Inextricable complexity of two centuries of demographic changes: A fascinating modeling challenge

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1 Introduction

In over two centuries, the world population has been transformed dramatically, under the effect of considerable changes induced by demographic, economic, technological, medical, epidemiological, political and social revolutions. The age pyramids of ageing developed countries look like "colossus with feet of clay", and the complexity of involved phenomena makes the projection of future developments very difficult, especially since these transitions are unprecedented.
The problem does not lie so much in the lack of data or empirical studies. For several years now, a considerable amount of data have been collected at different levels. A number of international organizations[1] have their own open databases, and national statistical institutes[2] have been releasing more and more data. On top of that, more than fifty public reports are produced each year. The private sector is also very active on these issues, especially pension funds and insurance companies which are strongly exposed to the increase in life expectancy at older ages.
However, the past few years have been marked by a renewed demand for more

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[1] For instance, the United Nations (UN) (unstats.un.org), the World Bank (WB) (data.worldbank.org) or the World Health Organization (WHO) (who.int/gho).
[2] such as the Institut National de la Statistique et des Etudes Economiques (INSEE) and the Institut National d'Etude Demographique (INED) in France, or the Office for National Statistics (ONS) in the United Kingdom.

efficient models. This demand has been motivated by observations of recent demographic trends which seem to be in contradiction with some firmly established ideas. New available data seem to indicate a paradigm shift over the past decades, toward a more complex and individualized world. Countries which had similar mortality experiences until the 1980s now diverge, and a widening of health and mortality gaps inside countries has been reported by a large number of studies. These new trends have been declared as key public issues by several organizations, including the WHO in its latest World report on ageing and health (World Health Organization (2015)), and the National Institute on Aging in the United States which created in 2008 a panel on Understanding Divergent Trends in Longevity in High-Income Countries, leading to the publication of a comprehensive report in National Research Council and Committee on Population (2011).

In the face of the considerable amount of literature, data and points of views concerning the evolution of human longevity and populations in the last two century, we came to the conclusion that it was necessary to highlight a number of key observations to avoid the pitfalls of an overly naive approach.

The goal of this cross-disciplinary survey is to help a modeler of human population dynamics to find a coherent way (for instance by taking into account the whole population dynamics and not only old ages) around this mass of multidisciplinary information. Based on numerous surveys from various academic disciplines and many contradictory readings, we offer a subjective selection of what we believe to be the most important ideas or facts, from a mathematical modeling perspective. As we will not be able to devote the necessary time to each point, we try to illustrate some of our points with examples that will support the intuition about mentioned phenomena. It should be emphasized from the start that if the discussion is greatly enriched by the multidisciplinary nature of the field, the presentation of ideas is also made more difficult, especially for matters of vocabulary. It should also be noted that issues related to medical advances and to the biology of human ageing are dealt with in a very cursory way, as we focus mainly on economic and social issues.

The survey is composed of three main parts which are summarized in the next subsection. The first part deals with the historic demographic transition. The importance of public health is dealt with, with a specific focus on the cholera epidemic outbreaks that took place in France and in the UK during the nineteenth century. Other features of the historic demographic transition are also considered. In particular, we explore the relationship between the economic growth and mortality improvements experienced during the past century.

In the second part of the survey, we examine the implications for population modeling and the key features of this shift in paradigm that have been observed since the 2000s. We first give a brief overview of the so-called demographic transition, and the

move toward the description of increased complexity and diverging trends that have been recently observed, based principally on the experience of developed countries. A special attention is paid to socioeconomic differences in health and mortality.
In the last part of the survey, we give a short review of microsimulation models and agent based models widely used in social sciences, and in particular in demographic applications. We first describe the main components of a dynamic microsimulation exercise to study heterogeneous individual trajectories in order to obtain macro outcomes by aggregation in the form of a data-driven complex model. Then, we present the agent based models which take into account individual interactions for explaining macroscopic regularities.

2 The historic demographic transition

Since the nineteenth century, most countries have experienced a remarkable evolution of their populations, referenced by demographers and economists as the *demographic transition* (Bongaarts (2009)). The historic demographic transition of the developed world[3] began in the nineteenth century and was completed in over a century ($\sim (1850 - 1960)$). This historical process is mainly referred to as "the secular shift in fertility and mortality from high and sharply fluctuating levels to low and relatively stable ones" (Lee and Reher (2011)). These substantial demographic changes caused life expectancy at birth to grow by more than 40 years over the last 150 ans (for instance, life expectancy at birth rose in the United Kingdom and France from about 40 years in the 1870s[4], to respectively 81 and over 82 years in 2013[5]), and the world population to grow from around 1 billion in 1800 to 2.5 billions by 1950 (Bloom and Luca (2016)). The treatment of infectious diseases constituted the vast bulk of the causes that explain the historic fall in mortality. For example, infectious diseases had virtually disappeared by 1971 in England and Wales while they were responsible for 60 percent of deaths in England and Wales in 1848 (Cutler et al. (2006)). The causes of this reduction have been extensively debated. Among the main causes that have been put forward are economic growth, improvement in living standards, education and most importantly social and public health measures (Bloom and Luca (2016), Cutler et al. (2006)). For instance, Cutler and Miller (2005) estimated that the purification of water explained half of the mortality reduction in the US in the first third of the twentieth century.

[3]The historic demographic transition affected most of European countries and countries with European roots (Argentina, Uruguay, the United States, Canada, New Zealand (Reher (2011)).
[4]Cambois et al. (2009), Cutler et al. (2006).
[5] Source: World Bank, (https://data.worldbank.org/indicator/SP.DYN.LE00.IN).

2.1 The cholera pandemic: a starting point of the demographic transition

In order to understand the unprecedented rise of life expectancy during the first half of the twentieth century, one has to go back 50 years which foreshadow the demographic transition. At the beginning of the nineteenth century, the Industrial Revolution led to a total upheaval of society, associated with unbridled urban sprawl and unsanitary living conditions. In Paris, the population doubled from 1800 to 1850 to attain over one million inhabitants (Jardin and Tudesq (1983)), while London grew by 2.5 fold during those 50 years, to attain more than 2 million inhabitants (Chalklin (2001)). In this context, epidemics were frequent and deadly. The cholera pandemic, which struck fear and left indelible marks of blue-black dying faces due to cyanose' on the collective imagination (hence the nickname "blue death"), had the most important social and economic consequences. It is often refered to as an iconic example where medicine was confronted to statistics (Dupaquier and Lewes (1989)) and was regarded as "the real spark which lit the tinder of the budding philanthropic movement, culminating in the social reforms and the foundation of the official public health movement seventeen years later" (Underwood (1948)). The cholera pandemics originated in India and spread to Europe in the 1830s. Four subsequent outbreaks (1831, $1848-1854$, $1866-1867$ and $1888-1889$) mainly affected France and England, causing 102.000 deaths in France in 1832 and 143.000 in the 1850s over a population of 36 million (Haupt and Laroche (1993)). In London, 6536 deaths were reported in 1831 and 14137 deaths during the 1848-1849 cholera outbreak (Underwood (1948)).
In the following paragraphs, we will focus on the cholera outbreaks in France and England, in order to illustrate the profound changes which occured at different levels (city, state and international), and which still give valuable insight on contemporary challenges.

2.1.1 Cholera in England

The intensity of the first cholera outbreak in London in 1831, combined with the growing influence of advocates of public health, brought to light the need for public measures to improve sanitation. At that time, a lot of reformers considered that statistics were a prerequisite for any intervention, and the enthusiasm in the field expanded very quickly, which is somehow reminiscent of the current craze for data science.
In this context, the General Register Office (G.R.O) was created in 1836, with the aim of centralizing vital statistics. England and Wales were divided in 2193 registration sub districts, administered by qualified registrars (often doctors). In charge

of compiling data from registration districts, W. Farr served as statistical superintendent from 1839 to 1880 and became "the architect of England's national system of vital statistics" (Eyler (1973)). The precise mortality data collected by the G.R.O during cholera outbreaks turned out to be instrumental in the analysis of the disease.

