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COVID-19 in China – outbreak, public health response and health economic analysis

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List of Abbreviations

2019-nCoV	Novel Coronavirus 2019
AIHW	Australian Institute of Health and Welfare
CHE	Current Health Expenditure
China CDC	China Centers for Disease Control and Prevention
COVID-19	Corona Virus Disease 2019
DES	Discrete Event Simulations
EU	European Union
ICTV	International Committee on The Classification of Viruses
IPC	infection prevention and control
GDP	Gross Domestic Product
GDPR	General Data Protection Regulation
GGHE-D	Domestic General Government Health Expenditure
IMF	International Monetary Fund
KFF	Kaiser Family Foundation
MERS-CoV	Middle East Respiratory Syndrome Coronavirus
NHC	National Health Commission of China
NPIs	Non-pharmaceutical interventions
OECD	Organization for Economic Co-operation and Development
PHSM	public health and social measures
PPE	personal protective equipment

PPP	theory of Purchasing Power Parity
SARS	Severe Acute Respiratory Syndrome
SARS-CoV	Severe Acute Respiratory Syndrome Coronavirus
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2
UK	United Kingdom
USA	United States of America
US CDC	United States Centers for Disease Control and Prevention
WHO	World Health Organization

1. Introduction

In December 2019, a Pneumonia of unknown cause broke out in Wuhan, Hubei Province, China. From 31 December 2019 to 3 January 2020, a total of 44 cases of “pneumonia of unknown causes” were reported to the World Health Organization (WHO) by the Chinese authorities (1). Since then the number of cases and deaths rose exponentially with tremendous challenges to the health care system and the society (2). On January 7, 2020, the China Centers for Disease Control and Prevention (China CDC) detected a new human coronavirus and sequenced the whole genome of the virus (3, 4), which was subsequently identified as the pathogen of the disease (5, 6). On January 12, 2020, China shared the genetic sequence of the novel coronavirus with the WHO for countries to use in developing specific diagnostic kits (7). On January 12, 2020, the WHO officially named the virus “Novel Coronavirus 2019” (2019-nCoV) (8), and on February 11, 2020 the International Committee on The Classification of Viruses (ICTV) named the virus as Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2), the disease was subsequently named Corona Virus Disease 2019 (COVID-19) (9).

The combination of high transmissibility and moderate severity made SARS-CoV-2 a perfect pathogen for a pandemic, unlike Severe Acute Respiratory Syndrome Coronavirus (SARS-CoV), Middle East Respiratory Syndrome Coronavirus (MERS-CoV) and flu (10-12). As SARS-CoV-2 is highly infectious, the new disease spread rapidly to other countries and continents, after infecting over 118,000 patients in over 100 countries, and causing more than 4200 deaths, WHO officially declared a “COVID-19 pandemic” on 11 March 2020 (13-15). However, while many countries and in particular Europe, North and South America are suffering from very strong waves of the disease with millions of cases and victims, China seems to have won the fight against the disease (16). It has been questioned whether China’s official statistics represent the real situation. Some argue that the number of cases and deaths during the peak of the epidemic must have been much higher than presented in the official statistics (17), while others question that the disease could disappear completely from Wuhan (18). Similar questions can still be heard today (19). It was estimated by Imperial College London, United Kingdom (UK) that the total number of confirmed diagnoses in Wuhan had reached 4000 by January 18, 2020 (20), which was much higher than the officially reported number. However, with the substantial enhancement of case detection and reporting, at the same time, with communications between Chinese governments and the WHO mission, the differences between the official numbers and the estimates are to be fewer and fewer.

Despite the skepticism, China managed to bring life in Wuhan back almost to normal within a short period. There is no doubt that the second wave with tremendous consequences for the public health situation could not have been hidden. Thus, irrespective of the reliability of the statistics basis, the measures taken by the Chinese government must have been quite successful in containing the outbreak and in preventing other waves of outbreaks. Outbreaks as people experience them in the United States of America (USA), Spain, Germany or France in particular in winter 2020/21 could not be hidden from WHO and the rest of the world. At the same time, the pandemic has also resulted in the loss of livelihoods due to prolonged shutdowns, which have had a rippling effect on the global economy, which could also not be concealed from the world.

Although China accounts for 19% of the world's population, only 0.05% of the global total of cases were reported in two years (21). According to the report of the WHO and National Health Commission of China (NHC), as of December 31, 2021, more than 280 million individuals worldwide had been confirmed as infected, with over 5.4 million deaths (21), but China has recorded only 102,314 confirmed cases and 4,636 deaths (22). This shows that even in the most unfavorable case where the virus could spread unimpeded until it was recognized as a deadly threat and until tests were available, it is possible to limit and ultimately stop its expansion. But during the

COVID-19 outbreak phase, more and more voices recommend a transition from containment to mitigation, and in particular suggest the uselessness of lockdowns, travel restrictions and contact tracing, once the number of cases exceeds a certain threshold (23). In other words: it is not realistic to eliminate a respiratory virus like SARS-CoV-2, any more than it is to eliminate the flu or the common cold (24).

The current situation is that the number of confirmed cases around the world continues to climb, and the global case fatality rate of COVID-19 reached 1.88 % as of 31 December 2021, based on Johns Hopkins University statistics (25). And the same time, one study showed that excess years of life lost associated with the COVID-19 pandemic in 2020 were more than five times higher than those associated with the seasonal influenza epidemic in 2015 (26). Today, the COVID-19 pandemic has challenged all areas of the economy, particularly with the emergence of virus variants, such as the Delta variant and the recently identified Omicron variant. They are more contagious than the original strain and even can infect people who have been vaccinated or recovered from infection, which makes fighting the pandemic much more difficult and could force the healthcare system into a new overloaded situation within a very short time (27, 28). By December 25, 2021, the United States Centers for Disease Control and Prevention (US CDC) estimated that the Omicron variant already made up 77% of all new infections in the USA (28). Consequently, researchers have to investigate the consequences of this increased infectivity and challenge the measures that should be taken.

The original medical infectivity of the Wuhan strain was estimated to be about 2.5 (2, 29-32). The Delta variant was far higher compared to the ancestral SARS-CoV-2 virus, with an R_0 of about 5 (33-37), and experts predict that the Omicron variant is even more infectious with R_0 of about 8 (28). This increase will challenge health policies and anti-COVID measures, for instance the Chinese “zero-COVID” strategy. Furthermore, it is likely that new variants will appear challenging the policies and measures even more and one has to ask for appropriate methods to stop the outbreak. For this purpose, it is relevant to know which measures were crucial in stopping the outbreak, and which ones might have been excessive? Does China really have the ability to stop the spread of the virus, or do their figures not match the facts? What do people know from anti-epidemic policies in other countries?

China has carrying out its time-tested dynamic clearance strategy across the country since the outbreak of COVID-19. This strategy emphasizes early detection, reporting, quarantine, and treatment. Its goal is to cut off the transmission chain quickly and accurately before an outbreak gains momentum and leads to major disruptions in social and economic activities. Firstly, a rapid reduction in numbers of infections to zero. Secondly, avoidance of further virus transmission or reintroduction through rigorous test, trace, and isolate systems, together with local travel restrictions. Thirdly, rapid outbreak management if new cases of COVID-19 occur sporadically. This policy was supported by the whole country and had proved to be impressively effective in fighting COVID-19. There is no doubt that this policy is a continuation of Wuhan's anti-epidemic policy. Consequently, this research will take Wuhan as an example to discuss the successful experience of China's response to COVID-19 and its role in preventing subsequent waves.

At a first glance, there might be three causes: Firstly, some external factors such as climate, genetics or culture might constitute a natural barrier against the diffusion of the disease. Secondly, a brilliant public health system with high resources might be capable to reduce the spread of the disease. Thirdly, in the absence of pharmaceutical prophylactic options, specific interventions against the disease, such as mask wearing, hand washing, social distancing, and restriction of public events and travel, which can also be called a non-Pharmaceutical Interventions (NPIs), combining massive human labor with high-tech tools might have managed to control the outbreak in the country which are not consistently implemented in the most severely hit countries. This research will focus on these three areas and analyze the relevance of these three factors. At the same time, the data from Wuhan will be used in this research to establish a model to analyze how the public health service system in Wuhan can effectively reduce the number of risk contacts and successfully keep the R_0 of coronavirus below 1.

The structure of this paper as follows: The second section outlines the characteristics of China’s public health system, including current situation of public health system in China and structural analysis of public health expenditure in China. As methods and results, this paper will present a simulation model of the diffusion of COVID-19 in Wuhan in section 3 and section 4, and then further discuss the effectiveness of public health and social measures (PHSM), including infection prevention and control (IPC) measures, to reduce COVID-19 cases, hospitalizations and deaths. Afterwards, in section 5, the issues raised earlier will be discussed, and the public health care system of China and its ability to produce results which are more likely to control the disease than in Europe or the USA. The instruments applied in China with other countries will also be compared in this paper to determine the underlying causes of this success story. Section 6 provides the conclusion. In consideration of the coherence and systematization of the data, 31 December 2021 is set as the deadline for COVID-19 statistics in this paper.

2. Public Health System in China

2.1 Current Situation of Public Health System

After decades of continuous efforts, China's public health system has experienced stages of initial development, functional improvement and reform, it gradually completed from system construction to development and improvement. As illustrated in Figure 1, the total health expenditure in China showed a relatively fast growth trend, which has soared from 74.74 billion yuan (15.64 billion US$ or 13.68 US$ p.c.) in 1990 to 5,912.19 billion yuan (894.43 billion US$ or 640.99 US$ p.c.) in 2018. In terms of relative numbers, the total health expenditure as a proportion of the Gross Domestic Product (GDP) has also been increasing in general in the last nearly three decades, from 3.96% in 1990 to 6.57% in 2018. The reasons behind this growth are manifold. Most important factors are the increasing living standards and the aging of the population.

Figure 2 shows the financing structure characteristics of the total health expenditure in China, including government health expenditure, social health expenditure and personal health expenditure. The proportion of government health expenditure and social health expenditure declined year by year from 1990. The proportion of government health expenditure bottomed out at 15.47% in 2000, and the proportion of social health expenditure reached the lowest in 2001, only 24.10%, and they have since risen slowly year by year. But starting in 2017, the share of government health spending showed downward trend again. Meanwhile, the proportion of personal health expenditure increased significantly since 1990, peaking at 59.97% in 2001, and decreased every year thereafter. Taking the data of 2018 as an example, the total national health expenditure in 2018 reached 5,912.19 billion yuan (894.43 billion US$), of which: the government health expenditure was 1,639.91 billion yuan (248.10 billion US$ accounting for 27.74%), the social health expenditure was 2,581.08 billion yuan (390.48 billion US$ accounting for 43.66%), the personal health expenditure was 1,691.20 billion yuan (255.85 billion US$ accounting for 28.61%). This is due to the Severe Acute Respiratory Syndrome (SARS) outbreak in 2003, when the Chinese government significantly increased investment in public health, resulting in a substantial increase in the scale of government public health expenditure, the absolute scale expanded to 111.69 billion yuan (13.49 billion US$), accounting for 16.96% of the national health expenditure. After the SARS crisis, Chinese government continued to invest a large amount of money in the construction of the public health system. From 2003 to 2005, the central government allocated 9.2 billion yuan (1.12 billion US$) as a special public health fund to support the medical treatment system, the disease information network system and the prevention and control of diseases in public health emergencies. Another 5.1 billion yuan (654 million US$) was allocated in 2006 to support the development of the public health system. China's public health system has since become increasingly mature.

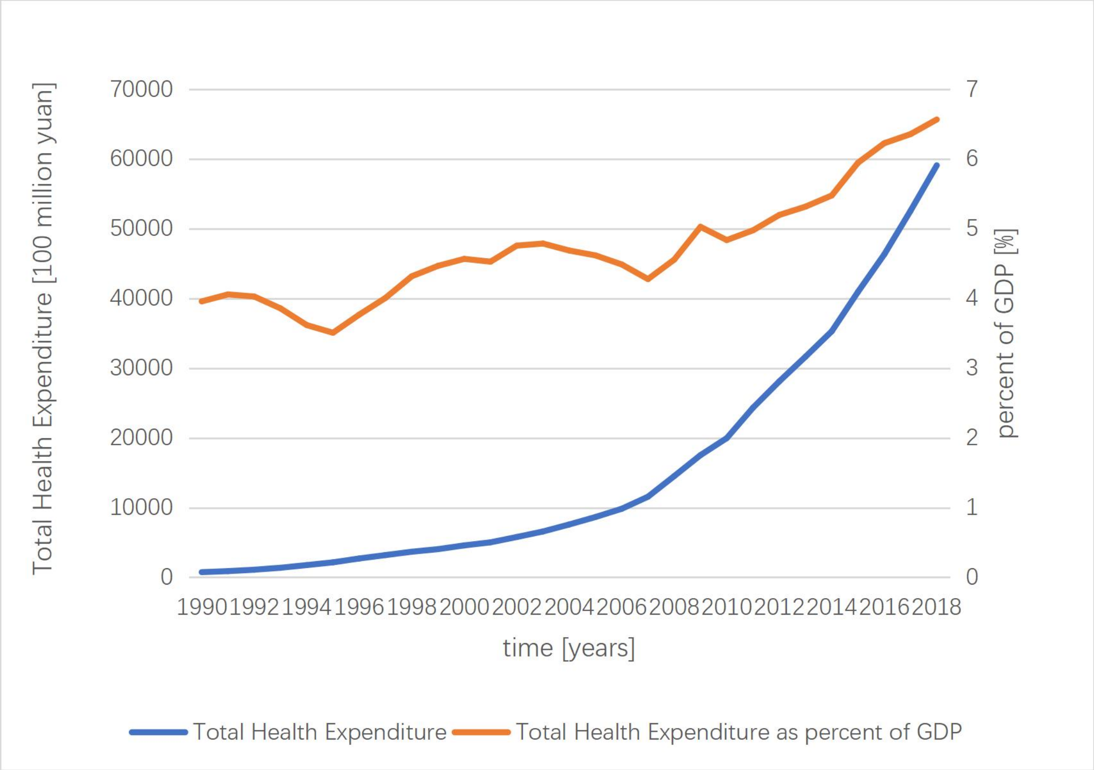

Figure 1 The Total Health Expenditure and as percent of GDP. Source: (38).

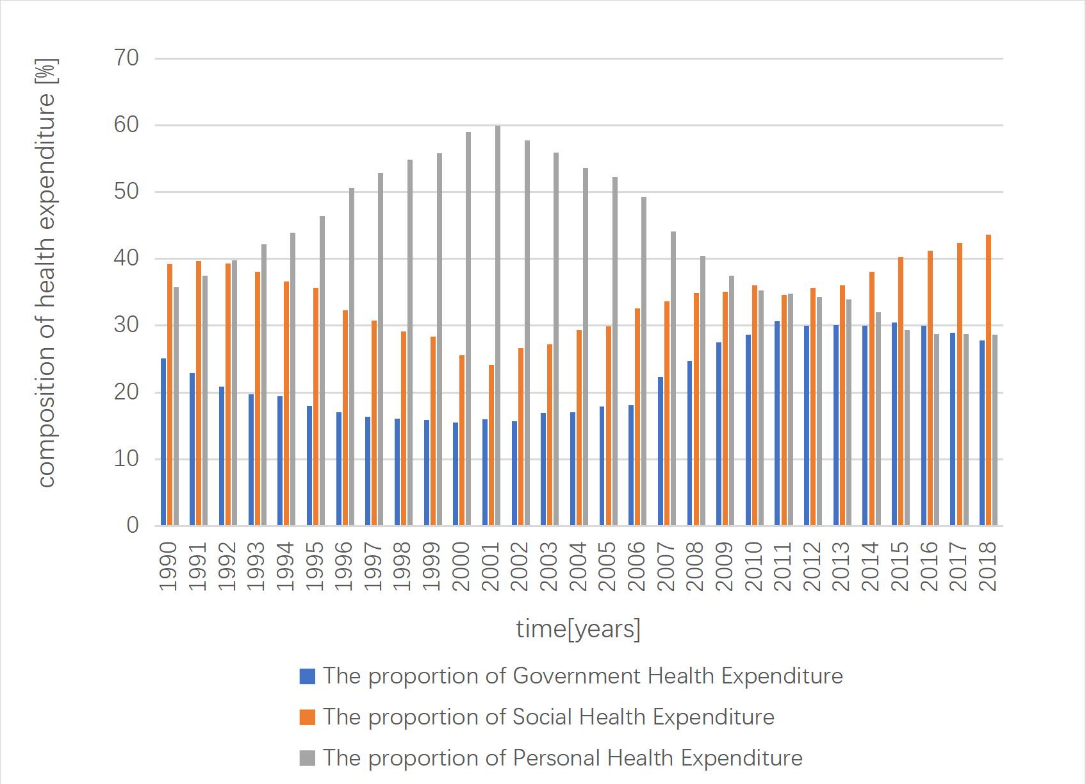

Figure 2 The composition of Total Health Expenditure. Source: (38).

2.2 Structural Analysis of Public Health Expenditure

2.2.1 Overall Structure

On the whole, China’s public health expenditure can be divided into public health service expenditure and public medical expenditure. Public health service expenditure is an important part of the government public health expenditure, it is a health care service fund provided to all members of society by the national financial budget. The main goal is to achieve the equalization of public health service, and to narrow and balance the gap of public health service between regions. It is of great significance in disease control, prevention of major epidemic and handling of sudden public health events. Public medical expenditure refers to the medical insurance fund provided by the government for part of the population, that is, the medical and health expenditure provided by the financial budget at all levels of the government for the public officials of the national administrative institutions.

In theory, the public health service funding should be the focus of Chinese government health expenditure, and preventive health care should be the core of government responsibility. However, in promoting the reform of public health institutions, the Chinese government regarded public health institutions as service intermediaries under the condition of market economy and did not pay enough attention to the importance of public health services. As shown in Figure 3, the public health service expenditure increased from 14.29 billion yuan (2.99 billion US$) in 1990 to 860.36 billion yuan (130.16 billion US$) in 2018, an increase of about 60 times. Simultaneously, the public medical expenditure raised from 4.43 billion yuan (927 million US$) in 1990 to 779.58 billion yuan (117.94 billion US$) in 2018, increased by 176 times. The public medical expenditure in China is increasing every year, which means that more and more funds from the government's limited health expenditure is devoted to clinical services for a small number of people, while the public health expenditure that benefit the whole people is relatively reduced.

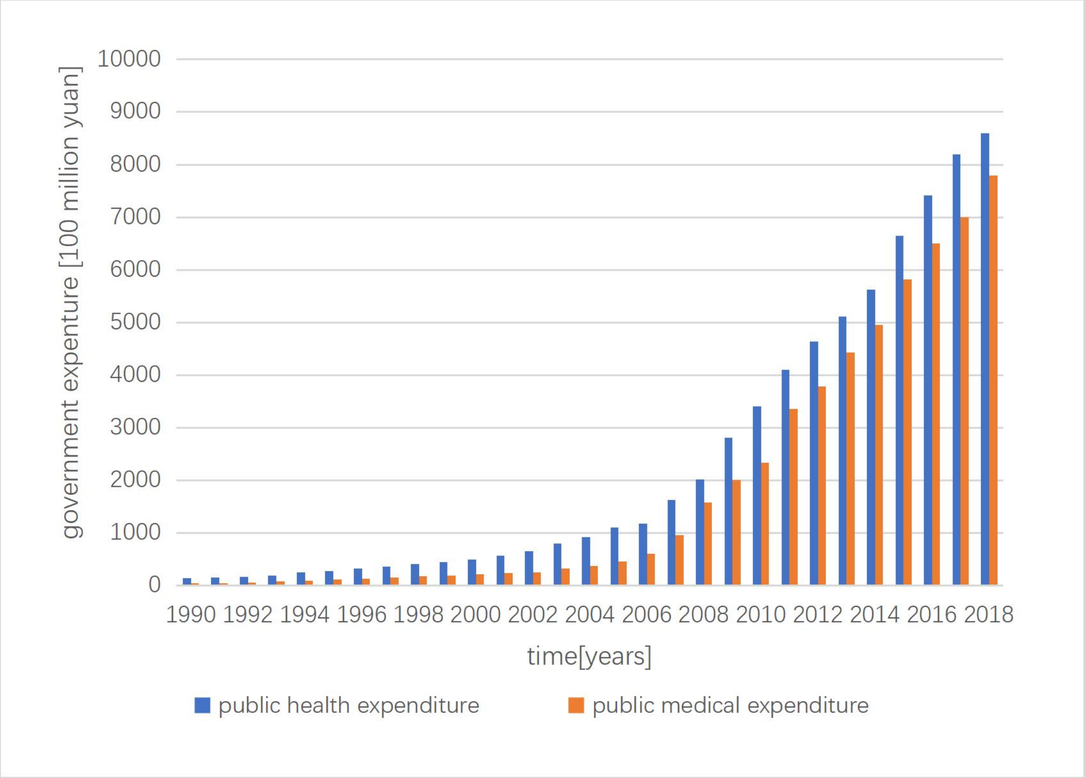

Figure 3 The Structure of Government Expenditure on public health. Source: (38).

2.2.2 Distribution Structure

2.2.2.1 Different Regions

According to the geographical location of provinces and cities, China is divided into eastern, central and western regions. Under normal conditions, economically developed regions have strong financial capacity, and the government has the ability to invest more funds in health, resulting in a higher level of public health. However, less developed areas have weak financial resources and less government investment in health, resulting in a lower level of public health. It can be seen that the public health expenditure in different regions is closely related to the GDP of the region. On the other hand, the urbanization is advanced in eastern China. The larger size and the higher density of populations mean that its operational costs of health services are relatively cheaper. Meanwhile, the decentralized governmental budgeting process means that the wealthy eastern provinces have a higher financial capacity to fund health services. The health services in the eastern region can also offer a better salary and welfare to health workers, enticing quality health workers from the less developed regions to move to the east.

