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Population and Greenhouse gas dynamics

An implementation of System Dynamics

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ABSTRACT:

As prosperous as the past century of human development has been, rapid change has lately led to several problems, overpopulation and global warming being two among others. Since the middle of the 20th century, scholars have made predictions that our population growth rate might lead to overshoot and collapse of our society in a foreseeable future. Our drive to develop has led humanity to strive for growth. The growth of industrial capital is today inducing a constantly growing need for energy that is harvested from unsustainable resources and creating pollution. The target of this thesis is to study and analyze world dynamics, and especially world population growth and greenhouse gas interdependencies under different scenarios. Emissions are caused mainly by developed industrialized countries with a low birth rate while the birth rate normal is highest in the least developed countries (LDCs) of the world. The method used in this thesis to study the dynamics of population and emissions is Jay Forrester's System Dynamics (SD). SD is a set of tools that enables the user to build dynamic models that can be used to receive a perspective of long-term effects that certain decisions might have. The scenarios simulated in this thesis include prospects of the world and LDCs with current global processes as well as prospects for a world where natural resources utilized are renewable. The simulations of our world where we continue the same development pattern does, like scholars' mention, predict a societal collapse. Consequently, the imaginary scenarios where 100% renewable resources are utilized open for possibilities to a stabilizing future. These renewable resource scenarios, however, have their problems of enhanced population growth and infinite capital growth. Researchers advocate rapid development of LDCs to slow down population growth. Developing unindustrialized countries will, on the other hand, negatively affect the world's emissions. Therefore, the development of undeveloped countries must go hand in hand with emission reductions in industrialized countries not to break the global carbon budget. A requirement for survival and equilibrium in the long run in any system is, after all, sustainability. Thus, we need to rapidly move towards a 100% sustainable way of living to eventually balance the dynamics of the future.

KEYWORDS: System dynamics, population growth, Sustainability, Greenhouse gases

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ABSTRAKT:

Trots den förhöjda livskvaliteten som den mänskliga utvecklingen har medfört, har snabba förändringar på den senaste tiden lett till flera problem, bland annat överbefolkning och global uppvärmning. Sedan mitten av 1900-talet har forskare förutspått att vår befolkningstillväxt kommer leda till överskridande av gränser och därpå kollaps av vårt samhälle inom en överskådlig framtid. Tillväxten av industriellt kapital framkallar idag ett ständigt växande behov av energi som huvudsakligen kommer från oförnybara resurser och som förorenar vår atmosfär. Syftet med denna avhandling är att studera och analysera världsdynamiken, och särskilt sambandet mellan befolkningstillväxt och växthusgasutsläpp. Utsläpp orsakas främst av industriländer med låga födelsetal medan födelsetalen är högst i de minst utvecklade länderna i världen. Metoden som används i denna avhandling för att studera dynamiken mellan befolkning och utsläpp är Jay Forresters systemdynamik (SD). SD är en uppsättning verktyg som gör det möjligt för användaren att bygga dynamiska modeller som kan användas för att skapa ett långsiktigt perspektiv av effekter som beslut kan medföra. I denna avhandling skapades en världsmodell som används för att simulera scenarier för olika samhällen. Scenarierna simulerade i denna avhandling inkluderar framtidsutsikter för hela världen samt för de minst utvecklade länderna med nuvarande direktiv och avtal. Utöver dessa simulationer skapades även prognoser för en värld där de använda naturresurserna är förnybara. Simuleringarna av vår värld med nuvarande utvecklings kurva förutspår, liksom forskare menar, en samhällskollaps. Följaktligen är de imaginära scenarierna där 100% förnybara resurser utnyttjas öppna för möjligheter till en ljusare framtid. Dessa scenarier har dock sina problem med stigande befolkningstillväxt och oändlig kapitaltillväxt. Forskare förespråkar en snabb utveckling av de minst utvecklade länderna för att bromsa befolkningstillväxten. Utvecklade ickeindustrialiserade länder kommer å andra sidan att påverka världens totala utsläpp negativt. Därför måste utvecklingen av outvecklade länder gå hand i hand med minskade utsläpp i industriländer för att inte överskrida den globala koldioxidbudgeten. En grund för överlevnad och jämvikt i alla system är på lång sikt hållbarhet. Därför måste vi snabbt gå mot ett 100% hållbart sätt att leva för att så småningom stabilisera framtiden.

Nyckelord: System dynamik, populationstillväxt, hållbar utveckling, växthusgaser

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Abbreviations

Carbon dioxide – CO_2

Chlorine-fluorine-carbon – CFC

Greenhouse gasses – GHG

Hydrofluorocarbons – HFC

Least developed country – LDC

Methane – CH4

Nitrous oxide – N2O

Perfluorocarbon – PGC

Quality of Life – QoL

Sulphur hexafluoride – SF6

System Dynamics – SD

Ultraviolet light – UV-B

1 Introduction

This chapter will provide a basic understanding of what is being studied and what has led us to the problem we as humans are facing. Since the subject is global warming and population growth, it is of great importance to our society right now.

1.1 Background

“The greatest constant of modern time is change” (Sterman J. D., 2000). The last 500 years of history has brought an increase in human power that has never been seen before. In the year 1500 there were around 500 million people in the world, today we are approaching 8 billion, a 16-fold increase. The overall value of goods and services produced in the world in 1500 is estimated to a value of 250 billion dollars, in today’s world the number is 60 trillion, a 240-fold increase. Finally, humanity now consumes 1500 trillion calories per day while the world’s population in the year 1500 consumed 13 trillion, a 115-fold increase. (Harari, 2012, p. 243). Until recently, mankind evolved in a relatively stable climate for 10000 years, but now it seems to be changing, posing challenges to our adaptive capacity. (Friedrichs, 2013, p. 16)

> *“A law of acceleration, definite and constant as any law of mechanics, cannot be supposed to relax its energy to suit the convenience of man. In every age man has bitterly and justly complained that Nature hurried and hustled him.”*
>
> \- Adams H. 1918

For thousands of years, man has fought for a better life with technology as his constant helper (Meadows D. H., Meadows, Randers, & Behrens III, 1973). In the past century, the human species has evolved and grown in numbers more than ever before. The industrialization of the world has led to higher living standards and longer life expectancy, and followingly the world population has increased exponentially due to vaccines, antibiotics, and food availability. The human population has reached the point in history where we affect our surroundings with such an impact that the earth with its ecosystems can no longer sustain its equilibrium (IPCC, 2014). The consequences are devastating. The industrialized world emits more greenhouse gasses (GHG) than ever before, breaking the earth’s ozone layer and hence warming up the earth. Land sinks that the earth uses to neutralize our emissions are being cut down and polluted and most of the variety of animal species on earth are rapidly following its path to extinction. Scientists have made it clear that the global warming issue can no longer be neglected, and the longer we wait, the smaller are our chances as a species to witness the earth's relapse to a natural equilibrium.

As technology, production and population grow exponentially the world dynamics are constantly getting more complex. To cope in this world requires effective decision making and learning, it requires us to become system thinkers. System thinking is the ability to see the world as a complex system where everything is connected to everything. In a complex, seemingly unpredictable system like this, many of the problems we face arise as side effects from our past actions. (Sterman J. D., 2000). The challenge is, according to Sterman (2000), to move on from generalizations about accelerating systems to tools and processes that help us understand complexity, design better operational policies, and guide change in systems to the better.

In 1971, Jay W. Forrester published the book *World Dynamics* along with the first dynamic world model. This book, together with *Limits to Growth (1972)* written by a group of Forrester’s followers called The Roman Club, caught the attention of the masses due to their suggestion that pollution, economic growth, and the earth’s limited natural resources combined with other factors, could lead to the collapse of our society in the 21st century. This suggestion is based on Jay Forrester’s computer-aided approach to dynamic problems called System Dynamics (SD). System Dynamics is a technical method for understanding and designing complex systems. On the other hand, real-world complex dynamic systems are more than technical mathematical tools, therefore SD is fundamentally interdisciplinary. (System Dynamics Society, 2020). SD is based upon the theory of nonlinear equations and feedbacks from mathematics, but it is applied to human behavior as well as technical and physical systems. Therefore, it draws on social sciences such as psychology and economics (Sterman J. D., 2000). It is with the help of these tools that this research focuses on finding clarity in the population growth and greenhouse gas dilemma of our time.

1.2 Purpose

The purpose of this thesis is to study the dynamics of our social system and the climate to locate relations between events such as population growth, rising GHG emissions, developing countries, and more. Greenhouse gases are pollution caused by our industrial society, the society that has driven the rapid human development since the industrial revolution. Specifically, the research statement is;

- To study world population growth and greenhouse gas interdependencies under different scenarios.

The question might at first seem trivial in the sense that population growth and emission growth could be thought to go hand in hand, but there are implications in research that suggest otherwise. The key objectives to this research question will demonstrate the underlying issues:

- Stabilizing the population.
- Developing unindustrialized countries without creating more global emissions.
- Decreasing greenhouse gas emissions by global climate-conscious decisions.
- The link between greenhouse gasses and population growth.

Research has found that population growth has diminished in industrialized countries while a remarkable increase in population is happening in the less developed areas of the world. (United Nations, Department of Economic and Social Affairs, Population Division, 2019). Therefore, developing unindustrialized countries could solve the globally growing population issue. The world’s most GHG emitting areas are, on the other hand, the industrialized countries. This leads us to the question of whether the development of unindustrialized countries leads to even higher levels of greenhouse gasses.

The purpose of this thesis is to study the relationship between population growth and greenhouse gas emissions to find out whether these factors are inversely related, correlated, or not connected at all. Furthermore, alternative ways of dealing with these issues simultaneously, without letting one of these factors soar, are discussed. The dynamics of the world's greenhouse gas emissions, population growth, and other factors is an important topic for building business scenarios in a variety of businesses such as the automotive-, oil- and energy industries. Industrial companies such as Shell from the oil- and Hewlett Packard from the technology industry have been creating scenario-driven long-term planning since the 1960s. (Georgantzas, 2010), (Wilkinson & Kupers, 2013).

1.3 Method

First, to demonstrate the problem, real-world data is analyzed. With the help of statistical tools such as R Studio, appropriate and informative graphs are created. Second, the method that will be used to study world-, and local dynamics in this thesis is System Dynamics modeling, a set of conceptual tools developed by Jay W. Forrester in the late 1950s. This method will enable us to gain insights into the structure and dynamics of complex systems. Therefore, SD will be used in this thesis to build simulations of the population growth and GHG problem.

1.4 Delimitations

The keywords used in this thesis are

- System Dynamics (SD),
- population growth,
- greenhouse gasses (GHG) and
- sustainability.

System dynamics refers to the dynamic modeling system created by Jay W. Forrester. SD is chosen as a keyword since it is the main method of this thesis and it is being thoroughly discussed. Population growth is one of the biggest concerns in the world today, and further, it is thought to be one of the drivers of another big issue, greenhouse gas emissions. Together, population growth and greenhouse gasses create the biggest threat to us humans today: global warming. Hence, they are chosen as keywords as well. To find long term balance in this dynamic system, we must start to solve problems sustainably. The definition of sustainability is, according to the Oxford Dictionary of English, "able to be maintained at a certain rate or level". And thereby, the keyword sustainability shall, in this thesis, refer to solutions that will not only solve the problem in short term but will conserve the dynamic balance independent of time.

In this thesis, the world dynamics will be studied over a period of 100 years. That is from the year 2000 to 2100. This relatively short time frame of 80 years ahead has been chosen in order to simulate conceivable prospects. Further, earlier research points out the importance that the coming 80 years will have for our species. Therefore, this timeframe is likely to contain remarkable turning points for many simulated variables. Population dynamics alone is a broad topic; therefore, many aspects will leave for future research to be processed. Topics that are outside the scope of this study are population structures, fertility drivers, and life expectancy. Population emissions will be handled mainly from a global-, and occasionally, from a national perspective.

2 Literature review

In this chapter, existing literature will be processed to form an understanding of the background and the variables that affect the outcome and have led to the modern state of the world. First system dynamics and implementations from the field will be presented before moving on to historical data and research from other fields.

2.1 System Dynamics

2.1.1 System Dynamic briefly

System Dynamics was developed in the mid-1950s by Professor Jay W. Forrester at the Massachusetts Institute of Technology (MIT). Due to Forrester's manager experience, he concluded that the biggest obstacle for progress comes, not from the engineering side of industrial business, but the management side. This is because of his conviction that physical systems are much easier to understand and control than social systems. (System Dynamics Society, 2021). Forrester's System Dynamics is a perspective and a thorough modeling method for building computer simulations of complex systems and use them to understand and develop more efficient processes and policies. The tools of SD allow for building micro-worlds where time and space can be compressed and slowed for us to understand the long-term effects of decisions. System Dynamics has been applied in the process to solve many difficult human issues, ranging from the human immune systems combat against HIV and the dynamics of diabetes to corporate management issues and wars. (Sterman J. D., 2000). To build a truthful model that represents the real world, multiple variables, loops, delays and flows must be built and controlled.

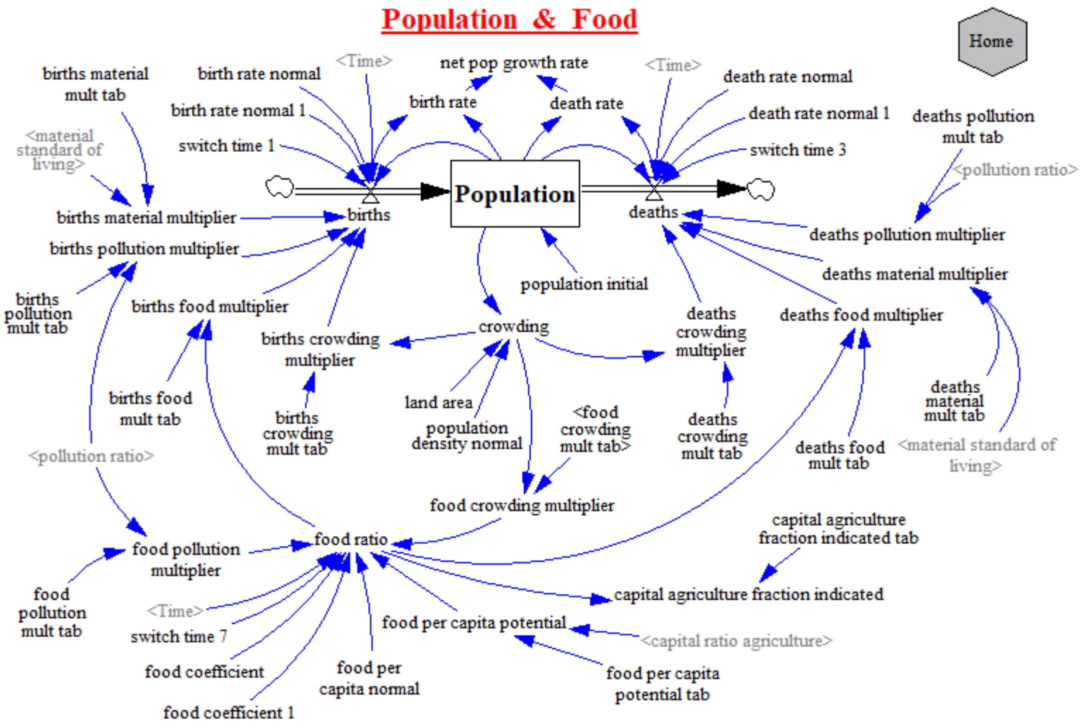

Figure 1. A model of the world’s Population and Food dynamics by Jay W. Forrester. Source: Ventana Systems, Inc. (2013).

Figure 3 represents an interface upgraded page of Forrester’s original world model. The page shown is considering the world’s population and food dynamics. When studying the diagram, the population can be perceived as a level of a measurable unit, in this case, people, with certain attributes affecting it. In this model, the population is mainly dependent on the rates of births and deaths, and further, the population depends on materialistic and pollution variables among others. Dynamic systems often contain causes and effects that create loops, such as births and population. The world’s population is highly dependent on births, while the births variable is dependent on, among others, the population that can give birth. These relations between variables, levels, and stocks are symbolized with arrows. System dynamics can be utilized in many other scenarios beyond population dynamics.

2.1.2 Companies interest in System Dynamics

Company management in diverse businesses is naturally interested in knowing what the future might bring. Therefore, scenario planning is implemented. Scenario planning is a way to explore possible futures by considering forces that affect business today and foresee how the dynamics of the forces will affect the future. By doing so, questions like; where is the market going? and how will certain regulations affect us? can be given educated answers. (Salesforce, 2021). According to (Georgantzas, 2010), Big industries and firms such as Airbus, General Motors, Hewlett-Packard and Intel use scenario-driven planning (sdP) with system dynamics to better understand scenarios like whether some effect from environmental change gets magnified or fades away by time.

In 1965 the oil company Shell started an initiative they called Long-Term studies. The idea of this experiment was to study the future of Shell’s business. In 1967 the “future” initiative started to take shape and a “Year 2000” study report was completed. After this the team started to deliver long term forecasts in the form of alternative futures, the criteria for Shell’s scenario planning is “plausibility”. Meaning that if the alternative future scenario can be logically deduced from the present, it must not be neglected. The idea of Shell’s initiative was never about predicting the future, but rather about how different scenarios are embedded in – and linked to – organizational processes. This created an understanding of the importance of leadership development and innovation among other things. Furthermore, scenario planning helped Shell’s corporate planning to break free from the habit of assuming that the future will be much like the present. (Wilkinson & Kupers, 2013).

