Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Preventive and control system for the life cycle of a pandemic

Chenyang Wang, Rui Ba, Ranpeng Wang, Hui Zhang

Department of Engineering Physics, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Keywords:
Pandemic
Life cycle
Prevention and control system

ABSTRACT

Herein, a matching method for varied epidemic phase characteristics and appropriate strategies is presented, aiming at the complexities of the novel coronavirus disease 2019 pandemic and the hysteresis of strategies. The classical diffusion dynamic models of the epidemic spread are compared. Furthermore, the Bass diffusion model is selected to study more characteristics of an epidemic, such as the diversities in regional internal and external infection rates. Thereafter, the classical division method vis-à-vis a pandemic life cycle is improved. A specific approach is proposed to portray more detailed characteristics of the pandemic by dividing it into more phases. Next, a four-level epidemic prevention and control measure system is concretized. The applicable phases and strategic effectiveness of each measure are integrated into the different phases of the pandemic life cycle. Finally, the matching method is applied to analyze two cases of the spread of the outbreak in cities and significant events. The findings provide a certain reference for the effectiveness of the matching method in the post-peak epidemic period.

1. Introduction

The emergence of the novel Corona Virus Disease 2019 (COVID-19) pandemic has engendered a substantial public safety threat and economic [1] loss worldwide, resulting in 450 million confirmed cases and 6 million deaths as of March 2022 [2]. It has been identified as a public health emergency of international concern because it has negatively impacted the financial income, daily life, and psychological health of the public in various countries. Notably, COVID-19 initially appeared in a few countries and subsequently propagated rapidly worldwide [3]. Furthermore, this caused a peak in the cumulative number of confirmed cases and deaths. The rise in infection rates has gradually leveled off, and the epidemic trend has gradually stabilized worldwide. The once global pandemic has reached a critical point in its transition to a post-peak period.

Since the outbreak of the pandemic, numerous scholars have simulated [4], fitted, and predicted its trend and spread on a global scale, especially during the early pandemic [5]. Han and Lei [6] used the Susceptible-Exposed-Infected-Removed (SEIR) model to study the global stability of endemic and disease-free equilibria by constructing appropriate Lyapunov functions. Ivanov [7] analyzed the spread of the epidemic to determine its impact on global supply chain performance and help policymakers identify elements of successful risk mitigation, preparedness, and recovery policies in an epidemic. Currie et al. [8] found the best solution to the set of different models needed to solve the range of problems related to disease transmission generated by the pandemic. Wang et al. [9] proposed a new two-layer multiplex network to study the multiple effects of awareness diffusion and epidemic spread. The results showed that the epidemic threshold was correlated with the topological outcome of the cognitive diffusion and epidemic network. He et al. [10] developed parameter-differentiated SEIR models corresponding to different COVID-19 scenarios based on general epidemic prevention and control measures, such as health screening, self-monitored quarantine, and population flow curbed, which were used to retrace the evolution of the outbreak in Hubei Province and further employed to predict the development of the COVID-19 pandemic. Rus et al. [11] used three models, including a generalized logistic growth model, a Richards growth model, and a sub-growth model, to conduct short-term simulations of the spread of the COVID-19 epidemic in Guangdong and Zhejiang, China. The results showed that the spread slowed in both provinces. Guo et al. [12] used a correlation analysis to determine the relationships between the number of confirmed cases and characteristic/distance variables in Wuhan, China. Wang et al. [13] derived the epidemic curve and predicted the epidemic trend in mid-2020 via a time series prediction model based on machine learning. Furthermore, a logistic regression model was integrated with epidemiological data to fit the novel COVID-19 epidemic and derive the upper limit of the pandemic trend. They predicted that the global number of infections would peak at 100 million in late October 2020. However, this now seems to considerably deviate far from the actual data.

Asselah et al. [14] have summarized the aforementioned epidemic models and data acquisition methods, showing that most mathematical...
modeling is based on Susceptible-Exposed-Infected-Removed SEIR and Susceptible-Infected-Removed (SIR) models [14]. Data collection included aggregated case reports, medical images, management strategies, healthcare workers, demographics, and mobility data [15] during the epidemic. They suggested that mathematical modeling and artificial intelligence were reliable tools for combating the epidemic.