In China, most quality health resources are concentrated in tertiary hospitals. Table 1 represents that the number of tertiary hospitals in the eastern region reached 1,047, which is significantly higher than the 551 in the central region and the 665 in the western region. Correspondingly, medical practitioners per 1,000 population, registered nurses per 1,000 population and general practitioners per 10,000 population are higher than those in the central and western regions. As illustrated in Figure 4, China’s per capita health expenditure in 2017 was 3,783.83 yuan (572.44 US$ p.c.). 4 provinces and 3 municipalities in the eastern region (including 8 provinces, 3 municipalities) exceeded the national average; 8 provinces in central region (including 8 provinces) did not reach the national average; 2 provinces, 4 autonomous regions and 1 municipality in western region (including 6 provinces, 5 autonomous regions and 1 municipality) exceeded the national average. This is because since the implementation of the western development strategy, the central government has strongly supported the public health expenditure in western region, significantly narrowing the gap between the per capita public health expenditure in the western region and the national average.

Table 1 Regional distribution of health resources in 2018. Source: (38).

	Tertiary hospital	**Medical practitioners per 1,000 population**	**Registered nurses per 1,000 population**	**General practitioners per 10,000 population**
Eastern	1047	2.4	3.1	2.93
Central	551	2.0	2.7	1.73
Western	665	2.0	3.0	1.66

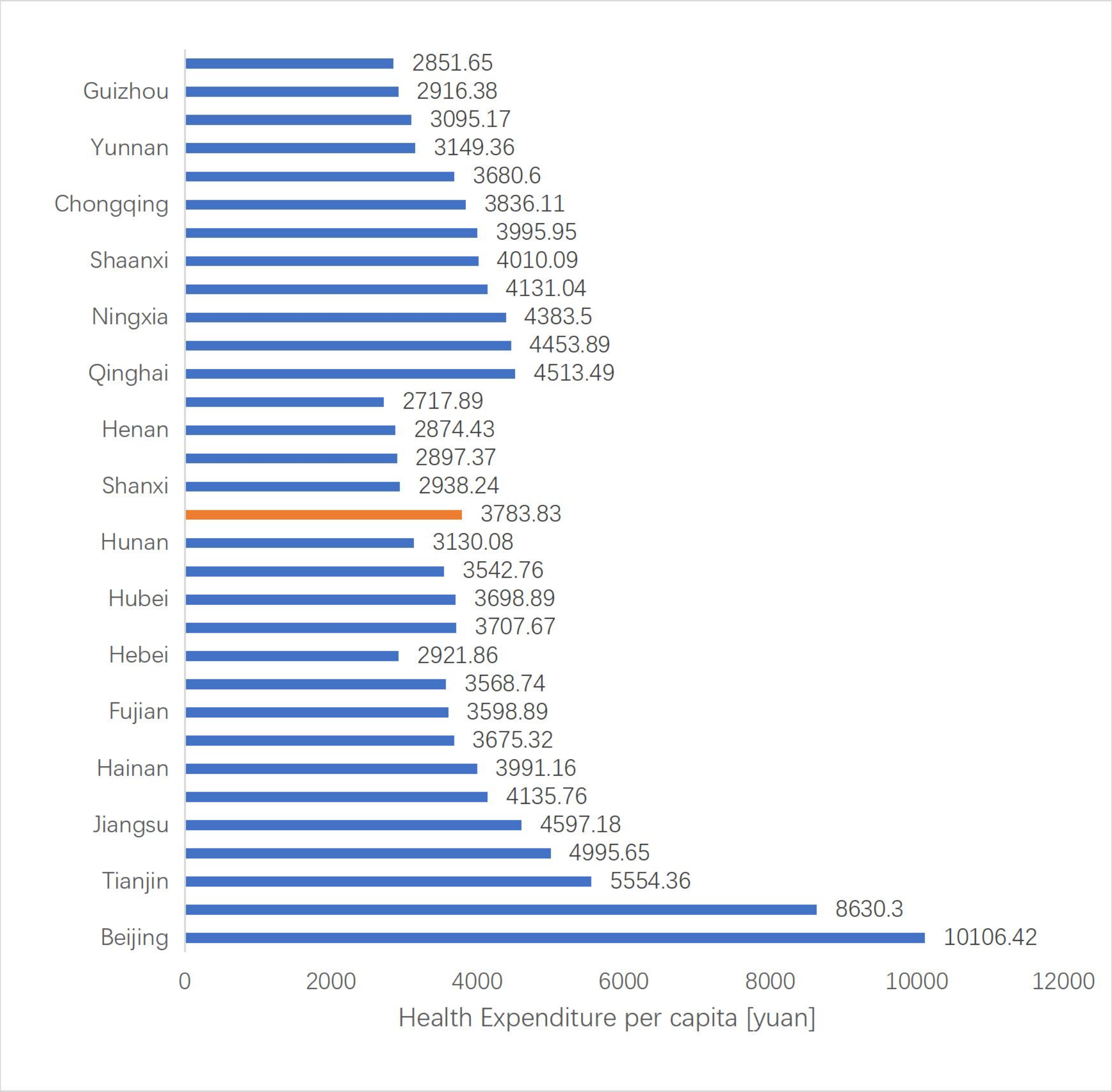

Figure 4 Health Expenditure per capita in different regions in 2017. Source: (38).

2.2.2.2 Urban and Rural Areas

The difference in the urban-rural distribution structure of public health expenditure is first reflected in the total health expenditure. As indicated in Figure 5, the health expenditure of urban population increased from 39.60 billion yuan (8.28 billion US$) in 1990 to 3,545.80 billion yuan (534.01 billion US$) in 2016, an increase of 89.54 times; simultaneously, the health expenditure of the rural population increased from 35.14 billion yuan (7.35 billion US$) in 1990 to 1,088.69 billion yuan (163.96 billion US$) in 2016, only increased by 30.98 times. Secondly, there was also a significant gap between health expenditure per capita of urban and rural areas. The gap of health expenditure per capita between urban and rural areas was 120 yuan (25.10 US$) in 1990, and it added up to 2,625.40 yuan (395.39 US$) in 2016. This is because health system in China has been funded by local finance since 1980. The revenue mainly comes from urban economy, and the financial expenditure, especially public service expenditure, is mainly used by urban residents, while rural medical and health work has not received enough attention. In 2016, for example, China's rural population accounted for 42.65% of the total population, but the per capita health expenditure was only 1,846.10 yuan (278.03 US$), while the per capita health expenditure in urban areas was 4,471.50 yuan (673.42 US$), much higher than that in rural areas.

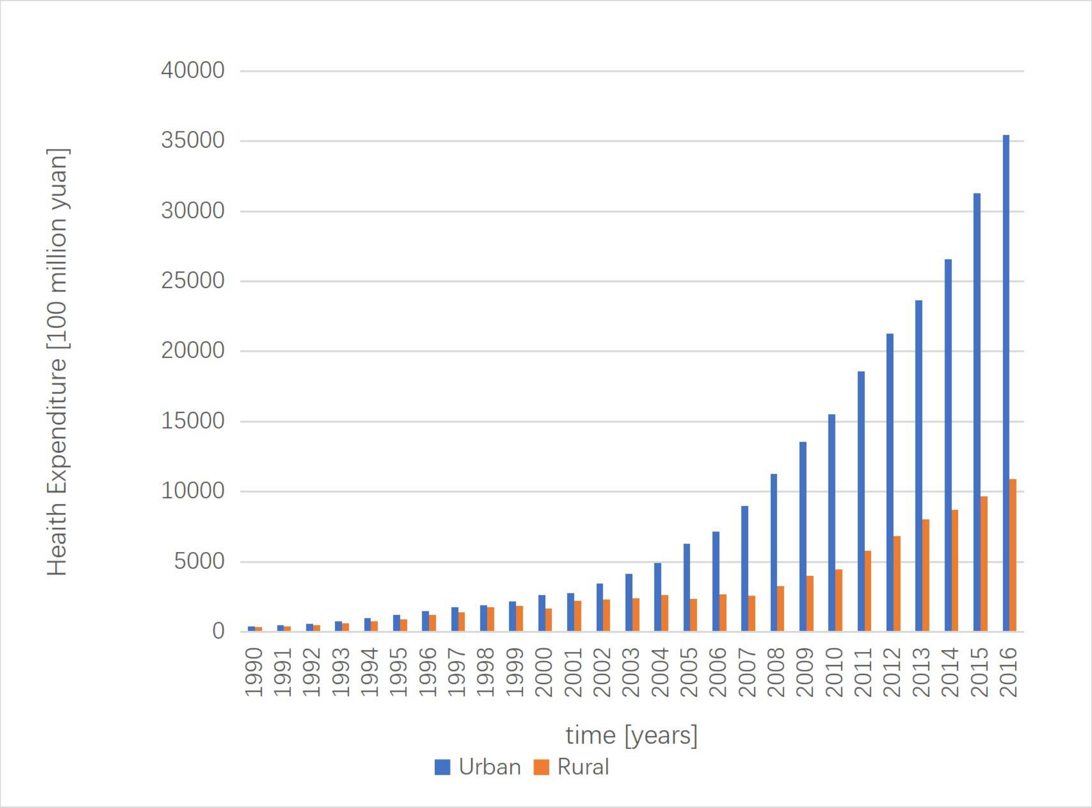

Figure 5 The health expenditure in urban and rural areas. Source: (38).

2.2.2.3 Central and Local Government

China's public health management system and financial system are mainly managed by local governments, which are subsidized by the central government in the form of financial transfer payments. The scale and proportion of health expenditure in the central and local finance of China is presented in Figure 6. The proportion of the central health expenditure in the national finance from 2002 to 2018 decreased year by year, from 2.72% to 1.35%, while the proportion of the local financial expenditure increased year by year, from 97.28% to 98.65%.

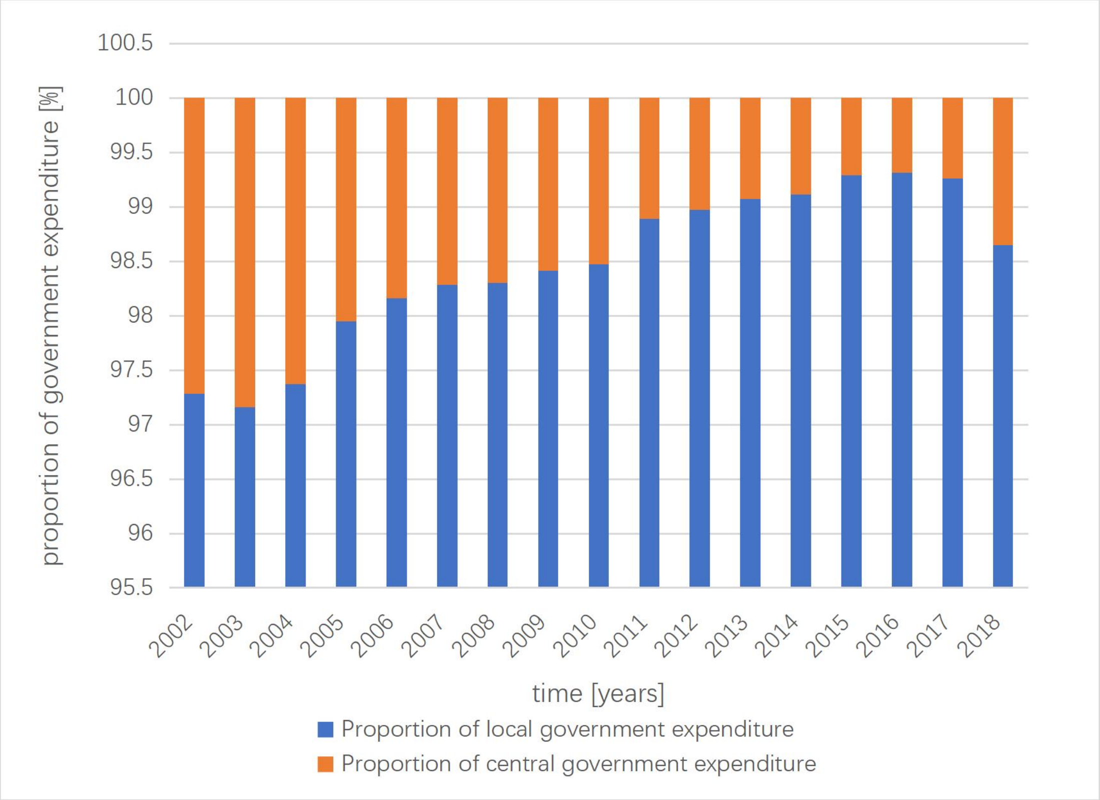

Figure 6 The proportion of public health expenditure between central and local government. Source: (39).

2.2.3 Shortcomings

2.2.3.1 The Overall Public Health Expenditure is Inadequate

As can be seen from Table 2, the financial subsidies provided by the Chinese government to professional public health institutions are much lower than those for hospitals that focus on clinical treatment. In 2018, for example, government subsidies to hospitals reached 44.46%, while subsidies to professional public health institutions were only 20.50%, less than half of that to hospitals.

On the other hand, Figure 7 represents that the number of disease prevention and control institutions in China has dropped from 3,618 in 1990 to 3,443 in 2018, this does not mean that infectious diseases are no longer a threat, in fact, according to the number of cases and deaths of Class A and B infectious diseases per 100,000 population provided by the NHC, the situation of infectious diseases in China are still severe (Figure 8). The number of cases of Class A and B infectious diseases in China continued to decline from 1990 to 2002, however, the number of Class A and B infectious diseases began to increase continuously after 2002, reaching 272.39 per 100,000 population in 2007. It wasn’t until 2010 that there was a slow decline in volatility, but it remained high at 220.51 per 100,000 population in 2018. The number of deaths from infectious diseases was 1.17 per 100,000 population in 1990 and has been decreasing every year since then, but the number of deaths has continued to increase since 2003 and reached 1.67 per 100,000 population in 2018, surpassing the 1990 figure. According to the global tuberculosis report 2020, China had about 840,000 tuberculosis patients in 2019, ranking third in the world after India and Indonesia (40). These surveys indicated that there is still a long way to go in the development of China's public health system, and lack of investment has to some extent weakened the ability of public health institutions to provide disease prevention and control services.

Table 2 Financial subsidies and proportions of various medical and health institutions in 2018. Source: (38).

Medical Institutions	**Government financial subsidies (thousand yuan)**	**Proportion of financial subsidies (%)**
Hospital	269,659,760	44.46
Community Medical Institutions	197,735,780	32.60
Professional Public Health Institutions	124,331,690	20.50
Other Medical and Health Institutions	14,758,600	2.43

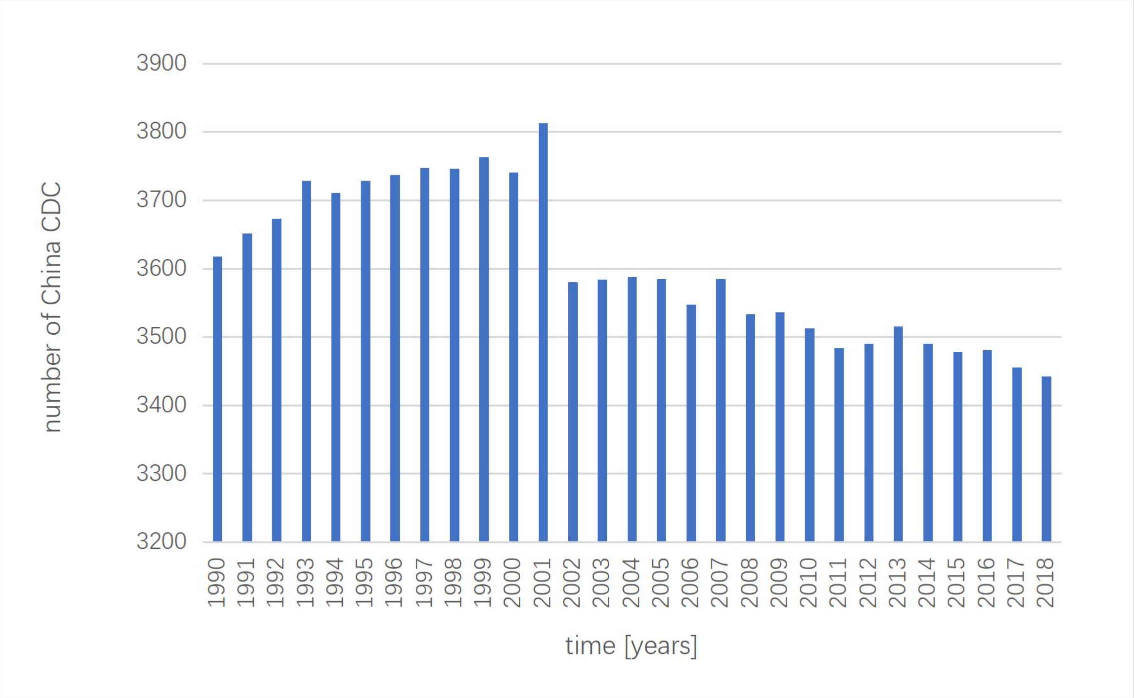

Figure 7 The number of China CDC. Source: (38).

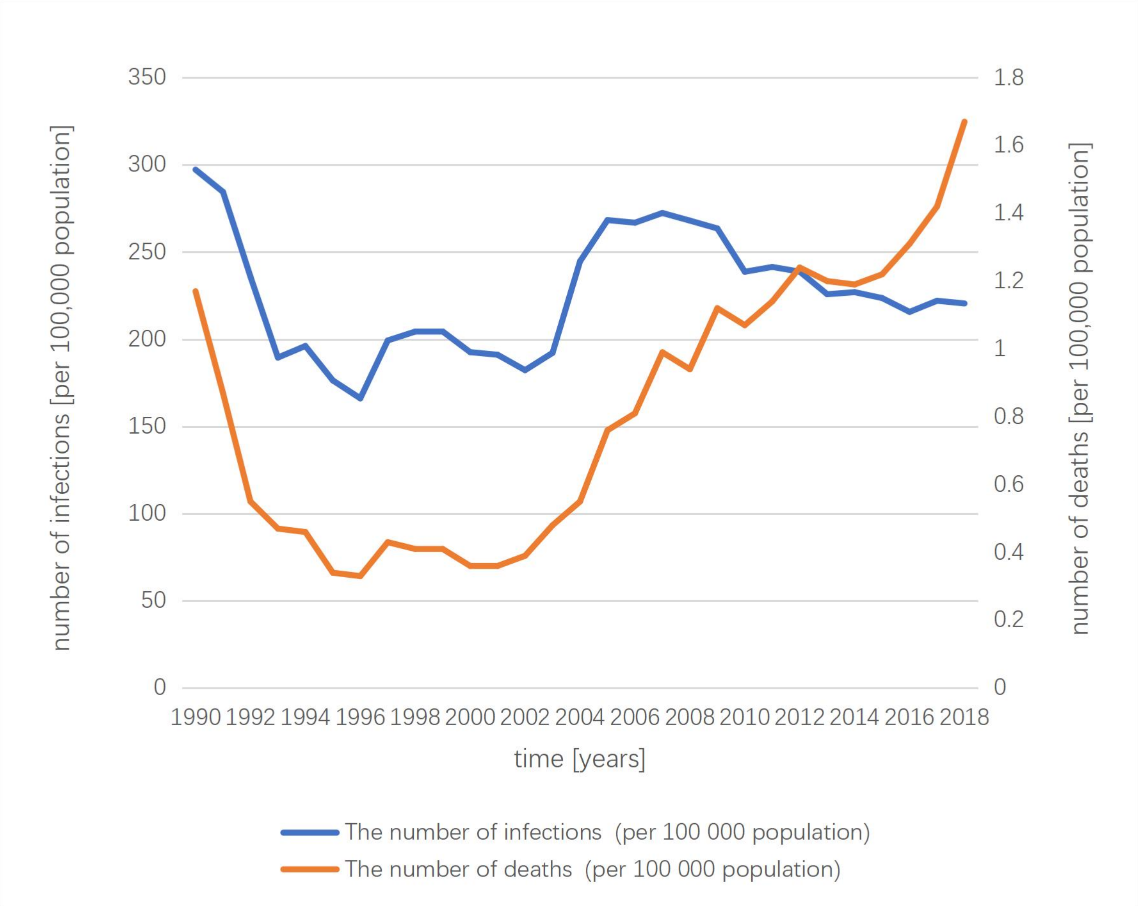

Figure 8 The number of infections and deaths per 100,000 people of Class A and B statutory reported infectious diseases. Source: (38).

2.2.3.2 Current Health Expenditure and per capita Current Health Expenditure are Insufficient

Statistics from the Organization for Economic Cooperation and Development (OECD) and the WHO show that Current Health Expenditure (CHE) and per capita CHE in China are obviously insufficient compared with high-income countries such as the USA and Germany. As shown in Figure 9, CHE as a percentage of GDP in 2019 was 16.8% in the USA and 11.7% in Germany, much higher than 5.4% in China. The second clear gap is reflected in the per capita CHE. Based on purchasing power parity theory (PPP), the per capita CHE of high-income countries represented by the USA and Germany was significantly higher than that of China in 2019, at 10,921 US$ and 6,378.7 US$ respectively, while it was only 880.2 US$ in China.

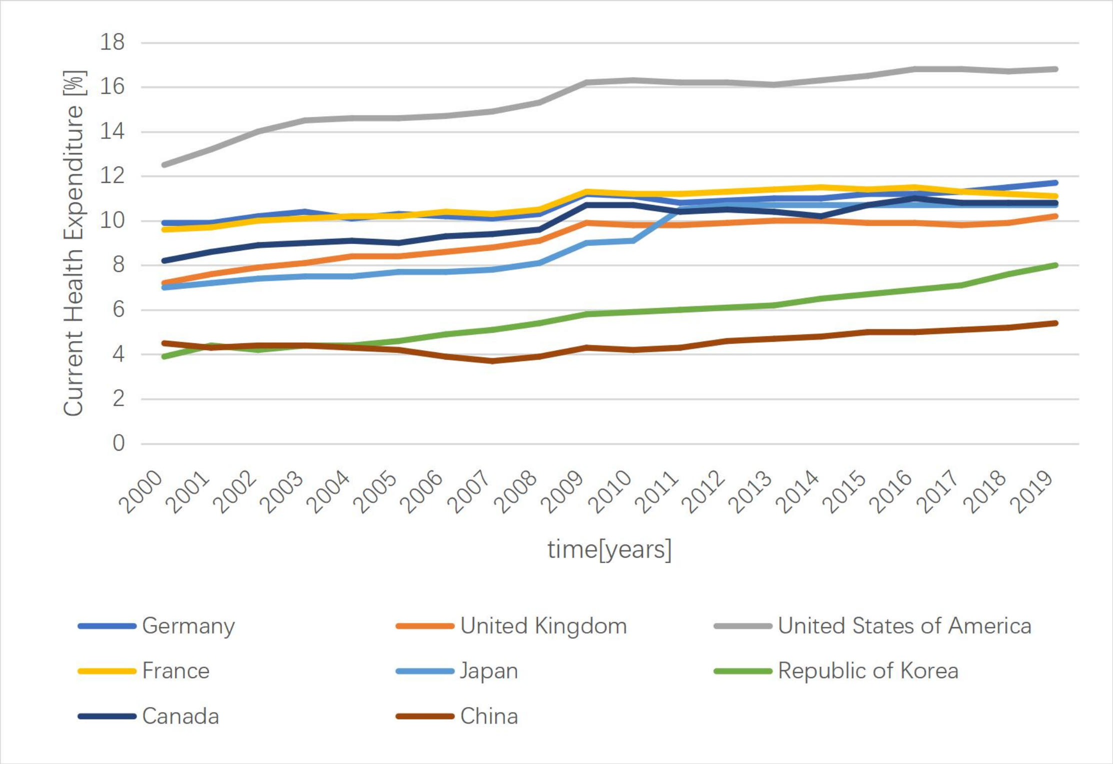

Figure 9 CHE as a percentage of GDP in China and some high-income countries. Source: (41, 42).