2.2 Development of the modern society

To understand the dynamics that are in play in the world, we must go back to when the development started. Wood remained the most important source of energy until the later part of the 18th century. Once Europeans colonized North- and South America, population growth started accelerating at a faster pace, leading to a dramatic decrease in Europe’s tree coverage. The tree coverage dropped from 95% at the time of the fall of the roman empire in 476, to around 20% by the time the scientific revolution begun in the 15th century. (Gore, 2009, p. 50). The combination of a vast shortage of wood and new energy devouring machines led to an accelerating use of coal, which earlier had been thought of as inferior to wood due to its air polluting qualities. Once mankind started to mine coal underground, more complex inventions such as the steam machine and metal wheels on railways were invented. Soon the industrial revolution led to the widespread use of coal as the primary fuel for factories. (Gore, 2009, p. 50). According to (Adams, 1919), edited by Steinhart (2011), the coal-output of the world doubled every ten years between 1840 and 1900. It was the ability to tame electricity for commercial use in the late 19th century that laid the foundation for the dominating use of coal we see in our time. (Gore, 2009, p. 50). It is important to notice that the world then was not as connected as it is today. Therefore, the world's population must be seen as related but autonomous "societies" rather than one society (Hopkins & Wallerstein, 1977, p. 1). Given this perspective, it is understandable that some societies started industrialization earlier than others, and some developed faster than others, thus creating developed – and undeveloped societies, which is a fact to this day.

2.2.1 Exponential growth

Growth and swift change are the first reasons for a dynamic system to overshoot. Many areas in the dynamic world system have experienced rapid growth for over a century now. The world's population, food production, industrial production, and natural resource utilization are examples of these. These examples follow a growth model, that is mathematically called exponential growth. (Meadows, Randers, & Meadows, 2004, p. 43). Exponential growth arises from self-reinforcing positive feedback loops. A remarkable property of pure exponential growth is that the doubling time is constant: no matter how large the state of the system, it will double in a constant time. This means that it takes the same length of time to grow from one unit to two, as it takes from 1 billion to 2 billion. (Sterman J. D., 2000, pp. 108-109).

For doubling time of differently growing quantities, see table 1. To describe the rapid acceleration rate happening today, (Friedrichs, 2013, p. 3) concretizes it followingly; If we assume that the world economic output would grow 3 percentage annually, that would mean that the global GDP would double in 24 years and quadruple in 46 years. If this would be the case, considering that other factors would stay put, this would imply a 16-fold resource consumption and pollution rate compared to today. Regarding coal use and technology in “The Law of Acceleration”, (Adams, 1919) exemplifies the steamboat; In 1905, a ticket on an ocean steamer would hire the use of 30000 steam-horse-power, and to go backward in time, the figure must be halved every 10 years, resulting in 234 horsepower for 1835. The structure of our system is driving the humanity and economy to strive for growth. But in a finite world, exponential growth must stop sooner or later. (Meadows, Randers, & Meadows, 2004, p. 45).

Table.1 The relationship between the percentual rate of growth and doubling time. (Meadows, Randers, & Meadows, 2004, p. 49).

Growth Rate (% per year)	**Approximate Doubling Times (years)**
0.1	720
0.5	144
1.0	72
2.0	36
3.0	24
4.0	18
5.0	14
6.0	12
7.0	10
10.0	7

2.2.2 Population growth

For centuries mankind lived as hunter-gatherers unable to sustain any larger populations, life was simple, and the goal was only to survive. Then man transitioned to agriculture, thus entering the Neolithic era. This transition is by many scholars considered a big mistake in the history of mankind (Harari, 2012). (Gowdy & Krall, 2013) states that the average human was worse of in the agricultural society, life became more painful and the agricultural chores were physically heavy for humans which were not evolutionarily prepared for such monochromatic labor. For better or worse, this led human society to start acting as a superorganism, a single unit designed by natural selection to produce economic excess. With agriculture came ultrasociality (Gowdy & Krall, 2013), which Campbell defines followingly; "Ultrasociality refers to the most social of animal organizations, with a full-time division of labor, specialists who gather no food but are fed by others, effective sharing of information about sources of food and danger…" (Campbell, 1982). Ultrasociality of organisms leads, according to Gowdy & Krall (2013), to consequences, even so in the case of mankind. These include (1) rapid population growth, (2) domination of the habited ecosystem, (3) extensive use of natural resources for excessive production, and (4) hierarchical organization of the society. And as follows, at the most habitable lands, early human agricultural societies exhibited explosive population growths. (Gowdy & Krall, 2013).

Since the Neolithic revolution, approximately 10 000 years ago, the modern human population has experienced dramatic growth, faster yet in the last 2000 years. (Gazave, et al., 2014). Our history has proven humanity to be unique in overcoming ecological limitations and reaching excessive population numbers. The extent of it has resulted in us becoming a geophysical force whose footprint marks a new geologic era unofficially called the Anthropocene (Weinberger, Quiñinao, & Marquet, 2017), or "the age of humans" (Gowdy & Krall, 2013). In the year 1650, there were 0.5 billion people in the world and the growth rate was 0.3% per year. This means that the doubling time of humanity then was approximately 250 years. In 1970 the corresponding numbers were 3.6 Billion people and a growth rate of 2.1%, meaning a doubling time of 33 years. This indicates that the interest has not been raised only by population size, but also with the growth rate. Thus, we can say that the population growth has been "super-exponential": the growth curve rises faster than it would if the growth was only exponential. (Meadows D. H., Meadows, Randers, & Behrens III, 1973, pp. 35-36).

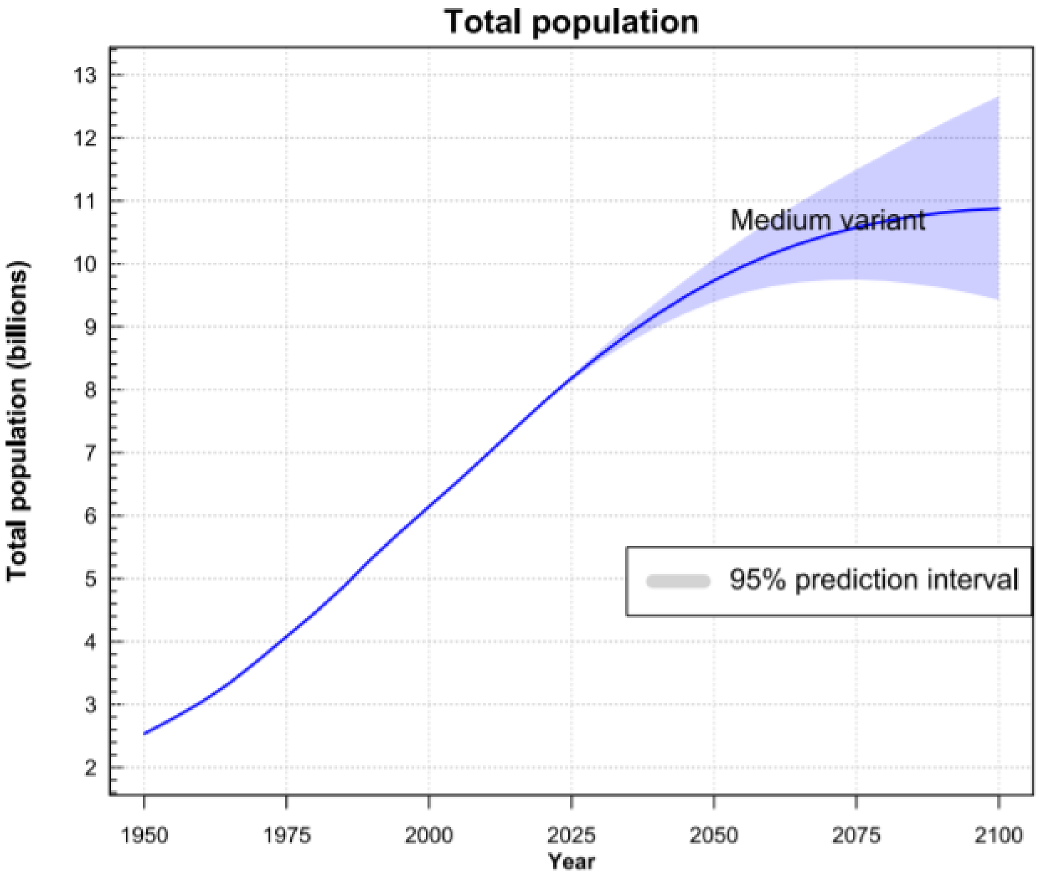

Figure 2. World population years 1950 – 2100. Source: (United Nations, Department of Economic and Social Affairs, Population Division, 2019)

The reasons for the super-exponential growth of the world's population can additionally to Gowdy & Krall's (2013) ultrasociality argument, be found in human inventions. Two trivial factors are balancing the population; births and deaths. According to (Meadows D. H., Meadows, Randers, & Behrens III, 1973, pp. 38-39), births and deaths were both relatively high before the industrial revolution, and births barely exceeded deaths. In fact, the human lifespan in the 17th century was approximately 30 years. Since then, mankind has developed many inventions that have had a deep effect on the system of population growth, especially on mortality. This results in that while the positive feedback to the population (births) has only decreased a bit, the negative feedback (deaths) is constantly decreasing. Therefore, the human population has, for the last century, grown super exponentially. (Meadows D. H., Meadows, Randers, & Behrens III, 1973, pp. 38-39).

2.2.3 Economic growth

Since the industrial revolution, the world economy has started to grow even faster than the population, this is due to industrial production. Industrial production is based on industrial capital such as factories, tools, and machines. The more capital, the more production. Most of the overall yearly production is consumables such as clothes and cars, but some produced goods are investments such as knitting machines and iron factories. Investments grow the industrial capital stock, which in its turn grows production, and thus the positive feedback loop in economic growth is the yearly growing capital. Just like the human population, industrial capital has a balancing loop since invested capital wears out. But just as with the population, the positive feedback loop rules in today's world, and the industrial capital stock keeps increasing its interest rates. (Meadows D. H., Meadows, Randers, & Behrens III, 1973).

A good example of economic growth is China. In the mid-20th century, China was a poor undeveloped country. With the economic reform starting in 1979, China opened for foreign trade and investments and implemented free-market reforms. This resulted in China becoming one of the world's fastest-growing economies with its gross domestic product (GDP) growing by 9,5% through 2018. This growth has enabled China to double its GDP every eight-year and lift approximately 800 million people from poverty. China's growth model has, however, like most other industrialized countries, emphasized heavy industry, resulting in high pollution. See figure 3. (Morrison, 2019).

2.3 Climate change

2.3.1 Greenhouse gases

The industrialization and economic growth of our society have their dark sides. During 1860 – 1985 mankind doubled its energy consumption 60 times thanks to the industrial revolution. Pollution is the result of industrialization and climate change is the result of pollution. (Meadows, Meadows, & Randers, 1992, p. 63). According to one of the United Nations operations to limit greenhouse gases, the Kyoto Protocol, six major greenhouse gases contribute to global warming: Carbon dioxide (CO_2), Methane (CH4), Nitrous oxide (N2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PGCs) and Sulphur hexafluoride (SF6). (United nations, 1998). (Gore, 2009, p. 47) adds soot to the list of contributors to global warming even though soot is technically not a gas. Several of these major greenhouse gases occur naturally in the atmosphere, but the soaring concentration of these during the last 250 years is largely due to human activity. (IPCC, 2007). These pollutants that we release into the atmosphere capture heat and increases the temperature of the air, water, and the earth's surface. (Gore, 2009, p. 32).

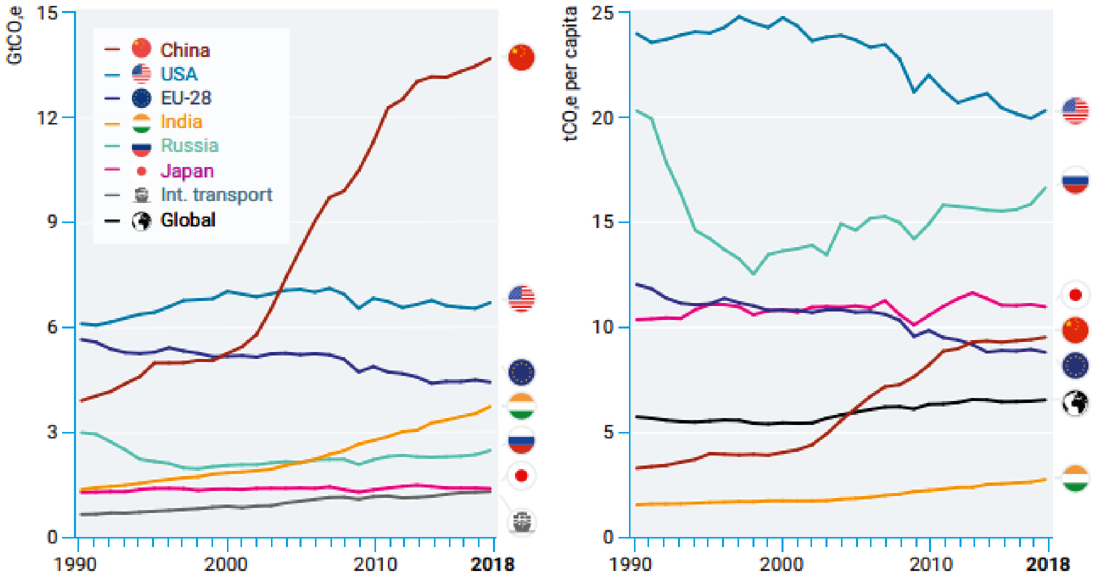

Figure 3. Top greenhouse gas emitters. Left absolute emissions and to the right emissions per capita. Source: (UNEP, 2019).

The Kyoto protocol was first introduced in 1997. 25 countries signed this protocol and admitted they are responsible for GHG emissions. (Haradhan, 2012). US government refused to sign this protocol, but in 2008 they agreed to limit their annual emissions to below 1990 levels. This promise was, however, never achieved. Haradhan (2012) states that according to the International Energy Agency (2007), the USA and China are the world's leading GHG emitters, this can also be seen in figure 3. Together China and the USA emit 40% of global CO_2 emissions and approximately 35% of total greenhouse gases. (Haradhan, 2012). The most common GHG, Carbon dioxide, is released into the atmosphere by the combustion of coal in order to produce heat and electricity, by combustion of oil-based fuels in the transport sector, and by the combustion of coal, oil, and natural gas in the industry sector. (Gore, 2009, p. 32).

2.3.2 Global warming

The human civilization and the ecosystem of the earth are colliding (Gore, 2009, p. 32). The effects of global warming are well documented: higher temperatures, more weather extremes, rising sea levels, and altered weather precipitation patterns (Friedrichs, 2013, p. 15). These effects will have consequences such as the extinction of species (Gowdy & Krall, 2013). There are many reasons for the global warming we are facing, and it is well established that the biggest driving factor for global warming is greenhouse gas emissions (Haradhan, 2012). The biggest reason for the pollution that mankind cause is energy production through the combustion of fossil fuels (Gore, 2009, p. 51). Therefore, many developed countries have agreed that GHG emissions have to be cut by up to 80% by 2050. However, global economic crises make it hard for some industrialized countries such as the USA, Canada, and India to promise to cut down on GHG emissions. (COP/CMP7, UN Climate Change Consensus 2011, Durban, South Africa), reported by (Haradhan, 2012). The emissions that industrial production generates has previously been absorbed by natural sinks, but we have now exceeded the limits that nature can handle, thus damaging the ecosystem and human societies. (Friedrichs, 2013, p. 13). The driving force of climate change is overconsumption in developed countries, while the impact of global warming will be most devastating for poor people in developing countries. High fertility rates followed by rapid population growth will hinder the reduction of poverty and put pressure on diminishing natural resources, weak infrastructures, and the ability to adapt to the effects of climate change. (Stephenson, Newman, & Mayhew, 2010).

Global warming is induced by exponential growth. For example, greenhouse gas emissions in the atmosphere increase the temperature, which in its turn accelerates the melting of the arctic ice. Thereby, methane gas stored in the ice is freed. Methane gas is a greenhouse gas that can increase the atmospheric temperature, hence creating a positive feedback loop that can lead to an exponential increase in temperature. (Meadows, Randers, & Meadows, 2004) .

(Gowdy & Krall, 2013) argue that ultrasociality has given human society features that make it exceptionally hard to change course even in the face of an approaching disaster. Further, Gowdy and Krall (2013) state that global capitalism is the present iteration of our ultrasocial transition and that it, as a system, has formidable flaws such as the inability to provide enough employment. Thus, Gowdy & Krall (2013) provokes the question of whether the flaws of the system will become obvious enough for a completely new system to develop, or whether the force of capitalism will hold together until ecological collapse becomes irreversible.

2.4 Limits to growth

“What goes up, must come down” (Gore, 2009, p. 32). In the history of mankind, there are, according to Meadows et al. (1973), many cases where man has failed to survive on the conditions of physical boundaries. Nevertheless, many societies today thrive because of their history of successfully breaking the physical limits. In fact, in the last 300 years, humanity has successfully pushed the limits of population and economic growth further and further away. As the recent history of mankind has been repeatedly prosperous, it is natural that most people assume that technological advancements will keep pushing the physical limits endlessly. (Meadows D. H., Meadows, Randers, & Behrens III, 1973, pp. 8-10). Our planet is nevertheless a finite resource and hence the only option to succeed is through sustainable choices. In Limits to Growth: A 30-year update, the authors are not concerned that the earth's energy and raw material would be ending. The problem is according to Meadows et al., the always rising recycling costs of pollution disposal sites. Recyclable resources are being used more, constantly increasing the filling rate and costs of recycling at disposal sites. In the long run, this will lead to the cost of recycling soar to a level where industrial capital’s negative feedback loop will become stronger than the reinforcing loop and thus the industrial capital will no longer grow. This in its turn, will turn the direction of our economy. (Meadows, Randers, & Meadows, 2004, pp. 74-75).