In his pioneering *Report on the Mortality of Cholera in England, 1848-49* (Farr (1852)), Farr and the G.R.O produced almost four hundred pages of statistics. His main finding, based on the collected data of the 1848-49 outbreak, was the existence of an inverse relationship between cholera mortality rates and the elevation of registration districts above the Thames. Farr was particularly pleased with this statistical law, since it validated his beliefs in the prevailing miasmatic theories, which predicted that the passing on of the disease was airborne. It was actually J. Snow who first claimed that cholera communication was waterborne, with his famous experiment of the Broad street pump (Brody et al. (2000)). However, Farr's statistics were decisive in supporting and validating his theory.

Although Snow's theory was not widely accepted, he contributed to raising the issue of water quality. Under the impulsion of the General Board of Health created in 1848, the Metropolis Water Act of 1852 introduced for the first time regulations for (private) water supply companies, to take effect by 1855. At the time of the 1853-54 cholera outbreak, Farr found out that only one company had complied with the new regulations, and that in a number of districts, it was competing with another company drawing water from a highly polluted area. The perfect conditions for a full-scale experiment were brought together, and Farr and Snow joined their investigations to conclude that without doubt, water played an important role in the communication of the disease. In 1866, a smaller outbreak hit London. More specifically, the reintroduction of sewage contaminated water by the *East London Water Company* caused in just one week 908 over 5596 deaths in London (Dupaquier and Lewes (1989),Underwood (1948)) . Despite the overwhelming amount of evidence, the Medical Officer himself tried to exonerate the company, causing the wrath of Farr. This event, however, was a wake-up call for the English political class to guarantee the supply of clean water. Several public health measures were taken from the 1850s in order to improve public health and water quality. A new administrative network was established in London in 1855, which undertook the development of the city's main drainage system which was completed in 1875. Among other measures were the Rivers Pollution act in 1876 and the carrying out of monthly water reports from the 1860s (Hardy (1984)).

2.1.2 Cholera in France

France's experience with cholera varied from England's, due to its different scientific environment and unstable political situation. The first epidemic reached Paris by the spring of 1832 causing, in four months, the death of almost 2.1% of the 774.338 Parisians (Paillar (1832)).
In his remarkable report addressed to the Higher Council of Health (Moreau de Jones (1831)[6]), the former military A. Moreau de Jonnès (1778 - 1870) gave considerable details on the international spread along trade routes of the pandemic that started in India in 1817, including the treatments and precautions taken against the disease. He clearly attested that cholera was "incontestably" contagious. In 1833, he became the first chief of the Statistique Generale de la France (SGF), the nearest equivalent to the G.R.O in England. Like Farr, Moreau de Jonnès published many reports (13 volumes) and contributed to the development of Statistics and its applications in France. Unfortunately, little attention was paid to his findings by the French health care community.
In the end of 1831, France was anticipating a cholera epidemic. Health commissions were established in Paris and in other departments in order to control the disease with the help of health councils (conseils de salubrité); but the organization was less systematic and data collection was less reliable than in England. During the first epidemic, social unrest among the lower classes, who saw the disease "as a massive assassination plot by doctors in the service of the state", were the worst fears of the government (Kudlick (1996)). The government was supported by the Faculty of medicine in its efforts to reduce fear and avoid a population uprising, and the latter stated in 1832 that the disease was not communicable (Fabre (1993)). In 1848, a public health advisory committee was created and attached to the Ministry of Agriculture and Commerce, in charge of sanitary issues (housing, water and protection of workers) and prophylactic measures to prevent the epidemic from spreading Le Mée (1998). As in 1832, this committee stated that cholera was not contagious (Dupaquier and Lewes (1989)).
In 1849, the second epidemic broke out after the 1848 revolution. Contrary to the first epidemic characterized by riots and tensions, the reaction to the outbreak was more peaceful, with more efficient collaboration between scientists and the administration. At the same time, the perception of the lower classes also changed with the idea of struggling against destitution in order to prevent revolt (Kudlick (1996)). As a consequence, the response to the second epidemic was better organized and social laws were passed in $1850 - 51$. In the following years, hygiene problems and unsanitary living conditions caused by the rapid growth of Paris's population were

[6]The report is available on the website of BNF.

addressed to by important public health measures. In particular, the massive public work projects led by Baron Haussman[7] in less than two decades from 1852 to 1870 remains as a symbol of the modernization of Paris at the end of the nineteenth century (Raux (2014)).

2.1.3 Cholera Pandemic and International Health Organization

The international dimension of the problem raised by cholera, reported in France by Moreau de Jonnès in 1824-31, was widely publicized by The Lancet, which published in 1831 a map on the international progress of cholera[8] (Koch (2014)). This map suggested a relation between human travel and the communication of the disease, accelerated by the industrial revolution in transport, in particular with steamships and railways. Cholera was regarded as an issue transcending national boundaries, which needed international cooperation to control it (Huber (2006)). Europe had succeeded in setting up an efficient protective system against the plague, based on ideas such as quarantine and "cordon sanitaire". But those measures were very restrictive and seemed inefficient against cholera. Moreover, in the second half of the nineteenth century, Western European countries were involved in competitive colonial expansion, and were rather hostile to travel restrictions, even if increased global circulation was a threat to populations. The opening of the Suez Canal in 1869 was an emblematic example of those changes.

Under the influence of French hygienist doctors, the first International Sanitary Conference opened in Paris in 1851 (Huber (2006)) gathering European states and Turkey. It was the first international cooperation on the control of global risk to human health, and so the beginning of international health diplomacy. It took more than ten international conferences over a period of over 50 years to produce tangible results. During the first five conferences[9], the absence of clear scientific explanation on the origin of cholera prevented any agreement. It was only with the formal identification of the *V. cholerae* bacterium by R. Koch in 1883[10] and the work of L. Pasteur that infectious diseases were clearly identified and efficiently fought against. Indeed, technological progress as evinced through disinfection machines could allow the technological implementation of new measures (Huber (2006)). Furthermore, advances on germ theory “allowed diplomats to shape better informed policies and rules” (Fidler (2001)).

At the Seventh Conference (1892), the first maritime regulation treaty was adopted

[7] Napoléon III appointed Baron Haussmann as Préfet de la Seine

[8] The map was completed in 1832 by Brigham to include Canada and the USA

[9] (1851,1859,1866, 1874 and 1881)

[10] The bacterium had been isolated before by other scientists such as F.Pacini in 1854, but his work did not had a wide diffusion.

for ship traveling via the Suez Canal. During the ninth conference (1894), sanitary precautions were taken for pilgrims traveling to Mecca. Participants finally agreed that cholera was a waterborne disease in 1903 during the eleventh conference.
The International Sanitary Conferences provided a forum for medical administrators and researchers to discuss not only on cholera but also on other communicable diseases, and brought about the first treaties and rules for international health governance. Ultimately, this spirit of international cooperation gave birth in 1948 to the World Health Organization, an agency of the United Nations, conceived to direct and coordinate intergovernmental health activities.

2.1.4 Discussion

In England, Farr's discoveries could not have been made without the cutting edge organization and the power of the G.R.O. It is worth noting that only a governmental organization such as the G.R.O was able to collect the data fast enough for the 1854 experiment of Farr and Snow (Dupaquier and Lewes (1989)) to be possible. The modern organization of the G.R.O undoubtedly contributed to the remarkable quality of today's England vital databases. Across the Channel, France did not manage to create the same kind of centralized authority. On the grounds of their hostility to the communicable disease theory, French doctors did not rely on statistics.
On the other hand, the use of statistics made by Farr contributed to a better understanding of the disease. It was only more than a century and a half later that a major breakthrough was made in the understanding of the origins of the disease, with the work of R. Colwell showing that the *V. cholerae* bacterium appears naturally in the environment. Yet the ambition to find causal factors by the sole analysis of data is not devoid of risks, and thus constitutes a major challenge for the data science era. Farr's elevation law is a textbook case of an unexpected correlation that turns out to have a great influence. Despite claimed impartiality, his choice to highlight the elevation law among all the findings mentioned in his report on the 1848-49 outbreak was clearly biased by his beliefs in the predominant (though false) miasma theory. While he later accepted that epidemics could be waterborne, Farr continued to believe in the prevailing role of elevation, even when deaths due to cholera during the 1854 and 1866 outbreak were not consistent with the elevation law. Rather than allowing the discovery of the causes of cholera, Farr's statistics were actually more useful for testing and validating the relationships predicted by Snow's theory.
Another point is that the conditions that made the 1854 experiment possible were quite extraordinary. Testing theories regarding the complex events of health and