2.2.3.3 The Financing Structure of Health Expenditure is Unreasonable

Another significant gap in China's public health expenditure compared with high-income countries is reflected in the financing structure. Figure 10 represents that the proportion of Domestic General Government Health Expenditure (GGHE-D) in CHE in China has increased year by year, reaching 56.0% in 2019. During the same period, the proportion in Germany and Japan was 77.7% and 83.9% respectively.

On the other hand, from the analysis of the proportion of GGHE-D in GDP, taking the data from 2019 as an example, the proportion of GGHE-D in GDP in China was 3.0%. However, in high-income countries such as Germany, France and Japan, the proportion reached 9.1%, 8.3% and 9.0% respectively, much higher than that in China (Figure 11). Under normal circumstances, government health expenditure mainly focuses on preventive expenditure, such as epidemic prevention and control expenditure, maternal and child health expenditure, environmental sanitation improvement expenditure, etc. Compared with medical expenditure, preventive expenditure can achieve twice the result with half the effort, which is of great significance for maintaining the health of residents. However, the insufficiency of government health expenditure in China means that there are a large number of personal and social expenditures in the structure of health expenditure, which is reflected in the concentration of health resources in the medical field and the insufficiency of public health with the preventive function. The unreasonable internal financing structure of health expenditure may directly affect the effect of emergency response to public health emergencies.

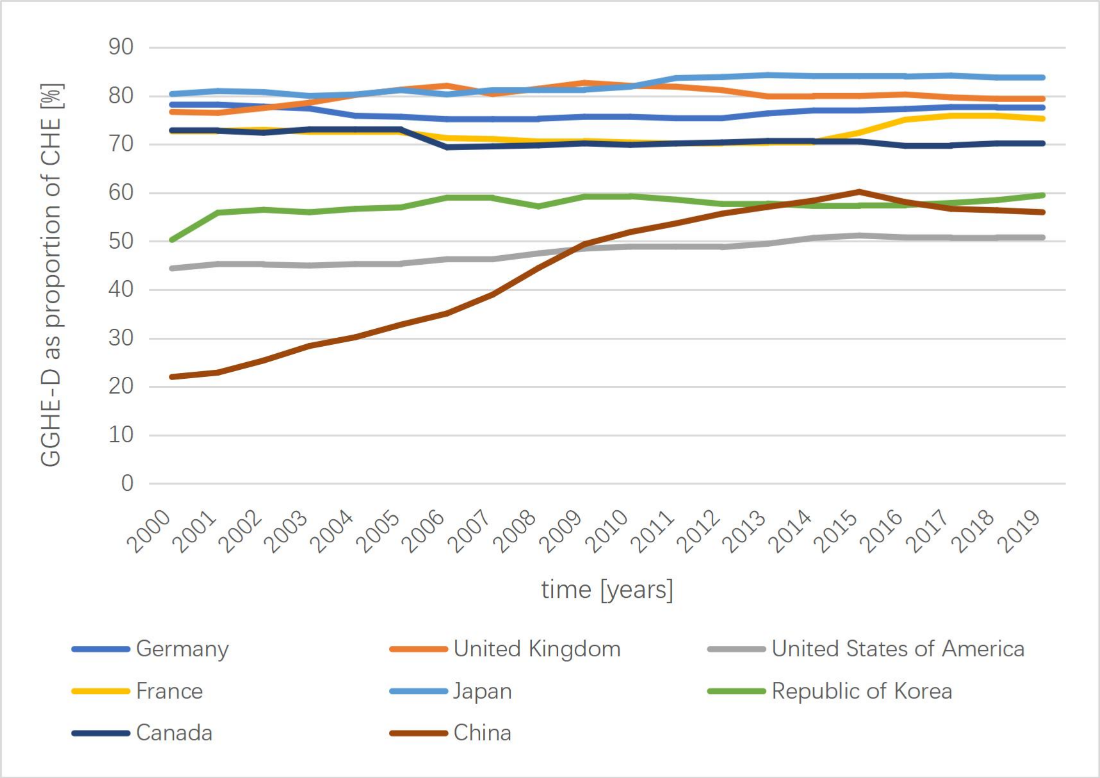

Figure 10 GGHE-D as proportion of CHE in China and some high-income countries. Source: (42).

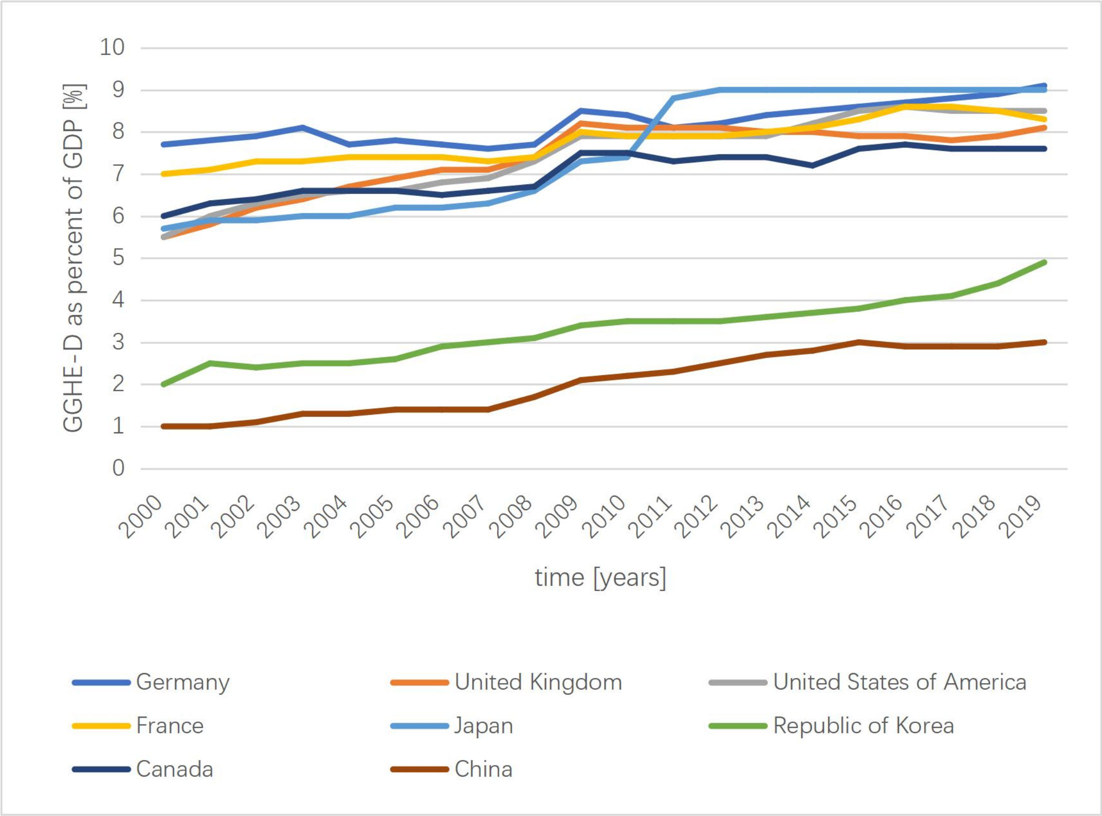

Figure 11 GGHE-D as percent of GDP in China and some high-income countries. Source: (42).

2.2.3.4 The Distribution of Public Health Expenditure Responsibility is Unreasonable

In terms of the distribution of health expenditures between the central government and local governments, central government expenditure is higher than that of local governments in most high-income countries. Take Australia as an example， according to the data released by Australian Institute of Health and Welfare (AIHW), in the 2017-2018 fiscal year, the total health expenditure of Australian government was 126.6 billion US$, of which 60.9% came from the Australian Federal Government and 39.1% came from state and territory governments (43). The difference between China and high-income countries like Australia is that the central government expenditure in China’s total health expenditure is far lower than that of local governments. As shown in Figure 6, taking the data from 2018 as an example, the proportion of health expenditure by the central government was only 1.4%, significantly lower than 98.7% by local governments. This means that local governments need to take more responsibility. However, local government spending on public health in China is largely dependent on the local economy. That is to say that regional differences in economic development and fiscal revenue will inevitably lead to great differences in regional public health expenditure. Therefore, public health development in some economically backward areas may face a shortage of funds, resulting in low efficiency of medical and health services and weakening the foundation of public health to some extent.

3. Methods

3.1 Modelling COVID-19 – An Overview

An epidemic is terminated if the net reproductive rate (N_t) at a point of time t is lower than one, i.e., if every newly infected will infect less than one other person. N_t is the product of the basic reproductive rate (R_0, under the condition that nobody is immune) with the likelihood that the contact partner is not immune, i.e., at a given share of immune population (x_t) at a point of time t, N_t can be calculated as

$$N_t = R_0 \cdot (1 - x_t)$$

If N_t is less than 1, a population has reached herd immunity (e.g., x_t =0.6 for R_0=2.5).

Consequently, this research has to analyze the dynamics of the diffusion of COVID-19 and estimate R_0 in order to assess the factors contributing to the success of interventions against the diseases in Wuhan. A huge variety of mathematical models has been developed to forecast the spread of a disease. The simplest approach calculates the basic reproductive rate as a function of some of variables (analytical models). As early as 1889, this model type was developed to calculate R_0 for malaria (reprint in English in 1989 (44)) and became the foundation of the well-known Ross-MacDonald model (45). The disadvantage of these simple models is that they cannot cover interdependencies and changes of variables.

Homogenous Markov models are also widely used to forecast the spread of a disease (46). They are capable to estimate the number of individuals in different health states as long as the transition probabilities are constant, i.e., if they do not depend on the number of individuals in the compartments (47). This is the case for chronic-degenerative diseases, but the probability of being infected depends on the infectious population. Thus, traditional (homogeneous) Markov models are not applicable for infectious diseases such as COVID-19.

An inhomogeneous Markov chain implies that the transition probabilities can change. It is, in principle, a system dynamics model. This type of model was developed by Forrester in 1964 (48) in order to account for feed-back loops (e.g. number of infectious population determining the risk of being infected). The principle has been applied in many fields, such as “Industrial Dynamics“ (48), “World Dynamics” (49), “Urban Dynamics” (50) or “Disease Dynamics” (51). The simplest system dynamics model of a disease is the so-called SI-model where S denotes the population susceptible to a disease and I the infectious population.

Figure 12 shows that the infection rate depends on the susceptible population (S), the infectious population (I), the contact rate (c), the total population (N) and the infectivity (i) of the infectious disease. The model can be easily enhanced to include the recovered population (SIR-model), exposed population (SEIR-model), different age-sets, re-infections, vaccinations, locations etc. The model has been applied to many infectious diseases, such as HIV/AIDS, malaria and cervical cancer (52-54).

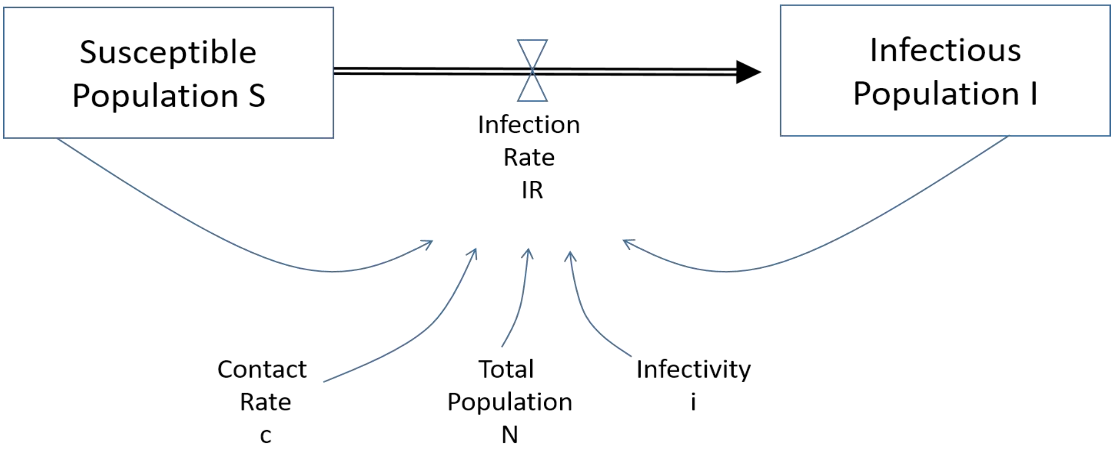

Figure 12 SI-Model. Source: (55).

Discrete Event Simulations (DES) and Agent-Based Simulations have also been used to predict the spread of infectious diseases (56, 57). The advantage of these models is that they do not simulate compartments but individuals allowing to attach personal characteristics (e.g., being a child of an individual mother or having certain comorbidities) to each person. Thus, they are more precise, but require many input variables frequently unknown. In addition, designing and validating these models is much more effort than for the other model types.

In principle, a model should not be more complex than necessary to give an answer to the specific research question. For the target of this paper of determining the reasons for the successful fight against COVID-19 in Wuhan, a rather simple system dynamics model seems appropriate. There is a tremendous number of COVID-19 models available. Stegmaier lists 53 different models of COVID-19 relevant to German public health research, the majority of them system dynamics (58). However, he also makes aware of the weaknesses of these models, such as poor data input, wrong assumptions, poor transparency, selective reporting etc. Ioannidis, Cripps and Tanner even state that “Forecasting for COVID-19 has failed” (59) because the results were frequently unreliable and of limited value for decision-makers.

The objective of the model presented in the next section is not to forecast the future development of COVID-19 in Wuhan. Instead, this research will focus on very few parameters influencing the spread of the disease and analyze how they must have developed in order to allow the epidemic dynamics of COVID-19 in Wuhan. While many of the models presented by Stegmaier (58) are much more complex than those used in this paper, the model in this paper also do not pretend to give a precise forecast. The intention is a “modelling for insights, not for numbers” (60), i.e., the purpose of modeling in this paper hopes to learn more about the prerequisites of the real spread of the disease than about the future dynamics.

3.2 Modelling COVID-19 – A Basic Model for Wuhan

For this purpose, a generic COVID-19 model is developed in this research (61) in order to analyze the factors determining the spread of the disease in Wuhan in the first year. The model does not consider age-sets, locations or social differentiations (e.g., schools, universities, traditional markets) as this is not necessary to answer the question how China managed to avoid a second wave. Instead, this research focus on the determinants of the basic reproductive rate *R₀*. The infection life cycle is presented in Figure 13 and modeled as a System Dynamics Models (62, 63).

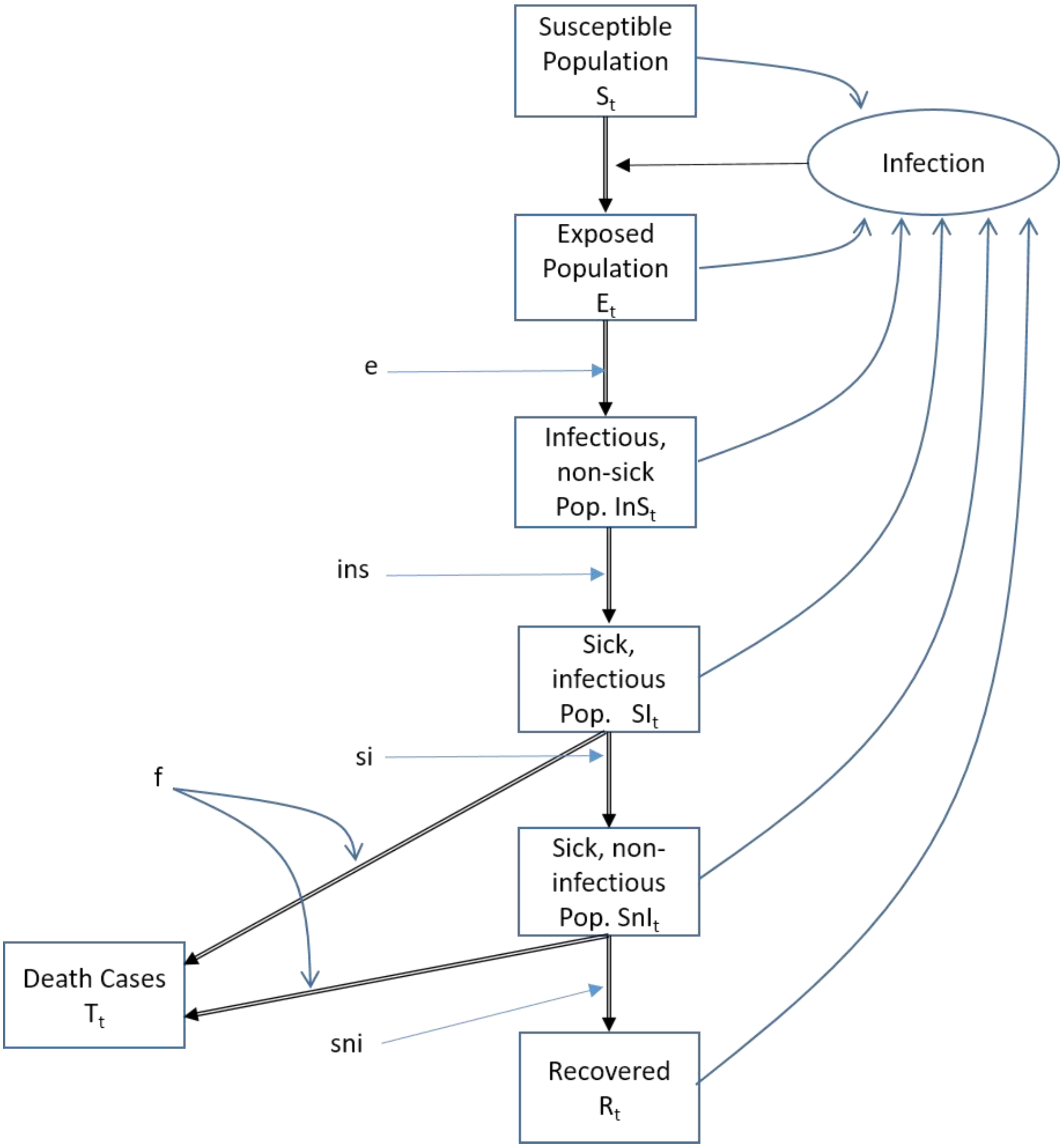

Figure 13 COVID-19 Model Structure. Source: (61).

The system dynamics model defines difference equations for the healthy, infected, sick and immune population:

1. $S_{t+1} = S_t - \frac{S_t}{S_t+E_t+InS_t+SI_t+SnI_t+R_t} \cdot \frac{InS_t+SI_t}{S_t+E_t+InS_t+SI_t+SnI_t+R_t} \cdot S_t \cdot \frac{R_0}{si+ins}$

2. $E_{t+1} = E_t + \frac{S_t}{S_t+E_t+InS_t+SI_t+SnI_t+R_t} \cdot \frac{InS_t+SI_t}{S_t+E_t+InS_t+SI_t+SnI_t+R_t} \cdot S_t \cdot \frac{R_0}{si+ins} - \frac{E_t}{e}$

3. $InS_{t+1} = InS_t + \frac{E_t}{e} - \frac{InS_t}{ins}$

4. $SI_{t+1} = SI_t + \frac{InS_t}{ins} - SI_t \cdot \frac{f}{(si+sni)} - \frac{SI_t}{si}$

5. $SnI_{t+1} = SnI_t + \frac{SI_t}{si} - SnI_t \cdot \frac{f}{(si+sni)} - \frac{SnI_t}{sni}$

6. $T_{t+1} = T_t + (SnI_t + SI_t) \cdot \frac{f}{(si+sni)}$

7. $R_{t+1} = R_t + \frac{SnI_t}{sni}$

8. $R_0 = \sum_{i=1}^{m} (1 - (1 - p)^{n_i})$

With the following variables and constants:

Variables	Description
S_t	Susceptible in t
E_t	Exposed in t
InS_t	Infectious but not sick in t
SI_t	Infectious and sick in t
SnI_t	Sick and non-infectious in t
R_t	Recovered in t
T_t	Death cases in t
R_0	Basic reproductive rate
N_t	Net reproductive rate in t

Constants	Description
f	infection fatality rate
e	Average length of stay in exposed compartment
ins	Average length of stay in compartment infectious but not sick
si	average length of stay in compartment sick and infectious
sni	average length of stay in compartment sick not infectious
$\overline{R_0}$	Basic reproductive rate without intervention
$\overline{R_i}$	Basic reproductive rate with intervention
d_1	last day without intervention
d_2	first day of maximum effect of intervention
d_3	last day of intervention
d_4	last day of effect of intervention
p	Infectivity
n_i	number of contacts with person i during infectious period
m	number of persons met during infectious period

In comparison to other models (58), the infection life cycle and the number of compartments is rather simple, but this research focus much more on the impact of contact rates on the basic reproductive rate. As (8) shows, R_0 depends on the infectivity (i.e., probability that one contact of an infectious person with a healthy person leads to an infection), the number of people an infectious person meets within the infectious period and number of contacts the infectious person has with each of the healthy persons.