Many models have been developed to evaluate scenarios for a sustainable future with current human population growth trends. (Weinberger, Quiñinao, & Marquet, 2017) discusses the possibility of innovations to cover the growing demands. Weinberger et.al (2007) presents a model where technological advancements, aimed at improving the habitat quality, increase with population size as well as has positive feedback on the generation of innovations. This model shows, that depending on the net impact of technology on the provision of ecosystem quality, and the strength of the positive feedback, different future scenarios can occur. Among these scenarios, one predicts that humankind can fill the planet while maximizing the quality of life without exhausting the ecosystem. This scenario requires green technologies that do not have negative impacts on the ecosystem but have a strong positive impact on the generation of new technologies. This scenario however assumes human ingenuity to be an unlimited resource (cornucopian perspective), which is also unrealistic in the long run (Friedrichs, 2013). The only other scenario where a fully populated world is in equilibrium, according to Weinberger et al. (2007), is if the technological stock is completely minimized. In the other possibilities in-between, innovations generate net-negative impacts, and hence they can be associated with a limited human population with the possibility of collapse.

The idea that exponential growth is unsustainable is not new. Thomas Malthus (1798) suggested that food production growth is linear and cannot keep up with exponential population growth, and therefore he expected periodic cycles of overpopulation (Malthus, 1798). This phenomenon is publicly referred to as the Malthusian trap. As history shows, Malthus got it wrong because of his core assumption that food production cannot be exponential. Agriculture has since the 19th century been able to keep pace with population growth thanks to technological advances, which were not predictable in 1798. (Friedrichs, 2013, pp. 5-6). Nevertheless, from a long-term viewpoint, industrial agriculture is problematic for the very reason that it has allowed population levels to overshoot long-term carrying capacity. Friedrichs (2013) states that Industrial agriculture largely relies on limited resources such as fossil fuels and clean water, which may have tragic consequences down the road.

> *“Infinite growth on a finite planet is impossible. Industrialism as we know it cannot last forever, and at some point industrial growth is bound to become unviable “*
>
> - *Friedrich (2013)*

2.4.1 Limits of population

Population growth will as well reach a turning point in a finite world. To avoid a collapse, we must find an equilibrium where we can sustain the world’s population. To exemplify what a population collapse can be, Sterman (2000) describes the overshoot and collapse on Easter Island during the 13th century. According to Sterman, radiocarbon dating indicates that mankind first settled on this remote island between years 400 and 690. The population is estimated to have grown slowly until about 1100 when an acceleration in population growth started. By the year 1400, the island’s tree coverage was nearly completely cut down, reducing the island’s carrying capacity dramatically. Scientists have found evidence of increased soil erosion due to deforestation and the rain effectively washed away the unprotected soil. Without the forests, wind speeds increased on Easter Island, carrying still more soil into the sea. Deforestation also increased evaporation from the soil, and the island with its streams dried up. Eventually fishing, the last source of food, also stopped, as boats and other wood-made tools were no longer replaceable. As the island’s carrying capacity diminished, population growth declined, peaking at general estimations of 6000 to 10000 people around the year 1600. Approximately 80 years later a steady population decline had set in, accompanied by changing political and religious structures. When the first Europeans arrived at Easter Island in 1722, they found poor, war-torn people, estimated by scientists to a population size of 2000. After the Peruvian slave raids and a smallpox epidemic, the population fell to 111 in 1877. (Sterman J. D., 2000).

Research agrees that the world’s population is still growing, and mostly in low-wage- and developing countries (Gore, 2009, p. 226) (Friedrichs, 2013, p. 4) (Andreev, Kantorova, & Bongaarts, 2013). Additionally, it is generally thought that the ongoing industrialization of these countries leads to further pollution of the environment. Therefore, a plan to solve the climate crisis must involve a plan to stabilize the world population (Gore, 2009, p. 226). According to Gore (2009), the world’s growing population issue is one of few problems where a global consensus prevails. In the last 25 years, progress in understanding the population growth dynamics has already led to a drastic decrease in population growth. If we continue this path, some research says we might face an equilibrium of just shy of 9 Billion people by the year 2050. (Gore, 2009, p. 226), others claim that the population will grow until the year 2100 when it will stabilize around 10.5 - 11 Billion people. (Andreev, Kantorova, & Bongaarts, 2013) (Friedrichs, 2013).

Decades ago, it was discovered that countries with a high gross income had a slower population growth and a higher industrialization rate compared to less industrialized, poorer countries (Gore, 2009, p. 228). It turns out, however, that the reason for high fertility rates is not un-development and poverty itself, but a series of underlying factors in the social dynamics that achieves the transition from high death-, high birthrates and big families to low death- and low birthrates. This transition is known as the demographic transition. (Andreev, Kantorova, & Bongaarts, 2013). The underlying factors that drive the demographic transition are, according to demography experts, 1. Widespread education of women. 2. Social and political autonomy for women which allows them to participate in the decision process in the family, community, and nations. 3. Low child mortality which gives parents confidence in that their children will survive to adult age. 4. Opportunity for women to decide the number of children and the time between births. Experience confirms that if all four of these factors occur, a transition to smaller families and slower population growth will occur. (Gore, 2009, pp. 228-229).

However, while the world population growth is slowly grinding to a halt, this will not solve everything: the problem in today's world is not overpopulation, but rather overconsumption. (Friedrichs, 2013, p. 9)

2.4.2 Limits of the industrial world

Our industrial society today runs on energy, and especially on oil. This means that a serious oil shortage can bring our society to the edge. There are two scenarios today that can result in energy scarcity (Friedrichs, 2013), the first being energy scarcity caused by climate change. Climate change can constrain the amount of greenhouse gasses that can be emitted; hence it might become inevitable to start rationalizing fossil fuel to keep climate change within boundaries. The second scenario that can cause energy scarcity is induced by resource depletion. A peak followed by a rapid decline of world oil production would result in a serious shortage of the resource that fuels or industrial society.

The economic system, global capitalism, has many structural problems. It cannot provide sufficient employment to the whole world's population. The system produces poverty, inequality, and unemployment faster than the generated growth can counteract them. Some countries in Europe have an unemployment rate of 25% and the emerging economies are now counting on the growth speed to take up surplus labor, but the Chinese and Indian economies cannot continue to double every 10 years. (Gowdy & Krall, 2013).

Furthermore, there is an ethical dilemma involved. In order to avoid dangerous climate change, the amount of GHG that we can emit into the atmosphere is limited, this is called the carbon budget. Climate justice is a collective term for discussion regarding ethics around the carbon budget. There are many discussions and opinions on how to share the carbon budget, but to do so ethically and most favorably is no easy task. The budget is now consumed by industrialized countries as it is needed to boost the economy, but for undeveloped countries to progress and rise out of poverty (and as a consequence slow down the population growth rate), they need to be able to use their share of fossil fuels. Hence, Industrialized countries need to cut down on emissions. (Moss, 2019).

2.5 Prospects

Energy scarcity is threatening our future quality of life. If energy runs short, it will bring the industrial society to the brink. This scenario can be driven by two things: climate change and lack of resources to produce energy. (Friedrichs, 2013). Mankind risks an overshoot followed by a collapse when using natural resources and emitting pollution unsustainably. The world is not yet in such a state where the system that monitors unsustainability would reduce it. This means that our ecological footprint is not yet big enough to trigger actions that would reduce the footprint, or there is a delay in the feedback of our actions. Overshoot happens when there is a delay in the feedback. (Meadows, Randers, & Meadows, 2004). This chapter focuses on what can happen if we continue down this path, and how we can avoid future global disasters.

2.5.1 What happens if we exceed our limits to growth and how to avoid it?

Let us look at two basic modes of growth (Sterman J. D., 2000, pp. 118-125) to understand some of the possibilities of a dynamic system such as our world. Nothing real can grow or decrease forever, there will always be one of many limiting factors to eventually stop the growth (Senaras, 2017). For a population to grow in an S-shaped curve, meaning first exponentially and then stabilizing around the systems equilibrium level, like the world’s population seems to do now, two critical conditions must, according to Sterman (2000), be met. First, the feedback that constraints growth needs to act swiftly to prevent overshoot. Secondly, the carrying capacity needs to be fixed. The carrying capacity of habitat is the limits to growth, the number of organisms it can support, and it is determined by the resources in the environment. In a perfect run, the population grows exponentially, and when it is approaching the habitats carrying capacity the negative feedback loop will halt the growth as fewer resources per capita becomes available and the population will find balance with the environment. (Sterman J. D., 2000, pp. 118-125).

It is common, however, that the environment's ability to support a growing population is consumed by the population itself, as in the example of Easter Island in chapter 2.2.1. When a population consumes the carrying capacity, a second negative feedback loop starts working to limit the growth. Now the population growth cuts available resources first by the negative loop that limits the resources available by capita, and secondly by the negative loop that reduces total resource and thereby reducing the carrying capacity. This means that when the population growth finally stops, is when the two negative feedback loops are most powerful. In this case, the population will not settle around the carrying capacity since the carrying capacity is declining. Followingly, the population will start to decline. Even though the state of the system is deteriorating, the population continues to consume the carrying capacity, resulting in that the resources per capita remain insufficient and the fall in population continues. If this is a case where the carrying capacity consists of non-renewables, the equilibrium of the system will be extinction. (Sterman J. D., 2000, pp. 118-125). According to (Sterman J. D., 2000, p. 119), thermodynamics dictate a limit to the earth's carrying capacity, though there is no understanding among scholars what that level is, if we should strive to stabilize around it or a bit under it, or whether stabilizing around the carrying capacity would provide a satisfying quality of life on earth or not.

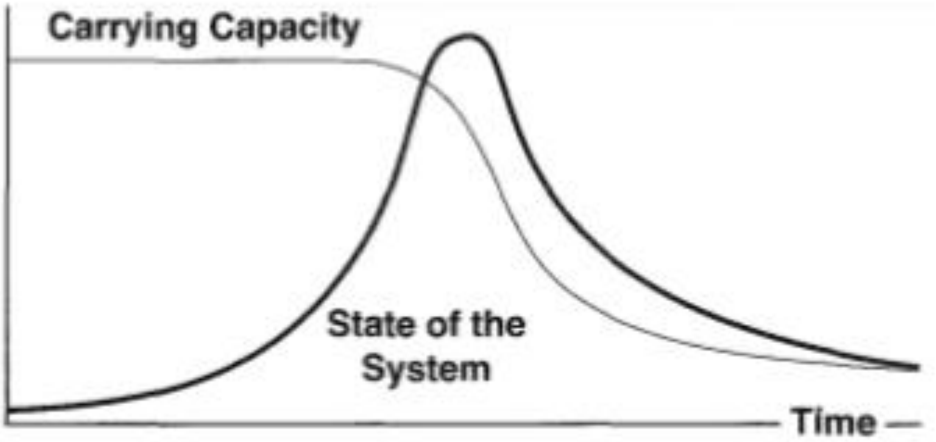

Figure 4. Overshoot and collapse. Source: (Sterman J. D., 2000, p. 124).

A good example, by (Meadows, Meadows, & Randers, 1992), of exceeding our limits and returning successfully is the ozone layer crisis that was discovered in the '70s. The ozone layer is found in the stratosphere and the ozone gas is very sensitive, it attacks other gases and oxidizes them. The ozone layer is important to all earth's living creatures because it filters ultraviolet light (UV-B) from sunlight. In 1974 scientists first noticed that the ozone layer is becoming thinner. This turned out to be largely due to chlorine-fluorine-carbon (CFC), also known as freons, a compound that was widely used in refrigerators and aerosol propellants. At first, the warnings of a disappearing ozone layer were not taken seriously by the governments, (Gowdy & Krall, 2013) emphasizes this behavior to be a major problem with downward causation in our ultrasocial society, but with international cooperation and the United Nation's environmental program UNEP, we finally managed to come to the Montreal agreement, which limited the use of CFCs and later, the London agreement which banned the use of CFCs altogether. (Meadows, Meadows, & Randers, 1992).

2.5.2 The ethics of population growth and GHG emissions

So far it has become evident that the population growth is strongest in the least developed countries (LDCs). This concordance with the research of Gore (2009) and Andreev et al. (2013) which suggest emphasizing the demographic transition in these countries in order to stabilize the population growth. The LDCs are also the world's least carbon-emitting nations while the developed countries can, according to Stephenson et al. (2010), be held responsible for emissions that drive climate change. But what happens when the less developed countries walk in the footprints of the industrialized nations and start contributing to the pollution of the earth's atmosphere? These countries are gaining more and more access to powerful techniques that usually damage the environment and contribute to climate change (Gore, 2009, p. 226).

To further complicate the situation, research indicates that to avoid dangerous global warming numbers, we can only consume one-third of the remaining fossil fuel reserves on earth. This raises another ethical question whether developed countries should be allowed to continue to extract fossil fuels while developing countries cannot utilize their reserves? (Moss, 2019). This is a critical and sensitive issue that has lately risen to debate by scholars. Stephenson et al. (2010) highlight the contraction and convergence strategy, which includes reducing carbon emissions and sharing the global emissions equally per person. This would result in industrialized countries reducing their emissions dramatically while developing countries would increase theirs to an internationally agreed level, and hence stimulate development.

Conclusively, if population growth is to halt while greenhouse gas emissions decrease, the less developed countries must start developing, thereby stagnating the population growth. If undeveloped countries ought to progress, they will contribute to the global GHG emissions. This is the research gap that this thesis aims at closing, can the global carbon budget hold as the unindustrialized countries develop and the population growth rate drops?

The review of this literature clarifies and underlines the problem our world is facing today. The common message from the research is that something needs to happen, we need to change our habits to avoid a global disaster. The faster we realize this, the more likely we will succeed.

3 Methodology

In this chapter, the choice of method of conducting this research is explained, motivated, and justified. Further, tools, software, data, and material are presented and explained for the reader to gain an understanding of how the study is conducted and what means has been taken to reach the result and validity of this research.

3.1 Research strategy

3.1.1 Quantitative

Since the research question is concerning a global sensitive issue, the research must be objective, the data must be meaningful and the framework and base for the research must be statistically justified for analysis. Therefore, a quantitative method has been chosen over the qualitative, arguably more subjective, method. (Logan, 1997). A quantitative model is based on variables that change over a certain field while being related through quantitative and causal relationships. (Bertrand & Fransoo, 2002). The qualitative method is good for in-depth research where it is unclear which variables and dependencies are going to be significant. Furthermore, it can be implemented in situations where the value lies in subjective meaning and values. (Logan, 1997). Quantitative model-based research such as this thesis is based upon the assumption that an objective model can be built that explains at least a part of the behavior of the real world's dynamics. (Bertrand & Fransoo, 2002).

Since the method of this thesis, systems dynamics, is a simulation of our surroundings that can be used as decision support, the method is purely theoretical.

3.1.2 Descriptive and normative

Model-based research may, according to (Bertrand & Fransoo, 2002) be classified into two categories, depending on what drives the research. Axiomatic research is primarily driven by the idealized model itself. The core interest of this research method is to find solutions within the defined model and to obtain an understanding of underlying factors, variables, and relations that leads to the outcome. Furthermore, axiomatic research produces behavioral knowledge of variables. This can eventually result in an understanding of how to manipulate control variables in the model to achieve a satisfactory outcome. Followingly, the axiomatic design is usually normative with the aspiration to understand the process that has been modeled and to obtain an optimal solution for the defined problem. (Bertrand & Fransoo, 2002).

The second class of model-based research is driven by empirical findings and measurements. In contrast to axiomatic research, this class emphasizes the importance of fit between the model and the reality it is meant to represent. Such research can be both normative and descriptive to its nature. This descriptive research focuses on recreating the reality with its variables and relations as adequately as possible to gain an understanding of the dynamic process going on. (Bertrand & Fransoo, 2002). Once the computerized model conforms with reality, future predictions can be made. A well-known example of this type of research is Jay Forrester's World dynamics (1971) where he modeled and predicted the future of the world through a series of conceptual tools he named system dynamics. The research method of this thesis is in fact system dynamics, and therefore, this research is descriptive and normative theoretical quantitative.

3.2 Data analysis

Before going into simulating societies, an analysis of available data will be carried out. This data is collected from different sources such as the population division from the United Nations Department of economic and social affairs, and from the Global carbon project. The data is processed with R programming in the R studio software. The goal of this analysis is to lay the theoretical ground for modeling population and GHG dynamics and to find out statistically interesting topics to study in the modeling phase.

3.3 System Dynamics as a research method

This research is focusing on the dynamics in the system that includes population growth and greenhouse gas emissions. Based on theory and earlier research, a System Dynamics model is built to obtain a theoretical view of the variables and relations that are in play in the system. The model will also give prospects about the future, and hence it can be to aid in answering the research question of this thesis. The model is downloadable through GitHub (see link below). The .mdl file in the repository is a text file containing the same source code as the appendix, it is readable with Vensim PLE. The .vpmx file, on the other hand, is readable with the Vensim model reader which can be downloaded for free through Vensim’s web site.

Link to GitHub repository: https://github.com/WiljamFors/WorldDynamics.git

Vensim is a product of Ventana Systems, Inc. of Harvard. It was first formed in 1985 to develop large scale simulation models to solve management problems. Over the years the company has released several updates and, in this thesis, Vensim's personal learning edition (PLE) 8.1.2 is used to create models and simulate scenarios.

3.3.1 Defining variables for the model

To simulate and analyze the dynamics between factors such as population and greenhouse gases, a System Dynamics model was created in Vensim. In order to be able to adapt and compare the model to real-world measures, CO_2, the most common GHG has been chosen as a pollutant. Beyond the mentioned measures, this system also simulates Capital and Quality of Life (QoL). The endogenous measures and their definition are listed in table 2.

Table.2 Definition of measured quantities in the model. (MOT Oxford Dictionary of English, 2021).