mortality in human communities is often nearly impossible. Only a handful of studies can take advantage of natural experiments. More often than not, as stated in National Research Council and Committee on Population (2011), “they are limited ethical opportunities to use randomized controlled trials to study the question at issue". Furthermore, governments failed to come to an agreement during the first international conferences because of the lack of scientific explanations on the origin of cholera. The need of theoretical arguments for public decisions to be made is still an important issue, especially when considering human health and longevity, for which no biological or medical consensus has emerged. As will be developed further in this survey, the use of a mathematical model and simulations can operate as a proxy to real life experiments and help decision making.
Even when theories are publicized, there are often important delays (one or two generations) before action is taken. For instance, even if Snow's theory was better known in 1866, and despite the development of germ theory in the early 1880s, political divergences prevented any action before 1892. The example of asbestos, which took 50 years to be banned after the exhibition of its link with cancer, shows us that these delays in public response did not diminish over time (Cicolella (2010)). More generally speaking, around 30 years elapsed between the first epidemic and the real development of public health policies in England and in France.
The example of cholera illustrates the complexity of studying mortality evolution, inseparable from societal and political changes. Although cholera outbreaks occurred at about the same time in France and in England, they were experienced very differently owing to the different political and scientific climates in both countries. This shows that the sole study of mortality data could not be sufficient to understand the future trends of mortality. In particular, the explosion of the London population, whose size was twice as large as that of Paris, brought about social problems on a much greater scale, which played a determining role as a catalyst of public health changes.
The cholera outbreaks contributed to the development of important public health measures, which played a major role in the reduction of infectious diseases. For instance, Cutler and Miller (2005) estimated that water purification explained half of the mortality decline in the United States between 1900 and 1930. In comparison, the discoveries of new vaccines for a number of diseases at the beginning of the twentieth century seem to have had little impact on the reduction of mortality from those diseases. For instance, the reduction in mortality due to those diseases (except tuberculosis) following the introduction of those vaccines is estimated to have contributed to the emergence of only 3 percent of total mortality reduction (Cutler et al. (2006)). The second half of the twentieth century was marked by the rise of more intensive medical interventions, and by an epidemiological transition from infectious

diseases to chronic diseases. But public health should not be underestimated in this new age of "degenerative and man-made diseases" (Bongaarts (2014)). Public health campaigns against tobacco have played an important role in reducing cardiovascular disease mortality caused by smoking (Cutler et al. (2006)), although with varying degrees of success depending on countries, gender or social classes. The increase of environmental risks constitutes one of the major challenges faced by contemporary societies, and public action will play a central role in preventing and successfully reducing those risks (Cicolella (2010)).

2.2 A century of economic growth

The twentieth century was the century of "the emergence for the first time in history of sustained increases in income per head" (Canning (2011)), and the association of economic growth and mortality improvements have been extensively discussed by economists. During the nineteenth century, individuals in rich and poor countries experienced similar health conditions. The 1870s were a turning point with the improvement of health in rich countries (Bloom and Canning (2007)). In his seminal article, Preston (1975) was one of the first economists to examine the relationship between life expectancy at birth and national income per head in different countries[11], for three different decades: the 1900s, 1930s and 1960s (see Figure 1). In each decade, Preston brought to light a strong positive association between life expectancy and national income. He also stated that the relationship was curvilinear. For instance, the so-called Preston curve of 1960 appeared "to be steeper at incomes under 400$ and flatter at incomes over 600$" Preston (1975).
Preston also noted an upward shift of the curve characterized by a rise of life expectancy over time at all income levels. These empirical results showed that economic growth alone did not explain the remarkable mortality decline. For instance, the income level corresponding to a life expectancy of 60 was about three time higher in 1930 than in 1960. Another example is China which had in 2000 the same income level as the USA in the 1880s, but the life expectancy level of the USA in 1970. Preston (1975) estimated that national income accounted for only 10 to 25 percent of the growth of life expectancy between 1930s and 1960s. Bloom and Canning (2007) also estimated that increases in income between 1938 and 1963 were responsible for about 20% of the increase in the global life expectancy.

[11]The national income per head was converted in 1963 U.S dollars.

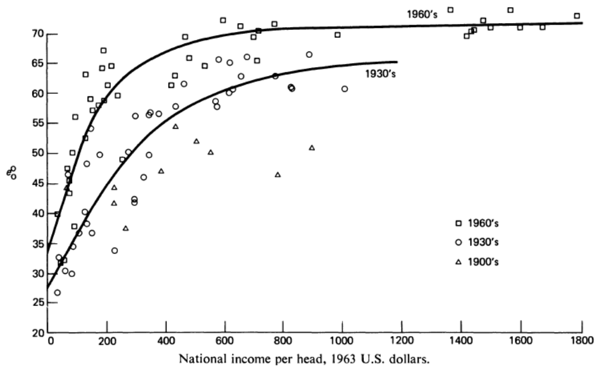

Figure 1: Preston curves, 1900, 1930, 1960, reproduced from Preston (1975)

Deaton (2003) represented the Preston curve in 2000 (see Figure 2), in which countries are represented by circles that are proportional to the size of population. The Preston curve in 2000 (see Figure 2) shows that correlation of income with life expectancy is more tenuous for high income countries.

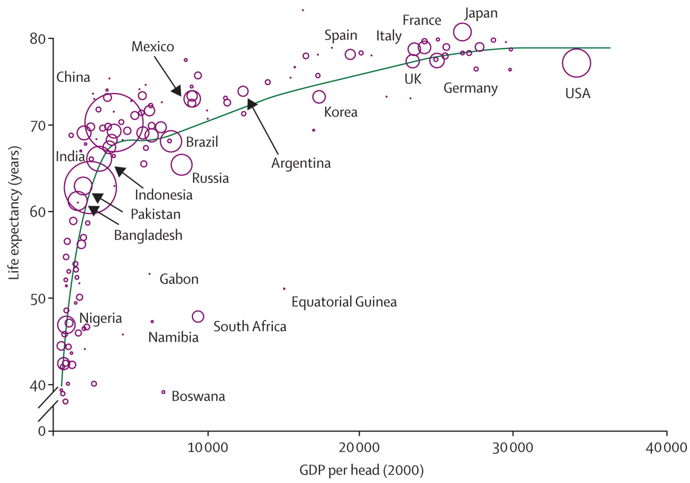

Figure 2: Preston curve in 2000, reproduced from Deaton (2003)

Furthermore, the relationship between mortality decline and level of income is often thought as bidirectional. This issue still generates a lot of debate (see e.g. Cutler et al. (2006), Bloom and Canning (2007), Acemoglu and Johnson (2007), Bloom et al. (2014), Acemoglu and Johnson (2014)). On the one hand, some studies on the causal link between health and wealth suggested that “health can be a powerful instrument of economic development” (Bloom and Canning (2007)). On the opposite side, Acemoglu and Johnson (2007) argue that improvements in population health, especially the reduction of children mortality, might have negative impacts on economic growth, due to the increase in the population size. They argue that a positive effect of economic growth on health may be counterbalanced by the negative effect of population growth on health. However, Reher (2011) describes the increase in the proportion of working age poeple in the population that occurred in developed countries during the twentieth century as a situation which had “profound economic implications for society, as long as the economy was able to generate enough jobs to accommodate the growing population of working age”.

For a more complete picture, it is thus interesting to go beyond “macro” environmental indicators such as public health and economic growth, and to look at mortality experiences on different scales, by exploring differences between countries, and within countries.

3 A new era of diverging trends

3.1 A second demographic transition?

In the early 1970s, many demographers and population scientists had supported for the idea that populations would ultimately reach the last stage of the classical demographic transition, described as an “older stationary population corresponding with replacement fertility (i.e., just over two children on average), zero population growth, and life expectancies higher than 70y” (Lesthaeghe (2014)). More generally speaking, populations were supposed to attain an equilibrium state, characterized by a significant level of homogeneity. For instance, the nuclear family composed of a married couple and their children was expected to become the predominant family model.