The probability that an infectious person infects a healthy person when meeting once is p. The probability that an infectious person does not infect a healthy person when meeting this person n_1 times is $(1-p)^{n_1}$. Thus, if an infectious person meets m healthy people during the infectious period and has n_i contacts with each of them during this time, is the basic reproductive rate and can be calculated (64) as

$$\text{(8a)} \quad R_0 = (1-(1-p)^{n_1}) + (1-(1-p)^{n_2}) + \dots + (1-(1-p)^{n_m}) = \sum_{i=1}^{m} (1-(1-p)^{n_i})$$

For this analysis of the COVID-19 diffusion in Wuhan, the disease spread without interventions for a certain time is assumed in this research. After d_1, the public health care system started interventions resulting in a reduction of R_0. However, it took some time until the rate had declined strongly. At d_2 all measures reached their maximum effectiveness, and this condition was sustained until d_3. Afterwards the interventions were relaxed until the old situation was reached again in d_4. The respective development is presented in Figure 14. This can be presented in the formula:

$$(9) R_0 = \begin{cases} \overline{R_0} & for\ t \le d_1 \\ \overline{R_0} - \frac{\overline{R_0} - \overline{R}_i}{d_2 - d_1} \cdot (t - d_1) & for\ d_1 < t < d_2 \\ \overline{R}_i & for\ d_2 \le t \le d_3 \\ \overline{R}_i + \frac{\overline{R_0} - \overline{R}_i}{d_4 - d_3} \cdot (t - d_3) & for\ d_3 < t \le d_4 \\ \overline{R_0} & for\ t > d_4 \end{cases}$$

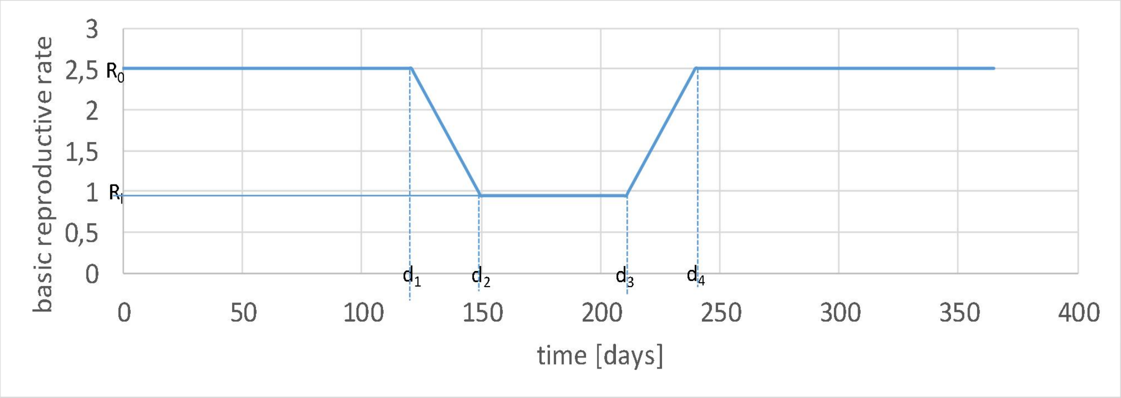

Figure 14 Development of R0 (assumption). Source: own.

Consequently, the net reproductive rate (N_t) can be calculated as

$$N_t = \frac{R_0 \cdot R_t}{S_t + E_t + InS_t + SI_t + SnI_t + R_t}$$

Based on this model, the diffusion of COVID-19 in a generic region with many characteristics of Wuhan can be simulated in this research. The simulations simulate under the assumption that no intervention had been taken (scenario I), that the reduction of the basic reproductive rate was sustained (scenario II) and that a successful intervention was relaxed too early so that basic reproductive rate returns to its original value (scenario III). The last scenario assumes that some measures are sustained but R_0 will be above 1 (scenario IV). Furthermore, the impact of different rates of infectivity (p), number of different contact partners (m) and contacts per partner (n_i) can be modeled in this research. Under the assumption that an infectious person has the same number of contacts with each person (for $n_1=n_2=\ldots=n_m=n$), the research receives

$$\text{(8b) } R_0 = \sum_{i=1}^{m} (1-(1-p)^n) = m \cdot (1-(1-p)^n)$$

or

$$\text{(8c) } n = \frac{\ln\left(1-\frac{R_0}{m}\right)}{ln(1-p)}$$

$$\text{(8d) } m = \frac{R_0}{1-(1-p)^n}$$

Finally, the basic reproductive rate under the assumption can be calculated that the total number of contacts as the product of people met and contacts per person is constant (for *m*n=k=const*) as

$$\text{(8e) } R_0 = m \cdot \left(1 - (1-p)^{\frac{k}{m}}\right)$$

4. Results

For the simulation used in this paper, it used data from Wuhan without assuming that the model will present all dimensions of the reality of this region. Table 3 shows the parameters. In some cases, the standard parameters used in other models could not be built on in this research because the purpose of this research wanted to simulate the situation in the very beginning of the pandemic where very little was known about the disease. For instance, the fatality rate in Wuhan was most likely higher than it is reported for other locations today because hardly anything was known about the diagnostics and therapy of the disease. For these parameters, the research built on assumptions and private communication from Chinese experts.

The original basic reproductive rate is assumed as 2.5 ($\overline{R_0}$) (65). According to (8d), this refers to 10.8 contact partners with an average frequency of 2.5 meetings per contact during the infectious period and an infectivity of 0.1 (p) (66, 67). Figure 15 shows the relationship between the number of contact persons (m), the number of contacts per contact person (n) and the basic reproductive rate for p=0.1. It is obvious that both variables strongly determine R_0.

Table 3 Basic parameters.

Constants	Description	Value	Source
S_0	Population in t=0	11,000,000	
f	infection fatality rate	0.015	(68) + p.i.*
e	Average length of stay in exposed compartment	3	(69) + p.i.*
ins	Average length of stay in compartment infectious but not sick	2	(69) + p.i.*
si	average length of stay in compartment sick and infectious	11	(69) + p.i.*
sni	average length of stay in compartment sick not infectious	7	(69) + p.i.*
$\overline{R_0}$	Basic reproductive rate without intervention	2.5	(65)
$\overline{R_i}$	Basic reproductive rate with intervention	Scenario I: 2.5 Scenario II: 0.95 Scenario III: 2.5-0.95-2.5 Scenario IV: 2.5-0.95-1.5	assumption
d_1	last day without intervention	120	assumption
d_2	first day of maximum effect of intervention	150	assumption
d_3	last day of intervention	210	assumption
d_4	last day of effect of intervention	240	assumption
p	Infectivity	0.1	(66, 67)

*p.i.: assumption based on private communication with Chinese colleagues.

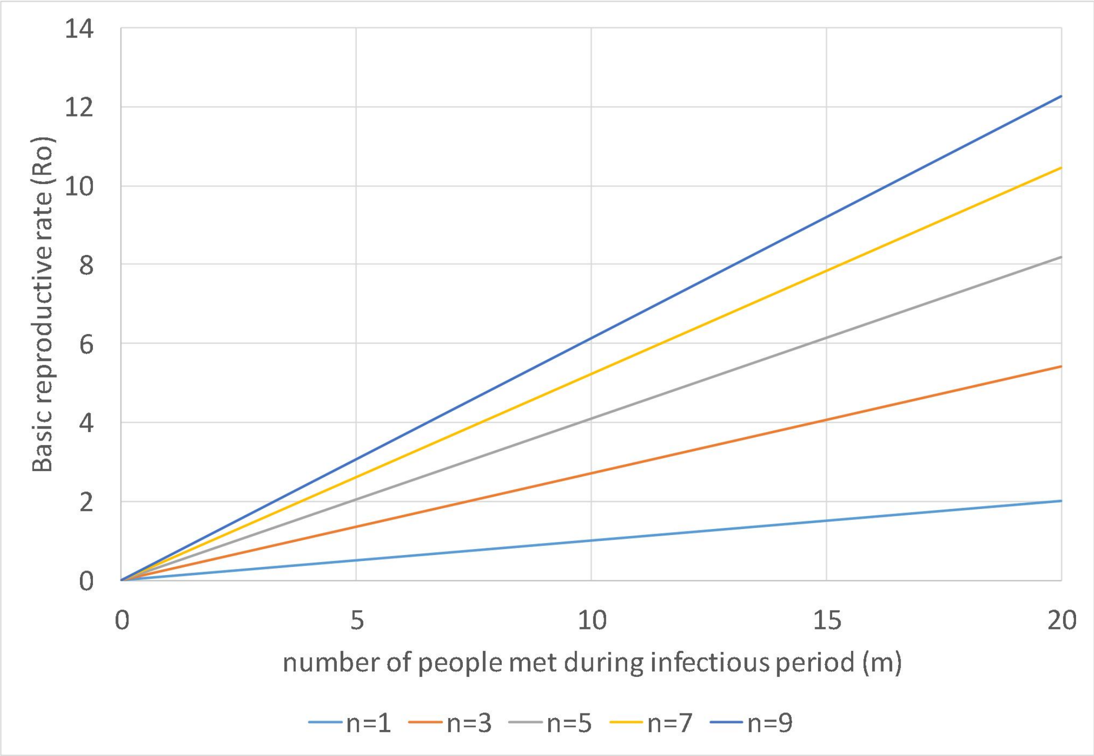

Figure 15 Basic reproductive rate and contacts. Source: own.

Figure 16 shows the number of COVID-19 cases for the scenarios. Scenario I assume that R_0=2.5 is constant, i.e., without any intervention. Scenario II assumes that interventions start at day 121 (d_1=120) and need 30 days (d_2=150) until they are fully effective so that $\overline{R}_i$=0.95. Afterwards all interventions are sustained. This parameter was not chosen because the simulation has evidence that the reproductive rate was exactly 0.95 in Wuhan. Instead, it is an assumption of a reproductive rate lower than but close to 1.

Scenario III assumes the same development as scenario II for the first 210 days, i.e., the interventions are sustained to 60 more days. Afterwards (d_3=210) the interventions are relaxed until $\overline{R}_i$ is back to its original value of 2.5 in d_4=240. Scenario IV follows the pattern of scenario III but assumes that some interventions are sustained so that the final $\overline{R}_i$ is 1.5.

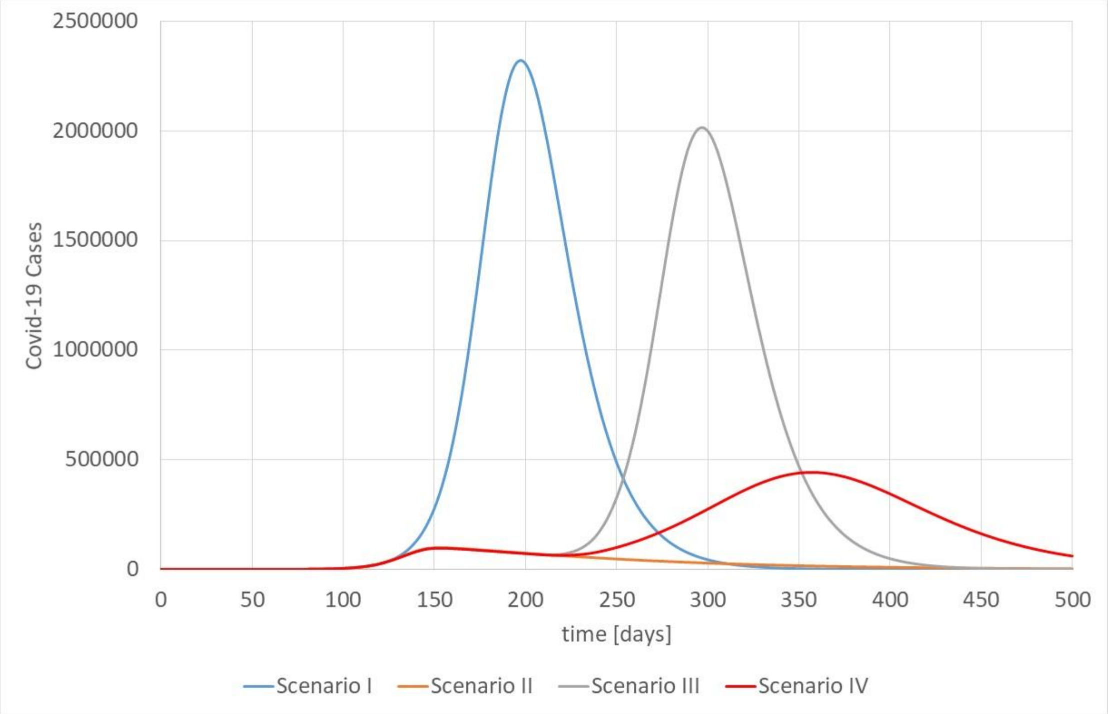

Figure 16 Number of COVID-19 Cases in Wuhan, Scenarios I-IV. Source: own.

For the unrealistic case of no interventions (scenario I), Wuhan would have experienced a very severe single wave. Most striking, it takes 87 days after the first case until 1000 patients are sick (variables *SI* and *SnI*) at the same time (10 per

100,000 inhabitants in Wuhan), i.e., the early break-out of the disease is difficult to detect even though the disease has a catastrophic potential leading to thousands of new cases per day. Scenario I is unrealistic as the health care system would have collapsed completely without interventions. The epidemic comes to a standstill after the herd immunity of 60 % is reached. Scenario II shows that the interventions are effective and manage to flatten the curve. However, as no herd-immunity is reached, COVID-19 will not disappear and there remains a need to sustain the interventions indefinitely (without vaccination). According to (8d), the number of contact persons must be less than 4.1 if p=0.1 and n=2.5 in order to achieve an R_i=0.95.

Scenario III simulates the second wave of the COVID-19 pandemic for Wuhan under the assumption that interventions are relaxed completely on day 210. The consequences are disastrous: An unrestricted second wave is much more dramatic than the first wave for scenario II and almost as strong as the first wave without any interventions (scenario I).

Scenario IV assumes – like scenario III – that the interventions are reduced after a period of successful reduction of infections, but some measures are sustained so that R_i returns to 1.5 on d_4=240. The consequence is a “milder” second wave, which is still stronger than the first wave but not as dramatic as the second wave of scenario III.

Consequently, the basic reproductive rate must be kept below 1 for a very long time. Based on (8d) this can be done by reducing the infectivity (p), number of contact partners (m) and number of contacts per partner (n).

Thus, at a rate of R_0=2.5, herd immunity is reached if 60 % of the population have been infected. At a rate of R_0=1.5, the respective figure can be 33.3 % under the assumption that the number of contacts remains on this low level.

Figure 17 shows the consequences of a changed infectivity (p) on the basic reproductive rate. If p increases from 0.1 to 0.15 (as for “UK variant” B.1.1.7), R_0

strongly increases. Assuming that a person meets any other person 2.5 times on averages, the increase of p by 50 % requires that the number of people met during the infectious period declines from 10.8 to 7.5 (see 8d). At the same time, a reduction of the infectivity by wearing surgical masks (estimated effectiveness of 50 %) for all contacts allows to increase the number of contact partners to 20.8 for the same R_0. Wearing an FFP-2 mask (estimated effectiveness of 90 %) for all contacts has a very strong impact on the basic reproductive rate. An infected person can meet 40.3 different people on average 2.5 times during the infectious period and still R_0 is below 1 if all contacts are with an FFP-2 mask.

Based on (8d), the simulations can calculate that a R_0 of 2.5 will result if an infectious person meets 11 different people on average 2.5 times during the infectious period (p=0.1). By wearing a surgical mask with an effectiveness of 50 % (p=0.05), R_0 will decline to 1.32, i.e., scenario IV can be implemented by merely sustaining the obligation of wearing surgical masks for all contacts. Scenario II could be achieved by wearing surgical masks and by reducing the number of contacts with different people from 10.8 to 7.5 during the infectious period with an average number of meetings per person of 2.5 (R_0=0.96). Thus, the system is highly sensitive to changes of the infectivity p, i.e., wearing effective masks for all contacts is one of the most efficient interventions.

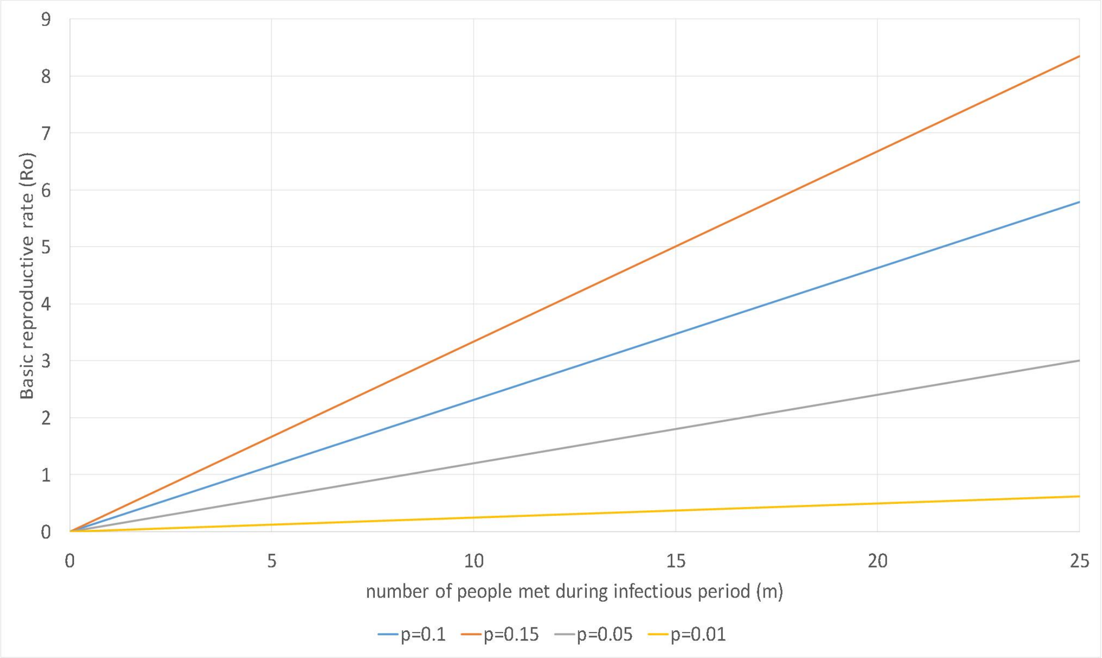

Figure 17 Change of infectivity. Source: own.

Figure 18 shows the impact of different numbers of contacts and different frequencies of meeting each person under the assumption $n_1=n_2=\ldots=n_m=n$.

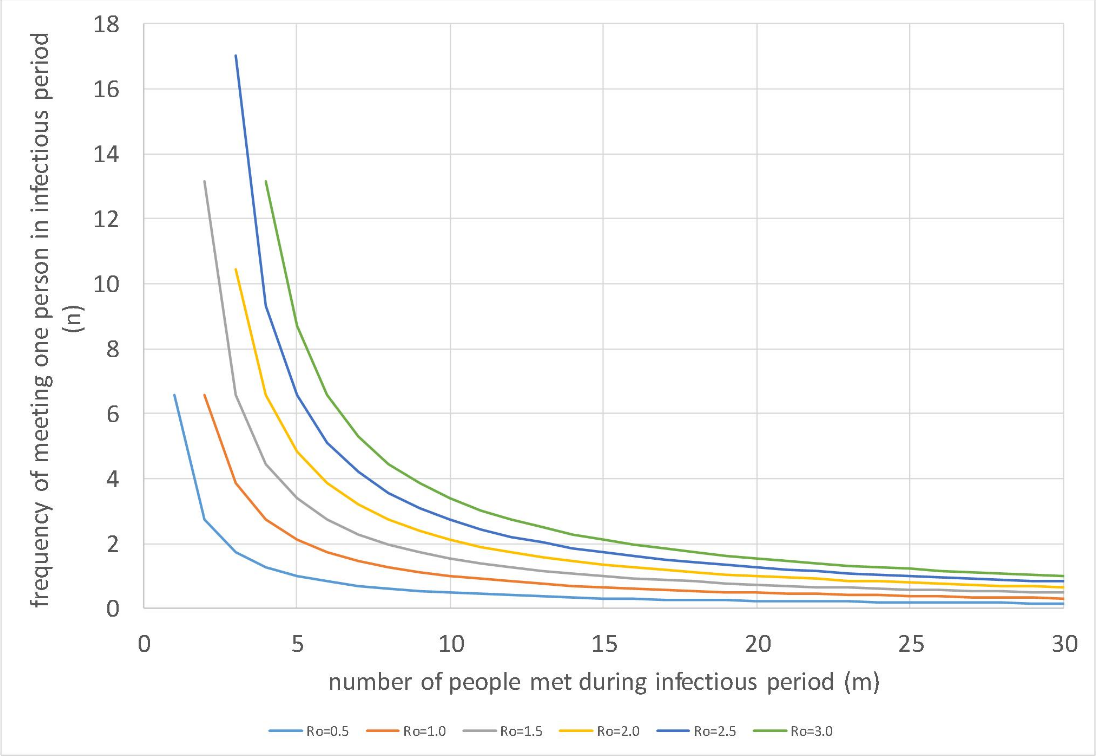

Figure 18 Impact of number of people met and frequency of meeting each person during infectious period. Source: own.

For instance, if an infectious person meets 20 different people during the infectious period, he can meet each of them on average 1.27 times during the infectious period in order to achieve a basic reproductive rate of 2.5. For an R_0 of 1, the average number of contacts must decline to 0.47 at 20 different contacts. Alternatively, the person could meet only two different people, but each one 6.68 time. Figure 19 assumes that the total number of contacts is given and the number of people met during the infectious period varies. It is obvious that it is better to meet few people frequently than many people rarely.