Factor	**Definition**
Population	The inhabitants of the modeled society.
CO_2 emissions	Carbon dioxide emitted into the atmosphere of the modeled society.
Capital	The industrial capital stock of the society.
Quality of Life	Standard of health, happiness, and comfort experienced by individuals in the modeled society.

The measures listed in table 2 are controlled by numerous variables. These variables are chosen to best match real-life scenarios. Table 3 presents the variables, their definitions, and units of measure.

Table.3 List of variables included in the model.

Variable	Definition	Units
Initial population	The population at time 0 of the simulation.	People
Birth rate	Fractional birth rate	births / person/ year
Death rate	Fractional death rate	deaths / person / year
Birth rate LDC	The birth rate for least developed countries	births / person/ year
Death rate LDC	The death rate for least developed countries	deaths / person / year
Demographic transition	Whether the society has undergone the demographic transition or not.	Dimensionless
Habitable land	Land that can be habited.	km^2
Density normal	The normal density of the society.	people/ km^2
Natural resources initial	Natural resources available initially.	Resource units
CO_2 per capita	The amount of CO_2 emitted per person.	Metric tonnes of CO_2 / year
CO_2 initial	The amount of CO_2 in the atmosphere at simulation time 0.	Metric tonnes of CO_2
CO_2 standard	The standard amount of CO_2 in the atmosphere.	Metric tonnes of CO_2
Capital initial	Industrial capital at time 0 of the simulation.	Capital units
Capital depreciation rate	The rate with which capital decrease in value.	Capital units/year
Capital investment rate	Per capita rate of capital investment.	Capital units/year
Capital ratio normal	Capital per population.	Capital units/person
Undernourishment index	The ratio of undernourished people in the simulation.	1 /person.
Renewable resource ratio	The ratio of renewable resources utilized of the natural resources.	Renewable resource utilization / natural resource utilization.

3.3.2 Model structure

The model consists of three pages with different topics: Population, CO_2 emissions & Natural resources, and Capital & Quality of life. Hereby follows a presentation of the three interconnected models.

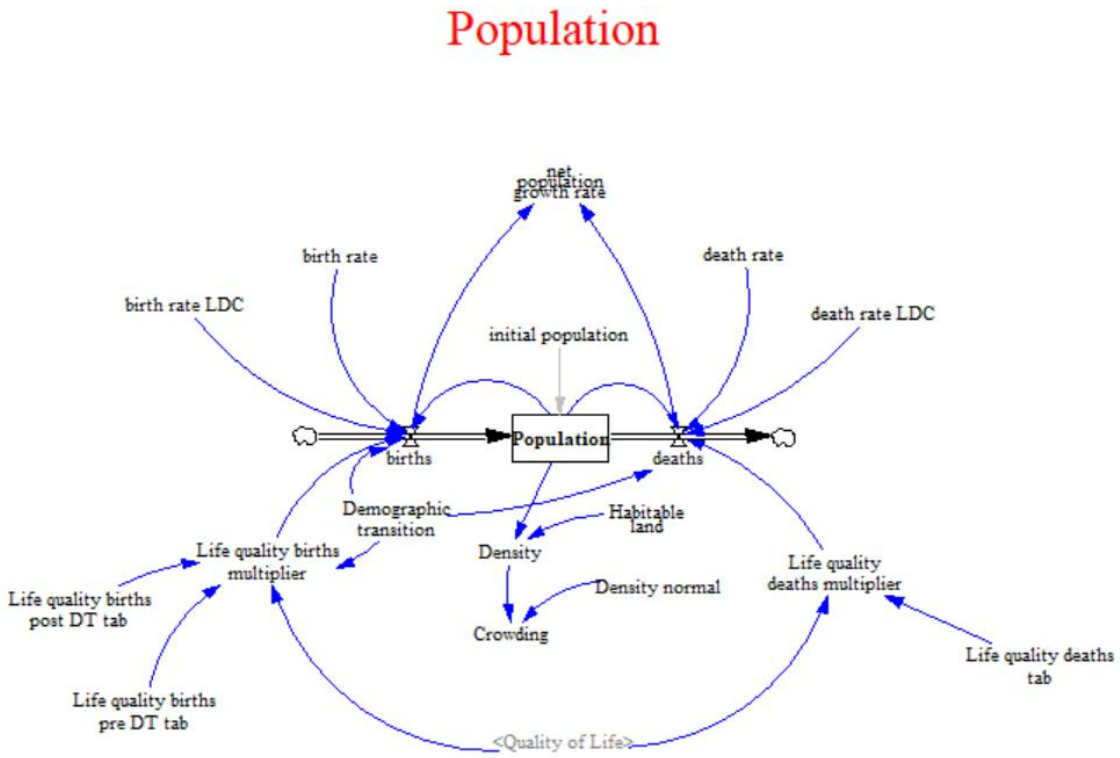

Figure 5. The population model.

This model presented in figure 5 simulates population dynamics with exogenous inputs such as birth rate, death rate, and initial population, and the endogenous input from the quality of life. Quality of life affects births in one way or another and according to research, a higher quality of life tends to foster a more fertile society. On the other hand, as discussed in chapter 2.5.2, the population growth is strongest in LDCs. Therefore, Life quality's impact on births is in this model controlled by an exogenous variable called "Demographic transition" that determines the state of the demographic transition in the simulated society. The birth rate in the world is currently approximately 18.5 births per 1000 inhabitants while the death rate is 7.5 deaths per 1000 inhabitants (United Nations, Department of Economic and Social Affairs, Population Division, 2019).

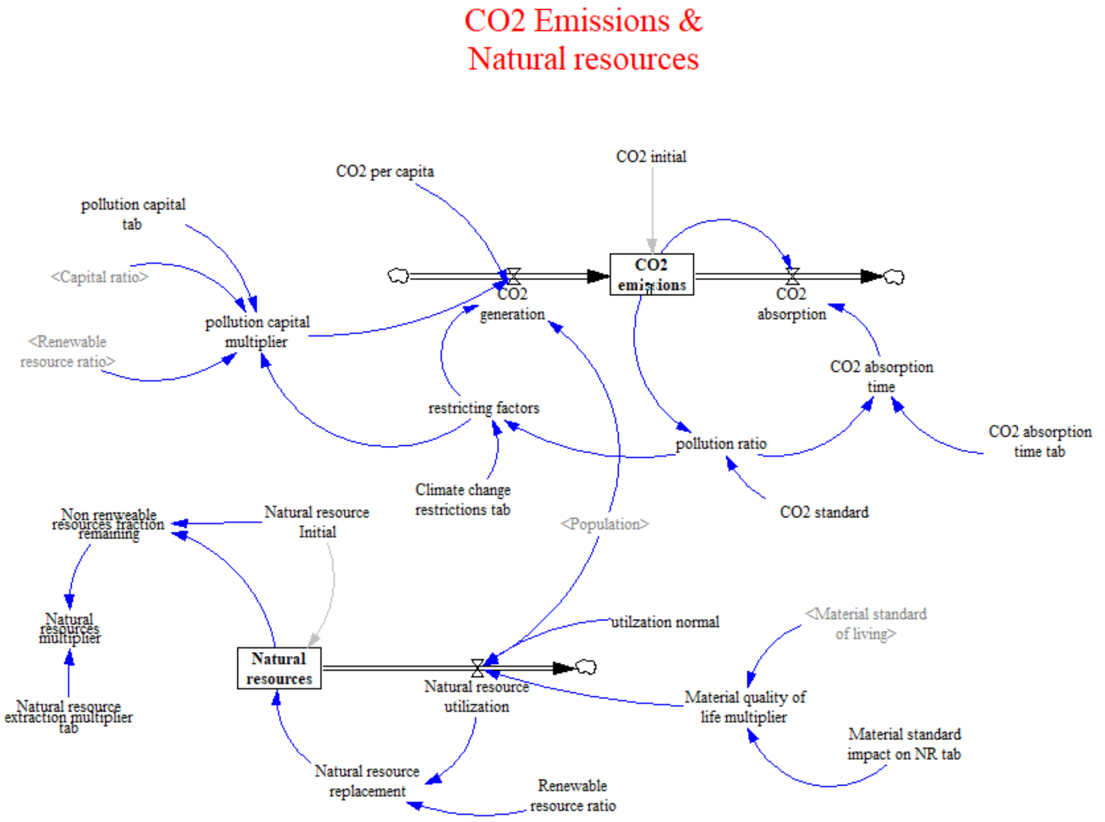

Figure 6. CO$_2$ Emissions & Natural resources model.

This is the model that simulates CO$_2$ emissions in the atmosphere and natural resources available in the simulation. These factors are connected since the capital is dependent on resources available and with fewer resources, there will be less emissions. Further, the level of CO$_2$ emissions is dependent on the exogenous variables CO$_2$ per capita, CO$_2$ initial, and CO$_2$ standard. The variable “restricting factors” that can, in figure 6, be seen to be connected to “CO$_2$ generation” is here simulating the manmade rules and obligations on restricting CO$_2$ emissions, such as the Kyoto Protocol and Paris agreement. Natural resource depletion is balanced with feedback of resource replacement, this variable is depending on the ratio of renewable resources utilized.

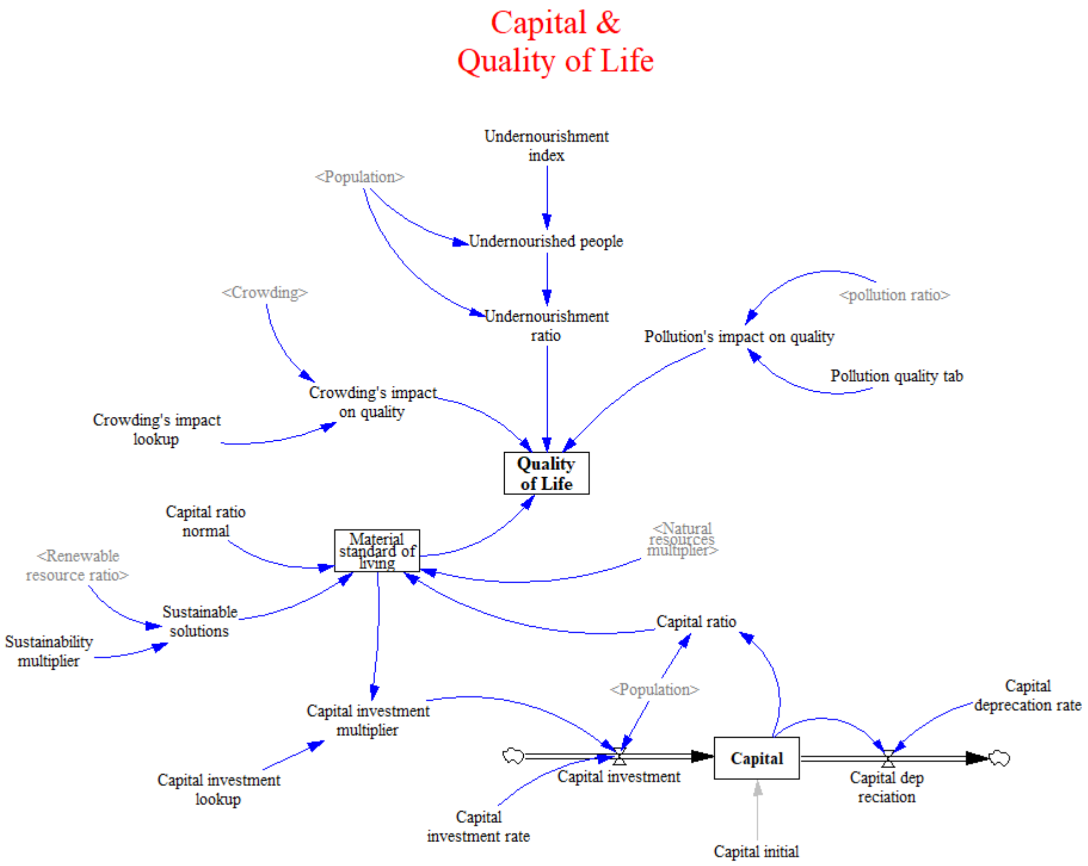

Figure 7. Capital & Quality of Life model.

The third model, seen in figure 7, simulates the industrial capital and the Quality of Life. QoL is an individual's observation of their situation in the context of the society's culture and value systems and in relation to their standards, concerns, and goals (World Health Organization, 2021). QoL was chosen for the simulation since the quality of a population's existence is thought to have a major impact on other factors. The QoL is in this case affected by endogenous variables such as crowding, pollution, material standard of living, and undernourishment ratio.

The Capital rate symbolizes the industrial capital, which plays a remarkable role in the world dynamics of today since the growth of capital is the main driver for the industrial society. In this simulation, capital is measured in the imaginary units "Capital units" to demonstrate the growth and decline of the capital, and to track its consequences. Capital is dependent on initial capital, capital investments, and capital depreciation. Capital is empowered by a feedback loop that is simulating the growth of capital. This loop also affects the material standard of living, as long as the capital is growing it will have a positive effect on the life standard. The material standard of living is also influenced by natural resources, and therefore it tends to decline with time. To possibly compensate for that, there is a variable “Sustainable solutions” that is affected by the renewable resource ratio. This variable represents green technology and that can positively influence the material standard of living and boost the capital return. This represents the green technology scenario by (Weinberger, Quiñinao, & Marquet, 2017) that was discussed in chapter 2.4.

3.3.3 Quantification

In a simulation model of the world, some relations are difficult to pinpoint analytically. Therefore, they need to be quantified. In this sense, quantification means modeling human behavior and rationality. As an example of quantification, figure 8 demonstrates that quality of life has an impact on births and deaths in the SD model. It is logical and justifiable to consider life quality when modeling deaths in society. But saying exactly how much one variable affects another is rather difficult. Life quality’s impact on births is more or less up to individualistic behavior. Figure 8 is a graph where the “Quality of Life” variable is on the x-axis and its impact on births on the y-axis. Thus, the life quality’s impact on births is the blue curve.

The relation between the two discussed variables is as mentioned problematic to foresee. The assumptions in this model are however widely based upon earlier studies. The case of life quality’s impact on births is built upon a study conducted by (Mencarini, Vignoli, Zeydanli, & Kim, 2018) where it is concluded that life satisfaction favors reproduction in developed countries.

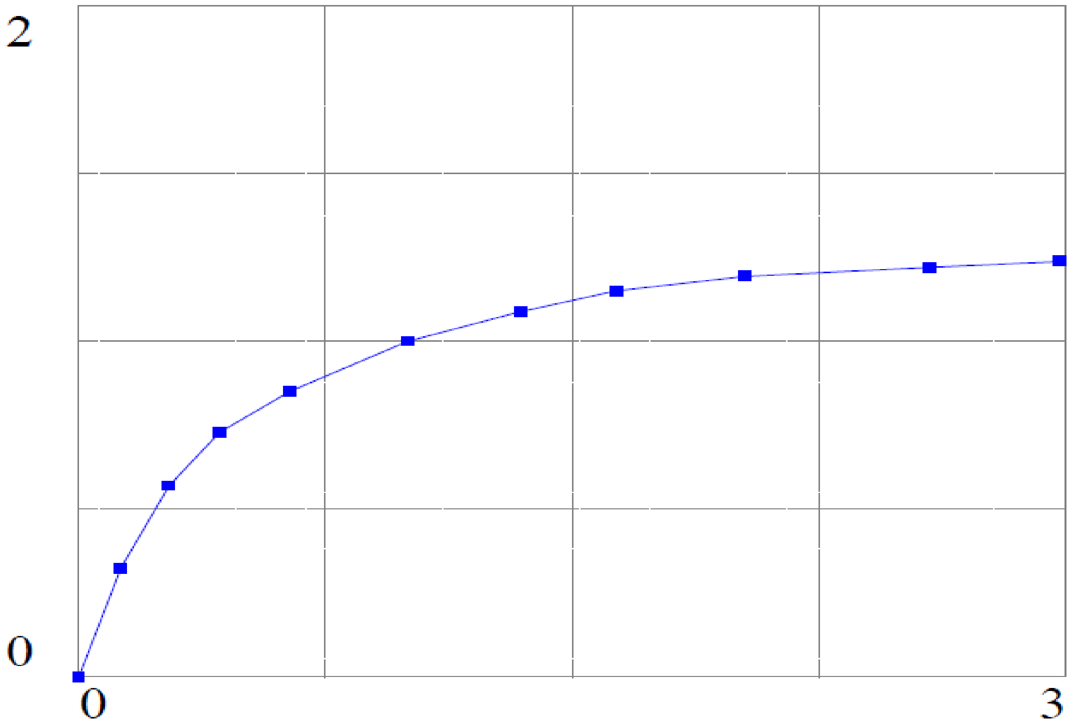

Figure 8. “Quality of Life” variable’s impact on births post demographic transition.

4 Results

This chapter presents the results obtained from the data analysis and the system dynamics modeling study.

4.1 Data analysis

To start processing the research statement of studying world population growth and greenhouse gas interdependencies under different scenarios, we must begin by analyzing some real population and emission data in order to find the interesting scenarios.

4.1.1 Population growth in different areas

In this chapter, population data is studied in order to locate the areas of great population growth. The data in table 4 is taken from the United Nations Department of Economic and Social Affairs.

Table.4 Population growth rate as percentual increase. Adapted from: (United Nations, Department of Economic and Social Affairs, Population Division, 2019).