Yet, in most countries which experienced the historic transition, the baby boom of the 1960s[12] was characterized by higher fertility rates, followed by a decline in fertility in the 1970s (baby bust). In response to these fluctuations, attempts were made to modify the original theory. For instance, Easterlin (1980) developed a cyclical fertility theory, linking fertility rates to labor-market conditions. Smaller cohorts would benefit from better living conditions when entering the labor market, leading to earlier marriage and higher fertility rates. On the contrary, larger cohorts would experience worse living conditions, leading to later marriage and lower fertility rates. However, it turned out that this state of equilibrium and homogeneity in populations was never realized. Actually, fertility rates remained too low to ensure the replacement of generations; mortality rates, especially at advanced ages, declined at a faster rate than ever envisaged; and contemporary societies seem to be defined by more and more heterogeneity and diverging trends. The idea of a renewed or sec-

[12]The baby boom affected several countries such as France, the United Kingdom or the United States, although with different timings from the early 1950s to 1970s.

ond demographic transition, distinct from the classical demographic transition, was originally formulated by Lesthaeghe and Van de Kaa (1986) in an article in Dutch, followed by a series of articles (Lesthaeghe (2010, 2014), Van de Kaa (2010)).
In the early 1980s, a number of researchers had already observed that a shift of paradigm (Van de Kaa (2010)) had occured. In particular, the French historian P. Ariès suggested that motivations explaining the decline birth rate in the West had changed (Ariès (1980)). During the historic demographic transition, the decline in fertility rates was assumed to originate from an increased parental investment in the child. P. Ariès explained more recent declines in fertility by an increasing interest of individuals in self-realization in which parenthood is only one particular life course choice among many others. More specifically, Lesthaeghe (2014) characterized the second demographic transition by multiple lifestyle choices and a more flexible life course organization. A striking example can be found in the emerging of multiple types of family arrangements.
Lesthaeghe and Van de Kaa also define the second demographic transition as a shift in the value system. The first phase of the demographic transition was a period of economic growth and aspirations to better material living conditions. In contrast, the past few years have seen a rise of "higher order" needs and individualization. In this new paradigm, individuals are overwhelmingly preoccupied by individual autonomy, self-realization and personal freedom of choice, resulting in the creation of a more heterogeneous world.
Even if the framework of the second demographic transition has been criticized, this viewpoint shed an interesting light on recent longevity trends. Indeed, divergences in mortality levels and improvements between and within high income countries are at the heart of numerous debates and research works. As the average life expectancy has been rising unprecedentedly, gaps have also been widening at several scales. What may be somehow surprising is that up until the 1980s, high income countries had roughly similar life expectancy levels. For example, the comparison of the female life expectancy at age 50 in ten high income countries[13] shows that the gap was of less than one year in 1980. By 2007, the gap had risen to more than 5 years, with the United States at the bottom of the panel with Denmark, more than 2 years behind Australia, France, Italy and Japan (National Research Council and Committee on Population (2011)). On another scale, a great amount of evidence shows that socioeconomic differentials have also widened within high income countries. For instance, the gap in male life expectancy at age 65 between higher managerial and professional occupations and routine occupations in England

[13] Australia, Canada, Denmark, England and Wales, France, Italy, Japan, Netherlands, Sweden and the United States.

and Wales was of 2.4 years in 1982 to 1986, and rose to 3.9 years in 2007 to 2011[14]. The following part focuses on two angles of analysis on these diverging trends: the impact of smoking behaviors and socioeconomic inequalities. The goal of the following discussion is not to detail further the impact of these risk factors, but rather to show the complexity of understanding current longevity trends, which cannot be disentangled from the evolution of the whole population, and which require a multiscale analysis of phenomena while keeping in mind that obtaining comparable and unbiased data is also a challenge in order to explain longevity.

3.2 Diverging trends between high-income countries: the impact of smoking behaviors.

In the comprehensive report of the National Research Council on explaining divergent levels of longevity in high income countries (National Research Council and Committee on Population (2011), a panel of experts have debated on the role of different risk factors for explaining the slower increase of life expectancy in the United States over the last 30 years, in comparison with other high income countries. From 1980 to 2015, the world ranking for life expectancy of the United States kept falling significantly. Furthermore, the gap between the United States and other high income countries widened, due to the slower increase of life expectancy at all ages in the United States. The ranking of the United States for male life expectancy at age 50 fell from 17th in 1980-85 to 28th in 2010-2015, with an increase of life expectancy of 4.58 years, smaller in absolute and relative terms than the average of high income countries[15]. The evolution is even more striking for women: the ranking for the female life expectancy at age 50 fell from the 13th to the 31th position, with an increase of only about 60 percent of the average increase of high income countries. In addition, the gap with higher achieving countries such as France or Japan grew from less than one year in 1980-85 to more than 3 years in 2010-15[16]. Netherlands and Denmark also show similar patterns of underachievement in life expectancy increases.

Although many methodological problems may arise when using cause-of-death statistics, a cause-of-death analysis can provide a powerful tool for understanding divergences in mortality trends. In a commissioned background article for the report, Glei et al. (2010) have studied cause-of-death patterns for 10 different countries in order to identify the main causes of death possibly responsible for diverging trends. The

[14]Source: Office for National Statistics (ONS).

[15]High income country classification based on 2014 GNI per capita from the World Bank.

[16] United Nations, Department of Economic and Social Affairs, Population Division (2015). World Population Prospects: The 2015 Revision, custom data acquired via website.

case of lung cancer or respiratory diseases, which are relevant indicators concerning smoking is particularly interesting. Age-standardized mortality rates from lung cancer among men aged 50 and older in the U.S decreased from 1980 to 2005 while they increased for women, although they remain higher for men than for women. In addition, the increase of age-standardized mortality rates due to lung cancer for women was much faster in the U.S, Denmark and Netherlands than the average increase of the studied countries and especially than Japan where age-standardized mortality rates remained flat.

These findings of Glei et al. (2010) clearly point out to smoking as the main underlying factor explaining those divergences. Over the past 30 years, evolution of mortality due to lung cancer and respiratory diseases has had a positive effect on gains in life expectancy for males, while the effect was negative for females. These gender differences can be linked to the fact that women began to smoke later than men, and have been quitting at a slower pace (Cutler et al. (2006)). In addition, fifty years ago, people smoked more intensively in the United States, Denmark and the Netherlands than in other European countries or in Japan.

These differences can give precious information as for future mortality patterns. Because of its delayed effects on mortality, the impact of smoking behaviors on future trends is somehow predictable. Just as the causes of death of individuals aged 50 and older give some insight on what happened in the past, current behaviors among younger individuals can be a useful indicator of future trends. Thus, life expectancy for males in the United States is likely to increase rather rapidly following reductions in the prevalence of smoking over the past twenty years, while slower life expectancy improvements can be expected for women in the coming years (National Research Council and Committee on Population (2011)). According to a panel of experts, life expectancy in Japan is also expected to increase at a slower pace in the future due to an increase in the prevalence of smoking. Differences in the timing of evolutions in smoking behaviors across gender and countries might also give additional information. The impact of smoking on male life expectancy in the past could help predict future trends for women, and the experience of the United States could shed light on the future impact of smoking in Japan.

But smoking is certainly not a sufficient explanation, and other risk factors may have contributed to the underachievement of the United States. In particular, the obesity epidemic may partly account for the slower increase in life expectancy experienced by the United States. Quantifying the impact of the obesity epidemic is much more complicated, since no clear markers are available such as lung cancer and respiratory diseases concerning smoking. According to some researchers, the obesity epidemic in the United States might even offset gains in life expectancy due to the decline of smoking (Stewart et al. (2009), Olshansky et al. (2005)).

Discussion The "predictable" effects of smoking could be integrated in a population dynamic framework taking into account the whole age structure of the population. Countries experiencing similar phenomena but with different timings could also be compared in a theoretical framework of population dynamics. Furthermore, a finer-grained model could help to better understand the future impacts of emerging issues such as the obesity epidemic, as well as the potential compensating effect of a decrease in smoking prevalence.

