as follows.

$$\tilde{U}(c, m_w, m_c, s; \gamma) = \frac{\alpha^{\alpha} \big[\beta(1-\gamma)\big]^{\beta(1-\gamma)}}{\big[\alpha + \beta(1-r)\big]^{\alpha+\beta(1-\gamma)}} \tilde{\tilde{y}}^{\,\alpha+\beta(1-\gamma)} \big(\Psi_c + \Psi_w\big)^{\frac{\beta(1-\gamma)(1-\rho)}{\rho}}$$
$$\big(b_w p_w b_c p_c\big)^{-\beta(1-r)} \big[\theta^q + (1-\theta)^q\big]^{-\frac{\beta(1-\gamma)}{\rho}} \cdot s^{(1-\beta)(1-\gamma)} \tag{7.110}$$

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