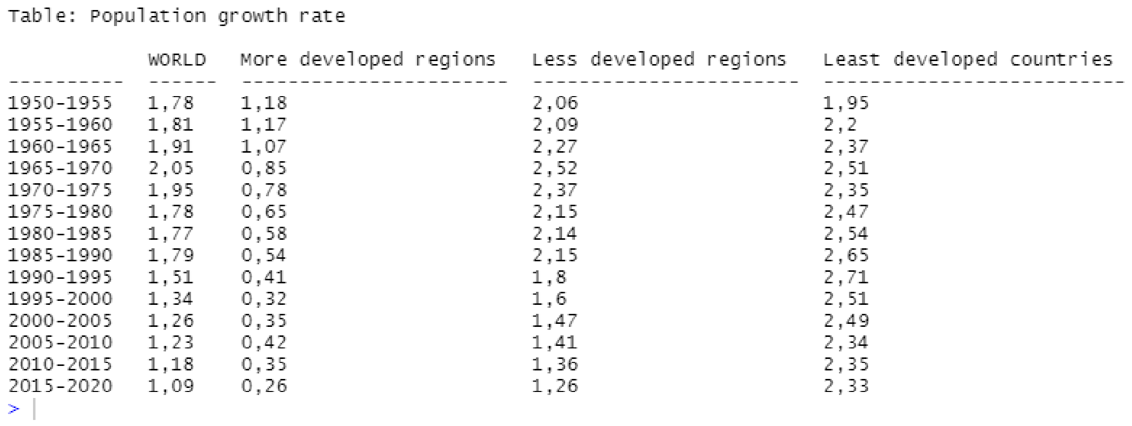

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Table: Population growth rate

            WORLD   More developed regions   Less developed regions   Least developed countries
----------  ------  -----------------------  -----------------------  --------------------------
1950-1955   1,78    1,18                     2,06                     1,95
1955-1960   1,81    1,17                     2,09                     2,2
1960-1965   1,91    1,07                     2,27                     2,37
1965-1970   2,05    0,85                     2,52                     2,51
1970-1975   1,95    0,78                     2,37                     2,35
1975-1980   1,78    0,65                     2,15                     2,47
1980-1985   1,77    0,58                     2,14                     2,54
1985-1990   1,79    0,54                     2,15                     2,65
1990-1995   1,51    0,41                     1,8                      2,71
1995-2000   1,34    0,32                     1,6                      2,51
2000-2005   1,26    0,35                     1,47                     2,49
2005-2010   1,23    0,42                     1,41                     2,34
2010-2015   1,18    0,35                     1,36                     2,35
2015-2020   1,09    0,26                     1,26                     2,33
> |
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Table 4 represents the world population growth rate. The world column to the left represents the average population growth on earth and the three following columns divide the world into categories depending on the countries socio-economic situation. Especially the least developed countries are of interest to this study. This category consists of the poorest and weakest segments of the international society. More than 1 million people live in the LDCs (12% of the world population), but they account for less than 2 percent of the world's GDP. The list of the world’s LDCs currently consists of 47 countries, 33 in Africa, 13 in Asia and the Pacific, and 1 in Latin America. (UN-OHRLLS, 2021). The data in table 4 is clear, the population growth rate has evidently plunged in developed regions, at least since the data recording started in 1950. On the other hand, population growth in LDCs is remarkably higher compared to developed regions, and the growth reached its peak as late as 1990 - 1995. This data agrees with research regarding population growth from (Gore, 2009, p. 226), (Friedrichs, 2013, p. 4) and (Andreev, Kantorova, & Bongaarts, 2013) that was reviewed in the literature chapter. The phenomenon of rising and falling population growth trends can, according to Andreev et al. (2013), be explained by the stage at where the nation is in its demographic transition. A post-transitional country typically has negative growth rates, fertility rates below replacement level, and a rapidly aging population. On the other side of the spectrum are countries that are still in an early stage in their transition. These areas are often characterized by rapid population growth, young age structure, and high fertility. These are mainly the LDCs. As stated earlier, according to Gore (2009), a plan to solve the climate crisis must involve a plan to stabilize the world population.

4.1.2 Emissions in different areas

This chapter studies emissions in different areas of the world. The Global Carbon Project is a global research project with the task to establish a common and mutually agreed on research base for debating, slowing down, and ultimately stopping the increase of greenhouse gasses in the atmosphere. (Global Carbon Project, 2020). Therefore, the global carbon project offers a global database with regional carbon emission data. For this study, the LDCs emission data has been filtered out to concretize the least developed countries' carbon emissions and compare them to more developed areas. The carbon emission data that follows is in million tonnes of carbon (1MtC) and can be transformed to million tonnes of carbon dioxide by multiplying by 3.664. 1MtC = 3.664 $MtCO_2$.

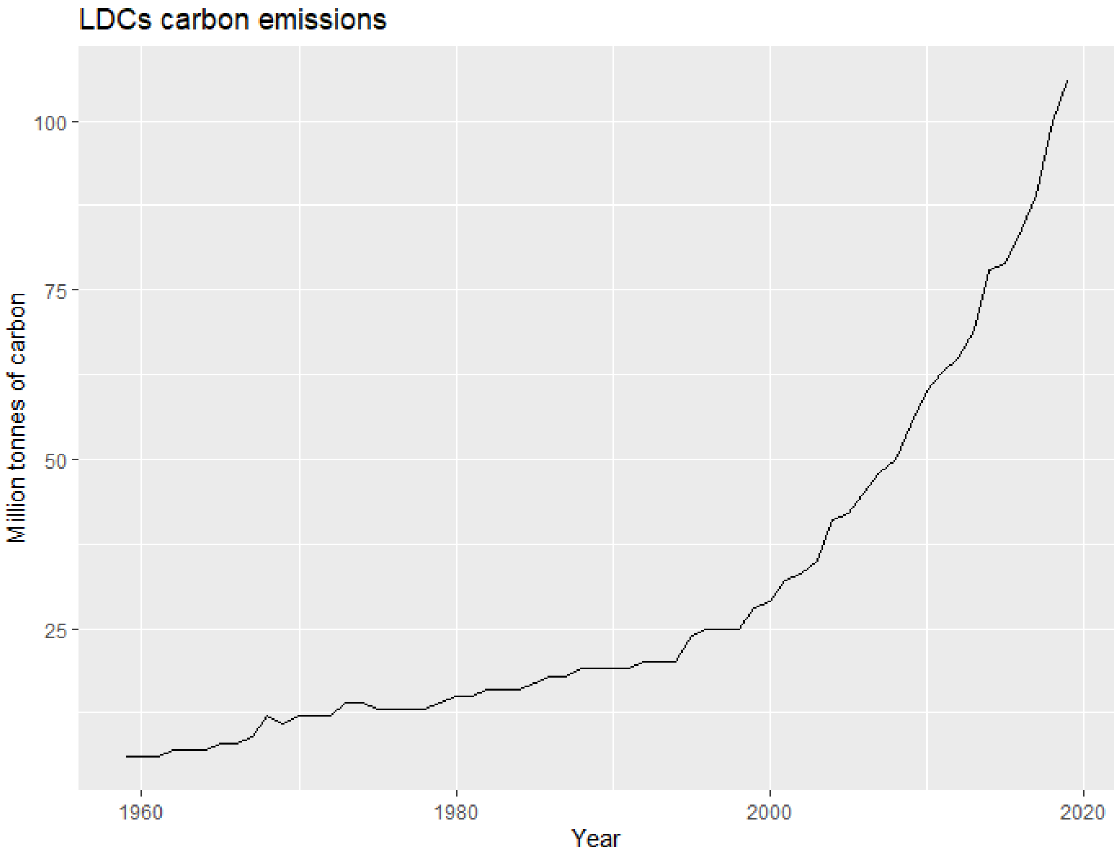

Figure 9. Carbon emissions of LDCs. Source: (Global Carbon Project, 2020)

In figure 9, the world’s 47 least developed countries' carbon emissions have been summed together. It is clear that they follow the trend of rising emissions once they develop over time. In the forefront of emitters is Bangladesh, with 27.9 of the total 106 million tonnes of carbon or 388.4 million tonnes of CO_2, emitted to the atmosphere by LDCs in 2019. (Global Carbon Project, 2020). Further, it can be calculated from the data that the average carbon emissions of the LDCs in 2019 were 2.57 million tonnes of carbon per country. To get a reference to these emission numbers, a comparison to the world’s top carbon-emitting country China, is in place.

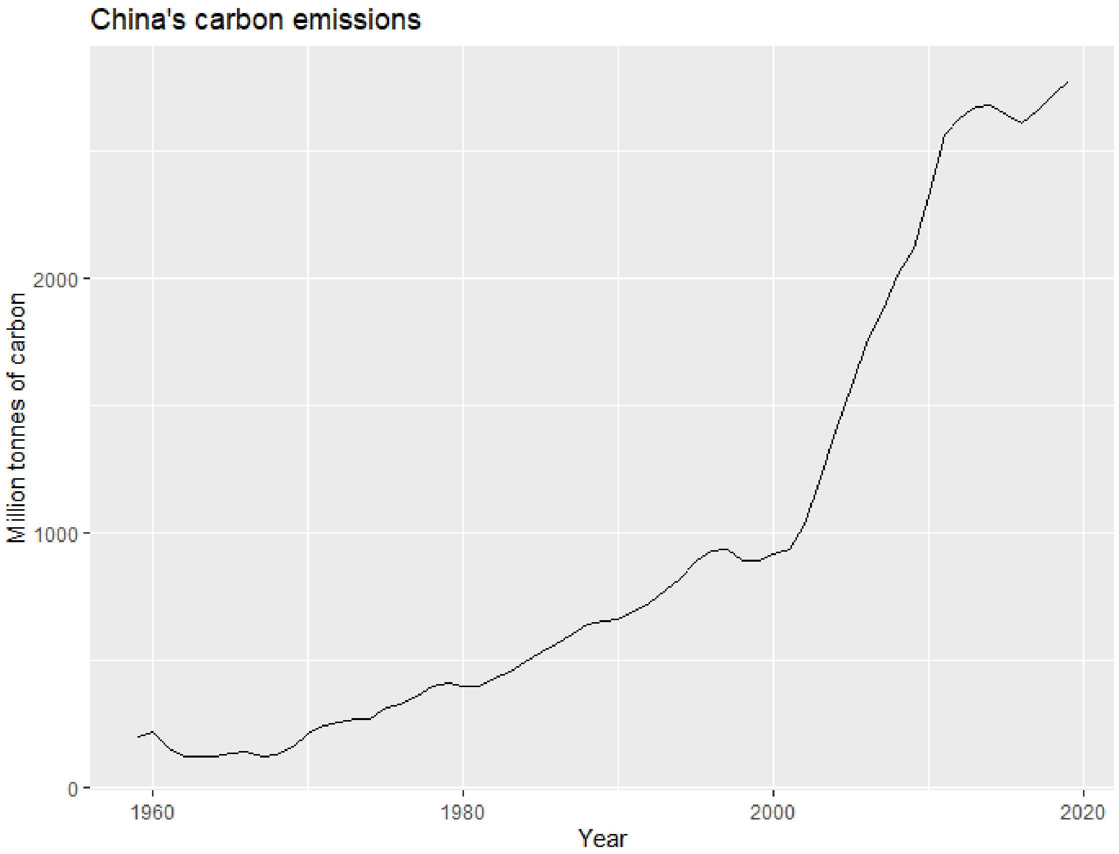

Figure 10. China’s carbon emissions. Source: (Global Carbon Project, 2020)

It can be seen in Figure 10 that China alone has emitted over 2500 million tonnes of carbon per year for the past years, the more exact number for 2019 is 2777 million tonnes, that is 10.17 billion metric tonnes of CO_2. (Global Carbon Project, 2020). However, it is not to forget what was discussed in chapter 2.1.2, China emits most greenhouse gases of all countries from an absolute perspective, but if the population is taken to account, the scoreboard looks different. The average carbon emissions per country were 44 million tonnes in 2019, this is of the 217 countries listed in the Global Carbon budget 2020. (Global Carbon Project, 2020).

4.2 System Dynamics

To study the dynamics in population and greenhouse gases, the System Dynamics model was taken into use. The SD model was utilized to run four different simulations, one with the inputs of the whole world, and another one with the inputs of the LDCs. The two other simulations were considering an imaginary scenario where no unsustainable resources are utilized. This chapter will present the results of the simulations.

4.2.1 World simulation

The first simulation was initialized with values that represent the world in its current state, following variable values were used:

Table.5 Table of initial values in world simulation. Adapted from: (United Nations, Department of Economic and Social Affairs, Population Division, 2019), (Our World in Data, 2021) and (Global Carbon Project, 2020).

Variable	**Value**
Birth rate	18.5 / 1000 people /year
Death rate	7.5 / 1000 people / year
Initial population	6.143 Billion
Habitable land	104 million km^2
Density normal	60 people / km^2
CO_2 per capita	4.8 metric tonnes/year
CO_2 initial	24.5 billion metric tonnes
CO_2 standard	36.15 billion metric tonnes
Renewable resource ratio	0.114
Undernourishment index	0.11

Figure 11 demonstrates the population and emission prospects of the simulation.

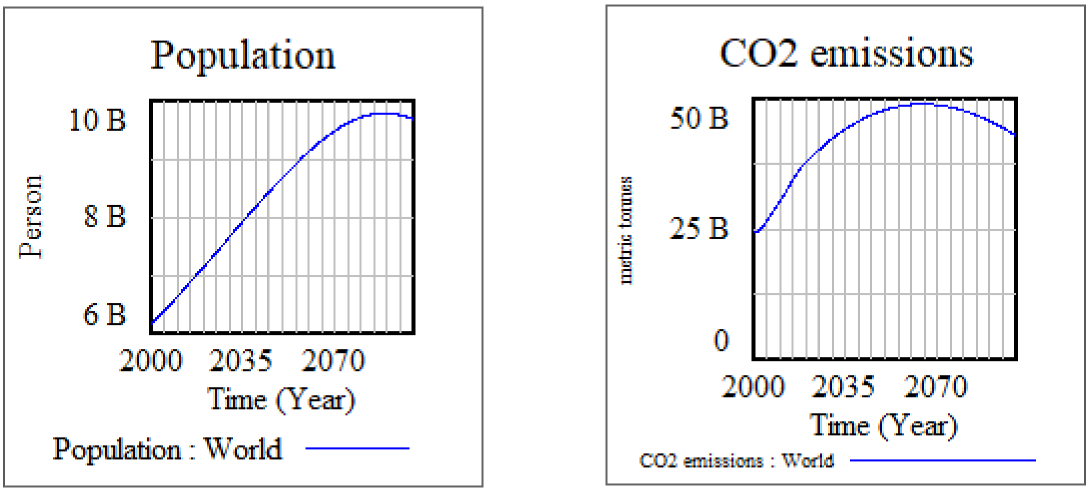

Figure 11. Population and CO_2 emissions prospects from the world simulation.

According to the simulation, the world's population would in 2021 be 7.1 billion people, an offset of approximately 9% compared to reality. Further, the population will keep growing until it peaks at just shy of 10 billion people in the year 2090. Likewise, CO_2 levels will continue to grow for some decades and peak around the year 2060 at 48.9 billion metric tonnes/year.

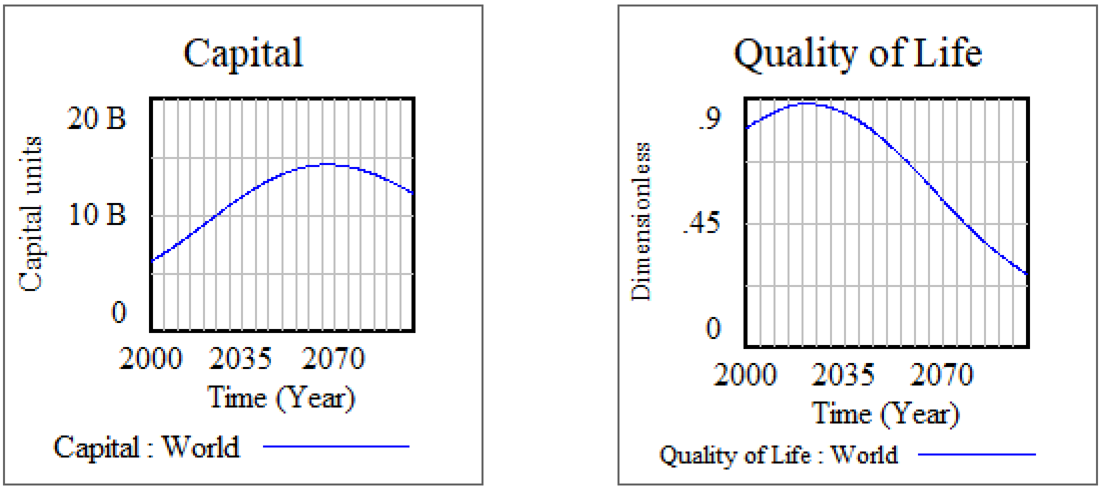

Figure 12. Capital and Quality of life prospects from the world simulation.

As figure 12 illustrates, the world's industrial capital stock will continue to grow and have a positive influence on the world market. But as stated in the theory, nothing can grow forever in a finite world. This simulation depicts that the world's capital stock will grow until 2065 when it reaches 14B capital units, a 2.3-fold capital stock compared to the starting point at 6B in the year 2000. The quality of life index indicates an increase in life quality from the start of this century and the QoL will peak in 2022 at the value of 0.89. After this, the quality of life will start decreasing and in 2042, we will be back on the same level as we started in the year 2000.

4.2.2 LDC simulation

The second simulation was considering the Least developed countries. The LDC simulation was initialized with the following values.

Table.6 Table of initial values in LDC simulation. Adapted from: (United Nations, Department of Economic and Social Affairs, Population Division, 2019), (Our World in Data, 2021) and (Global Carbon Project, 2020).