3.3 Differences within countries: the impact of social inequalities

Research on the relationship between socioeconomic status and mortality and health can be traced back as far as the nineteenth century. In France, Villermé (1830)compared mortality rates in Paris' boroughs with the rates of non-taxable households in each borough (Mireaux (1962)). In England and Wales, a systematic documentation of mortality by occupational class was made by the G.R.O starting from 1851 (Elo (2009)). Since then, studies have consistently exhibited a pervasive effect of socioeconomic inequalities on longevity, regardless of the period or country. A recent study based on the French longitudinal survey[17] has found out that males with managerial and higher professional occupations have a life expectancy 6.3 years higher than working-class males (in the mortality conditions of 2000-2008, Blanpain (2011)). Numerous other examples can be found in the review of Elo (2009).
Moreover, despite unprecedented rise in life expectancy during the 20th century, evidence shows that socioeconomic inequalities have widened in many developed countries in recent decades (Elo (2009)), or have remained identical at best (Blanpain (2011)). For instance, Meara et al. (2008) (cited in National Research Council and Committee on Population (2011)) argue that the educational gradient in life expectancy at age 25 rose from the eighties to the nineties of about 30 percent. Similarly in England, socioeconomic status measurements using the geographically based Index of Multiple Deprivation (IMD) (see next paragraph for more details) have shown that the average mortality improvement rates at age 65 and older have been about one percent higher in the least deprived quintile that in the most deprived quintile during the period 1982-2006 (Haberman et al. (2014),Lu et al. (2014)).
The persistence and widening of socioeconomic inequalities in longevity has created a new paradigm, in which the increased heterogeneity has brought out even more complexity in understanding longevity evolution, and which has now to be taken into account in mortality predictions. New interlinked problems have arisen on mul-

[17] description EDP

tiple scales. On an individual level, underlying factors linking individuals' health to their socioeconomic status are still debated. Another subject of no little interest to us is the critical challenge of understanding the impact of this rising heterogeneity on aggregated variables.
In the following part, we will focus on some selected topics which have been discussed by sociologists, demographers, social epidemiologists and other scientists, with the aim of highlighting modeling challenges and solutions hidden beyond these reflections.

3.3.1 Measuring the socioeconomic status

The concept of socioeconomic status (SES) is broad and can encompass numerous characteristics, observable or not. Translating socioeconomic status into empirical measurements in order to better understand the links between SES and health and mortality, is in itself a challenge. Proxy variables such as educational attainment, occupation, income or wealth usually serve as SES measures, with different practices and habits in different countries (Elo (2009)). However, their ability to model the complexity of the social hierarchy and to produce comparable data through different times and places are often quite limited. Educational systems, even in groups of similar countries, can differ substantially from one country to another and make cross-national comparisons difficult (Elo (2009)). Furthermore, there is a real difficulty in comparing certain groups at different periods in time. Important changes can occur in group sizes and composition. For instance, the proportion of women in France with higher managerial and professional occupations increased from about 2 percent in 1975 to 6 percent in 1999 (10 to 14 percent for males). The evolution in the number of women long term unemployed or not in the labor force is even more striking. Their proportion decreased from 45 percent in 1975 to only 21 percent in 1999. Besides, Blanpain (2011) observed an important widening of mortality inequalities between this subgroup and other occupational subgroups over the period. The widening of these gaps is actually a typical consequence of important changes in the composition of the long term unemployed or not in the labor force subgroup. The major decrease in the size of the subgroup can be explained by the important decrease of the number of housewives over time, leaving only the most precarious in the subgroup.
Proxies for the SES can be measured at different periods in the life course of an individual, and can have different causal relations with health or mortality. Education is rather consistent across the lifespan (which allows for an easier dynamic modeling), and permits to assess the stock of human capital accumulated early in life and available throughout the individual life course (Elo (2009)). On the

other hand, occupation, income or wealth allow to take into account latter parts of the life course and might allow to capture impacts of public policies better than educational attainment measurements (National Research Council and Committee on Population (2011)). However, the variability of the occupational status through the life course and the difficulty of assigning an occupational group to individuals is important when studying socioeconomic gradients by occupational rankings. For instance, the issue of assigning an occupational group to individuals who are not in the labor force or retirees is classical. Interpretations can also differ significantly depending on the period in the life course at which occupational status is measured. Additional complexity is also generated by the potential bidirectionality of causation, especially concerning economic measures of SES such as income or wealth, for which causal pathways are debated. Evidence from the economic literature has shown that ill health can also lead to a decrease in income or wealth. This is particularly true in countries like the United States with poorer national health care coverage than most Western Europe countries, and where poor health is a significant contributor to bankruptcy (Himmelstein et al. (2009)), retirement or unemployment (Smith (2007), cited in National Research Council and Committee on Population (2011), Case and Deaton (2005), cited in Cutler et al. (2006)).

3.3.2 Explaining the socioeconomic gradient in health and mortality

The difficulty in interpreting results of empirical measurements of the SES gradient in mortality reflects our little understanding of the risk factors that underlie the repercussions of socioeconomic inequalities on health and mortality. Theories explaining the SES gradient are still being debated, and their testing is often not straightforward and not unbiased as far as the measurements are concerned (see below the discussion on absolute versus relative measures). Furthermore, the impact of inequalities on aggregated variables or on the interpretation in terms of public policy can differ substantially according to different theories.

The mechanisms through which SES is assumed to generate inequalities in health and longevity are usually grouped in three broad categories: material, behavioral and psychosocial (Cutler et al. (2006)).

Material risk factors Maybe one of the most natural explanation of socioeconomic differences in health is that wealthier individuals have better access to health care, even in countries with national health care coverage where potential two-tiered systems can also create inequalities. Individuals with a higher income can also maintain a healthier lifestyle, being able to buy expensive organic food or pay for gym memberships. However, access to health care or material resources does not appear to be the primary factor explaining the SES gradient (National Research Council and Committee on Population (2011),Cutler et al. (2006)). For instance, the education gradient in the U.S steepened between the sixties and the eighties, even though the Medicare program was enacted in 1965 (Pappas et al. (1993), cited in Elo (2009)).

BEHAVIORAL RISK FACTORS The second explanation is that individuals with higher educational attainment are more likely to adopt healthier behaviors and to avoid risks. By accumulating knowledge, skills and ressources, individuals who are higher on the SES ladder should be able to take better advantage of new health knowledge and technological innovations, as well as to turn more rapidly toward healthier behaviors. This behavioral explanation of socioeconomic inequalities is linked to the theory of Link and Phelan of fundamental causes (Link and Phelan (1995), Phelan et al. (2010)). The aim of Link and Phelan's theory is to explain the persistence of pervasive effects of social class inequalities through time, despite dramatic changes in diseases and risk factors. According to the theory, the accumulation among other resources of so-called human capital allows more educated individuals to use resources and develop better protective strategies, whenever they can and no matter what the risks are. Let us take the example of smoking, described in (Link (2008)). When first evidence linking smoking to lung cancer emerged in the fifties, smoking was not correlated to SES. But as the knowledge of the harm caused by smoking spread, strong inequalities in smoking behavior appeared, reflected in the fact that more educated individuals quit smoking earlier. However, a number of studies (see National Research Council and Committee on Population (2011) for examples) have shown that if behavioral differences play a significant role in explaining the SES gradient in mortality, it does not explain everything, and may not even account for the major part of the differentials. For instance, the famous study of Whitehall civil servants (Marmot (1994)) showed that health differentials subsisted even when factors such as smoking or drinking were controlled.

PSYCHOSOCIAL FACTORS Another prominent and rather recent theory explaining socioeconomic differentials in mortality is that health is impacted by the SES through pyschosocial factors (Cutler et al. (2006), Wilkinson and Pickett (2009)). Among pyschosocial factors are stress, anxiety, depression or anger. Accumulated exposure to stress has received particular attention in literature, due to its pervasive effects on health. Indeed, prolonged exposure to chronic stress affects multiple physiological systems by shifting priorities from systems such as the immune, digestive or cardiovascular systems in favor of systems responding to threat or danger (Wilkinson and Pickett (2009)), and by leading to a state of so-called "allostatic load". The link between low social status and stress has been supported by a number of studies on primates. For instance, Sapolsky (2004, 2005) showed that among wild baboons, subordinate animals presented higher level of glucocorticoids, a hormone with a central role in stress response.