The prolonged global spread of the epidemic has occasioned the continuous threat of high infection and mortality rates. Jakovljevic et al. [16] believed that it triggered many individual and group psychological problems, such as panic, anxiety, post-traumatic stress disorder, paranoia, infodemic, xenophobia, racism, and others. Kocak et al. [17] tested 3287 Turkish participants for COVID-19-related burnout in response to the abovementioned issues and found that the stress from the COVID-19 epidemic increased burnout among the public. They believed that protecting individual health from COVID-19-induced stress and reducing burnout were essential for interventions in the post-peak period.

Afzal et al. [18] reported that community work increased owing to the COVID-19 event. They argued that planning, coordination, and partnership were critical issues for the long-term effectiveness of community work in new situations. Moreover, in a follow-up study, they reflected on the problem of untimely healthcare response. They concluded that lack of preparedness was the main reason for the plight of healthcare organizations worldwide, such as shortage of sterilization and medical supplies for healthcare workers and lack of equipment for health institutions. Therefore, countries need to develop preparedness and action plans as guides to forestall future disasters and/or pandemics. Tsao et al. [19] examined the role of social media by surveying public attitudes, identifying informational epidemics, assessing psychological health, detecting or predicting COVID-19 cases, analyzing government responses to pandemics, and assessing the quality of health information in prevention education videos. They conclude that social media plays a significant role in disseminating health information, responding to epidemics, and spreading misinformation. Hedima et al. [20] argue that community health workers are crucial to public health-related activities and reduce pressure on global science and health service sectors in the fight against the COVID-19 epidemic. Lyu and Webby [21] explored the regulations issued by 15 US states and Washington DC regarding the use of masks and found that embracing the use of masks in public places could help decelerate the spread of COVID-19 through the analysis of raw experimental data. Budd et al. [22] discussed digital technologies to support the global public health response to the COVID-19 outbreak. They believed that optimal epidemic prevention could be achieved by integrating digital applications into systematic approaches to public health by evaluating interventions, including population surveillance, case identification, contact tracing, and mobile data-based communication with the public. Wilder-Smith et al. [23] concluded from a comparison with the severe acute respiratory syndrome response that if countries had the political will to swiftly implement measures to curb the spread of COVID-19, it would not necessarily degenerate into a rapidly growing and massive outbreak. Gkiotsalitis and Cats [24] investigated the impact of the novel COVID-19 epidemic on public transportation. They concluded that existing public transportation levels must be adjusted to further support epidemic interventions.

The aforementioned studies analyzed the transmission characteristics and evaluated the response measures taken during the previous phases of the COVID-19 epidemic. However, the mutated Omicron strain showed characteristics that differed from those of the Delta variant. This resulted in the inapplicability of the previous assessment models and corresponding measures to the post-peak period [25,26]. For example, China’s prevention and control measures have been successful since the onset of the COVID-19 epidemic [27,28]. However, it shows different propagation characteristics, such as the rapid transmission of the epidemic, and more asymptomatic carriers from the Omicron strain appeared. Some of the previous government response measures [29] are invalid for controlling the new Omicron variant of the epidemic, resulting in another small-scale outbreak of the novel COVID-19 within provinces in China since March 10, 2022 [30]. Therefore, a fundamental problem entails the determination of the adequate measures that should be taken and the choice of the appropriate domestic management measures regarding the opening-up strategies adopted overseas in the face of different epidemic risks than hitherto in the post-peak period [31,32]. There are various scenarios, such as importation of confirmed cases from overseas, holding significant gatherings, community activities, and quarantine in hospitals or hotels [33]. Selecting adjustable and systematic measures that address the characteristics of the transmission of different virus strains and cope with complex epidemic risks is essential [34]. Moreover, quantitatively evaluating and conducting case studies [35,36] regarding the effects of the prevention and control measures for epidemics, and dynamically adjusting them to ensure that economic development is not critically hampered while the domestic epidemic is duly controlled are crucial issues during the epidemic phase.