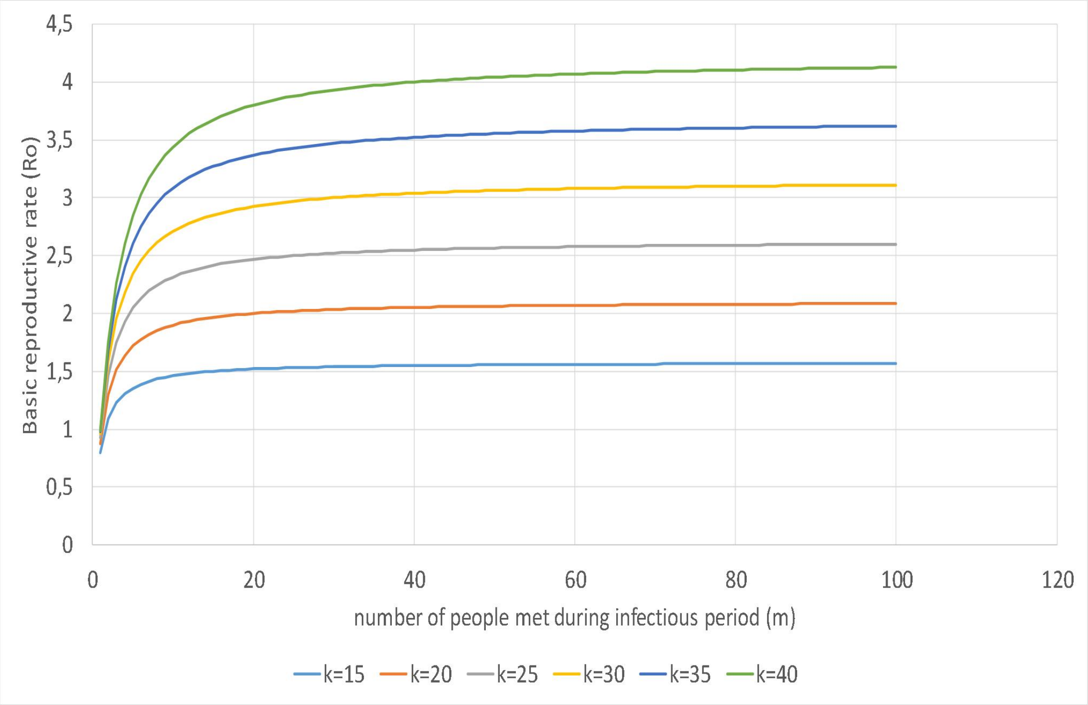

Figure 19 Basic reproductive rate for different total contacts. Source: own.

5. Discussion

5.1 Relevance of Simulation Results

Based on these calculations, the public health care system in Wuhan managed to reduce the risky contacts strongly. The success of keeping R_0 under 1 for several months can only be explained by effective efforts to exclude infectious people from contacts. This was mainly based on a lock-down, but also on case management and detection.

The results also indicate that it was very difficult in the beginning of any epidemic to see its pandemic potential. The simulations show that it took almost three months after the first case until 1,000 patients were sick at the same time. It is obvious that the traditional routines of case detection (focusing on the number of cases) cannot work with highly infectious new diseases, and consequently they could not work with COVID-19. Once the figures are visible, it is already too late, and the exponential growth has started.

The results also indicate that it is likely that Wuhan had much more cases and deaths in the first wave than reported. Even scenario II results in 8,269 death cases in the first year while Wuhan reported “only” 2,997. The statistics of Wuhan have been questioned elsewhere (70, 71) and the computations in this paper show equal results.

The simulations also show that wearing surgical masks is highly effective to reduce the basic reproductive rate and the spread of the epidemic (an effect that can hardly be proven by empirical data as to many interventions take place at the same time). The simulation results are highly sensitive to changes of the infectivity, which can be strongly influenced by wearing masks. This instrument of protecting oneself and others has been quite common in China before, but it has become almost a universal habit since the pandemic started. Chinese citizens wear surgical masks, not only in public transport but almost everywhere. It has become a common habit as a population response to air pollution (72) and hardly anybody would see it as an insult to their liberty rights as citizens.

Finally, the simulation results show that a second wave can only be avoided if interventions are sustained. The reduction of the medical infectivity (*p*), the number of contact persons (*m*) and the number of contacts per contact person (n) is the key to control the pandemic. It seems that China managed well to sustain a low R_0 by controlling these variables.

5.2 Geography

There was some discussion in the beginning whether Wuhan managed to control the pandemic because of the geographical location and the respective climate (73). However, while other states located at the same altitude (e.g., Florida, Louisiana, Texas, Egypt) are facing a second wave, Wuhan has not reported Corona cases since March, i.e., the geographical location cannot explain the difference. Without doubt, spring and summer helped to control COVID-19 in Wuhan in 2020. There is a clear negative correlation between temperature and COVID-19 incidence, but for other parameters (e.g., humidity, wind speed, rain fall) the results are not significant (73, 74). It is likely that temperature does not have a direct impact on the transmission of the virus but increases the parameter *m* and *n*, i.e., during the cold season people have more and closer contact in rooms. However, this argument is true for all cities on the same latitude and does not explain the successful avoidance of a second wave in Wuhan. Geography does not explain this success.

5.3 Public Health System

The simulation results show that an early detection of cases and the implementation of early and effective control measures would require an excellent public health system. However, this does not seem to be the case. Instead, a number of shortcomings of China CDC have become visible during the epidemic (75). Firstly, the communication between the national the local CDCs as well as with the healthcare facilities did not work well. Although an infectious disease information system had been developed after SARS, it did not work properly during phase I of COVID-19, resulting in insensitivity of the epidemic dynamics assessment and prediction, and incomplete information reporting and distribution. Secondly, the China CDC had a very limited influence on the Government. As early as January 6, 2020, the China CDC initiated the second-level response to the epidemic, which was upgraded to a first-level response on January 15. However, these emergency responses were almost ignored by the Government (2). Thirdly, China’s public health emergency management system is composed of a four-level disease control and prevention network of “central-province-city-county”. However, the lack of professional emergency personnel leads to the inefficiency of the health emergency command and decision-making system, which makes governments at all levels lack the ability to deal with public health emergencies. Fourthly, in terms of hospital management system, Chinese hospitals are managed by different departments and regions, and there is a lack of effective communication between departments. As a result, medical resources and information are not shared in a timely manner in the face of an outbreak, and the allocation of health resources is inefficient.

In addition, the public health system of the middle-income country China suffers from low resources. As shown in Table 4, financial (health expenditure p.c.) and personnel resources of the system are much lower than in high income countries. In particular, the funds allocated to primary services have been declining for years (Figure 20). The absolute amount of public health expenditure in China increased tremendously from 14.3 billion yuan (2.99 billion US$ or 2.63 US$ p.c.) in 1990 to 860 billion yuan (130 billion US$ or 93.16 US$ p.c.) in 2018. However, the proportion of preventive and promotive public services in the total public health expenditure decreased from 76.3% in 1990 to 52.5% in 2018. It seems that the Government of China puts less emphasis on prevention than treatment. On the other hand, in terms of the adequacy of public health investment, the number of tertiary hospitals in many cities in China is insufficient, and the allocation of medical facilities is inadequate (Table 1).

Table 4 Health resources per capita in China and some high-income countries in the world in 2016. Source: (39, 41, 42).

Country	**Current Health Expenditure p.c. [PPP US$]**	**Hospitals per million population**	**Number of beds per 1,000 population**	**Doctors per 1,000 population**	**Nurses per 1,000 population**
Germany	5568.27	37.64	6.06	4.19	10.84
United Kingdom	4182.18	29.29	2.57	2.78	6.45
United States of America	9941.35	17.14	2.77	2.59	----
Japan	4424.98	66.51	13.11	2.43	11.34
Republic of Korea	2745.07	73.92	11.98	2.29	6.82
Canada	4809.28	19.99	2.60	2.69	9.96
Australia	4634.65	55.93	3.84	3.58	9.55
China	*762.98*	*21.07*	*4.02*	*1.88*	*2.54*

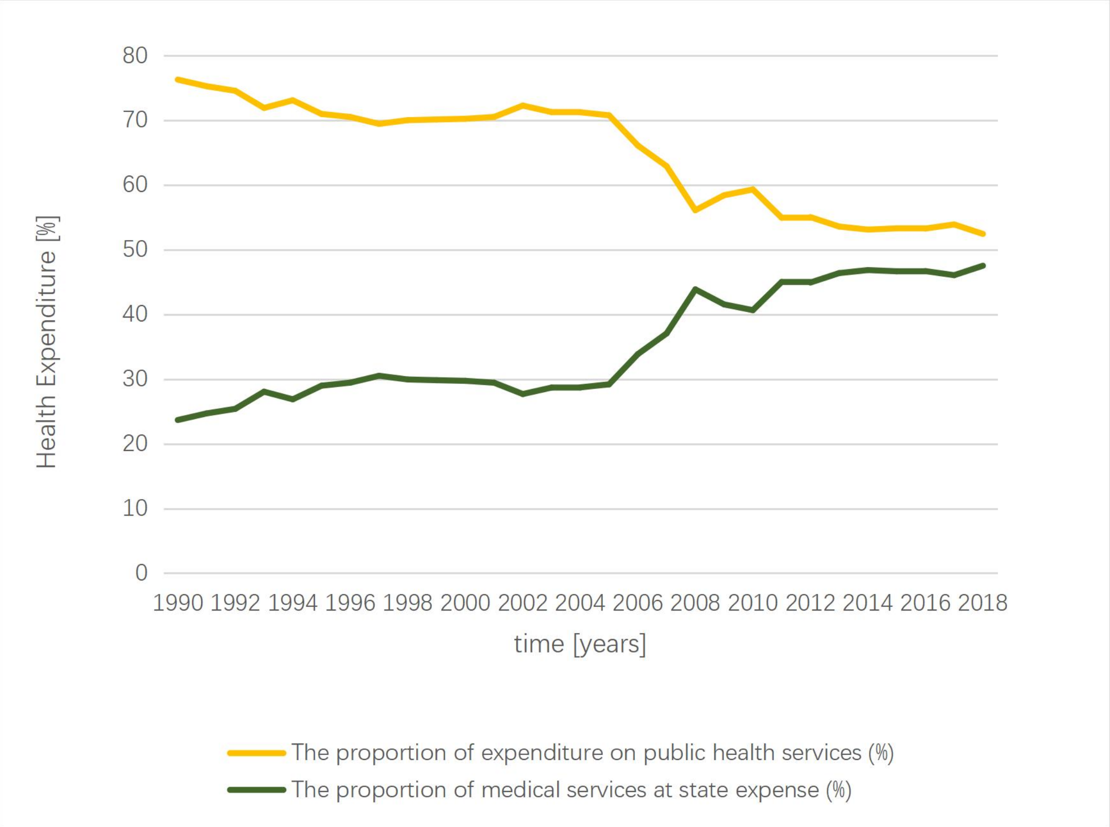

Figure 20 Government expenditure on public health. Source: (38).

During the COVID-19 outbreak, the Chinese government has borne the cost of all confirmed and suspected COVID-19 patients. It is estimated that the respective costs amounted to 15.696 billion US$, mainly on treatment of patients, subsidies for epidemic prevention and control personnel, and purchase of personal protective equipment (PPE). In comparison to the total health expenditure, the cost of the epidemic amounted to 1.65 % of total public health expenditure (11.21 US$ per capita resp. 0.1 % of GNP p.c.), i.e., a rather small amount. Consequently, neither a brilliant, well-financed and well-staffed public health system nor tremendously high health care expenditure are the key to understand the effective control of the Wuhan epidemic.

5.4 Portfolio of Interventions

A number of analyses have been published that provide a taxonomy of different interventions against the diffusion of COVID-19 and assess their effectiveness. For instance, Baker et al. (76) listed the components of pandemic control of COVID-19. China has not implemented any measures that are not practiced elsewhere as well. Improvement of hygiene (e.g., hand washing, surgical masks), contact tracing, quarantine of sick and suspected, high volume testing, physical distancing, movement restrictions, and border management (incl. exclusion and quarantine) are the international standards to fight COVID-19 (76).

Other studies analyzed the effectiveness of interventions in 40 countries. They record the strongest reduction of R_0 if gatherings of more than 5 people are banned followed by closing stores, restaurants, bars and schools (66, 77-79). China implemented all of these intervention measures — so as many other countries that experienced a few waves. Consequently, it seems that there is no “magic bullet” against the pandemic; China has not implemented different measures, but it seems that the timing and intensiveness was different.

China is now one of the last countries in the world to continue with a strict “zero-COVID” strategy, which sometimes entails locking down entire cities if a single case is detected. For instance, a recent breakout in Xi'an (13 Mio. inhabitants) in Shaanxi province exemplifies this “no-tolerance against COVID-19”. After the public health system recorded 207 cases (i.e., 1.59 cases per 100,000), the comprehensive program to combat the outbreak started and began to seal off the city on December 23, 2021. The objective is clearly described by “zero-COVID” (80). While European countries discuss whether interventions should be relaxed at a rate of 50:100,000, China implements its full portfolio at a rate of 1.59:100,000.

Without doubt, this is only possible with strong limitations of citizen rights. In particular, the Chinese intervention system builds on the App-based location analyses. Every contact is recorded and access to gatherings is only permitted if the smart phone gives green light. This seems quite restrictive for Western societies. There are three forms of “zero-COVID" policies in China. The "zero community transmission policy" applies to the period when containment measures are needed for epidemic prevention and control; the "dynamic zero-case policy" applies to the period when the epidemic has rebounded but has not yet formed a scale; the "strict zero-case policy" applies to the period when the epidemic is basically under control and relatively safe. Among them, "dynamic zero-case policy" is the basic general policy of China's fight against COVID-19. However, China is not alone in its “zero-COVID” paradigm. For instance, Australia (81) and New Zealand (76) and Southern Korea (82) were quite successful in their eradication campaigns. New Zealand, for instance, never wanted to live with COVID-19, but eradicate it. When it started its campaign on March 23, 2020, the country just had about 100 COVID-19 cases and no deaths. As Philippe and Marques have shown for 11 G10 counties, countries following this strategy of early elimination are epidemiologically and economically more successful that countries pursuing a mitigation or suppression strategy (82). This “go early go hard” approach is exactly what China is doing, it seems to work even in a liberal Western society like New Zealand (83). As the global epidemic enters its third year, a combination of mass vaccination, social pressure and highly transmissible new variants has persuaded other once “zero COVID” countries including Australia, New

Zealand and Singapore to begin slowly opening up again to the world, with only China is continuing its efforts to eradicate COVID-19 completely.

Finally, China invests efforts to vaccinate its population against SARS-CoV-2 (84). However, there is evidence that the combination of limited coverage (i.e. share of population able and willing to be vaccinated) and effectiveness of the vaccine will now allow to reduce completely the other interventions (85). A certain part of the population will not be vaccinated because they will refuse or because age and/or health conditions do not allow (86, 87). Moreover, the effectiveness of the vaccine to prevent the spread of the disease is decreasing because highly infectious virus variants can escape vaccine-induced humoral immunity. As a result, there will be waves of COVID-19 even after the vaccination program will have been completed. No doubt, the Chinese government will continue to strengthen existing PHSM and IPC measures because of the determination to implement the “zero-COVID” policy.

5.5 Limitations

The results presented in this paper are subject to a number of limitations. Firstly, this research did not model and simulate the precise reality of Wuhan. For a detailed analysis, age-sets, locations (e.g., city quarters) and social interaction (e.g., schools, workplace etc.) would have to be distinguished. The model in this paper is generic, but it permits the conclusion that the public health care system of China managed to control the most important parameters (number of persons contacted and number of contacts per person).

Secondly, some of the data applied to the simulation are uncertain. For instance, as the real number of infections in Wuhan is unknown (and will most likely remain unknown for political reasons) it is difficult to assess the infection fatality rate (f). As Meyerowitz-Katz & Merone show (68), the parameter f strongly differs from place to place with an average of 0.68 % and a highest estimate of 1.7%. This research assumes that the case and consequently the infection fatality rate was towards the higher end in Wuhan in January and February 2020 as no diagnostic and treatment standards had been developed for COVID-19 patients. However, the fact is that this is an assumption.

For scenario II, an f of 0.015 (see Table 3) results in 8,269 death cases within the first year, an f of 0.02 in 10,745, an f of 0.01 in 5,656 and an f of 0.005 in 2,901 death cases. Consequently, the results react on changes on the parameters, but it is difficult to believe that medical care in Wuhan in the first months of the unknown diseases was as effective as health care systems that had months to learn how to diagnose and treat COVID-19 patients. Therefore, the simulation results might be challenged because of the uncertainty of input data, but the general finding that the number of death cases must be higher than reported is still valid.

Finally, the model presented in this paper does only present the situation in Wuhan in the first year of the epidemic. Consequently, vaccination programs, temporary immunity or re-infections in this research did not consider. As the objective in this paper was the analysis of the public health response in Wuhan in 2020, there was no need to include these aspects. Further research will have to focus on these issues much more.

Summarizing, the model presented in this paper must not be used to predict the future spread of the disease. Instead, it is “modelling for insights, not for numbers” (60).

6. Conclusions

China was the first country to be affected by COVID-19, China's actions and government controls rendered it capable of controlling the first wave of the COVID-19 epidemic. China has maintained a number of interventions against COVID-19 until today (as of December 2021). Surgical masks, temperature and social distancing are a must in all public places, travelling abroad and visiting friends is strongly restricted, the risk level of the epidemic is strictly graded, screening and quarantining people who have overlapping footprints with a COVID-19 patient. Access to public gatherings is only permitted if the smartphone app shows "green". The app "Health Code" has become the daily companion of all citizens. Anyone who hasn't been tested or vaccinated can't be out in public.

The shortcomings of the Chinese public health care system make people expect that China would be very badly in the Corona pandemic. In the beginning, China had very big problems in Wuhan, but it mastered the situation after a very short time. And since then, it managed to control the pandemic and avoid subsequent waves. The question is: If the public health care system is so poor, how does it manage to control a pandemic which other nations with much better health care systems cannot master? What is the "secret" of China to avoid subsequent waves although the public health care system is so poorly financed and managed? In fact, China has not implemented unique interventions. Masks, social distancing and mass testing are well-known instruments all over the world. The "secret" of China's success in fighting COVID-19 seems to be the early reaction and rigor with which the public health system reacts at comparably low prevalence rates and the implementation of "zero-COVID" policy throughout the country. Without these determined measures, the situation would have become much worse than it has ever been in Wuhan, with no possible improvement before the end of the epidemic. Currently (deadline of research: 31.12.2021), the epidemic situation shows a pattern of sporadic and concentrated outbreaks in local areas. Local outbreaks of COVID-19 were in urban areas with strict control of the population. Whether a rural outbreak could be managed as effectively in China, is questioned (88). At the same time, we doubt that an outbreak with a variant with a much higher basic reproductive rate (e.g., Omicron) could be controlled with the same instruments.

Since the first case of COVID-19 was reported in Wuhan, the number of confirmed COVID-19 cases have grown rapidly and spread to countries across the world. Four interconnected factors have contributed to the trend: The large number of asymptomatic or mild symptom cases; The relatively long incubation period whereby most symptomatic infected individuals experience symptoms by the 11th or 12th day; A high reproduction number; The capacity of the coronavirus responsible for COVID-19 to last on surfaces for up to three days, in the case of plastic and steel (89). As a result, epidemiologists have warned that this disease is likely not be fully contained and is likely to become endemic (90-92). As the simulations in this paper demonstrate, a return to “normal” life with the same frequency and intensity of contacts as before the intervention would inevitably trigger a new wave if sufficient herd immunity had not previously been achieved. However, in real-world populations, the situation is often much more complex. This is because that epidemic control depends largely on R_0, according to the celebrated dynamic models in epidemiology and Grönwall’s inequality in math, an epidemic decay exponentially when the reproductive number $R_0<1$, but may also blow up in the same exponential manner once $R_0>1$.

Assuming an R_0 of 2.5 for COVID-19, the herd immunity would have to be around 60%, i.e., 60% of the population would have to be immune against the virus to eradicate the disease. Even assuming that 90% of the infections in Wuhan were asymptomatic (71), the herd immunity would be about 40%, i.e., Wuhan is still at risk of COVID-19. Apparently, with the measures taken it is possible to keep the effective reproduction number below 1. The study found that the mean R_0 of the Delta variant was about 5.0, much higher than that of the original strain (33). This means that it is more urgent and important to rapidly increase vaccine coverage while strengthening public health and social measures, with the ultimate goal of achieving 80% herd immunity so that widespread and sustained transmission of the virus can be avoided. While Delta continues to be the dominant SARS-CoV-2 variant prevalent worldwide, the emergence of the new variant Omicron (B.1.1.529) is causing serious concerns among the public health authorities due to the reports on its heavily mutated spike protein that could make the Omicron variant much more transmissible and may make the vaccine much less effective (93, 94). As a result, although vaccines are the great hope, with the virus's agility and ability to mutate, they can only be a part of the solution unless the infection rates are reduced to close to zero.

As of December 28, 2021, 85.6% of China's 1.4 billion people had have been vaccinated with two shots – a high percentage globally (95). It should be noted that the natural infection rate is negligible in China considering the small number of cases with respect to its huge population size (96), it is completely dependent on vaccination to build an immune barrier. The low natural infection rate, which was a great achievement in the past, is now a weakness. On the other hand, the numbers of people who received two doses of vaccine decline with age, with the figure dropping to 82% for those between 70-79 and about 51% of above 80 (97). That means 52 million of the 264 million Chinese over the age of 60 have not yet been fully vaccinated (97). Therefore, for the current situation in China, the premise of "living with COVID-19" does not exist: First, the population of the mainland of China is 1,411,778,724 based on the 7th National Census (98), which yields a countrywide population density of 147 people/km^2. In particular, the population of the eastern region, which is 563,300,220, yielding a much higher population density of 661 people/km^2. Data released by the China CDC suggested that there were only around 4.3 intensive care unit beds per 100,000 people in China in 2021. Therefore, the China CDC predicted that once China adopts the control and prevention strategies of some typical western countries, the number of the daily new confirmed cases in China would likely rise up to hundreds of thousands of cases, and among which more than 10,000 cases would present with severe symptoms, which would have a devastating impact on the medical system of China and cause a great disaster within the nation (99). Second, it is impossible for the government to dispel the public's fear that the virus variant will weaken the efficacy of the vaccine; And third, considering that the virus variants are more transmissible and more elusive, the government needs to protect those who cannot be vaccinated for their own reasons, and cannot expect herd immunity to protect them. Thus, when faced with the question of whether China should adjust its “zero-COVID” strategy, the Chinese government must consider the consequences of changing its strategy: What should it do if other variants enter China because of the open border? So far, China has not found an effective alternative to its “zero-COVID” strategy. Therefore, the country's dynamic clearance strategy may be the most acceptable and implementable choice by the people at this moment.