3.3.3 The impact on aggregated variables

On an aggregated level, socioeconomic inequalities impact national mortality not only through the importance of the SES gradient, but also through the composition of the population and its heterogeneity. For instance, in a study based on the comparison of the United States with 14 European countries, Avendano et al. (2010) observed that the unusually high educational gradient in mortality in the United States seems to be counterbalanced by an attractive educational distribution. As a consequence, they found out that the Relative Index of Inequality (RII)[18] of the United States was not especially high in comparison with other countries with an educational gradient of lower magnitude. The age structure of the population also plays a determining role, and the socioeconomic composition of different age classes can vary a lot (see Chapter 4 for a more detailed discussion on this subject).
From a material point of view, the relationship between income and health or mortality was initially thought of as a curvi-linear relation (Preston (1975), Rodgers (1979)). According to this analysis, a reditribution of income from the wealthiest groups to the poorest would result in improving the health of the poor rather than endanger the health of the wealthy. This non-linear relationship shows that the impact of inequality at the aggregated level of a country is not trivial. For instance, if a country experiences a high level of income inequalities, the overall mortality in the country can be higher than in a country with the same average level of income but with a lower level of inequality.
But recent studies, based on the pyschosocial explanation of the SES gradient, seem to indicate that the relation between aggregated mortality and inequality is even more complicated. They argue that the presence of inequality itself impacts the health and mortality of individuals. For instance, Wilkinson and Pickett (2010) studied the association between life expectancy and income inequality[19] among the 50 richest countries of more than 3 million inhabitants, and found out a correlation of 0.44 between life expectancy and the level of inequalities, while no significant association was found between life expectancy and the average income. These results suggest that health and mortality are impacted by the *relative* social position of individuals, rather than their absolute material living standards (Wilkinson and Pickett (2009), Pickett and Wilkinson (2015)). This is closely linked to the theory

[18] The RII is an index of inequality which takes into account differences in mortality as well the populations composition, see Regidor (2004) for details on the computation of the index.

[19] Income inequality was measured in each country as the ratio of income of the poorest 20% to the richest 20%.

of psychosocial factors, which assumes that it is the relative social ranking which determines the level of exposure to psychosocial problems and the ability to cope with them. Wilkinson and Pickett (2009) go even further and argue that inequalities affect not only individuals at the bottom of the socioeconomic ladder, but the vast majority of the population. For instance, Wilkinson and Pickett (2008) compared standardized mortality rates in counties of the 25 more equal states in the US and in counties of the 25 less equal states[20] (see Figure 3). They found out that for counties with the same median income, mortality rates were higher in counties in the more equal states than in counties in less equal states. The relation held at all levels of median income, with more important differences for counties with lower median income.

When measuring the impact of inequality on health, the size of the area appears to be an important variable to take into account. On the one hand, the relationship between health and inequalities, when measured at the level of large areas such as states of big regions, seems to be fairly strong. On the other hand, Wilkinson and Pickett (2009) note that at the level of smaller areas such as neighborhoods, the average level of income seems to matter more than one's relative social position in the neighborhood. This "neighborhood effect" has been studied by many authors and constitutes a field of research in itself (se e.g Kawachi and Berkman (2003), Diez Roux (2007), Diez Roux and Mair (2010), Nandi and Kawachi (2011)). Societal inequalities, neighborhood environment and individual socioeconomic characteristics thus impact health and mortality at multiple scales, making the analysis of factors responsible for poorer health highly difficult. It is even more difficult to understand what happens at the aggregated level.

[20]The measure of inequality was based on the Gini coefficient of household income.

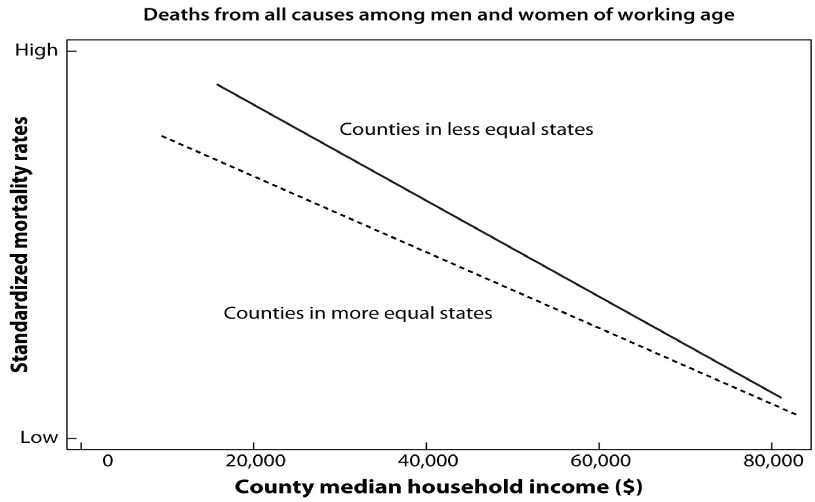

Figure 3: Relationship between median county income and standardized mortality rates among working-age individuals, reproduced from Wilkinson and Pickett (2009) (Figure 11)

3.3.4 Discussion

The problems surrounding the measure of the SES is revealing of the issues at hand. The interpretation of data across time and places is a delicate matter. As illustrated by the major changes in the composition of women occupational subgroups, the effects of composition changes have to be carefully addressed to. Besides, it is rather unlikely that a single measure of SES, at only one point in the life course of individuals, could capture accurately the many pathways by which social status can affect health and mortality (Elo (2009)). However, there are many limitations in the ability to obtain reliable data from multiple measures of SES.

There are often limited opportunities for the empirical testing of complex theories such as the fundamental cause theory or the theory of psychosocial factors. The design of empirical test is not straightforward, to say the least. Natural experiments, such as the evolution of smoking behavior, or experiments on non-human populations, such as Saplosky's study of baboons, can give valuable insights on theories. However, as stated in the conclusion of the report of National Research Council and Committee on Population (2011), " it is sometimes difficult, expensive, and ethically challenging to alter individual behavior".

Pathways involved in translating SES into mortality outcomes can differ substantially according to the theory taken into account. Moreover, the impact of these underlying mechanisms on aggregated variables can also differ a lot, ranging from composition effects due to the curvilinear relation between material resources and longevity, to the global (non-linear) effects of the social stratification on individu-

als. From the fundamental causes point of view, new advances in knowledge and technology related to health will probably increase the SES gradient in health and mortality (Phelan et al. (2010), Cutler et al. (2006)).
This illustrates how different underlying factors explaining the SES gradient can influence our views on the impact of socioeconomic inequalities on aggregated quantities, and in turn influence choices of public policies. Different types of policy recommendation can be made, according to the underlying factors or measures of SES which are considered to be most prominent. For instance, Phelan et al. (2010) recommend two types of public interventions. The first type focuses on reducing socioeconomic inequality itself in order to redistribute resources and knowledge. This would be consistent with the views of Wilkinson and Pickett (2009) on the general impact of inequality in a country. The second type of recommendations falls into the domain of public health. Governments should be careful and design interventions which do not increase inequalities, by favouring for instance health interventions which would benefit everyone automatically.

We believe that the dynamic modeling of the evolution of the population may help to address these issues. A fine-grained modeling of the population dynamic could help to evaluate the impact of changes in the composition of socioeconomic subgroups. In addition, modeling the population dynamics can serve as a simulation tool in order to take into account various measures of SES, when empirical data are limited. It can also be used to test hypotheses regarding which aspects of SES are the most important for reducing socioeconomic inequalities in health and mortality. By using population simulation as an experimenting tool when real life experiences are not possible, theories can be tested by comparing the aggregated outcomes produced by the model to what is observed in reality.
However, the above paragraph shows us the complexity of the phenomena involved. Socioeconomic inequalities impact health and mortality through complicated pathways. Phenomena are often non-reproducible - risk factors, as well as the economic, social or demographic environment have changed dramatically over the recent years - with effects which are often delayed. Furthermore, findings suggest that the impact of socioeconomic inequalities is highly non-linear. Individual characteristics do not fully explain the longevity of individuals. Mechanisms acting at different scales appear to be equally important. For instance, the neighborhood effect, the relative social position of individuals or the global level of inequality in society are also important factors to take into account.
From these examples, it is quite easy to see the modeling challenges brought about by the new paradigm of the second demographic transition. At yet, there is also an urgent need for complex population models, for a better understanding of the

observed data, as well as to serve as an alternative when empirical testing is not possible.

4 Modeling complex population evolutions

Before the 1980s, demographic models were principally focused on the macro-level, and used aggregate data to produce average indicators. In view of the previous considerations, producing a pertinent modeling directly at the macro-level appears to be a more and more complicated-if not impossible-task. Hence, demographic models have increasingly shifted towards a finer-grained modeling of the population in the last decades.