2. The life cycle of a pandemic

Diffusion dynamic models, such as the SIR model, fit and predict the spread of the novel COVID-19 epidemic. The equations of the SIR model are proposed as (1). It is appropriate to predict the epidemic spread within a region because its fixed infection and recovery rates occasionally lead to huge discrepancies with reality.

\[
\begin{align*}
\frac{dS(t)}{dt} & = -\beta S(t)I(t) \\
\frac{dI(t)}{dt} & = -\beta S(t)I(t) - \gamma I(t) \\
\frac{dR(t)}{dt} & = \gamma I(t)
\end{align*}
\]

\(S(t)\) is the number of susceptible cases; 
\(I(t)\) is the number of infected cases; 
\(R(t)\) is the number of recovered cases; 
\(\beta\) is the infection rate; 
\(\gamma\) is the recovery rate.

In this study, the Bass diffusion model is used to describe the propagation process of the pandemic. The equation is proposed as (2). It is regularly used to analyze emerging products and technologies to forecast product sales. The Bass diffusion equations present the interactions between people because of the excellent asymmetric characteristics by considering different transmission factors for internal and external environments, whereas the SIR model cannot work. It reflects more characteristics, such as the external infection rate, which varies because imported cases are changeable in different phases of a pandemic. The number of product users \(N(t)\) is treated as the number of confirmed cases when applied to epidemics. The internal diffusion coefficient \(p\) and external diffusion coefficient \(q\) are used as the infection rates of the regional internal and external propagation, respectively.

\[
\frac{dN(t)}{dt} = p[m - N(t)] + q \frac{N(t)}{m}[m - N(t)]
\]

\(N(t)\) is the cumulative number of confirmed cases until time \(t\); 
\(m\) is the number of confirmed cases when time \(t\); 
\(F(t)\) is the percentage of confirmed cases compared to susceptible cases; 
\(f(t)\) is the probability density of confirmed cases compared to susceptible cases; 
\(p\) is the external infection rate; 
\(q\) is the internal infection rate; 
\(m\) is the final cumulative number of the confirmed cases.

An S-curve diagram of the Bass diffusion model is shown in Fig. 1. Curve A shows the cumulative confirmed cases, while Curve B shows the cumulative confirmed cases under prevention and control measures. Curve C shows new confirmed cases, and Curve D shows new confirmed cases.
cases under prevention and control measures. The life cycle of a pandemic is roughly divided into three periods, namely, rising, rapid spread, and spread saturation periods, by this model. The curves are not the same as those of the SIR model equations because of the varied internal and external infection rates. Therefore, they can better reflect how propagation is effectively controlled through measures that decrease the total number of infections \( m \) and reduce the internal infection rate \( q \) and external infection rate \( p \). The \( p \), \( q \), and \( m \) values are reduced with the measures, as shown in Fig. 1.

The more commonly accepted division method of a pandemic by the World Health Organization, in addition to the basic division method, includes six phases. In Phase one, influenza viruses circulate continuously among animals, and they have not been reported to cause human infections. In Phase two, the virus circulates in animals and humans. In Phase three, the virus has caused limited human-to-human transmission but has not resulted in human-to-human transmission sufficient to sustain community-level outbreaks. Phase four is a community-level epidemic, and it significantly increases the risk of a pandemic. In Phase five, transmission has occurred in at least two countries. Phase six is the pandemic phase.

The confirmed case levels in most countries with adequate surveillance will drop below the observed peak levels during the post-peak period, and pandemic activities will appear to be decreasing. However, it is uncertain whether additional waves will occur, and countries must be prepared for a second wave. Waves of activity spread over months have characterized previous pandemics, so it is not advisable to relax the strategies prematurely.

Moreover, in the post-pandemic period, epidemic activity will return to the levels typically observed for seasonal influenza. At this stage, it is essential to maintain surveillance and update pandemic preparedness and response plans accordingly. An intensive recovery and evaluation phase is required.