Although SARS-CoV-2 is now no longer a new virus, governments around the world continue to meet the new challenges it presents. The fact proved that the more citizens trust their government, or trust each other, the more effectively countries will be able to respond to COVID-19. And yet, on average across OECD countries, only about half of people say that they trust their national government (100). Currently, the global scientific community generally believes that the most effective way to defeat the COVID-19 pandemic is through the mass vaccination of populations around the world. However, there are data from seven OECD countries and Kaiser Family Foundation (KFF) showed that a quarter of the population in France, Germany and the USA may refuse COVID-19 vaccination, even if it were free and deemed safe, and an even higher proportion among younger population cohorts (101, 102). Vaccine hesitancy makes it even more difficult to reach the population-wide vaccination level rates that confer herd immunity. At the same time, many low-income countries currently do not receive enough doses to vaccinate all adults (103). Therefore, while the development of COVID-19 vaccines has been an extraordinary success, vaccinating most of the global population is an enormous challenge. As the number of infections in the world continues to increase, it is almost certain that the new coronavirus is likely to continue to evolve, and eventually emerge a new variant that completely avoids the current vaccine. Therefore, the risks of prematurely thinking the pandemic are over are undoubtedly enormous. The WHO timely warned against treating COVID-19 as an "endemic" illness at this time (104). So, what should governments do until the world reaches equilibrium with COVID-19? Given public fatigue and the lessons of the past two years, finding the right combination of public-health measures will be critical, but in implementing these policies, it is also a top priority for the government to unite the public and win their understanding and support.

According to the World Economic Outlook released by the International Monetary Fund (IMF) in April 2020, the epidemic has had a greater impact on developed economies than emerging markets and developing economies (105). On the basis of the data provided by the World Bank, the GDP growth ratio of high-income countries in 2020 was –4.7%, much lower than the global GDP –3.5% (106). However, governments in these countries must consider the acceptance of their people as they contain the epidemic and restore their economies, and many are no longer accepting the strict quarantine measures imposed at the start of the outbreak. Some people contended that China’s containment measures could only have been implemented by an authoritarian government with a compliant population used to following its orders. In other words, coercive mass quarantines were not considered to be a viable option for most other countries. From a European perspective, door-to-door inspections and tight controls via apps are seen as serious violations of individual rights. At the same time, measures to closely track contacts of COVID-19 patients cannot be implemented in most countries due to the large number of confirmed cases However, these measures have prevented subsequent epidemic waves and saved lives so far. Some other countries have started seeing the mobile location data technology as an important component in the fight against COVID-19 without sacrificing citizen rights, such as the General Data Protection Regulation (GDPR) of the EU (107, 108). There is no doubt that the lessons learned from COVID-19 in terms of disease prevention by governments are improving improve the global public health infrastructure and surveillance systems.

There is no doubt that the Omicron variant will not be the last variant of SARS-CoV-2. The continuous emergence of new SARS-CoV-2 variants has made the control of the COVID-19 pandemic more complicated. The optimistic view is that enough people will gain immune protection from vaccination and from natural infection such that there will be less transmission and much less COVID-19-related hospitalization and death. As vaccination, treatment and quarantine measures have improved, some countries have taken the lead in exploring co-existence with the virus in practice. Some Chinese scholars have also begun to put forward the model of "Chinese-style co-existence with virus" and stressed that the “zero-COVID” policy is not set in stone, and it will change under different circumstances. In other words, normalizing people's lives should be as important as the "dynamic zero-COVID" policy so that it can ensure that the rights of its people are valued and protected. In fact, many people have become so tired of the strict quarantine measures that the fear of quarantine has overtaken the fear of the virus itself, meanwhile, people can also not tolerate a large number of secondary disasters caused by the strongest anti-epidemic measures. The premise of "living with COVID-19", however, is that each country must do it scientifically, responsibly and at its own pace. There is reason to believe, therefore, that the new wave could no longer require the return to pandemic-era and population-wide lockdowns. At the same time, there is also reason to believe that the approach to control this pandemic will only make more sense in case of international collaborations in the matters of disease prevention and treatment.

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RESEARCH

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Overcoming COVID-19 in China despite shortcomings of the public health system: what can we learn?

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Abstract

Background and objective: The COVID-19 pandemic started in Wuhan, China, in December 2019. Although there are some doubts about the reporting of cases and deaths in China, it seems that this country was able to control the epidemic more effectively than many other countries. In this paper, we would like to analyze the measures taken in China and compare them with other countries in order to find out what they can learn from China.

Methods: We develop a system dynamics model of the COVID-19 pandemic in Wuhan. Based on a number of simulations we analyze the impact of changing parameters, such as contact rates, on the development of a second wave.

Results: Although China's health care system seems to be poorly financed and inefficient, the epidemic was brought under control in a comparably short period of time and no second wave was experienced in Wuhan until today. The measures to contain the epidemic do not differ from what was implemented in other countries, but China applied them very early and rigorously. For instance, the consequent implementation of health codes and contact-tracking technology contributed to contain the disease and effectively prevented the second and third waves.

Conclusions: China's success in fighting COVID-19 is based on a very strict implementation of a set of measures, including digital management. While other countries discuss relaxing the lock-down at a rate of 50 per 100,000 inhabitants, China started local lock-downs at a rate of 3 per 100,000. We call for a public debate whether this policy would be feasible for more liberal countries as well.

Keywords: COVID-19, Health care system, System dynamics model, Health codes, Contact-tracking technology

Introduction

In December 2019, a Pneumonia of unknown cause broke out in Wuhan, Hubei Province, China. The number of cases and deaths rose exponentially with tremendous challenges to the health care system and the society [1]. On January 7, 2020, the China Centers for Disease Control and Prevention (CDC) detected a new human coronavirus and sequenced the whole genome of the virus [2, 3], which was subsequently identified as the pathogen of the disease [4, 5]. On January 12, 2020, the World Health Organization (WHO) officially named the virus "Novel Coronavirus 2019" (2019-nCoV), and on February 11, 2020 the International Committee on The Classification of Viruses (ICTV) named the virus as SARS-CoV-2. The disease was subsequently named Corona Virus Disease 2019 (COVID-19).

As SARS-Cov-2 is highly infectious [6, 7], the new disease spread rapidly to other countries and continents and less than 3 months after the first reported cases in Wuhan WHO officially declared a COVID-19 pandemic [8, 9] (11.03.2020). However, while many countries and in particular Europe, North and South America are suffering from very strong waves of the disease with millions of cases and victims, China seems to have won the

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fight against the disease [10]. While one might challenge the quality and transparency of public health information from China, it is a matter of fact that China has comparably few cases of COVID-19. Outbreaks as we experience them in the United States of America (USA), Spain, Germany or France in particular in winter 2020/21 could not be hidden from WHO and the rest of the world.

Consequently, we have to ask for the reasons of this success. At a first glance, there might be three causes. Firstly, some external factors such as climate, genetics or culture might constitute a natural barrier against the diffusion of the disease. Secondly, a brilliant public health system with high resources might be capable to reduce the spread of the disease. Thirdly, specific interventions against the disease might have managed to control the outbreak in the country which are not consistently implemented in the most severely hit countries.

In this paper, we will analyze the relevance of these three factors. Consequently, the next section discusses the outbreak of COVID-19 in Wuhan in order to investigate external factors influencing the spread of the disease as well as the instruments applied in the region. As methods and results, we will present a simulation model of the diffusion of COVID-19 in Wuhan. Afterwards we will discuss the public health care system of China and its ability to produce results, which are more likely to control the disease than in Europe or the USA. We will also compare the instruments applied in China with other countries in order to determine the underlying causes of this success story.

COVID-19 in Wuhan

Wuhan is the name of a city with about 8 million and of the respective metropolitan region of about 11 million inhabitants within the Hubei region of China. With a gross national product of about 23,000 US$ p.c. p.a., Wuhan is comparable wealthy. Wuhan is around 30° North, such as Cairo, Jacksonville, New Orleans and Houston.

The origin and the first cases of COVID-19 in Wuhan are under dispute, but the disease became a medical issue in December 2019 [11]. China's response to the epidemic can be divided into four stages according to the dynamic process of the epidemic, i.e., December 2019 to 19.01.2020, 20.01.-20.02.2020, 21.02.-28.04.2020 and 29.04.2020 until today.

Phase I

Between December 2019 and 19th of January 2020, the number of patients grew exponentially, but it was too small that officials did not recognize it as a public health threat. When WHO was informed about the new disease of unknown etiology on 31st of December 2019, 27 patients had been diagnosed with viral pneumonia of unknown cause. On the 19th of January, already 198 patients had been recorded which is an increase of 11% per day (geometric mean).

In this phase, most official activities were confidential and not transparent, but the National Health Commission of China started with the pathogen detection and epidemiological investigation, issued technical guidelines to Wuhan, and notified other regions. However, it seems that Wuhan and other parts of China did not implement any significant epidemic prevention actions except for case detection and disease surveillance (Table 1). For instance, a community in Wuhan held the annual "10,000 Family Banquet" as scheduled on 18th of January.

Phase II

Phase II was the phase of high incidence from 20th of January to 20th of February 2020. The emergence of COVID-19 coincided with the world's largest annual human migration, the Chinese Spring Festival travel season. Under normal circumstances, China could have expected some 3 billion trips in China during the 40-day holiday period from 15 days before the Spring Festival to 25 days after the Spring Festival. For this "spring transit", the Chinese language has even a special word called "Chunyun" where almost the entire population moves back to their place of origin. As the largest transportation hub in central China, Wuhan would have expected to transfer at least 15 million passengers during the Spring Festival holiday. According to Wuhan Transport Bureau, Wuhan counted a total of 15,223,900 passengers leaving Wuhan and 14,662,200 passengers arriving in Wuhan during the 2018 Spring Festival with a total of 271,339,500 travel activities during this period in Wuhan. There is no reason to assume that the situation would have been different in 2020 without COVID-19 and the Spring Festival 2020 could have become the super-spreader event for the entire country. In fact, it was reported that about 5 million people had already left Wuhan before the city was locked down on January 23, 2020 [18].

After it had been detected that the new disease was contagious [19, 20], the Government of China took emergency measures to reduce the risk of spreading the disease all over China, such as cancelling the Spring Festival, postponing work and school opening, restricting travel, closing entertainment venues and banning public gatherings (Table 2) [27]. However, during this period the number of cases and deaths strongly increased reaching a peak of 32,994 cases on 12th of February (Fig. 1). However, during this period the statistical detection of cases changed so that the jump from 11th to 12th of February is mainly due to different reporting than to a real increase of cases.

Table 1 Measures taken in Wuhan in Phase I [12–17]

Day	Measures
Dec. 27	Cluster of Cases of pneumonia of unknown origin first reported to China CDC
Dec. 29	Pneumonia cases linked to the Huanan Seafood Wholesale Market
Dec. 30	Case-finding activated
Dec. 31	Outbreak announced by Wuhan Health Commission (WHC); National Health Commission (NHC) and China CDC involved in investigation and response
Jan. 01, 2020	Huanan Seafood Wholesale Market closed
Jan. 02	China CDC carried out pathogen identification
Jan. 03	Emergency monitoring, case investigation, close contact management, and market investigation initiated, technical protocols for Wuhan released; NHC notified WHO and relevant countries and regions; gene sequencing completed by China CDC
Jan. 06	China CDC Level 2 emergency response activated
Jan. 07	Coronavirus isolated and named 2019-nCOV
Jan. 08	A novel coronavirus was officially announced as the causative pathogen of the outbreak by China CDC
Jan. 09	The second group of experts from the NHC went to Wuhan to carry out epidemic prevention work
Jan. 10	China CDC publicly shared the gene sequence of the novel coronavirus; completed (Polymerase Chain Reaction) PCR diagnostic reagent development and testing; China begins its annual Spring Festival travel rush
Jan. 11	PCR diagnostic reagents provided to Wuhan; First fatal case reported
Jan. 14	The airport, railway station and wharf of Wuhan city carry out temperature check for departing passengers
Jan. 15	China CDC emergency response level upgraded to Level 1 (the highest level); national technical protocols for 2019-nCoV released by NHC
Jan. 16	Strict exit screening measures activated in Wuhan, people with body temperature 37.3 °C were restricted from leaving
Jan. 18	The third group of experts from the NHC went to Wuhan to carry out epidemic prevention work

A crucial component of the intervention portfolio became the “Health Code Model”. On February 11, 2020, the Health Code model was first launched in Hangzhou, Zhejiang Province, China [29], and has been implemented in other provinces and cities in China since then. The smartphone-based application (app) registers the visited locations and all encounters and transfers it to a national database (whereby – from a western perspective – little value is placed on data protection rights). It gives the users an individual “health code” according to the traffic light scheme. The color green means that users can move around freely. Those who receive the yellow warning signal have to stay at home for 7 days, and red means a two-week quarantine [30]. These measures enable a relatively “normal” life, but they interfere with the privacy of citizens.

Phase III

The third phase concentrated on stabilization of the epidemic (21 February - 28 April). As shown in Fig. 1 the incidence remained at a very low level since mid-March, and since April 1, there were no new infections. Consequently, the number of deaths also strongly declined. However, a new number of 1290 deaths was added in Wuhan on April 17, which was mainly a recalculation of the number of unreported deaths in the early stage of the epidemic, rather than the current number of deaths [31]. On April 26, all COVID-19 hospitalized cases in Wuhan had died or were discharged from the hospital. The epidemic situation was generally stable; the Chinese government began to coordinate the epidemic prevention and control with economic and social development, and to resume work and production.

Phase IV

The interventions against COVID-19 in Wuhan are still in the fourth phase concentrating on early detection of cases and in particular efforts of epidemic prevention and control. However, Wuhan is not seen an exceptionality any longer but the countrywide measures to control the epidemic in the country are applied in Hubei Province as well. At this stage, China mainly focuses on “preventing import from outside and preventing rebound from inside” [22], so as to comprehensively promote the resumption of work, production and school, and restore the normal economic and social order. On April 30, the level of emergency response to public health emergencies in the Beijing-Tianjin-Hebei region was adjusted from level 1 to level 2, on June 13; the adjustment was lowered to level 3. On May 2, the emergency response level of public health emergencies in Hubei province was adjusted from level 1 to level 2. From May 14 to June 1, nearly 9.9 million nucleic acid tests were conducted in Wuhan, and no confirmed cases were found.

Table 2 Measures taken by China in Phase II [12, 15, 16, 21–26]

Day	Measures
Jan. 20	Novel Coronavirus Infected Pneumonia (NCIP) categorized as a Category B infectious disease and managed under Category A infectious diseases; Infection in health-care workers caring for 2019-nCoV patients; Close contacts of COVID-19 are monitored household in residential areas on a daily basis
Jan. 21	The central government and local governments at all levels bear the cost of hospital care for COVID-19 patients; Ministry of Transport launches Level 2 emergency Reagent probes and primers shared with the public by China CDC
Jan. 22	Hubei province launched a level II emergency response to a public health emergency; Wuhan residents must wear face masks in public places
Jan. 23	Wuhan city travel ban; first 3 provinces begin Level 1 response; Wuhan begins to seal off the city; Wuhan city traffic suspension; The airport and railway station are temporarily closed; Wuhan bans travel All public events have been cancelled
Jan. 24	Hubei province and other 14 provinces begin Level 1 response; Since that day, 346 national medical teams, 42,600 medical personnel and 965 public health workers have supported Wuhan and Hubei province
Jan. 25	13 provinces begin Level 1 response; Vehicles are prohibited in the central city of Wuhan; All kinds of emergency relief materials were dispatched to Wuhan
Jan. 26	China State Council approves an extension of the Spring Festival holidays; University, primary and secondary schools, kindergartens postponed the start of school
Jan. 27	Ministry of Education postpones start of the spring semester in 2020
Jan. 28	Ministry of Transport refunds all public rail, road, and water travel tickets
Jan. 29	Last province begins Level 1 response
Jan. 30	14,000 health checkpoints set up at bus and boat terminals, service centers, and toll gates nationwide
Feb. 02	Wuhan implements centralized treatment for confirmed patients, suspected patients, febrile patients and close contacts of confirmed patients, Conduct the most detailed screening
Feb. 03	Wuhan strives to build makeshift hospitals; Travel permits to Hong Kong and Macau suspended
Feb. 04	Huoshenshan hospital with 1000 beds was put into operation
Feb. 05	The makeshift hospital was opened for the first time to treat patients with mild COVID-19
Feb. 08	Leishenshan hospital with 1600 beds was put into operation
Feb. 10	19 provinces supported 16 cities, prefectures and county-level cities except Wuhan, Hubei province
Feb. 11	Residential districts in Hubei province put under closed management; Wuhan has reported 1102 confirmed cases among medical staff; Beijing, Tianjin, Shanghai and Chongqing have successively declared closed management of residential areas Health Code Model launched
Feb. 15	Seven diagnostic test reagents have been approved for market; some drug screening and treatment programs have made progress
Feb. 16	In Wuhan city, 11 makeshift hospitals have been put into operation in Wuhan city to meet the requirement of receiving as much as possible
Feb. 17	The Chinese government has deployed targeted prevention and control measures at different levels in different regions and departments to restore production and life order in an orderly manner
Feb. 18	The number of new cured and discharged cases in China exceed the number of new confirmed cases, and the number of confirmed cases begin to decline
Feb. 19	The number of new cured and discharged cases in Wuhan exceed the number of new confirmed cases for the first time
Feb. 20	The largest makeshift hospital in Wuhan was officially put into use, providing 3690 beds for patients with mild COVID-19

Meanwhile, according to the severity of the epidemic, the Chinese government splits up their counties (cities, districts) into low-risk areas, medium-risk areas and high-risk areas. High risk or medium risk areas can be very small units, such as a community, a street and a housing estate. The number is updated every day. As of February 17, China has dropped to 1 high-risk area and 5 medium risk areas.

As shown in Table 3, the specific prevention and control measures are adjusted according to the situation of provinces, counties and even communities, environmental capacity and the nature of the spread of novel coronavirus. “Low-risk areas” are areas where no new cases are confirmed for 14 consecutive days. “Medium-risk areas” have newly confirmed cases within 14 days, but the cumulative number of confirmed cases does not exceed 50, or the cumulative number of confirmed cases exceeds 50, and no cluster epidemic occurs within 14 days. “High-risk areas” refers to more than 50 cumulative cases and a cluster of epidemics occurred within 14 days. People can enter the “State Council Client” applet and perform the “Inquiry on Epidemic Risk

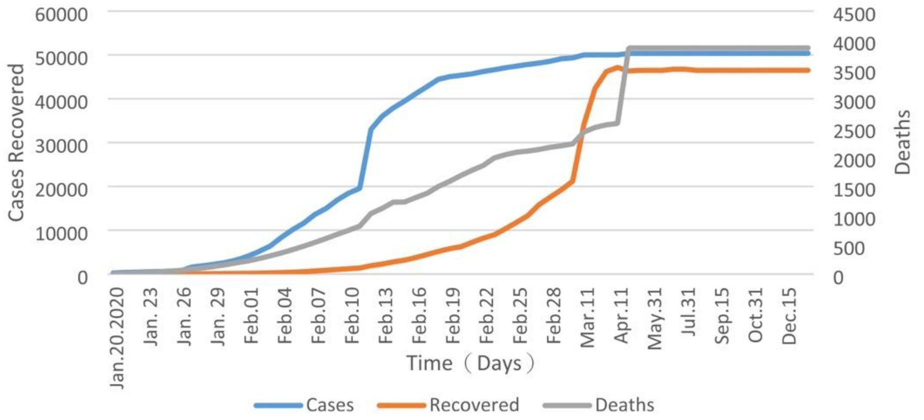

Fig. 1 Confirmed and dead COVID-19 patients in Wuhan in Phase II-IV. Source: [28]

Level" to show which epidemic risk level each person is in. For instance, on February 17, 2021, the data base showed 1 high-risk region and 5 medium-risk regions [34]. People are still required to go outside with a mask, take their temperature, and show a health code and a negative certificate of nucleic acid.

It has been questioned whether China's official statistics represent the real situation. Some argue that the number of cases and deaths during the peak of the epidemic must have been much higher than presented in the official statistics [35], while others question that the disease could disappear completely from Wuhan [36]. While these arguments might be true, it is a matter of fact that China managed to bring life in Wuhan back almost to normal within a short period. A second wave with tremendous consequences for the public health situation could not have been hidden. Thus, irrespective of the reliability of the statistics basis, the measures taken by the Chinese government must have been quite successful in containing the outbreak and in preventing

Table 3 Prevention and control measures taken by the Chinese government in areas with different levels of risk [12, 32, 33]

Measures	High-risk areas	Medium-risk areas	Low-risk areas
Area traffic control	√		
Close public facilities	√		
Close business	√		
Close primary schools and kindergartens	√		
Close colleges and universities	√		
Delayed start of school	√	√	√
Gathering activities are prohibited	√	√	Reduce crowd gathering activities
Suspected cases are quarantined	√	√	
Close contacts are subject to isolation medical observation	√	√	√
Use a mobile app	√	√	√
Comprehensive screening of fever patients	√	√	Medical institutions strengthen the monitoring, detection and reporting of fever cases
Door to door testing	√	√	
Wear masks in public places	√	√	√
Measuring body temperature	√	√	√
Keep social distance	√	√	√
Information registration of outsiders	√	√	√
Check health code, itinerary card	√	√	√
Negative nucleic acid test certificate	√	√	√
Disinfect relevant places	√	√	√

a second or third wave of outbreaks. In other words: The measures shown in Table 3 must have made it possible to keep the basic reproductive rate low.

Consequently, we have to analyze the parameters determining the dynamics of the spread of COVID-19 in order to understand how the second wave was prevented in Wuhan. For this purpose, we develop a simple and basic model predicting the spread of the disease in the region in order to analyze the influence of different parameters on it.

Methods

Modelling COVID-19 – an overview

An epidemic is terminated if the net reproductive rate (N_t) at a point of time t is lower than one, i.e., if every newly infected will infect less than one other person. N_t is the product of the basic reproductive rate (R_0, under the condition that nobody is immune) with the likelihood that the contact partner is not immune, i.e., at a given share of immune population (x_t) at a point of time t, N_t can be calculated as

$$N_t = \frac{R_0(100 - x_t)}{100}$$

If N_t is less than 1, a population has reached herd immunity (e.g. 60% for $R_0 = 2.5$).

Consequently, we have to analyze the dynamics of the diffusion of COVID-19 and estimate R_0 in order to assess the factors contributing to the success of interventions against the diseases in Wuhan. A huge variety of mathematical models has been developed to forecast the spread of a disease. The simplest approach calculates the basic reproductive rate as a function of some of variables (analytical models). As early as 1889, this model type was developed to calculate R_0 for malaria (reprint in English in 1989 [37]) and became the foundation of the well-known Ross-MacDonald model [38]. The disadvantage of these simple models is that they cannot cover interdependencies and changes of variables.