There is thus an intrinsic interest in describing the variability and heterogeneity of the population on a more detailed level, in order to obtain *macro*-outcomes by aggregation, to be used forecasting/projections and/or policy recommendations, or in a broader sense for the analysis of social economic policies.

Over the last two decades, the increase of computing power and improvements in numerical methods have made it possible to study rich heterogeneous individual models. Indeed, a wide variety of models simulating individual behavior have been developed for different purposes and used in different domains. In this section, we give an overview of two types of models widely used in demography: Standard microsimulation models (MSMs) and Agent based models (ABMs) which are derived from the idea of Orcutt (1957) (see Morand et al. (2010)).

4.1 Dynamic microsimulation

4.1.1 Microsimulation models

Microsimulation issues A dynamic microsimulation model provides a simulation tool of individual trajectories in order to obtain macro outcomes by aggregation. It provides a way of combining different processes (biological, cognitive, social) describing the lives of people who evolve over time. One main feature of this class of model is its capacity to interpret macro level changes, represented by macroeconomic complex quantities (or indicators) (e.g life expectancy, mortality rate,...), resulting from the simulation of the dynamic life courses of individuals, also called micro units. A dynamic microsimulation model, usually relying on an important amount of empirical data, is parametrized with micro-econometrics and statistical methods (Spielauer (2011)).

Examples of microsimulation models The history of microsimulation in social sciences goes back to the work of Orcutt (1957), who developed so-called data-driven dynamic microsimulation models. Following the original model of Orcutt, the first large-scale dynamic microsimulation model called DYNASIM[21] was developed for the forecasting of the US population up to 2030. This model considered different demographic and economic scenarios, meant to analyse the socioeconomic status and behavior of individuals and families in the US (cost of teenage childbearing for the public sector, unemployment compensations and welfare programs...). Since then, most statistical or demographical government bodies in developed countries have used their own microsimulation models, developed for different purposes. A comprehensive description of various microsimulation models can be found in the surveys of Morand et al. (2010), Zaidi and Rake (2001), Li and O'Donoghue (2013). For instance DYNACAN in Canada was designed to model the Canada Pension Plan (CPP) and analyze its contributions and benefits at individual and family level. In Australia, DYNAMOD was developed to carry out a projection of the outlook of Australian population until the year 2050. In Europe, the MICMAC project[22] was implemented by a consortium of research centers whose objective is to provide demographic projections concerning detailed population categories, that are required for the design of sustainable (elderly) health care and pension systems in the European Union. The specificity of the micmac consists in providing a micro-macro modeling of the population, with micro level projections that are consistent with the projections made by the macro model.
In France, the INSEE developed different versions of a microsimulation model, the current version being DESTINIE 2 (Blanchet et al. (2009)). This model is used for instance to measure the efficiency of reforms on state pension systems, and is based on a representative sample of the national population.

4.1.2 A dynamic microsimulation exercise

A demographic micro-model can be viewed as a population database, which stores dynamically information (characteristics) on all members (individuals) of the heterogeneous population (Willekens (2005)). Zinn (2011) gives the main steps of a microsimulation exercise which consist of:
(i) *State space and state variables:* The state space is composed of all the combinations of the values (attributes) of individuals' characteristics, called state variables. Age, sex, marital status, fertility and mortality status, education or emigration are

[21] Since then, updated versions were developed, with for example DYNASIM3 in 2004 (Li and O'Donoghue (2013)).
[22] The MICMAC project is documented in Willekens (2005).

examples of state variables. An example of a state is given by the possible values of state variables: (Female, Married, 1 Child, Alive, Not emigrated, Lower secondary school)[23].

(ii) *Transition rates:* Events occurring during the life course of individuals are characterized by individual hazard functions, or *individual transition rates / probabilities.* Each of the transition probabilities is related to an event, i.e. a change in one of the state variables of the individual. These probabilities are estimated conditionally on demographic covariates (i.e explanatory variables such as gender, age, educational attainment, children born, ethnicity), and other risk factors that affect the rate of occurrence of some events (environmental covariates that provide external information on the common (random) environment) (Spielauer (2011)). In microsimulation models, the covariates are often estimated by using logit models (see Zinn (2011)).

(iii) *Dynamic simulation:* Dynamic simulation aims at *predicting the future state* of the population, by making the distinction between events influencing the population itself and those affected by it (population ageing, concentration of wealth, sustainability of social policies...).

(iv) *Internal consistency:* Microsimulation models can handle links between individuals, which can be qualified as “internal consistency” (Van Imhoff and Post (1998)). Individuals can be grouped together in the database into “families” (for instance, if they are married or related). When a state variable of an individual in the group changes, the state variables of the other members are updated if needed. For example, this can be the case when such events as marriage, divorce or a child leaving the parental home take place.

(v) *Output of microsimulation exercise and representation:* The output of a dynamic microsimulation model is a simulated database with longitudinal information, e.g. in the form of individual virtual biographies, viewed as a sequence of state variables. The effects of different factors can be revealed more clearly when grouping individuals with life courses embedded in similar historical context. Usually, individuals are grouped in cohorts (individuals with the same age) or in generations. The aggregation of individual biographies of the same cohort yields a bottom-up estimate of the so-called cohort biography. Nevertheless, in the presence of interactions, all the biographies have to be simulated simultaneously, which is challenging for large populations.

[23]The state variables Dead and Emigrated are considered as absorbing states, i.e. once they have been entered, they will never be left again.

4.1.3 Sources of randomness

Microsimulation models are subject to several sources of uncertainty and randomness which have been discussed in detail in the work of Van Imhoff and Post (1998). The so-called "inherent randomness" is due to the nature of Monte Carlo random experiments (different simulations produce variable sets of outcomes). This type of randomness can be diminished when simulating large populations (increasing the number of individuals in the database) or repeating random experiments many times to average the results, which implies important computational cost[24]. In the presence of interactions, one should be careful since the two techniques are not equivalent. Such is the case of agent based models, which are discussed in the next section.

The starting population, which is the initial database for the microsimulation model, can be either a sample of the population based on survey data, or a synthetic population created by gathering data from different information sources. This initial population is subject to random variations and sampling errors. Moreover, at the individual level, the state variables and the covariates must be known before starting the simulation, and their joint distribution within the initial database is random. Van Imhoff and Post (1998) note that any deviation of the sample distribution may impact future projections.

These previous sources of randomness can be mitigated by increasing the size of the database and are probably less important in comparison with the so-called specification randomness. The outputs of a microsimulation model can be subject to a high degree of randomness when an important number of covariates are included. Indeed, there are calibrating errors resulting from the estimation of empirical data each relationship between probabilities of the model and covariates. Moreover, each additional covariate requires an extra set of Monte Carlo experiments, with a corresponding increase in Monte Carlo randomness.

The *specification randomness* can be reduced by using sorting or alignment methods, a calibration technique that consists in selecting the simulated life course in such a way that the micro model respects some macro properties, including the property of producing the expected values. In DESTINIE 2, this alignment is ensured by adjusting the individual transition rates to obtain the annual number of births, deaths and migration consistent with some macro projections (Blanchet et al. (2009)).

4.1.4 Discussion

In many cases, behaviors are more stable or better understood on the micro level than on aggregated levels that are affected by structural changes when the number

[24] Various techniques to accelerate Monte Carlo simulation coupled with variance reduction has been developed in many areas.

or size of the micro-units in the population changes. Thus, microsimulation models are well suited to explain processes resulting from the actions and interactions of a large number of micro-units. For instance, according to Spielauer (2011), an increase of graduation rates[25] at the macro level can lie entirely in the changing composition of the parents' generations, and not necessarily in a change of individuals' behaviors. In order to produce more micro-level explanations for population change, microsimulation models require an increasing amount of high quality data to be collected. Silverman et al. (2011) point out the "Over-dependence on potentially immense sets of data" of microsimulation models and the expensive data collection required to provide inputs for those models. Most of the time, only large entities such as national or international institutions are able to complete this demanding task. The size of the samples also has an impact on the run time of the model; the larger the sample's size is, the longer the run speed will be, which will result in a trade-off.
Silverman et al. (2011) argue in favour of the use of more abstract computational models rather than on highly data-driven research. More recently, Agent Based Models (ABM), which also derived from individual-based models, have been increasingly applied in various areas to analyze macro level phenomena gathered from micro units. These models emphasize interactions between individuals through behavioral rules and individual strategies. In this context, Zinn (2017) stressed the importance of incorporating behavioral rules through ABM models (e.g kinship, mate matching models..) since demographic microsimulation is well suited for population projection, if only the model considers independent entities.