It is evident that the six-phase division method is not sufficiently refined because the post-peak and post-epidemic periods are not included. Therefore, we reclassify the propagation process into 23 phases according to the change in the spatiotemporal state of the pandemic and the consideration of a pandemic’s life cycle, including the transmission object change and the propagation area expansion over time. Furthermore, the virus variations that have appeared in past pandemics are duly considered. The characteristics of each phase are also presented. In Phase A, the virus spreads between animals, and there is no apparent threat to humanity. In Phase B, the virus spreads between humans and animals, and this phenomenon should raise attention to the possibility of epidemics. The virus spreads between humans in Phase C, and small-scale outbreaks emerge. In Phase D, the virus spreads within a community. This is the first crucial phase for controlling the spread of the outbreak and requires rapid assessment, decision-making, and isolation for the cases. In Phase E, the virus spreads between two communities. The outbreak begins to spread and develop at multiple points, and restrictions on public transportation in the region are required. In Phase F, the virus diffuses within a province or city. The city needs to be rapidly locked down because the outbreak has spread. In Phase G, the virus spreads between two provinces and cities, indicating an imminent epidemic outbreak within a country. In Phase H, the virus spreads within a country or region. At this time, the country is required to screen for confirmed cases and control the spread of the epidemic. In Phase I, the virus spreads between two countries or regions, heralding the arrival of a pandemic. In Phase J, the virus spreads between more than two countries, and the relevant countries should implement measures to trace and isolate cases. In Phase K, the virus spreads globally. Countries should cooperate to prevent unnecessary human casualties and economic losses due to the pandemic. In Phase L, the virus mutates and spreads faster. The previous measures become inapplicable, and herd immunization should be achieved through vaccines or other approaches to prevent the rapid spread of the pandemic. The subsequent propagation phases of the mutated virus strain are similar to those of the original virus. However, the transmission characteristics are different, and strategies must be adjusted based on the experience garnered from the previous measures.

In Phase M, the new virus spreads in one community. In Phase N, the new virus spreads between two communities. In Phase O, the new virus spreads within a province or city. In Phase P, the new virus spreads between two provinces and cities. In Phase Q, the new virus spreads within one country. In Phase R, the new virus spreads between two countries. In Phase S, the new virus spreads to more than two countries. In Phase T, the new virus spreads globally. In Phase U, herd immunization or a high death rate leads to slower transmission. In Phase V, other waves may occur. In Phase W, it turns into regular seasonal influenza. The life cycle of a pandemic is shown in Fig. 2.

3. Multi-levels of prevention and control systems

Different countries have adopted several strategies in response to the epidemic owing to their various historical, social, cultural, and political systems. Some scholars have proposed models to assess the effectiveness of the measures taken by different countries. However, they cannot dynamically provide a reference for the strategy adoption by governments during an evolving epidemic with varied characteristics. At the country level, the promotion of vaccination and provision of medical resources play an essential role in controlling the rapid development of the epidemic. Strict civil aviation importation, cargo, customs, land borders, and immigration control measures are essential in preventing and controlling confirmed cases imported overseas in the post-peak epidemic period.

At the city level, appropriate planning to prevent and control public gatherings for significant events or holidays is key to preventing the diffusion of confirmed cases in all epidemic phases. Furthermore, in the severe stages of the epidemic, a city must adopt multiple measures, such as lockdown measures based on territorial capacities, nucleic acid testing, health codes, and trip codes based on big data technology transportation and logistics efforts to avoid out-of-control epidemics. At the community or organization level, the crucial points of effective prevention and control logistics, management of visitors, regular disinfection, vaccination, and nucleic acid testing of service staff are required. Self-protection, isolation, social distancing, and other behavioral guidelines need to be observed at the individual level.

The focus of epidemic prevention and control measures varies at different levels. Furthermore, the measures should match the varied char-
acteristics that appear in different epidemic phases. Therefore, we summarize the epidemic prevention and control strategies at the country, city, community, and individual levels based on the effectiveness of epidemic control measures, while referring to the Bass diffusion model, which includes decreasing the total number of infections and reducing the internal and external infection rates, as shown in Table 1. Moreover, the effects and applicable epidemic phases of the 86 measures are presented therein. The basis for strategy formulation in the phases of the post-peak epidemic period is established.

The roles of different epidemic prevention and control measures significantly vary from one another. Appropriate strategies must be adopted, dynamically applied, and adjusted to match the characteristics of the epidemic phases to achieve satisfactory control effectiveness.