Homogenous Markov models are also widely used to forecast the spread of a disease [39]. They are capable to estimate the number of individuals in different health states as long as the transition probabilities are constant, i.e., if they do not depend on the number of individuals in the compartments [40]. This is the case for chronic-degenerative diseases, but the probability of being infected depends on the infectious population. Thus, traditional (homogeneous) Markov models are not applicable for infectious diseases such as COVID-19.

An inhomogeneous Markov chain implies that the transition probabilities can change. It is, in principle, a system dynamics model. This type of model was developed by Forrester in 1964 [41] in order to account for feed-back loops (e.g. number of infectious population determining the risk of being infected). The principle has been applied in many fields, such as "Industrial Dynamics "[41], "World Dynamics "[42], "Urban Dynamics" [43] or "Disease Dynamics" [44]. The simplest system dynamics model of a disease is the so-called SI-model where S denotes the population susceptible to a disease and I the infectious population. Figure 2 shows that the infection rate depends on the susceptible population (S), the infectious population (I), the contact rate (c), the total population (N) and the infectivity (i) of the infectious disease. The model can be easily enhanced to include the recovered population (SIR-model), exposed population (SEIR-model), different age-sets, re-infections, vaccinations, locations etc. The model has been applied to many infectious diseases, such as HIV/AIDS, malaria and cervical cancer [46–48].

Discrete Event Simulations (DES) and Agent-Based Simulations have also been used to predict the spread of infectious diseases [49, 50]. The advantage of these models is that they do not simulate compartments but individuals allowing to attach personal characteristics (e.g. being a child of an individual mother or having certain comorbidities) to each person. Thus, they are more precise, but require many input variables frequently unknown. In addition, designing and validating these models is much more effort than for the other model types.

In principle, a model should not be more complex than necessary to give an answer to the specific research question. For the target of this paper of determining the reasons for the successful fight against COVID-19 in Wuhan, a rather simple system dynamics model seems appropriate. There is a tremendous number of COVID-19 models available. Stegmaier lists 53 different models of COVID-19 relevant to German public health research, the majority of them system dynamics [51]. However, he also makes aware of the weaknesses of these models, such as poor data input, wrong assumptions, poor transparency, selective reporting etc. Ioannidis, Cripps and Tanner even state that "Forecasting for COVID-19 has failed" [52] because the results were frequently unreliable and of limited value for decision-makers.

The objective of the model presented in the next section is not to forecast the future development of COVID-19 in Wuhan. Instead, we would like to focus on very few parameters influencing the spread of the disease and analyse how they must have developed in order to allow the epidemic dynamics of COVID-19 in Wuhan. While many of the models presented by Stegmaier [51] are much more complex than ours, we also do not pretend to give a precise forecast. Our intention is a "modelling for insights, not for numbers" [53], i.e., we want to learn more about the prerequisites of the real spread of the disease than about the future dynamics.

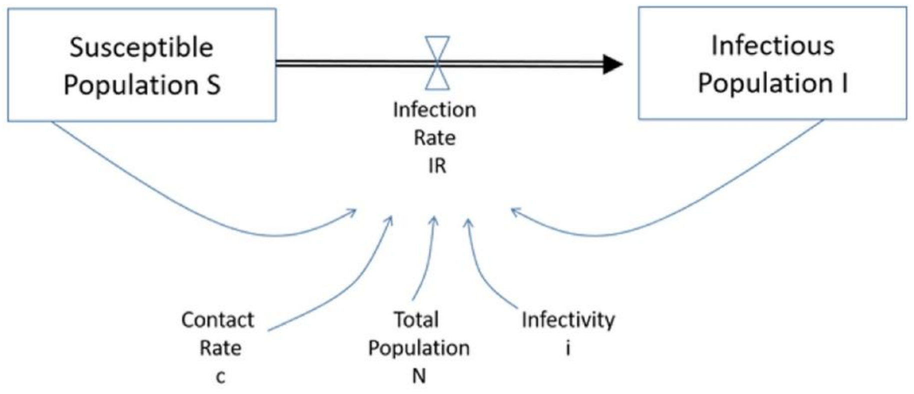

Fig. 2 SI-Model. Source: [45]

Modelling COVID-19 – a basic model for Wuhan

For this purpose, we develop a generic COVID-19 model [54] in order to analyze the factors determining the spread of the disease in Wuhan in the first year. The model does not consider age-sets, locations or social differentiations (e.g. schools, universities, traditional markets) as this is not necessary to answer the question how China managed to avoid a second wave. Instead, we focus on the determinants of the basic reproductive rate R_0. The infection life cycle is presented in Fig. 3 and modelled as a System Dynamics Models [55, 56].

The system dynamics model defines difference equations for the healthy, infected, sick and immune population:

$$S_{t+1} = S_t - \frac{S_t}{S_t + E_t + InS_t + SI_t + SnI_t + R_t} \cdot \frac{InS_t + SI_t}{S_t + E_t + InS_t + SI_t + SnI_t + R_t} \cdot S_t \cdot \frac{R_0}{si + ins}$$

$$E_{t+1} = E_t + \frac{S_t}{S_t + E_t + InS_t + SI_t + SnI_t + R_t} \cdot \frac{InS_t + SI_t}{S_t + E_t + InS_t + SI_t + SnI_t + R_t} \cdot S_t \cdot \frac{R_0}{si + ins} - \frac{E_t}{e}$$

$$InS_{t+1} = InS_t + \frac{E_t}{e} - \frac{InS_t}{ins}$$

$$SI_{t+1} = SI_t + \frac{InS_t}{ins} - SI_t \cdot \frac{f}{(si + sni)} - \frac{SI_t}{si}$$

$$SnI_{t+1} = SnI_t + \frac{SI_t}{si} - SnI_t \cdot \frac{f}{(si + sni)} - \frac{SnI_t}{sni}$$

$$T_{t+1} = T_t + (SnI_t + SI_t) \cdot \frac{f}{(si + sni)}$$

$$R_{t+1} = R_t + \frac{SnI_t}{sni}$$

$$R_0 = \sum_{i=1}^{m} \left(1 - (1-p)^{n_i}\right)$$

With the following variables and constants:

Variables	Description
S_t	Susceptible in t
E_t	Exposed in t
InS_t	Infectious but not sick in t
SI_t	Infectious and sick in t
SnI_t	Sick and non-infectious in t
R_t	Recovered in t
T_t	Death cases in t
R_0	Basic reproductive rate
N_t	Net reproductive rate in t

Constants	Description
f	infection fatality rate
e	Average length of stay in exposed compartment
ins	Average length of stay in compartment infectious but not sick
si	average length of stay in compartment sick and infectious
sni	average length of stay in compartment sick not infectious
$\overline{R_0}$	Basic reproductive rate without intervention
$\overline{R_i}$	Basic reproductive rate with intervention
d_1	last day without intervention
d_2	first day of maximum effect of intervention
d_3	last day of intervention
d_4	last day of effect of intervention
p	infectivity
n_i	number of contacts with person i during infectious period
m	number of persons met during infectious period

In comparison to other models [51], the infection life cycle and the number of compartments is rather simple, but we focus much more on the impact of contact rates on the basic reproductive rate. As (8) shows, R_0 depends on the infectivity (i.e. probability that one contact of an

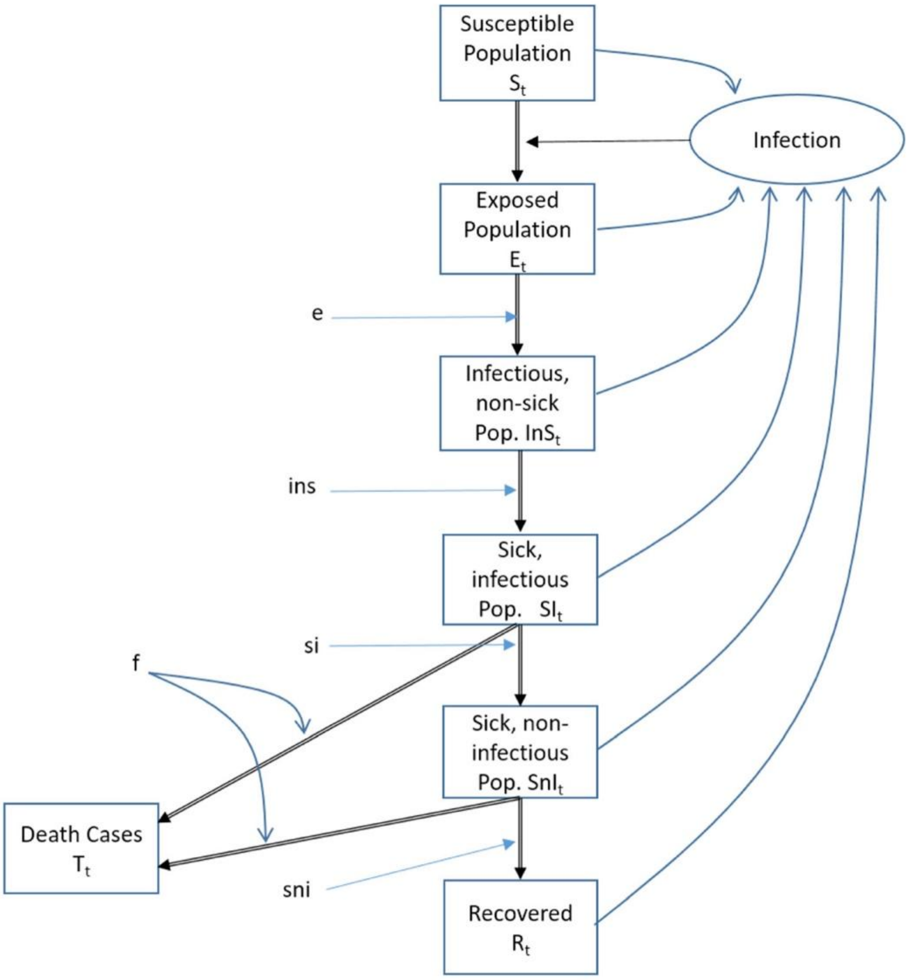

Fig. 3 COVID-19 Model Structure. Source: [54]

infectious person with a healthy person leads to an infection), the number of people an infectious person meets within the infectious period and number of contacts the infectious person has with each of the healthy persons.

The probability that an infectious person infects a healthy person when meeting once is p. The probability that an infectious person does not infect a healthy person when meeting this person n_1 times is $(1-p)^{n_1}$. Thus, if an infectious person meets m healthy people during the infectious period and has n_i contacts with each of them during this time, is the basic reproductive rate and can be calculated [57] as

$$(8a)\ R_0 = (1-(1-p)^{n_1}) + (1-(1-p)^{n_2}) + \dots + (1-(1-p)^{n_m}) = \sum_{i=1}^{m} (1-(1-p)^{n_i})$$

For our analysis of the COVID-19 diffusion in Wuhan, we assume that the disease spread without interventions for a certain time. After d_1, the public health care system started interventions resulting in a reduction of R_0. However, it took some time until the rate had declined strongly. At d_2 all measures reached their maximum effectiveness and this condition was sustained until d_3. Afterwards the interventions were relaxed until the old situation was reached again in d_4. The respective development is presented in Fig. 4. This can be presented in the formula:

$$(9) R_0 = \begin{cases} \overline{R_0} & \text{for } t \le d_1 \\ \overline{R_0} - \dfrac{\overline{R_0} - \overline{R_i}}{d_2 - d_1} \cdot (t - d_1) & \text{for } d_1 < t < d_2 \\ \overline{R_i} & \text{for } d_2 \le t \le d_3 \\ \overline{R_i} + \dfrac{\overline{R_0} - \overline{R_i}}{d_4 - d_3} \cdot (t - d_3) & \text{for } d_3 < t \le d_4 \\ \overline{R_0} & \text{for } t > d_4 \end{cases}$$

Consequently, the net reproductive rate (N_t) can be calculated as

$$N_t = \frac{R_0 \cdot R_t}{S_t + E_t + InS_t + SI_t + SnI_t + R_t}$$

Based on this model, we can simulate the diffusion of COVID-19 in a generic region with many characteristics of Wuhan. We simulate under the assumption that no intervention had been taken (scenario I), that the reduction of the basic reproductive rate was sustained (scenario II) and that a successful intervention was relaxed too early so that basic reproductive rate returns to its original value (scenario III). The last scenario assumes that some measures are sustained but R_0 will be above 1 (scenario IV). Furthermore, we can model the impact of different rates of infectivity (p), number of different contact partners (m) and contacts per partner (n_i). Under the assumption that an infectious person has the same number of contacts with each person (for $n_1 = n_2 = \ldots = n_m = n$), we receive

$$(8b)\ R_0 = \sum\nolimits_{i=1}^{m} \left(1-(1-p)^n\right) = m \cdot \left(1-(1-p)^n\right)$$

or

$$(8c)\ n = \frac{\ln\left(1-\frac{R_0}{m}\right)}{\ln\ (1-p)}$$

$$(8d)\ m = \frac{R_0}{1-(1-p)^n}$$

Finally, we can calculate the basic reproductive rate under the assumption that the total number of contacts as the product of people met and contacts per person is constant (for $m{*}n = k = const$) as

$$(8e)\ R_0 = m \cdot \left(1-(1-p)^{\frac{k}{m}}\right)$$

Results

For our simulation, we used data from Wuhan without assuming that the model will present all dimensions of the reality of this region. Table 4 shows the parameters. In some cases we could not build on the standard parameters used in other models because we wanted to simulate the situation in the very beginning of the pandemic where very little was known about the disease. For instance, the fatality rate in Wuhan was most likely higher than it is reported for other locations today because hardly anything was known about the diagnostics and therapy of the disease. For these parameters, we built on assumptions and private communication from Chinese experts.

The original basic reproductive rate is assumed as 2.5 ($\overline{R_0}$) [60]. According to (8d), this refers to 10.8 contact partners with an average frequency of 2.5 meetings per contact during the infectious period and an infectivity of 0.1 (p) [61, 62]. Figure 5 shows the relationship between the number of contact persons (m), the number of contacts per contact person (n) and the basic reproductive rate for $p = 0.1$. It is obvious that both variables strongly determine R_0.

Figure 6 shows the number of COVID-19 cases for the scenarios. Scenario I assumes that $R_0 = 2.5$ is constant, i.e., without any intervention. Scenario II assumes that interventions start at day 121 ($d_1 = 120$) and need 30 days ($d_2 = 150$) until they are fully effective so that $\overline{R_i}$ = 0.95. Afterwards all interventions are sustained. This parameter was not chosen because we have evidence that the reproductive rate was exactly 0.95 in Wuhan.

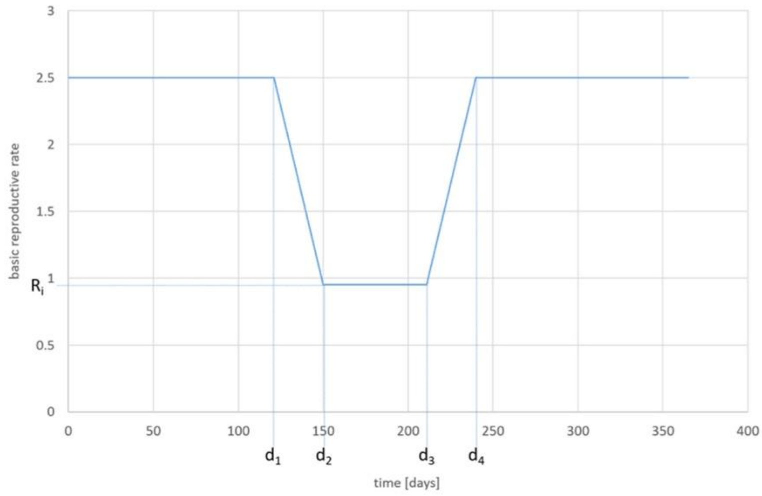

Fig. 4 Development of R_0 (assumption). Source: own

Table 4 Basic parameters

Constants	Description	Value	Source
S_0	Population in t = 0	11,000,000	
f	infection fatality rate	0.015	[58]+ p.i.[a]
e	Average length of stay in exposed compartment	3	[59] + p.i.[a]
ins	Average length of stay in compartment infectious but not sick	2	[59] + p.i.[a]
si	average length of stay in compartment sick and infectious	11	[59] + p.i.[a]
sni	average length of stay in compartment sick not infectious	7	[59] + p.i.[a]
$\overline{R_0}$	Basic reproductive rate without intervention	2.5	[60]
$\overline{R_i}$	Basic reproductive rate with intervention	Scenario I: 2.5 Scenario II: 0.95 Scenario III: 2.5–0.95-2.5 Scenario IV: 2.5–0.95-1.5	assumption
d_1	last day without intervention	120	assumption
d_2	first day of maximum effect of intervention	150	assumption
d_3	last day of intervention	210	assumption
d_4	last day of effect of intervention	240	assumption
p	infectivity	0.1	[61, 62]

[a] pi: assumption based on private communication with Chinese colleagues

Instead, it is an assumption of a reproductive rate lower than but close to 1.

Scenario III assumes the same development as scenario II for the first 210 days, i.e., the interventions are sustained to 60 more days. Afterwards ($d_3 = 210$) the interventions are relaxed until $\overline{R_i}$ is back to its original value of 2.5 in $d_4 = 240$. Scenario IV follows the pattern of scenario III but assumes that some interventions are sustained so that the final $\overline{R_i}$ is 1.5.

For the unrealistic case of no interventions (scenario I), Wuhan would have experienced a very severe single wave. Most striking, it takes 87 days after the first case until 1000 patients are sick (variables *SI* and *SnI*) at the same time (10 per 100,000 inhabitants in Wuhan), i.e., the early break-out of the disease is difficult to detect even though the disease has a catastrophic potential leading to thousands of new cases per day. Scenario I is unrealistic as the health care system would have collapsed completely without interventions. The epidemic comes to a standstill after the herd immunity of 60% is reached. Scenario II shows that the interventions are effective and manage to flatten the curve. However, as no herd-immunity is reached, COVID-19 will

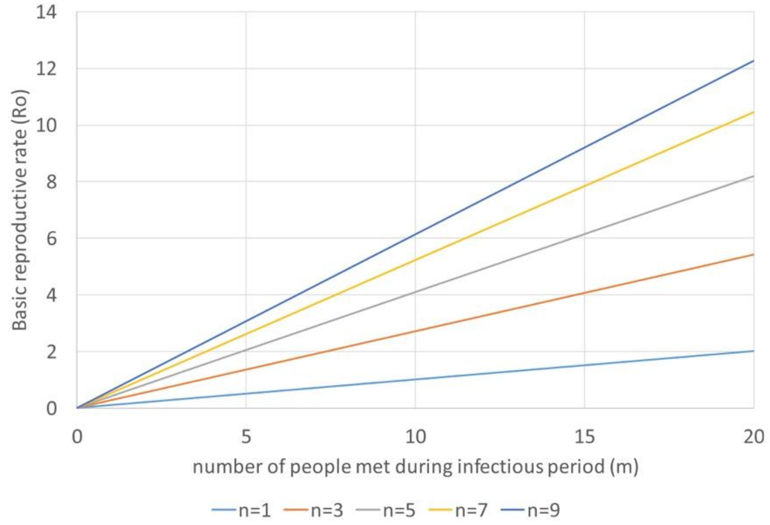

Fig. 5 Basic reproductive rate and contacts. Source: own

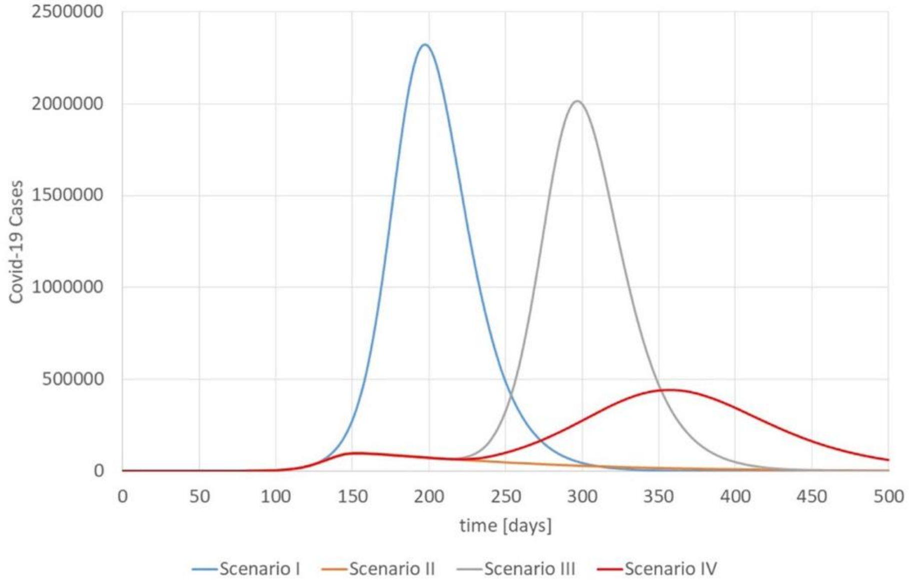

Fig. 6 Number of COVID-19 Cases in Wuhan, Scenarios I-IV. Source: own

not disappear and there remains a need to sustain the interventions indefinitely (without vaccination). According to (8d), the number of contact persons must be less than 4.1 if $p = 0.1$ and $n = 2.5$ in order to achieve an $R_i = 0.95$.

Scenario III simulates the second wave of the COVID-19 pandemic for Wuhan under the assumption that interventions are relaxed completely on day 210. The consequences are disastrous: An unrestricted second wave is much more dramatic than the first wave for scenario II and almost as strong as the first wave without any interventions (scenario I).

Scenario IV assumes – like scenario III – that the interventions are reduced after a period of successful reduction of infections, but some measures are sustained so that R_i returns to 1.5 on $d_4 = 240$. The consequence is a “milder” second wave, which is still stronger than the first wave but not as dramatic as the second wave of scenario III.

Consequently, the basic reproductive rate must be kept below 1 for a very long time. Based on (8) this can be done by reducing the infectivity (p), number of contact partners (m) and number of contacts per partner (n).

Thus, at a rate of $R_0 = 2.5$, herd immunity is reached if 60% of the population have been infected. At a rate of $R_0 = 1.5$, the respective figure can be 33.3% under the assumption that the number of contacts remains on this low level.