4.2 Agent Based Models (ABM)

4.2.1 What is ABM?

The main purpose of the Agent Based Models (ABM) is to explain macroscopic regularities by replicating the behavior of complex, real-world systems with dynamical systems of interacting agents based on the so-called bottom-up approach (Tesfatsion (2002), Billari (2006)). ABM consists basically of the *simulation* of interactions of *autonomous agents* i.e independent individuals (which can be households, organizations, companies, or nations...depending on the application). As in microsimulation, agents are defined by their attributes. Each single agent is also defined by *behavioral rules*, which can be simple or complex (e.g utility optimization, complex social patterns...), deterministic or stochastic, on whose basis she/he interacts with other agents and with the simulated environment (Morand et al. (2010), Billari (2006)).

[25] Graduation rate represents the estimated percentage of people who will graduate from a specific level of education over their lifetime.

Applications The applications of ABM range from social, economic or political sciences to demography (Billari (2006)). For instance, Tesfatsion (2002) used Agent-based Computational economies (ACE) in order to model decentralized economic markets through the interaction of autonomous agents. In demography, ABM are used in Diaz et al. (2011) to explain trends in fertility by simple local interactions, in order to solve the difficult problem of age-specific projection of fertility rates. Billari et al. (2007) developed an ABM based on the interaction between heterogeneous potential partners, which typically takes place in the marriage market (partnership formation) and which is called "The Wedding Ring model". The purpose of this model is to study the age pattern of marriage using a bottom-up approach. This model was implemented using the software package NetLogo (Wilensky (1999)) which is designed for constructing and exploring multilevel systems[26]. Burke and Heiland (2006) suggested the use of an agent based model to explain the differences in obesity rates between women with different educational attainment in the United States. The model integrates biological complex agents (variation of women's metabolism) interacting within a social group, and is able to reproduce the fact that better educated women experience on average lower weights and smaller dispersion of weights. For more examples of agent based models applications, we refer to the work of Morand et al. (2010) that details different examples of ABM in spatial demography, family demography and historical demography. The book of Billari (2006) also presents various applications of agent-based computational modeling, in particular in demography.

4.2.2 A dynamic exercise of an ABM

The key defining feature of an ABM model is the interactions between heterogeneous individuals. Moreover, an agent based model is grounded on a dynamic simulation, which means that agents adapt dynamically to changes in the simulated environment. They act and react with other agents in this environment at different spatial and temporal scales (Billari (2006)). This contrasts with Microsimulation models (MSM) which rely on transition rates that are determined a priori (and once).
Agent based models are based on some rules, or heuristics, which can be either deterministic or stochastic, and which determine the decision-making process. For example, in an agent based marriage market model, the appropriate partner can be chosen as the one who has the most similar education level to the considered agent, or an ideal age difference (Billari et al. (2007)).
Besides, in comparison with Microsimulation models, which operate on a realistic

[26]Multi-level agent based models integrate different levels (complementary points of view) of representation of agents with respect to time, space and behavior.

scale (real data), but use very simple matching algorithms (often a Monte Carlo "roll the dice" styled decision rule), agent based models use small and artificial data sets, but show more complexity in modeling how the agents viewed and chose partners.

4.2.3 Limitations

The design of agent based model needs a certain level of expertise in the determining of behavioral rules. Furthermore, when modeling large systems (large number of agents), computational time rises considerably. Indeed, ABM models are not designed for extensive simulations.
The parameters of an agent based model can be either calibrated using accurate data, or consider sensitivity analysis incorporating some level of comparison with actual data. For instance, Hills and Todd (2008) compare the results of their Agent-Based Marriage and Divorce Model (MADAM) to real age-at-marriage distributions. But the outputs of an agent based model also depend on the "internal" structure of the model, determined by the behavioral rules (Gianluca (2014)). Consequently, the strategies to calibrate parameters, and to overcome the problem of dependency on the model's structure, rely on available empirical information. It is important to note that ABMs are designed to focus on process related factors or on the demonstration of emergent properties, rather than to make projections.

4.3 Conclusion

The interest of dynamic microsimulation is to constitute both a modeling exercise, and an exercise to run the model and experiment with it (Spielauer (2011)). In addition to helping to test theory or to picture the future, the exercise may be used as a simulator by policy makers (or citizens) or for a better assessment of the impact of public policies. The results/outputs of microsimulation models are population projections rather than forecasts, which is what would happen if the assumptions and scenarios chosen were to prove correct on what the future will probably be.
The discussion on demographic modeling demonstrated that Microsimulation models (MSM) strongly depend on data Silverman et al. (2011). Then, it faces pragmatic challenges in collecting and cleaning data, in addition to the different sources of randomness discussed above. In parallel with the spread of microsimulation models, there is a growing interest in Agent Based Models, which are suited to model complex systems that take full account of interactions between heterogeneous agents. The major difficulty in using of Agent based model is the absence of theoretical model. Indeed, there is no codified set of recommendations or practices on how to use these models within a program of empirical research. It is essentially based on the cognition and expertise of the developer.

In this context, new hybrid applications (combining MSM and ABM models) have been recently proposed in literature. For instance, Grow and Van Bavel (2016) present many examples that combine MSM and ABM in demographic models. These new models aim at describing the heterogeneous movements, interactions and behaviors of a large number of individuals within a complex social system at a fine spatial scale. For instance, Zinn (2017) uses a combination of MSM and ABM for modeling individuals and couples life courses by integrating social relations and interactions. The efficiency of these combined and "sophisticated" models to overcome the loopholes of the simple models is an open issue.

5 General conclusion and perspectives

Facing all these modeling challenges, we advocate the development of a new mathematical theoretical framework for the modeling of complex population dynamics in demography. As we have seen in Section 3, a number of questions cannot be answered by the sole study of data, and models allow us to generate and experiment with varyous scenarios, so as to test theories or causal links for instance. Theoretical models can help us "to escape from the tyranny of data", as claimed by Silverman et al. (2011).

On the other hand, empirical evidence point out a number of key issues which cannot be overlooked, and which demonstrate the "inextricable complexity" of dynamic modeling of realistic human populations. Variables such as mortality or fertility rates are by no means stationary; populations are more and more heterogeneous, with socioeconomic inequality playing an important role at several levels (individual, neighborhood and societal); interactions between individuals and their environment are bidirectional. These are just a few examples illustrating the complexity of modeling. An adapted mathematical framework could contribute significantly to better understand aggregation issues and find out adequate policy recommendations, in concordance with this new paradigm of heterogeneity and non-linearity. More specifically, theoretical models often allow us to reduce complexity by deriving and/or justifying approximations in population dynamics. By changing point of view, data can also be represented differently,and thus permit to go beyond what is usually done.

The historical analysis of these two centuries of demographic transitions show that populations have experienced dramatic changes and upheavals. But we can also see, a number of phenomena and timescales present remarkable regularities. These profound regularities, or "fundamental causes", have been noted by several authors, in very different contexts. In our opinion, the identification and understanding of

these regularities or cycles is fundamental.
Age is also a critical dimension when studying human population dynamics. The age structure of a population generates a lot of complexity in the representation and statistical analysis of data. This so-called Age Period Cohort (APC) problem has been well documented in statistical literature, and should be a main focus in the dynamical modeling of populations. Furthermore, the human life cycle is composed of very different periods, with transition rates of a different order and phenomena of a different nature at each stage. Understanding how to take into account this heterogeneity in age is a critical point. The notion of age itself changes over time. Individuals seem to have rejuvenated, in the sense that today's 65-year-olds are "much younger" than individuals of the same age thirty years ago.
Thus, the shift in paradigm observed in recent demographic trends has highlighted a number of new issues which force us to reconsider many aspects of the traditional modeling of human populations. Multiple questions are still open, with difficult challenges ahead, but also exciting perspectives for the future.

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