4. Case study and discussion

4.1. Applications at the city level

Different epidemic phases require appropriate strategies owing to their varied characteristics. Otherwise, this may lead to deplorable consequences. For example, at the city level, the spread of the epidemic in Hong Kong, China, led to widespread transmission in Shanghai. The number of confirmed cases in Hong Kong rapidly increased from February 3, 2022, to April 5, 2022, as shown in Fig. 3.

The rapid spread of the Omicron variant has attacked the public in Hong Kong. The phases of the outbreak are divided using the 23-phase method, as shown in Fig. 3. Prevention and control measures in Hong Kong before the emergence of the Omicron variant had achieved good results. However, the Omicron virus spreads faster than the Delta virus and generates more asymptomatic carriers. It is challenging to proactively detect spreaders and track close contacts, which has led to a lag in prevention and control measures.

The outbreak in Hong Kong would spread quickly with a high probability in Phases M and N. Therefore, the confirmed cases should be rapidly identified and isolated with the cooperation of the public to block the entry to Phase O from the perspective of strategies. However, universal nucleic acid testing was not conducted as soon as possible to identify confirmed cases in Phases M and N because it was assumed that testing multiple types of personnel in Hong Kong was impossible. During Phase O, the significant increase in confirmed cases dramatically increased the demand for medical resources and placed a tremendous strain on the local government. No effective strategies had guaranteed the hospitals to operate normally, and hotels were insufficient for isolation, which led to the rapid propagation of the outbreak in the short term. Meanwhile, public perspectives on prevention and control strategies were wildly divergent during the outbreak because of the lack of appropriate leadership. A portion of the public was misled by malicious information and attempted to achieve herd immunization by refraining
Table 1

Four levels of prevention and control systems.