Variable	**Value**
Birth rate	28.3 / 1000 people /year
Death rate	6.9 / 1000 people / year
Initial population	657 million
Habitable land	20.14 million km^2
Density normal	50 people / km^2
CO_2 per capita	0.2 metric tonnes / year
CO_2 initial	109.92 million metric tonnes
CO_2 standard	388.4 million metric tonnes
Renewable resource ratio	0.014
Undernourishment index	0.236

We assume that since LDCs cover 20.14 million km^2 of habitable land (19%), they possess 19% of the initial natural resources from the world simulation. Furthermore, the LDCs account for barely 2% of world GDP (UN-OHRLLS, 2021), and hence their initial capital stock will be 2% of the world simulations. Finally, the capital ratio normal, the ratio that determines the impact that the individual's capital has on his perception of life quality is adjusted from 1 to 0.5.

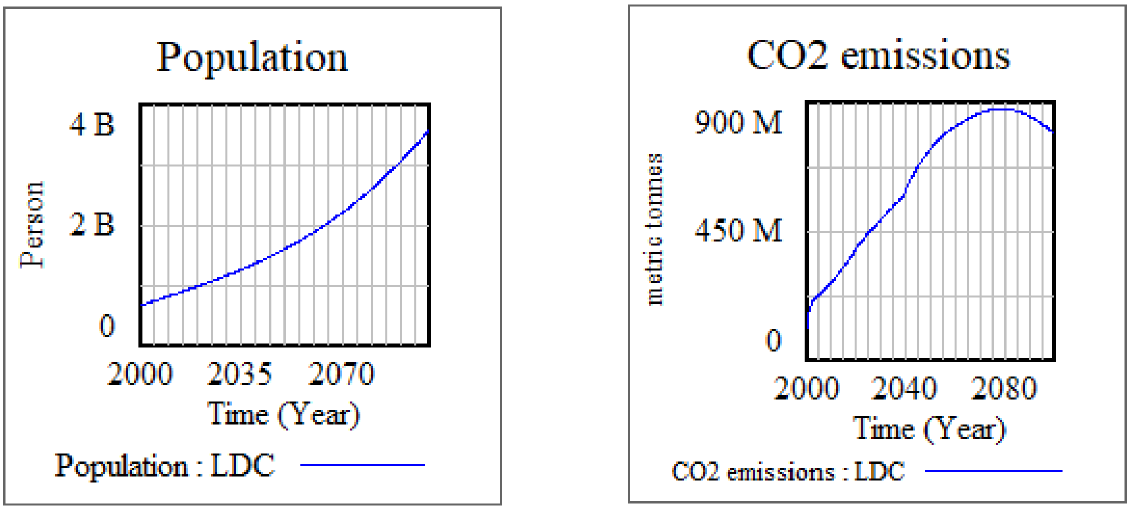

Figure 13. Population and CO_2 emission prospects from the LDC simulation.

Figures 13 and 14 represent the simulation results of the LDC simulation. As the population graph shows, the population in LDCs will continue to grow steadily and reach 3.5

billion people in 2100. The United nations projects this number to be 3.05 billion (United Nations, Department of Economic and Social Affairs, Population Division, 2019). As the population grows, so do the emissions. This simulation predicts rapid growth in CO_2 emissions, by 2020 the emissions are 389 million metric tonnes of CO_2 which corresponds to the global carbon budget's (2019) data. The emissions will peak at 876 million metric tonnes in 2080.

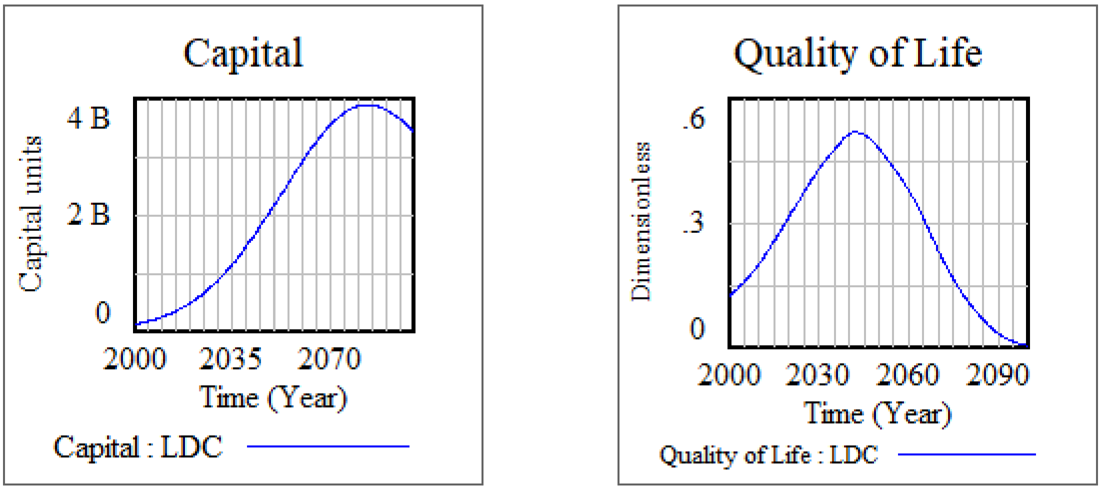

Figure 14. Capital and Quality of Life prospects from the LDC simulation.

The LDCs industrial capital stock will start a fast growth once the countries start to develop. This Growth will peak at 3.8B capital units in the year 2082, a 31.6-fold increase in industrial capital. Followingly, the quality of life will as well start rising. The QoL will however turn around in 2042 after reaching a value of 0.52.

4.2.3 100% Renewable resource scenario

This is an imaginary scenario where all natural resources used are renewable. All initial values are the same as in the first world simulation in chapter 4.2.1 except for the "Renewable resource ratio" which is in this case 1. As figure 15 shows, the population would continue to grow as capital grows and no pollution is limiting the ascend. Still, the quality of life derivate turns negative at last. The population would stabilize at 24 billion people in the year 2200 and the quality of life would then stabilize at approximately 0.3. CO_2 emissions would instantly drop to zero since it is, in this case, assumed that utilizing renewable resources will not emit CO_2 emissions and since this is a measure of CO_2 emitted, not actual CO_2 levels in the atmosphere.

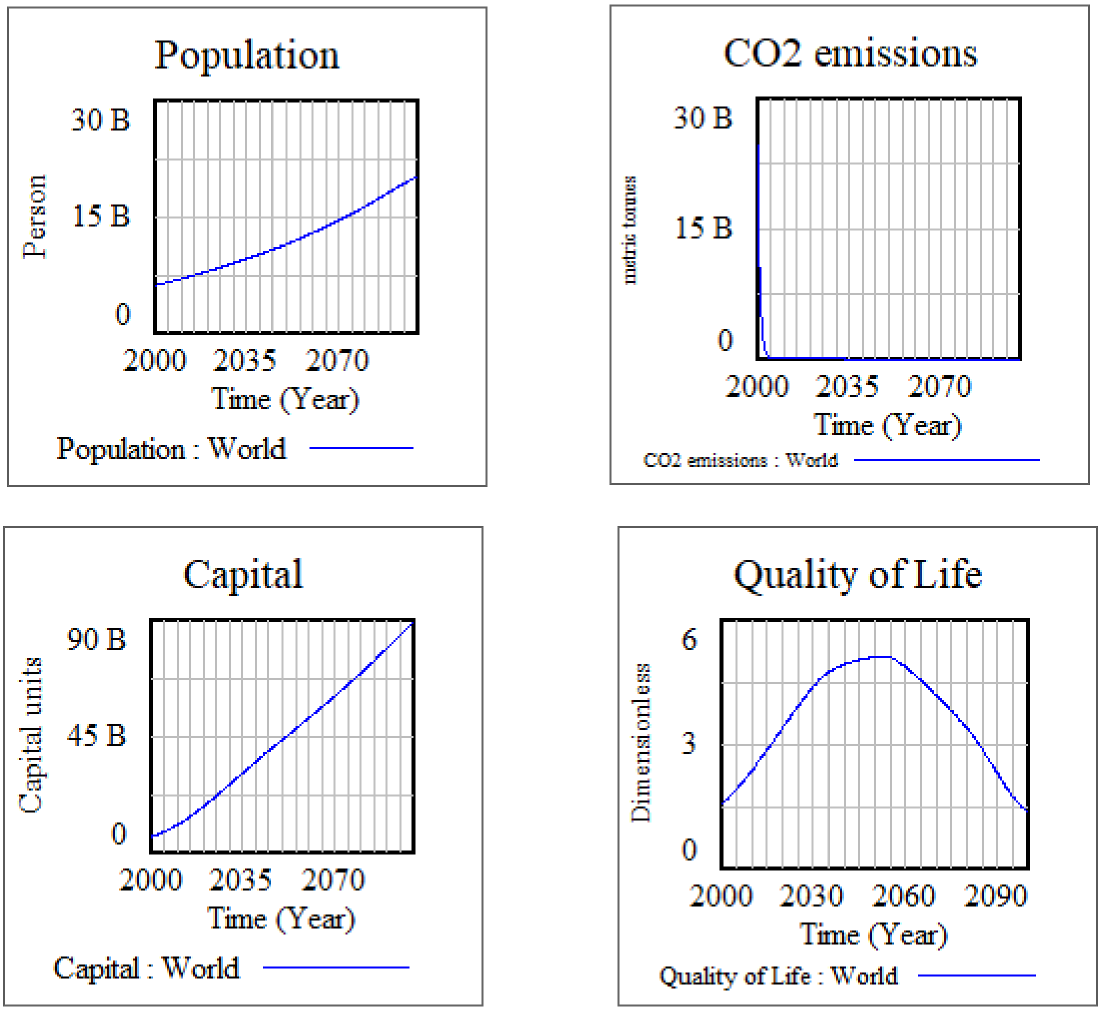

Figure 15. World dynamics with 100% renewable resource ratio.

The model was finally adjusted to reach a more credible population equilibrium compared to Figure 15. Since a hundred percent renewable resource usage is a demand for equilibrium, the renewable resource ratio setting was kept as in the previous run. The balancing factor that after the renewable resource ratio sets the population equilibrium is quality of life and the variable that affects the quality of life the most in this scenario is crowding. Therefore, the density normal variable is changed from 60 to 26.5. The density normal defines the standard population density that change is compared to. The results can be seen in Figure 16.

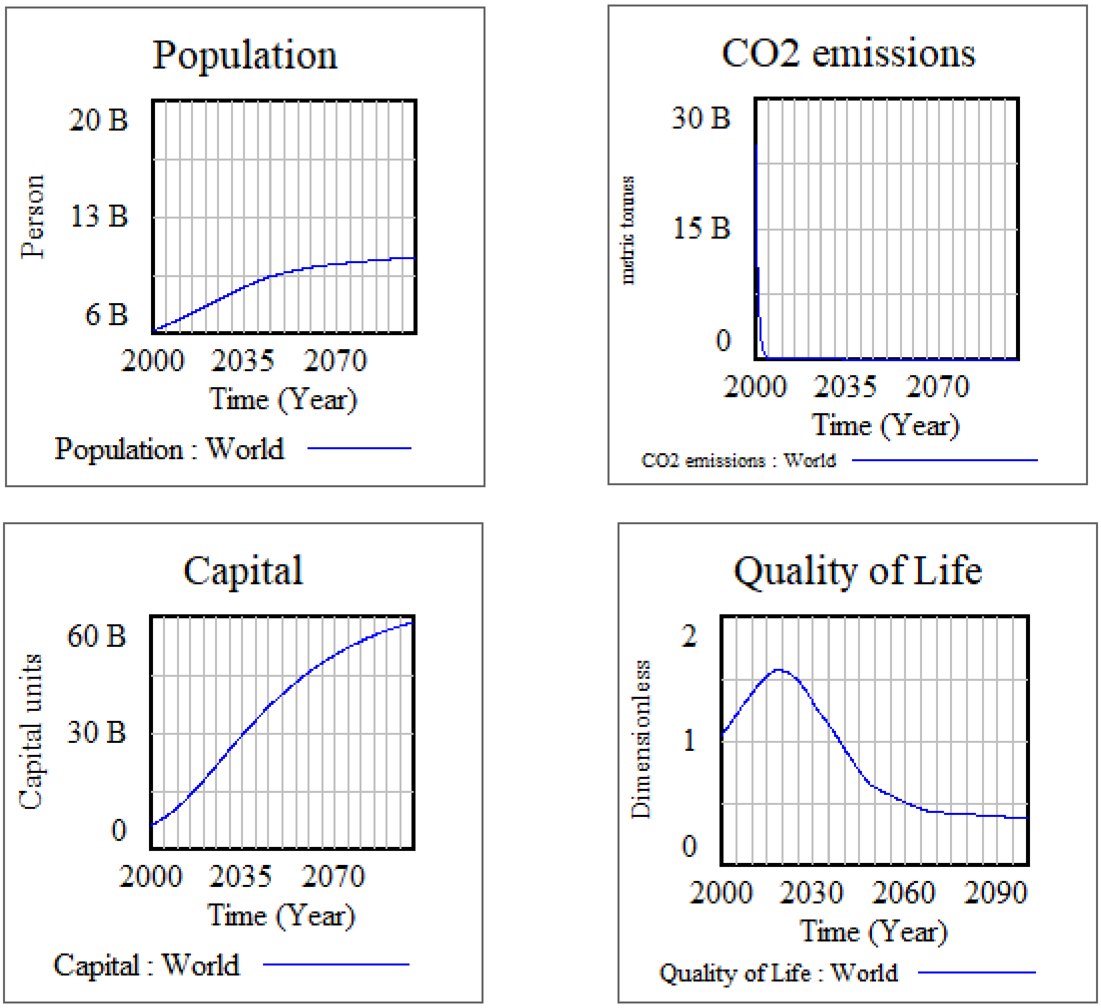

Figure 16. World dynamics with 100% renewable resource ratio and a lower density normal.

The result of this experiment is a world population that stabilizes after 10 billion, a growing capital, and a relatively low but stabilizing quality of life.

5 Conclusions of the result

This chapter will present and conclude the results obtained in chapter 4.

5.1 The underlying dynamics of the system

According to chapter 4.1, the population growth rate is, and will be strongest in the least developed countries. This claim is strengthened by the dynamic model (see figure 17).

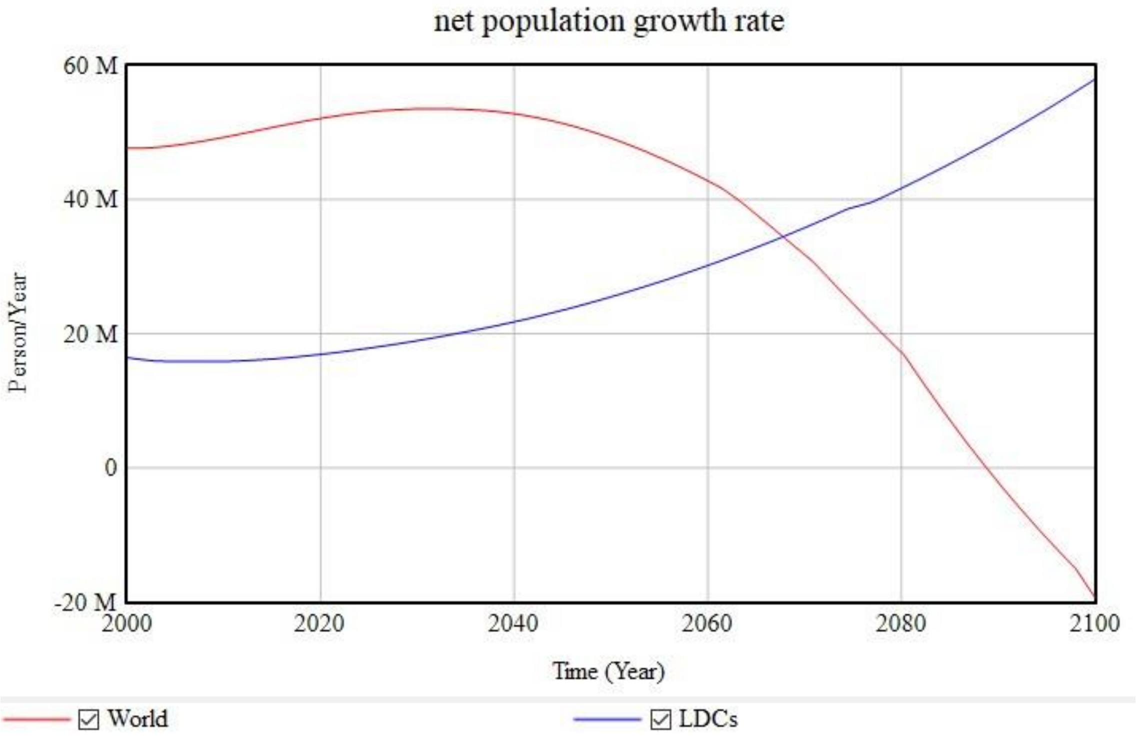

Figure 17. The population growth rate in the world and LDCs.

The population growth rate is, in the model, highly dependent on the quality of life variable. This is a valid dependency since the quality of life variable is, in this model, determined by undernourishment ratio, pollution levels, crowding, and material standard of living. The material standard of living plays an important role in the quality of life value since the material standard of living variable is involved in the capital investment loop. Therefore, also capital is indirectly involved in the population growth dynamics. While the capital return rate is positive and the capital stock keeps growing, the quality of life, and thereby also population growth, keep rising. This is the case until a certain point where atmospheric pollution levels and overcrowding turns the quality of life into a decline.

5.1.1 The link between Greenhouse gasses and population growth

When studying the world simulation in chapter 4.2.1, population growth and greenhouse gas emissions do seem to correlate with a certain delay. The chain of events is as follows: First, the quality of life starts declining in the year 2021 as a consequence of natural resource scarcity. Secondly, the emissions plunge in the year 2064 due to a mitigated capital growth rate combined with stricter climate change restrictions. In 2067 the industrial capital stock starts following the negative trend as capital investments decline as a reaction to a sinking material standard of living. Finally, as represented in figure 17, the net population growth rate of the world passes zero in the year 2088 because of the inferior quality of life. This negative causation could be stopped right in the beginning by not depleting natural resources. Chapter 5.2 presents a scenario where all resources used are renewable.