Figure 7 shows the consequences of a changed infectivity (p) on the basic reproductive rate. If p increases from 0.1 to 0.15 (as for “UK variant” B.1.1.7), R_0 strongly increases. Assuming that a person meets any other person 2.5 times on averages, the increase of p by 50% requires that the number of people met during the infectious period declines from 10.8 to 7.5 (see 6d). At the same time, a reduction of the infectivity by wearing surgical masks (estimated effectiveness of 50%) for all contacts allows to increase the number of contact partners to 20.8 for the same R_0. Wearing an FFP-2 mask (estimated effectiveness of 90%) for all contacts has a very strong impact on the basic reproductive rate. An infected person can meet 40.3 different people on average 2.5 times during the infectious period and still R_0 is below 1 if all contacts are with an FFP-2 mask.

Based on (8d), we can calculate that a R_0 of 2.5 will result if an infectious person meets 11 different people on average 2.5 times during the infectious period ($p = 0.1$). By wearing a surgical mask with an effectiveness of 50% ($p = 0.05$), R_0 will decline to 1.32, i.e., scenario IV can be implemented by merely sustaining the obligation of wearing surgical masks for all contacts. Scenario II could be achieved by wearing surgical masks and by reducing the number of contacts with different people from 10.8 to 7.5 during the infectious period with an average number of meetings per person of 2.5 ($R_0 = 0.96$). Thus, the system is highly sensitive to changes of the infectivity p, i.e., wearing effective masks for all contacts is one of the most efficient interventions.

Figure 8 shows the impact of different numbers of contacts and different frequencies of meeting each person under the assumption $n_1 = n_2 = \ldots = n_m = n$.

For instance, if an infectious person meets 20 different people during the infectious period, he can meet each of

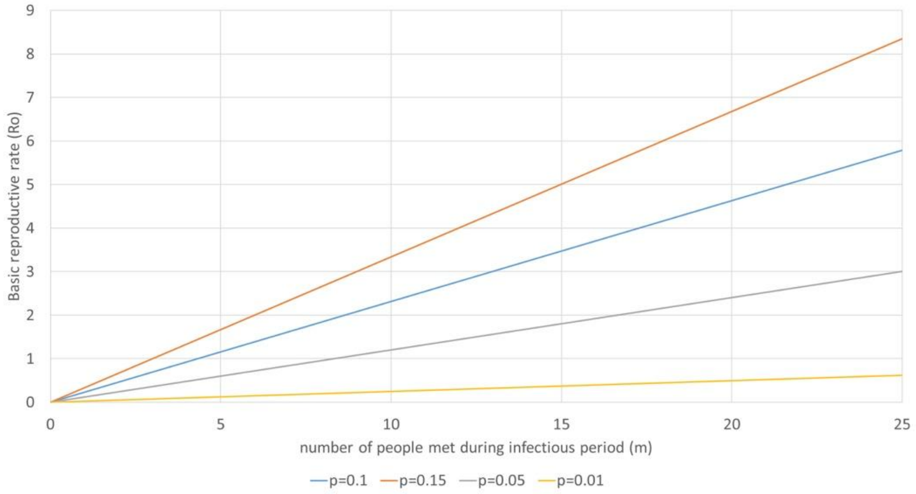

Fig. 7 Change of infectivity. Source: own

them on average 1.27 times during the infectious period in order to achieve a basic reproductive rate of 2.5. For an R_0 of 1, the average number of contacts must decline to 0.47 at 20 different contacts. Alternatively, the person could meet only two different people, but each one 6.68 time. Figure 9 assumes that the total number of contacts is given and the number of people met during the infectious period varies. It is obvious that it is better to meet few people frequently than many people rarely.

Discussion

Relevance of simulation results

Based on these calculations we can state that the public health care system in Wuhan managed to reduce the risky contacts strongly. The success of keeping R_0 under 1 for several months can only be explained by effective efforts to exclude infectious people from contacts.

The results also indicate that it was very difficult in the beginning of the epidemic to see its pandemic potential. Our simulations show that it took almost 3 months after the first case until 1000 patients were sick at the same time. It is obvious that the traditional routines of case detection (focusing on the number of cases) could not work with COVID-19. Once the figures are visible, it is already too late and the exponential growth has started. Only an excellent public health system could have determined the pandemic potential early enough.

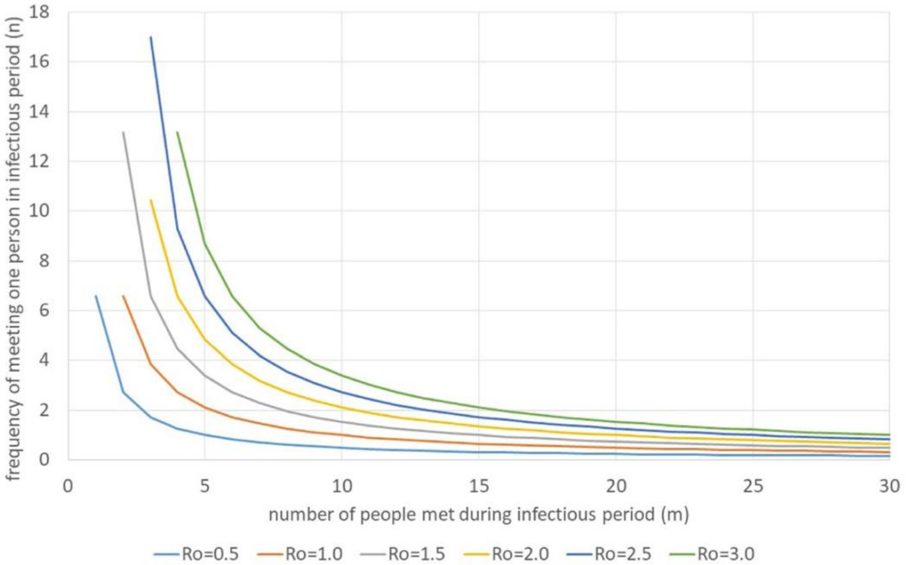

Fig. 8 Impact of number of people met and frequency of meeting each person during infectious period. Source: own

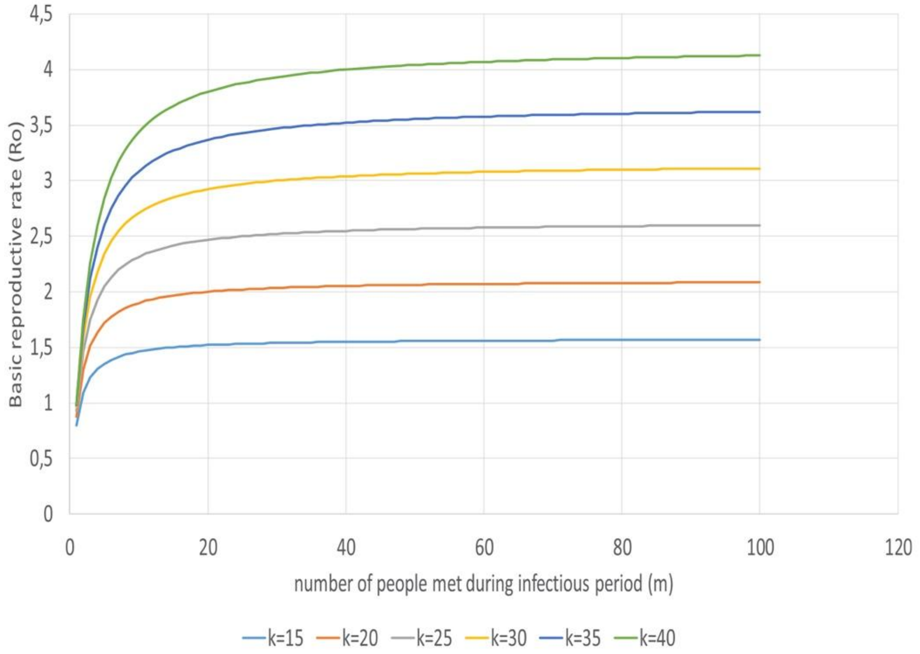

Fig. 9 Basic reproductive rate for different total contacts. Source: own

Our results also indicate that it is likely that Wuhan had much more cases and deaths in the first wave than reported. Even scenario II results in 8269 death cases in the first year while Wuhan reported "only" 2997. The statistics of Wuhan have been questioned elsewhere [63, 64] and our computations show equal results.

The simulations also show that wearing surgical masks is highly effective to reduce the basic reproductive rate and the spread of the epidemic. Our simulation results are highly sensitive to changes of the infectivity, which can be strongly influenced by wearing masks. This instrument of protecting oneself and others has been quite common in China before, but it has become almost a universal habit since the pandemic started. Chinese citizens wear surgical masks, not only in public transport but almost everywhere. It has become a common habit as a population response to air pollution [65] and hardly anybody would see it as an insult to their liberty rights as citizens.

Finally, the simulation results show that a second wave can only be avoided if interventions are sustained. The reduction of the medical infectivity (p), the number of contact persons (m) and the number of contacts per contact person ($_n$) is the key to control the pandemic. It seems that China managed well to sustain a low R_0 by controlling these variables.

Geography

There was some discussion in the beginning whether Wuhan managed to control the pandemic because of the geographical location and the respective climate [66]. However, while other states located at the same altitude (e.G. *Florida*, Louisiana, Texas, Egypt) are facing a second wave, Wuhan has not reported Corona cases since March, i.e., the geographical location cannot explain the difference. Without doubt, spring and summer helped to control COVID-19 in Wuhan in 2020. There is a clear negative correlation between temperature and COVID-19 incidence, but for other parameters (e.g. humidity, wind speed, rain fall) the results are not significant [66]. It is likely that temperature does not have a direct impact on the transmission of the virus but increases the parameter m and n, i.e., during the cold season people have more and closer contact in rooms. However, this argument is true for all cities on the same latitude and does not explain the successful avoidance of a second wave in Wuhan. Geography does not explain this success.

Public health system

The simulation results also show that an early detection of cases and the implementation of early and effective control measures would require an excellent public health system. However, this does not seem to be the case. Instead, a number of shortcomings of China's CDC have become visible during the epidemic [67]. Firstly, the communication between the national the local CDCs as well as with the healthcare facilities did not work well. Although an infectious disease information system had been developed after SARS-1, it did not work

Table 5 Health resources per capita in China and some high-income countries in the world in 2016. Source: [68, 69]

Country	Current Health Expenditure p.c. [PPP US$]	Hospitals per million population	Number of beds per 1000 population	Doctors per 1000 population	Nurses per 1000 population
Germany	5568.27	37.64	6.06	4.19	10.84
United Kingdom	4182.18	29.29	2.57	2.78	6.45
United States of America	9941.35	17.14	2.77	2.59	–
Japan	4424.98	66.51	13.11	2.43	11.34
Republic of Korea	2745.07	73.92	11.98	2.29	6.82
Canada	4809.28	19.99	2.60	2.69	9.96
Australia	4634.65	55.93	3.84	3.58	9.55
China	*762.98*	*21.07*	*4.02*	*1.88*	*2.54*

properly during phase I of COVID-19. Secondly, the CDC of China had a very limited influence on the Government. As early as January 6, 2020, the Chinese CDC initiated the second-level response to the epidemic, which was upgraded to a first-level response on January 15. However, these emergency responses were almost ignored by the Government [1].

Thirdly, the public health system of the middle-income country China suffers from low resources. As shown in Table 5, financial (health expenditure p.c.) and personnel resources of the system are much lower than in high income countries. In particular, the funds allocated to primary services have been declining for years (Fig. 10). The absolute amount of public health expenditure in China increased tremendously from 14.3 billion yuan (2.99 billion US$ or 2.63 US$ p.c.) in 1990 to 860 billion yuan (130 billion US$ or 617 US$ p.c.) in 2018. However, the proportion of preventive and promotive public services in the total public health expenditure decreased from 76.3% in 1990 to 52.5% in 2018. It seems that the Government of China puts less emphasis on prevention than treatment.

During the COVID-19 outbreak, the Chinese government has borne the cost of all confirmed and suspected COVID-19 patients. It is estimated that the respective costs amounted to 15.696 billion US$, mainly on treatment of patients, subsidies for epidemic prevention and control personnel, and purchase of equipment and protective materials. In comparison to the total health expenditure, the cost of the epidemic amounted to 1.65% of total public health expenditure (11.21 US$ per capita resp. 0.1% of GNP p.c.), i.e., a rather small amount. Consequently, neither a brilliant, well-financed and well-staffed public health system nor tremendously high health care expenditure are the key to understand the effective control of the Wuhan epidemic.

Portfolio of interventions

A number of analyses have been published that provide a taxonomy of different interventions against the diffusion of COVID-19 and assess their effectiveness. For instance, Baker et al. [71] listed the components of pandemic control of COVID-19. A comparison with the interventions of Table 3 shows that China has not implemented any measures that are not practiced elsewhere as well. Improvement of hygiene (e.g. hand washing, surgical masks), contact tracing, quarantine of sick and suspected, high volume testing, physical distancing, movement restrictions, and border management (incl. Exclusion and quarantine) are the international standards to fight COVID-19 [71].

Other studies analyzed the effectiveness of interventions in 40 countries. They record the strongest reduction of R_0 if gatherings of more than 5 people are banned followed by closing stores, restaurants, bars and schools [61, 72–74]. China implemented all of these intervention measures – so as many other countries that experienced a second wave. Consequently, it seems that there is no "magic bullet" against the pandemic; China has not implemented different measures, but it seems that the timing and intensiveness was different.

China follows a "zero-COVID" strategy. For instance, a recent breakout in Shijiazhuang (10.9 Mio. inhabitants) in Hebei province exemplifies this "no-tolerance against COVID-19". After the public health system recorded 300 cases (i.e. 2.75 cases per 100,000), the full program shown in Table 3 started. The objective is clearly described by „zero-COVID "[75]. While European countries discuss whether interventions should be relaxed at a rate of 50:100,000, China implements its full portfolio at a rate of 2.75:100,000.

Without doubt, this is only possible with strong limitations of citizen rights. In particular, the Chinese intervention system builds on the App-based location analyses (see section 2.2). Every contact is recorded

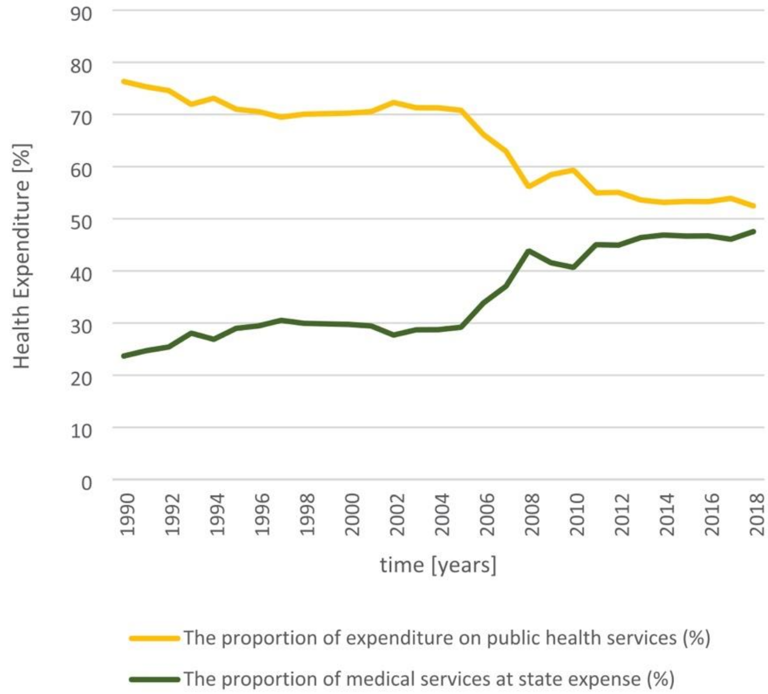

Fig. 10 Government expenditure on public health. Source: [70]

and access to gatherings is only permitted if the smart phone gives green light. This seems quite restrictive for Western societies. However, China is not alone in its "Zero-COVID" paradigm [76]. For instance, Australia [77], New Zealand [71] and Southern Korea [78] were quite successful in their eradication campaigns. New Zealand, for instance, never wanted to live with COVID-19, but eradicate it. When it started its campaign on March 23, 2020, the country just had about 100 COVID-19 cases and no deaths. As Philippe and Marques have shown for 11 G10 counties, countries following this strategy of early elimination are epidemiologically and economically more successful that countries pursuing a mitigation or suppression strategy [78]. This "go early go hard' approach is exactly what China is doing – it seems to work even in a liberal Western society like New Zealand [79].

Finally, China invests efforts to vaccinate its population against SARS-Cov-2 [80]. However, there is evidence that the combination of limited coverage (i.e. share of population able and willing to be vaccinated) and effectiveness of the vaccine will now allow to reduce completely the other interventions [81]. A certain part of the population will not be vaccinated because they will refuse or because age and/or health conditions do not allow [82, 83]. Moreover, the effectiveness of the vaccine to prevent the spread of the disease might be less than 90%. Consequently, there will be (smaller) waves of COVID-19 after the vaccination program will have been completed. Consequently, the instruments described in Table 3 will still have to be employed for a longer time.

Limitations

The results presented in this paper are subject to a number of limitations. Firstly, we did not model and simulate the precise reality of Wuhan. For a detailed analysis we would have to distinguish age-sets, locations (e.g. city quarters) and social interaction (e.g. schools, work place etc.). Our model is generic, but it permits the conclusion that the public health care system of China managed to control the most important parameters (number of persons contacted and number of contacts per person).

Secondly, some of the data applied to the simulation are uncertain. For instance, as the real number of infections in Wuhan is unknown (and will most likely remain unknown for political reasons) it is difficult to assess the infection fatality rate (f). As Meyerowitz-Katz & Merone show [58], the parameter f strongly differs from place to place with an average of 0.68% and a highest estimate of 1.7%. We assume that the case and consequently the infection fatality rate was towards the higher end in Wuhan in January and February 2020 as no diagnostic and treatment standards had been developed for COVID-19 patients. However, we are aware of the fact that this is an assumption.

For scenario II, an f of 0.015 (see Table 4) results in 8269 death cases within the first year, an f of 0.02 in 10, 745, an f of 0.01 in 5656 and an f of 0.005 in 2901 death cases. Consequently, the results react on changes on the parameters, but it is difficult to believe that medical care in Wuhan in the first months of the unknown diseases was as effective as health care systems that had months to learn how to diagnose and treat COVID-19 patients. Therefore, the simulation results might be challenged because of the uncertainty of input data, but the general finding that the number of death cases must be higher than reported is still valid.

Finally, the model presented in this paper does only present the situation in Wuhan in the first year of the epidemic. Consequently, we did not consider vaccination programs, temporary immunity or re-infections. As our objective was the analysis of the public health response in Wuhan in 2020, there was no need to include these aspects. Further research will have to focus on these issues much more.

Summarizing we can state that the model presented in this paper must not be used to predict the future spread of the disease. Instead, it is “modelling for insights, not for numbers” [53].

Conclusions

Although daily life in Chinese schools and work places is almost back to normal, China has maintained a number of interventions against COVID-19 until today (as of February 2021). Surgical masks and social distancing are a must in all public places, travelling abroad and visiting friends is strongly restricted, and access to public gatherings is only permitted if the smartphone app shows “green”. The app “Health Code” has become the daily companion of all citizens.

As our simulations demonstrate, a return to “normal” life with the same frequency and intensity of contacts as before the intervention would inevitably trigger a second wave if sufficient herd immunity had not previously been achieved. Assuming an R_0 of 2.5 for COVID-19, the herd immunity would have to be around 60%, i.e., 60% of the population would have to be immune against the virus to eradicate the disease. Even assuming that 90% of the infections in Wuhan were asymptomatic [64], the herd immunity would be about 40%, i.e., Wuhan is still at risk of COVID-19. Apparently, with the measures taken it is possible to keep the effective reproduction number below 1.

China has not implemented unique interventions. Masks, social distancing and mass testing are well-known instruments all over the world. The “secret” of China’s success in fighting COVID-19 seems to be the early reaction and rigor with which the public health system reacts at comparably low prevalence rates. Currently, the epidemic situation shows a pattern of sporadic and concentrated outbreaks in local areas. Until the herd immunity is reached by the (ongoing) vaccination program, the interventions will have to be maintained. Local outbreaks of COVID-19 were in urban areas with strict control of the population. Whether a rural outbreak could be managed as effectively in China, is questioned [84].

From a European perspective, door-to-door inspections and tight controls via apps are seen as serious violations of individual rights. However, these measures have prevented a second wave and saved lives so far. Some other countries have started seeing the mobile location data technology as an important component in the fight against COVID-19 without sacrificing citizen rights, such as the General Data Protection Regulation (GDPR) of the EU [85, 86]. Learning from the successful intervention program of China does not mean copying the entire portfolio of instruments, but it requires reflecting on the pros and cons of the instruments.

Abbreviations

CDC: Center for Disease Control; COVID-19: Corona Virus Disease 2019; ICTV: International Committee on The Classification of Viruses; NCIP: Novel Coronavirus Infected Pneumonia; 2019-nCoV: 2020-Novel Coronavirus 2019; NHC: National Health Commission; PCR: Polymerase Chain Reaction; USA: United States of America; WHC: Wuhan Health Commission; WHO: World Health Organization

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None

Authors’ contributions

MW initiated the research and collected all information in the Chinese literature. She drafted the paper and did all corrections. SF adopted the model and made the simulations. The author(s) read and approved the final manuscript.

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Publisher's Note

Eidesstattliche Erklärung

Hiermit erkläre ich, dass ich die vorliegende Dissertation selbständig verfasst und keine anderen als die angegebenen Hilfsmittel benutzt habe.

Die Dissertation ist bisher keiner anderen Fakultät, keiner anderen wissenschaftlichen Einrichtung vorgelegt worden.

Ich erkläre, dass ich bisher kein Promotionsverfahren erfolglos beendet habe und dass eine Aberkennung eines bereits erworbenen Doktorgrades nicht vorliegt.

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List of Publications

1. Meimei Wang, Steffen Flessa. Modelling Covid-19 under uncertainty: what can we expect? The European Journal of Health Economics. 2020; 21(5): 665–668. DOI 10.1007/s10198-020-01202-y

2. Biao Cheng, Meimei Wang, Steffen Fleßa. Covid-19 in Wuhan: Was können wir vom Ursprungsort der Pandemie lernen? Medizinisch Wissenschaftliche Verlagsgesellschaft. 2020. DOI https://doi.org/10.32745/WCFM-16

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