| Levels       | Id  | Measures                                                                 | Phases | Effects                              |
|--------------|-----|---------------------------------------------------------------------------|--------|--------------------------------------|
| Country      | 1   | Legislation/policy in response to the epidemic                           | F-V    | Reduce infection rate                |
|              | 2   | Guarantee medical resources such as masks                                | H-V    | Reduce internal infection rate       |
|              | 3   | International humanitarian assistance                                    | K-W    | Avoidance of global epidemics       |
|              | 4   | Border control                                                           | J-V    | Reduce external infection rate       |
|              | 5   | Rapid border crossing                                                    | I-W    | Reduce external infection rate       |
|              | 6   | Rapid reporting (cases)                                                  | C-V    | Reduce external infection rate       |
|              | 7   | Rapid nucleic acid testing                                               | E-V    | Reduce internal infection rate       |
|              | 8   | Rapid early treatment of confirmed cases                                 | C-W    | Prevention of death and infection   |
|              | 9   | Secure supply of drugs and protective supplies                          | H-W    | Prevention of death and infection   |
|              | 10  | Effective contact tracing                                                | G-V    | Reduce internal infection rate       |
|              | 11  | Risk communication                                                       | C-V    | Public cooperation                   |
|              | 12  | Vaccine development                                                      | H-V    | Herd immunization                    |
|              | 13  | Collaboration with other countries and international organizations       | K-V    | Avoidance of global epidemics       |
|              | 14  | Supporting governments/communities/organizations                          | F-W    | Prevention of infection             |
|              | 15  | Balancing individual rights and societal interests                       | C-W    | Public cooperation                   |
|              | 16  | Considering groups with higher risk                                      | D-V    | Public cooperation                   |
|              | 17  | Guiding public cooperation                                               | C-W    | Public cooperation                   |
|              | 18  | Regional coordination                                                    | B-W    | Prevention of infection             |
|              | 19  | Scientific direction for preventive and control measures                 | G-V    | Enhancing measures effectiveness     |
|              | 20  | Economic measures                                                        | H-V    | Economy conservation                |
|              | 21  | Social resource solicitation/call                                         | H-V    | Public cooperation                   |
|              | 22  | Technology to solve online meeting/schooling                             | A-W    | Technology for epidemic prevention   |
| City         | 23  | Lockdown                                                                 | F-V    | Decrease the number of infections   |
|              | 24  | Public health emergency response                                         | D-V    | Reduce internal infection rate       |
|              | 25  | Closure of cinemas and theaters                                         | F-V    | Avoid exposure                       |
|              | 26  | Cancellation of bars/parties and other gatherings                        | F-V    | Avoid exposure                       |
|              | 27  | Closure of factories                                                     | H-L    | Avoid exposure                       |
|              | 28  | Online teaching                                                          | H-V    | Avoid exposure                       |
|              | 29  | Travel bans                                                              | J-V    | Reduce external infection rate       |
|              | 30  | Shopping center crowd control                                            | F-V    | Avoid exposure                       |
|              | 31  | Hospital management measures                                             | H-V    | Prevention of infection             |
|              | 32  | Opening of fever clinics                                                 | H-V    | Prevention of infection             |
|              | 33  | Guarantee essential supply                                                | F-W    | General life assurance               |
|              | 34  | Implementation of phased measures                                        | B-W    | Enhancing measures effectiveness     |
|              | 35  | Support the construction of public health facilities                     | F-W    | Reduce internal infection rate       |
|              | 36  | Reporting reward system                                                  | H-V    | Preventing missing inspections      |
|              | 37  | Ensure the authority of data                                             | H-V    | Public cooperation                   |
|              | 38  | Expansion of medical staff                                               | H-V    | Reduce internal infection rate       |
|              | 39  | New/remodeled epidemic hospitals                                         | H-L    | Assurance of medical resources      |
|              | 40  | Reasonable grading of patient treatment                                 | D-V    | Reduce internal infection rate       |
|              | 41  | Meet basic medical needs                                                 | F-W    | Assurance of medical resources      |
|              | 42  | Reinforce online access to medical care                                  | H-V    | Prevention of propagation           |
|              | 43  | Prevent cross-infection within hospitals                                 | E-V    | Reduce internal infection rate       |
|              | 44  | Reduce the exposure risk of medical staff                                | E-V    | Decrease the number of infections   |
|              | 45  | Epidemic prevention publicity                                            | F-V    | Public cooperation                   |
|              | 46  | Communication channels with the public                                   | F-W    | Public cooperation                   |
|              | 47  | Close scenic spots                                                       | G-V    | Reduce internal infection rate       |
|              | 48  | Two-week observation period                                               | E-L    | Reduce internal infection rate       |
| Community    | 49  | Curbing population flow                                                  | F-V    | Decrease the number of infections   |
|              | 50  | Visitor control                                                          | E-V    | Avoid exposure                       |
|              | 51  | Body temperature monitoring                                               | D-V    | Prevention of infection             |
|              | 52  | Use of health codes                                                      | G-V    | Reduce internal infection rate       |
|              | 53  | Reducing unnecessary contact                                             | E-V    | Avoid exposure                       |
|              | 54  | Isolation of suspected cases                                             | F-V    | Reduce internal infection rate       |
|              | 55  | Enhance public education                                                 | H-V    | Public cooperation                   |
|              | 56  | Community protective services                                            | D-V    | Decrease the number of infections   |
|              | 57  | Requirement to wear masks                                                | C-V    | Reduce internal infection rate       |
|              | 58  | Vaccine promotion and popularization                                      | H-V    | Herd immunization                    |
|              | 59  | No-contact scenarios optimization                                         | H-V    | Avoid exposure                       |
|              | 60  | Bubble control                                                           | I-V    | Avoid exposure                       |
|              | 61  | Precise delineation of region management                                 | F-V    | Avoid exposure                       |
|              | 62  | Improve disposal capabilities                                            | F-W    | Decrease the number of infections   |
|              | 63  | Emergency training and drills organization                                | A-W    | Enhancing measures effectiveness     |
|              | 64  | Sensor and information management system                                  | G-V    | Prevention of propagation           |
|              | 65  | Community disinfection                                                   | D-V    | Decrease the number of infections   |
|              | 66  | Service staff nucleic acid testing                                       | D-V    | Avoid exposure                       |
|              | 67  | Community staff health information                                        | D-V    | Avoid exposure                       |
|              | 68  | Abnormal body temperature personnel traceability                         | D-V    | Reduce internal infection rate       |
|              | 69  | Reasonable division of functional areas                                  | D-V    | Reduce internal infection rate       |
|              | 70  | Equipped with access control/security check equipment                    | E-V    | Avoid exposure                       |
|              | 71  | Strengthen garbage confinement and classification management            | B-V    | Prevention of propagation           |
|              | 72  | Broadcast/electronic screen information promotion                         | D-V    | Public cooperation                   |
|              | 73  | Health screening                                                         | E-V    | Reduce internal infection rate       |
|              | 74  | Disinfectant and masks supply                                            | G-V    | Avoid exposure                       |