5.1.2 Dynamics of the LDCs

Chapter 4.2.2 presents the results of the simulation of the least developed countries. The simulation shows that the population will grow exponentially and reach 4 billion people before the year 2100. Further, their CO_2 emissions will rise to almost 900 million metric tonnes before starting to decline. This simulation is initialized with values selected to correspond to an undeveloped country that has not gone through the demographic transition. It is, however, likely that these countries develop during the upcoming 80 years and thus altering the results obtained in chapter 4.2.2. A gradually changing behavior towards the world's normal values would mean a gradual growth in emissions and a decline in population growth rate. With current numbers, the LDCs would peak at 876 million metric tonnes of CO_2 emitted in 2080, corresponding to slightly over double the amount emitted today and less than 2 percent of the whole world’s emissions. As an alternative to the scenario of the LDCs, let us reflect on China’s explosive development from chapters 2.2.3 and 4.1.2: In the last 40 years, the country's emissions have grown almost 7-fold. (Global Carbon Project, 2020).

5.2 Reaching the target of 100% renewable resources

A common trend in the graphs from the simulations in chapters 4.2.1 and 4.2.2 is that every measure starts declining by time, the population of LDCs as well, the delay between population and births is just prolonging this fact to beyond the year 2100. By time, all the meters in these first two simulations will inevitably approach zero. This phenomenon is because the simulation is built upon values from our world with current operations, in other words, a non-sustainable world. The restricting factor that is sooner or later turning all meters into a decline in this model is natural resources. The present values for renewable resource utilization in comparison to all available natural resources are, as stated in chapters 4.2.1 and 4.2.2, 11.4 percent on average in the world, and 1.14 percentage in the least developed countries. With current dynamics used in the SD model, a 100 percent renewable resource ratio would result in the scenario depicted in chapter 4.2.3.

Population and capital continue growing in a seemingly infinite world when suddenly the quality of life starts decreasing. This is a consequence of rapid population growth; overcrowding. Therefore, while renewable resource utilization is the solution to many dilemmas, this might encourage the population growth to escalate. Overcrowding becomes an issue that affects the quality of life once the population is approaching the carrying capacity of the habitat, food, and water among other vital things becomes inadequate. Even though the only natural resources used in this scenario are renewable, they cannot be renewed at a pace to support endless amounts of people. The simulation in figure 15 exemplifies a scenario where greenhouse gasses (in this case CO_2) decrease, but the world's population keeps growing. Since there are no strong negative balancing loops, such as finite resources, controlling the growth in the scenario of figure 15, the population keeps growing exponentially, thereby risking an overshoot and collapse as discussed in chapter 2.2.1 and 2.5.1. In this case, however, the population would stabilize at 24 billion people in the year 2200 and the quality of life would then stabilize at approximately 0.3, implying a relatively unsatisfactory quality of life. In reality, the world's carrying capacity can be assumed to be lower than this, but as discussed in chapter 2.5.1, there is no mutual agreement in science on what the carrying capacity is and if life around the world's carrying capacity would offer a satisfactory life quality (Sterman J. D., 2000, p. 119). Furthermore, overcrowding might trigger a collapse of the society in a real scenario.

In order to reach a more credible future scenario, the population was in figure 16 forced to stabilize around 10.5 billion. This was done by dropping the density normal. In practice, this means that people would be used to live with a population density of 26.5 people per square kilometer instead of 60, which is the world average. Now the human behavior would be to feel less satisfied with life since they feel more compressed and hence be less reproductive. This scenario would enable capital growth for at least another century but at a cost of a 50% lower quality of life compared to today.

6 Discussion

The human population eventually learned to sustain a larger population and to work for a common goal, we became an ultrasocial superorganism (Gowdy & Krall, 2013). This started accelerating human development and resulted in the state of the world we know today, where our society relies on an economic system, and this economic system relies on economic growth. Besides the fact that infinite growth is impossible on a finite planet (Friedrichs, 2013), the growth we have witnessed in the past century has emphasized heavy industry, with high pollution as result. Therefore, global change is now required to aim for a sustainable future.

6.1 The interdependencies of world population growth and greenhouse gases

Simulating a problem like the case of this thesis gives a perspective of the dynamics of the modeled system (Sterman J. D., 2000). When studying the results, it becomes clear that to find equilibrium, the values measured must be in balance. Meaning that if something is better than normal, another factor must balance this indifference out by being worse than normal. Therefore, in the case of the world simulation and the LDC simulation, population and emissions decrease on the cost of quality of life and capital. But neither of these simulations results in equilibrium because of the unsustainable depletion of natural resources.

The scenarios of 100% renewable resource utilization on the other hand might give us a hint of a brighter future. When assuming that unrenewable resources such as oil are no longer needed to support our society, a long-term balance can be found, and the population can stabilize. Research is fairly united when it comes to population growth; the population will peak somewhere between 9 and 11 billion people during this century (Gore, 2009, p. 226), (Andreev, Kantorova, & Bongaarts, 2013), (Friedrichs, 2013). This corresponds to the world simulation in chapter 4.2.1 and the 100% renewable resource simulation with a tweaked density normal in chapter 4.2.3. All prospects simulated in this thesis have however one thing in common; a declining quality of life. A scenario where pollution keeps doubling would certainly affect our life quality, but so would a scenario without the amenities that unrenewable resource depletion serves us. Luckily, quality of life is merely a relative perspective, an attempt to quantify human behavior and emotions, it is nothing absolute. Therefore, other factors not considered in this thesis, influencing the quality of life positively, can assumably be found now and in the future. In the real world, nothing is as black and white as in the simulations of this thesis. There will not be a tomorrow when suddenly all unrenewable resource depletion stops. It will happen gradually, and if it happens fast enough, we can reach a 100% renewable resource scenario before overshooting the limits to growth. World order can be achieved by giving the less developed countries tools to advance and hence drop their birth rates to the same level as developed countries. This cannot however break the global carbon budget, meaning that the developed countries must cut their emissions and thereby possibly lower their life satisfaction to make room for less developed countries in the carbon budget as proposed by Stephenson et al. (2010) in chapter 2.5.2. When the development gaps have been erased, overpopulation and global warming disasters can be avoided, and we can face the new issues of a sustainable world united.

6.2 Crowding

In the system dynamics model created for this thesis, quality of life is in many ways a crucial factor. This is because it serves as a link between the consequences of population growth and the population growth dynamics. Crowding, for instance, is one factor that is affected by population growth, and that in its turn is affecting the quality of life perception. The population density normal in the world is 60 people per square kilometer. In the normal world simulation of chapter 4.2.1 crowding impairs quality of life by approximately 10% while this number was higher for the LDC simulation since a smaller habitable land area was assumed. The direct effects of crowding on life satisfaction are however challenging to interpret since urbanization has been a trend for the last 120 years and the share of the population living in urban areas has gone from 16 to 54%. The densest cities of the world have population densities of over 10000 people/ km^2.

Nevertheless, living standards tend to be higher in urban areas compared to rural life. (Our World in Data, 2021). With the knowledge of current urbanization trends, it is bold to claim that crowding would affect the perception of life quality negatively on an individual level. A fact however is that a globally rising statistical population density normal means a growing population and a risk for overshooting the world's carrying capacity.

6.3 Validity and reliability

Validity and verification of a model are impossible. (Sterman J. D., 2000, p. 846). The word "verify" derives from Latins verus – truth (MOT Oxford Dictionary of English, 2021), and valid implies being supported of the objective truth. Since models are simplified and limited representations of the world, they differ from reality in small and big ways. (Sterman J. D., 2000, p. 846). Therefore, models are useful for understanding problems and guiding further research, but not to be taken for the objective truth. When the black and white dualism of right and wrong is abandoned we can start asking the real questions that matter: is the model useful? And in that case, to whom? Do the shortcomings of the model matter? A modeler must be critical to the created model and assess the time horizon, boundaries, and results. The limitations of the system determine whether a variable is treated endogenously (system dependent), exogenously (determined by forces outside the system), or left out altogether. (Sterman J. D., 2000, p. 851).

In the light of Sterman's statement of validity and reliability of simulations, it must be concluded that the model created for this thesis is no exception, it is merely a simplified representation of the world with quantified measures and an attempt to model and understand human behavior. With this in mind, both the model and the modeling process itself has opened numerous new perspectives and given insights to the writer of this thesis. The model is, if nothing else, a good start to begin understanding our world's complex dynamics and relations.

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Appendix. Source code of the system dynamics model

```
{UTF-8}
Life quality births pre DT tab(
[(0,0)-
(2,2)],(0,1.40351),(0.140673,1.28947),(0.348624,1.21053),(0
.611621,1.10526),(\

1.00306,0.991228),(1.21101,1.07018),(1.32722,1.08772),(1.46
177,1.15789),(1.5841,1.16667\

),(1.59633,1.16667),(1.77982,1.16667),(1.98777,1.19298))
~
~         |

birth rate LDC=
0.0283
~    1/Year [0,0.1]
~         |

births=
DELAY1( Population  , 20 )  *

             IF THEN ELSE (Demographic transition > 0,
              birth rate,
              birth rate LDC)

              * Life quality births multiplier
~    Person / Year
~    The total number of births.
|

pollution capital tab(
[(0,0)-
(5,6)],(0.030581,0.342105),(0.29052,0.5),(1,1),(2,2.7),(2.7
2171,4.34211),(3.33333\

,5.07895),(3.99083,5.57895),(4.78593,5.86842),(4.96942,5.97
368))
~    Dimensionless
~         |

Natural resource replacement=
Natural resource utilization*Renewable resource ratio
~    Resource units/Year
~         |

pollution ratio=
CO2 emissions/CO2 standard
~
~         |
```

```
Pollution's impact on quality=
Pollution quality tab (pollution ratio)
~    Dimensionless
~         |

Capital investment=
Population * Capital investment multiplier * Capital invest-
ment rate
~    Capital units / Year
~         |

CO2 per capita=
4.8
~    metric tonnes/Year
~    LDC:0.2
     World: 4.8
|

Capital investment multiplier=
Capital investment lookup(Material standard of living)
~    Dimensionless
~         |

death rate LDC=
0.0069
~    1/Year [0,0.1]
~         |

Capital ratio=
Capital/Population
~    Capital units/Person
~         |

Natural resource utilization=
Population*utilzation normal*Material quality of life multi-
plier
~    Resource units / Year
~    https://www.ecocivilization.info/three-tons-carbon-di-
oxide-per-person-per-y\
     ear.html
|

Natural resources= INTEG (
Natural resource replacement-Natural resource utilization,
     Natural resource Initial)
~    Resource units
~         |

CO2 absorption time=
CO2 absorption time tab(pollution ratio)
~    Year
~         |
```

```
Sustainable solutions=
Sustainability multiplier(Renewable resource ratio)
~    Dimensionless
~         |

CO2 emissions= INTEG (
CO2 generation - CO2 absorption,
     CO2 initial)
~    metric tonnes
~    https://ourworldindata.org/grapher/annual-co2-emis-
sions-per-country?tab=cha\
     rt&time=1800..latest&country= OWID_WRL&region=World
|

CO2 generation=
DELAY1( restricting factors , 2 ) *

Population
*CO2 per capita
*pollution capital multiplier
~    metric tonnes/Year
~         |

deaths=
Population *

           IF THEN ELSE (Demographic transition > 0,
           death rate,
           death rate LDC)
           *Life quality deaths multiplier
~    Person/Year
~         |

Density=
Population/Habitable land
~    Person / (Kilometer * Kilometer)
~         |

Demographic transition=
1
~    Dimensionless [0,1,1]
~         |

restricting factors=
Climate change restrictions tab(pollution ratio)
~    Dmnl [0,10]
~         |

Population= INTEG (
births-deaths,
     initial population)
~    Person
~         |
```

```
Life quality births multiplier=
IF THEN ELSE (Demographic transition > 0,
              Life  quality  births  post  DT  tab(Quality  of
Life),
              Life quality births pre DT tab(Quality of Life))
~    Dimensionless
~         |

Renewable resource ratio=
0.114
~    Dimensionless [0,1]
~    Our world in data
     LDC: 0.014
     World: 0.114
|

pollution capital multiplier=
(pollution  capital  tab(Capital  ratio)*restricting  fac-
tors)*(1-Renewable resource ratio\
     )
~    Dimensionless
~         |

Sustainability multiplier(
[(0,0)-
(1,2)],(0,0.8),(0.116208,0.921053),(0.3,1),(0.553517,1.1052
6),(0.75841,1.23684\
     ),(0.859327,1.38596),(0.932722,1.57895),(1,1.8))
~    Dimensionless
~         |

Undernourished people=
Population * Undernourishment index
~    Person
~         |

Undernourishment ratio=
Population/(Undernourished people)*0.1
~    Dimensionless
~         |

Material standard of living=
Capital  ratio  *  Natural  resources  multiplier  *  Sustainable
solutions /Capital ratio normal
~    Dimensionless
~         |

Density normal=
60
~    Person/(Kilometer*Kilometer)
~    LDC:50
     World: 60
```

```
|

Capital= INTEG (
Capital investment-Capital depreciation,
     Capital initial)
~    Capital units
~         |

Capital depreciation=
DELAY1(Capital*Capital deprecation rate,10)
~    Capital units/Year
~         |

Capital deprecation rate=
0.025
~    1/Year [0,1]
~         |

Capital initial=
6e+09
~    Capital units
~    LDC: 6e+09*0.02
     World: 6e+09
|

Capital investment lookup(
[(0,0)-(5,3)],(0,0.1),(1,1),(2,1.8),(3,2.4),(4,2.8),(5,3))
~    Dimensionless
~         |

Capital investment rate=
0.05
~    Capital units / Person /Year [0,1]
~         |

Capital ratio normal=
1
~    Capital units / Person [0,2]
~    LDC: 0.5
     World: 1
|

Climate change restrictions tab(
[(0,0)-
(4,2)],(0,1),(0.990826,0.815789),(1.61468,0.54386),(2.12844
,0.359649),(2.6055\
    ,0.22807),(3.02141,0.131579),(3.40061,0.0614035),(4,0))
~    Dimensionless
~         |

CO2 absorption=
CO2 emissions/CO2 absorption time
~    metric tonnes/Year
```

```
~         |

utilzation normal=
1
~    Resource units/Person/Year
~         |

Pollution quality tab(
[(0,0)-
(4,2)],(0,1),(1,1),(1.22324,0.982456),(1.60245,0.938596),(2
,0.8),(3,0.4),(3.47401\
     ,0.236842),(4,0.1))
~    Dimensionless
~         |

Life quality births post DT tab(
[(0,0)-
(3,2)],(0,0),(0.12844,0.324561),(0.275229,0.570175),(0.4281
35,0.72807),(0.642202\

,0.850877),(1,1),(1.34557,1.08772),(1.6208,1.12281),(1.7981
7,1.15789),(1.93884,1.16667\
    ),(2.02446,1.19298),(2.6055,1.19298),(2.99083,1.21053))
~    Dimensionless
~         |

Crowding=
Density/Density normal
~    Dimensionless
~         |

Crowding's impact lookup(
[(0,0)-
(4,2)],(0,1),(0.978593,0.973684),(1.24771,0.929825),(1.4923
5,0.912281),(1.70031\

,0.850877),(1.95719,0.789474),(2.31193,0.614035),(2.6789,0.
45614),(3.08257,0.245614\

),(3.47401,0.0964912),(3.68196,0.0526316),(4.0367,0.0263158
))
~    Dimensionless
~         |

Crowding's impact on quality=
Crowding's impact lookup(Crowding)
~    Dimensionless
~         |

Life quality deaths tab(
[(0,0)-
(3,2)],(0,2),(0.171254,1.6),(0.53211,1.24561),(1,0.982456),
(1.55046,0.868421)\
```

```
,(1.99083,0.815789),(2.24771,0.780702),(2.57798,0.763158),(
2.87156,0.72807),(2.98165\
     ,0.719298))
~    Dimensionless
~        |

Undernourishment index=
0.11
~    Dimensionless [0,1]
~    https://ourworldindata.org/hunger-and-undernourishment
     LDC:0.236
     World: 0.11
|

Material quality of life multiplier=
Material standard impact on NR tab(Material standard of liv-
ing)
~    Dimensionless
~        |

Habitable land=
1.04e+08
~    (Kilometer * Kilometer)
~    https://ourworldindata.org/global-land-for-agriculture
     LDC: 20.14e+6
     World: 1.04e+08
|

Natural resource extraction multiplier tab(
[(0,0)-(1,1)],(0,0),(1,1))
~    Dimensionless
~        |

Non renweable resources fraction remaining=
Natural resources/Natural resource Initial
~    Dimensionless [0,1]
~        |

Life quality deaths multiplier=
Life quality deaths tab(Quality of Life)
~    Dimensionless
~        |

Material standard impact on NR tab(
[(0,0)-
(2,2)],(0,0),(0.0428135,0.149123),(0.122324,0.342105),(0.24
4648,0.491228),(0.409786\

,0.605263),(0.691131,0.815789),(1,1),(1.24159,1.14035),(1.4
6789,1.25439),(1.72477,1.33333\
     ),(1.99388,1.37719))
~    Dimensionless
```

```
~         |

Quality of Life=
Undernourishment ratio * Material standard of living * Pol-
lution's impact on quality\
      * Crowding's impact on quality
~    Dimensionless [0,2]
~         |

Natural resource Initial=
9e+11
~    Resource units
~    LDC: 1.74e+11
     World: 9e+11
|

Natural resources multiplier=
Natural resource extraction multiplier tab (Non renweable
resources fraction remaining\
     )
~    Dimensionless
~         |

birth rate=
0.0175
~    1/Year [0.01,0.05]
~    The normal fractional birth rate (18,5 births/ 1000 peo-
ple)
|

net population growth rate=
births-deaths
~    Person/Year
~         |

CO2 initial=
2.45e+10
~    metric tonnes
~    LDC: 3e+7
     World: 2.45e+10
|

CO2 standard=
3.615e+10
~    metric tonnes
~    LDC:1.06e+08
     World: 36.15e+09
|

CO2 absorption time tab(
[(0,0)-
(3,4)],(0,1.01754),(0.972477,1.31579),(1.46789,1.54386),(1.
85321,1.94737),(2.27523\
```

```
,2.4386),(2.6422,3.05263),(2.82569,3.50877),(2.98165,3.9298
2))
~    Year
~      The time it takes to incorporate pollution back into
the
              environment
              table.
|

death rate=
0.0075
~    1/Year [0,0.01,0.001]
~    The normal fractional rate of death
|

initial population=
6.143e+09
~    Person [0,1.5e+10]
~    The world population at the beginning of the simulation
     LDC: 6.57e+08
     World: 6.143e+09
|

********************************************************
.Control
********************************************************~
     Simulation Control Parameters
|

FINAL TIME  = 2100
~    Year
~    The final time for the simulation.
|

INITIAL TIME  = 2000
~    Year
~    The initial time for the simulation.
|

SAVEPER  =
        TIME STEP
~    Year [0,?]
~    The frequency with which output is stored.
|

TIME STEP  = 0.25
~    Year [0,?]
~    The time step for the simulation.
|

\\\---/// Sketch information - do not modify anything except
names
```

```
V300  Do not put anything below this section - it will be ignored
*View 1
$192-192-192,0,Times New Roman|12||0-0-0|0-0-0|0-0-255|-1--1--1|-1--1--1|96,96,90,0
12,1,48,716,461,10,8,0,3,0,0,-1,0,0,0,0,0,0,0,0,0
1,2,3,1,100,0,0,22,0,0,0,-1--1--1,,1|(761,461)|
11,3,48,802,461,6,8,34,3,0,0,1,0,0,0,0,0,0,0,0,0
10,4,births,802,478,19,9,40,131,0,0,-1,0,0,0,0,0,0,0,0,0
11,5,288,1022,461,6,8,34,3,0,0,1,0,0,0,0,0,0,0,0,0
10,6,deaths,1022,480,22,11,40,3,0,0,-1,0,0,0,0,0,0,0,0,0
10,7,initial population,924,378,51,11,8,3,0,0,0,0,0,0,0,0,0,0
12,8,3409646,1595,302,150,150,3,44,0,0,2,0,0,0,0,0,0,0,0,0
Population,Graph
10,9,Time,204,883,26,11,8,2,0,3,-1,0,0,0,128-128-128,0-0-0,|12||128-128-128,0,0,0,0,0,0
10,10,birth rate,745,313,52,11,8,3,0,0,0,0,0,0,0,0,0,0
10,11,death rate,1076,312,55,11,8,3,0,0,0,0,0,0,0,0,0,0
1,12,11,5,1,0,0,0,0,64,0,-1--1--1,,1|(1068,406)|
12,13,1576926,1595,606,150,150,3,44,0,0,2,0,0,0,0,0,0,0,0,0
births,Graph
12,14,1245944,284,317,150,150,3,44,0,0,2,0,0,0,0,0,0,0,0,0
deaths,Graph
10,15,Time,205,820,26,11,8,2,0,3,-1,0,0,0,128-128-128,0-0-0,|12||128-128-128,0,0,0,0,0,0
12,16,0,921,127,88,24,0,4,0,10,0,0,0,0,-1--1--1,0-0-0,|30||255-0-0,0,0,0,0,0,0
Population
10,17,net population growth rate,925,252,37,19,8,3,0,0,0,0,0,0,0,0,0,0
1,18,3,17,1,0,0,0,0,64,0,-1--1--1,,1|(836,360)|
1,19,5,17,1,0,0,0,0,64,0,-1--1--1,,1|(995,359)|
10,20,Crowding,885,624,32,11,8,3,0,0,0,0,0,0,0,0,0,0
10,21,Habitable land,997,529,35,16,8,131,0,0,0,0,0,0,0,0,0,0
10,22,Density,884,556,25,11,8,3,0,0,0,0,0,0,0,0,0,0
1,23,22,20,1,0,0,0,0,64,0,-1--1--1,,1|(882,581)|
1,24,21,22,1,0,0,0,0,64,0,-1--1--1,,1|(921,534)|
10,25,Density normal,1005,585,47,11,8,3,0,0,0,0,0,0,0,0,0,0
1,26,25,20,1,0,0,0,0,64,0,-1--1--1,,1|(940,584)|
10,27,Life quality deaths multiplier,1151,573,56,19,8,3,0,0,0,0,0,0,0,0,0,0
1,28,27,5,1,0,0,0,0,64,0,-1--1--1,,1|(1098,503)|
10,29,Life quality deaths tab,1319,650,58,19,8,3,0,0,0,0,0,0,0,0,0,0
1,30,29,27,0,0,0,0,0,64,0,-1--1--1,,1|(1241,614)|
10,31,Life quality births multiplier,685,564,56,19,8,3,0,0,0,0,0,0,0,0,0,0
1,32,31,3,1,0,0,0,2,64,0,-1--1--1,|12||0-0-0,1|(727,495)|
10,33,Life quality births post DT tab,531,603,55,19,8,3,0,0,0,0,0,0,0,0,0,0
```

```
1,34,33,31,1,0,0,0,0,64,0,-1--1--1,,1|(590,572)|
10,35,Quality of Life,928,712,54,11,8,2,0,3,-1,0,0,0,128-
128-128,0-0-0,|12||128-128-128,0,0,0,0,0,0
1,36,35,27,1,0,0,0,0,64,0,-1--1--1,,1|(1081,682)|
1,37,35,31,1,0,0,0,0,64,0,-1--1--1,,1|(774,694)|
12,38,0,200,720,40,68,8,7,0,0,-1,0,0,0,0,0,0,0,0,0
https://bmcpublichealth.biomedcentral.com/arti-
cles/10.1186/s12889-020-09639-9#Tab3
10,39,Population,926,463,40,20,3,3,0,16,0,0,0,0,-1--1--1,0-
0-0,|12|B|0-0-0,0,0,0,0,0,0
1,40,3,39,4,0,0,22,0,0,0,-1--1--1,,1|(847,461)|
1,41,5,39,100,0,0,22,0,0,0,-1--1--1,,1|(991,461)|
12,42,48,1109,463,10,8,0,3,0,0,-1,0,0,0,0,0,0,0,0,0
1,43,5,42,4,0,0,22,0,0,0,-1--1--1,,1|(1063,461)|
1,44,7,39,0,0,0,0,0,64,1,-1--1--1,,1|(924,409)|
10,45,Population,206,852,43,11,8,2,0,3,-1,0,0,0,128-128-
128,0-0-0,|12||128-128-128,0,0,0,0,0,0
1,46,39,22,0,0,0,0,0,64,0,-1--1--1,,1|(905,507)|
1,47,39,3,1,0,0,0,0,64,0,-1--1--1,,1|(869,415)|
1,48,39,5,1,0,0,0,0,64,0,-1--1--1,,1|(977,417)|
1,49,10,3,1,0,0,0,0,64,0,-1--1--1,,1|(750,411)|
10,50,Demographic transi-
tion,792,529,43,19,8,3,0,0,0,0,0,0,0,0,0,0,0
1,51,50,31,1,0,0,0,0,64,0,-1--1--1,,1|(763,559)|
10,52,Life quality births pre DT
tab,584,687,55,19,8,3,0,0,0,0,0,0,0,0,0,0,0
1,53,52,31,1,0,0,0,0,64,0,-1--1--1,,1|(618,606)|
1,54,50,4,1,0,0,0,0,64,0,-1--1--1,,1|(757,488)|
1,55,50,6,1,0,0,0,0,64,0,-1--1--1,,1|(928,513)|
10,56,birth rate
LDC,617,354,47,11,8,3,0,0,0,0,0,0,0,0,0,0,0
1,57,56,3,1,0,0,0,0,64,0,-1--1--1,,1|(691,424)|
10,58,death rate
LDC,1181,361,50,11,8,3,0,0,0,0,0,0,0,0,0,0,0
1,59,58,5,1,0,0,0,0,64,0,-1--1--1,,1|(1105,427)|
\\\---/// Sketch information - do not modify anything except
names
V300 Do not put anything below this section - it will be
ignored
*View 2
$192-192-192,0,Times New Roman|12||0-0-0|0-0-0|0-0-255|-1--
1--1|-1--1--1|96,96,80,0
10,1,CO2 emissions,681,357,40,20,3,3,0,16,0,0,0,0,-1--1--
1,0-0-0,|12|B|0-0-0,0,0,0,0,0,0
12,2,48,436,360,10,8,0,3,0,0,-1,0,0,0,0,0,0,0,0,0
1,3,5,1,4,0,0,22,0,0,0,-1--1--1,,1|(596,360)|
1,4,5,2,100,0,0,22,0,0,0,-1--1--1,,1|(492,360)|
11,5,48,545,360,6,8,34,3,0,0,1,0,0,0,0,0,0,0,0,0
10,6,CO2 genera-
tion,545,387,33,19,40,3,0,0,0,0,0,0,0,0,0,0,0
12,7,48,905,362,10,8,0,3,0,0,-1,0,0,0,0,0,0,0,0,0
1,8,10,7,4,0,0,22,0,0,0,-1--1--1,,1|(855,360)|
1,9,10,1,100,0,0,22,0,0,0,-1--1--1,,1|(762,360)|
```

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11,10,48,809,360,6,8,34,3,0,0,1,0,0,0,0,0,0,0,0,0
10,11,CO2 absorption,809,387,34,19,40,3,0,0,-1,0,0,0,0,0,0,0,0,0
1,12,1,10,1,0,0,0,0,64,0,-1--1--1,,1|(735,310)|
10,13,CO2 initial,676,247,36,11,8,3,0,0,0,0,0,0,0,0,0,0,0
1,14,13,1,0,0,0,0,0,64,1,-1--1--1,,1|(677,290)|
10,15,CO2 absorption time,894,455,54,19,8,3,0,0,0,0,0,0,0,0,0,0,0
1,16,15,11,1,0,0,0,0,64,0,-1--1--1,,1|(892,433)|
10,17,CO2 absorption time tab,1044,516,54,19,8,3,0,0,0,0,0,0,0,0,0,0,0
10,18,CO2 standard,840,583,56,11,8,3,0,0,0,0,0,0,0,0,0,0,0
12,19,1708412,1355,345,150,150,3,12,0,0,2,0,0,0,0,0,0,0,0,0
CO2 emissions,Graph
10,20,restricting factors,518,485,54,11,8,3,0,0,0,0,0,0,0,0,0,0,0
10,21,Climate change restrictions tab,498,572,49,19,8,3,0,0,0,0,0,0,0,0,0,0,0
1,22,21,20,1,0,0,0,0,64,0,-1--1--1,,1|(529,533)|
1,23,20,6,1,0,0,0,0,64,0,-1--1--1,,1|(476,441)|
10,24,Time,1491,55,26,11,8,2,0,3,-1,0,0,0,128-128-128,0-0-0,|12||128-128-128,0,0,0,0,0,0
12,25,0,612,136,119,36,8,7,0,10,-1,0,0,0,-1--1--1,0-0-0,|24||255-0-0,0,0,0,0,0,0
CO2 Emissions & Natural resources
10,26,Natural resources,324,731,40,20,3,3,0,16,0,0,0,0,-1--1--1,0-0-0,|12|B|0-0-0,0,0,0,0,0,0
12,27,48,614,731,10,8,0,3,0,0,-1,0,0,0,0,0,0,0,0,0
1,28,30,27,4,0,0,22,0,0,0,-1--1--1,,1|(560,731)|
1,29,30,26,100,0,0,22,0,0,0,-1--1--1,,1|(434,731)|
11,30,48,511,731,6,8,34,3,0,0,1,0,0,0,0,0,0,0,0,0
10,31,Natural resource utilization,511,758,54,19,40,3,0,0,-1,0,0,0,0,0,0,0,0,0
10,32,utilzation normal,689,687,51,11,8,3,0,0,0,0,0,0,0,0,0,0,0
1,33,32,30,1,0,0,0,0,64,0,-1--1--1,,1|(591,691)|
10,34,Natural resource Initial,360,593,54,19,8,3,0,0,0,0,0,0,0,0,0,0,0
1,35,34,26,1,0,0,0,0,64,1,-1--1--1,,1|(372,674)|
10,36,Natural resource extraction multiplier tab,124,777,62,19,8,3,0,0,0,0,0,0,0,0,0,0,0
10,37,Natural resources multiplier,126,694,54,19,8,3,0,0,0,0,0,0,0,0,0,0,0
10,38,Non renweable resources fraction remaining,163,595,59,19,8,3,0,0,0,0,0,0,0,0,0,0,0
1,39,26,38,1,0,0,0,0,64,0,-1--1--1,,1|(283,639)|
1,40,34,38,0,0,0,0,0,64,0,-1--1--1,,1|(270,593)|
1,41,38,37,1,0,0,0,0,64,0,-1--1--1,,1|(133,631)|
1,42,36,37,0,0,0,0,0,64,0,-1--1--1,,1|(124,742)|
10,43,Material quality of life multiplier,764,768,58,19,8,3,0,0,0,0,0,0,0,0,0,0,0
1,44,43,30,1,0,0,0,0,64,0,-1--1--1,,1|(619,758)|
```

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10,45,Material standard of living,879,689,61,19,8,2,0,3,-
1,0,0,0,128-128-128,0-0-0,|12||128-128-128,0,0,0,0,0,0
1,46,45,43,1,0,0,0,0,64,0,-1--1--1,,1|(791,706)|
10,47,Material standard impact on NR
tab,916,803,69,19,8,3,0,0,0,0,0,0,0,0,0,0,0,0
1,48,47,43,1,0,0,0,0,64,0,-1--1--1,,1|(781,811)|
12,49,1378406,1356,683,150,150,3,44,0,0,2,0,0,0,0,0,0,0,0,0
Natural resources,Graph
10,50,Population,632,595,43,11,8,2,0,3,-1,0,0,0,128-128-
128,0-0-0,|12||128-128-128,0,0,0,0,0,0
1,51,50,6,1,0,0,0,0,64,0,-1--1--1,,1|(622,447)|
1,52,50,30,1,0,0,0,0,64,0,-1--1--1,,1|(587,674)|
10,53,CO2 generation,1362,57,60,11,8,2,0,3,-1,0,0,0,128-
128-128,0-0-0,|12||128-128-128,0,0,0,0,0,0
10,54,CO2 per cap-
ita,424,261,60,11,8,3,0,0,0,0,0,0,0,0,0,0,0,0
1,55,54,6,1,0,0,0,0,64,0,-1--1--1,,1|(498,302)|
10,56,pollution capital multi-
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tab,185,301,50,19,8,3,0,0,0,0,0,0,0,0,0,0,0,0
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ment,408,838,54,19,8,3,0,0,0,0,0,0,0,0,0,0,0,0
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tio,602,851,44,19,8,3,0,0,0,0,0,0,0,0,0,0,0,0
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tio,736,517,43,11,8,3,0,0,0,0,0,0,0,0,0,0,0,0
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10,19,Capital depreciation,936,806,38,19,40,3,0,0,-1,0,0,0,0,0,0,0,0,0
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10,24,Capital investment multiplier,453,744,58,19,8,3,0,0,0,0,0,0,0,0,0,0,0,0
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10,27,Capital investment lookup,314,808,58,19,8,3,0,0,0,0,0,0,0,0,0,0,0,0
10,28,Capital initial,815,866,41,11,8,3,0,0,0,0,0,0,0,0,0,0,0,0
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10,30,Time,1664,415,26,11,8,2,0,3,-1,0,0,0,128-128-128,0-0-0,|12||128-128-128,0,0,0,0,0,0
10,31,Capital ratio,759,651,39,11,8,3,0,0,0,0,0,0,0,0,0,0,0,0
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10,33,Capital ratio normal,302,558,40,19,8,3,0,0,0,0,0,0,0,0,0,0,0,0
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Capital & Quality of Life
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1,40,8,6,0,0,0,0,0,64,0,-1--1--1,,1|(619,249)|
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tio,619,376,58,19,8,3,0,0,0,0,0,0,0,0,0,0
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1,44,7,2,1,0,0,0,0,64,0,-1--1--1,,1|(851,439)|
10,45,Crowding's impact on qual-
ity,457,447,60,19,8,3,0,0,0,0,0,0,0,0,0,0
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lookup,256,473,60,19,8,3,0,0,0,0,0,0,0,0,0,0
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Quality of Life,Graph
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Capital,Graph
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128,0-0-0,|12||128-128-128,0,0,0,0,0,0
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10,61,Sustainable solu-
tions,296,652,36,19,8,3,0,0,0,0,0,0,0,0,0,0
10,62,Sustainability multi-
plier,156,679,42,19,8,3,0,0,0,0,0,0,0,0,0,0
1,63,62,61,1,0,0,0,0,64,0,-1--1--1,,1|(227,684)|
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V300 Do not put anything below this section - it will be
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CO2 emissions,Graph
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Capital,Graph
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Quality of Life,Graph
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128,0-0-0,|12||128-128-128,0,0,0,0,0,0
10,13,CO2 standard,595,588,55,11,8,2,0,3,-1,0,0,0,128-128-
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10,14,Capital initial,966,408,50,11,8,2,0,3,-1,0,0,0,128-
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net population growth rate,Graph
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