(continued on next page)
from embracing the measures. A lack of consensus leads to a low level of willingness to cooperate by the public. There was a complete mismatch between the strategies and the outbreak phases, with the inability to trace confirmed cases and isolate suspected cases promptly, as well as the lack of public cooperation. Numerous confirmed cases flowed to Shanghai in the absence of control, which pushed the outbreak in Hong Kong into Phase P.

Fig. 4 shows a reasonable time lag between the peak of the confirmed cases in Hong Kong and the rapid increase of the confirmed cases in Shanghai. The number of confirmed cases increased sharply after February 23, 2022. The newly confirmed cases in Hong Kong and Shanghai were infected with the Omicron variant of the virus GRK type, which suggested that the failure of the prevention and control strategies in Hong Kong facilitated the importation of confirmed cases into Shanghai. It is evident that mismatched strategies during the outbreak will cause aggravated damage to cities and even other regions.

Shanghai should have conducted universal nucleic acid testing and contact tracing in Phase M. Reasonable methods to delineate regions should also have been adopted because the Omicron virus spreads faster than hitherto, and the regions where prevention and control should be divided should be larger to inhibit the spread. No effective application of the dynamic zero-COVID policy has resulted in the continuous spread of the outbreak.

The data from March 23 showed a rapid increase in confirmed cases because of the beginning of the universal nucleic acid testing in Shanghai. However, the time was insufficient for the strategy to take effect because the outbreak had entered Phase O and spread widely in Shanghai. The Bass diffusion model concludes that when the number of infectious cases in a region is high, the epidemic is likely to spread more rapidly. Therefore, it is recommended to apply the lockdown strategy to reduce the cumulative number of infectious cases and block entry into Phases P and Q, which leads to multi-provincial or nationwide spread.

4.2. Applications in significant events

The 2020 Olympics in Tokyo, Japan, and the 2022 Winter Olympics in Beijing, China, were selected for comparison. Owing to the COVID-19 epidemic, the Tokyo Olympic Games were postponed to be held between July 23 and August 8, 2021. This study selected the change in the number of confirmed cases during the Tokyo Olympic Games from July 10, 2021, to October 1, 2021, as shown in Fig. 5.

The Beijing Winter Olympic Games were held from February 4, 2022, to February 20, 2022. The change in the number of confirmed cases during the Beijing Winter Olympics in Beijing, China, and its two closely associated provinces, Hebei and Tianjin, from January 23, 2022, to March 4, 2022, are shown in Fig. 6.

The strategy for managing the epidemic at the Tokyo Olympics was a semi-closed bubble. The athletes from abroad could take domestic public transportation in Japan to convenient stores and nearby places for other activities apart from accommodations, awards, interviews, training, and competitions after a 14-day quarantine. According to the Tokyo Olympic
Committee, there were 276 confirmed cases among Olympic-related personnel, including 24 athletes, as of August 2, 2021. The management strategies of allowing athletes and followers from abroad to access the public in the presence of confirmed cases tended to spread the infection from abroad in Japan. Therefore, the epidemic spread quickly from the athlete community to multiple communities, then to cities, and finally to the whole country. The number of confirmed cases in Japan reflected the progress, which continued to rise during the Tokyo Olympics and declined thereafter, as shown in Fig. 5. It can be seen that the mismatched semi-closed-bubble strategy to prevent the epidemic spread has resulted in the failure of the prevention and control strategy.

During the Beijing Olympic Games, China adopted a closed-bubble form of management. Athletes from abroad and other accompanying staff started to enter the closed bubble upon reaching Beijing. First, athletes with different vaccination statuses were categorized, and those who were not vaccinated needed to be isolated. Their subsequent activities were zoned, with transportation designed between each zone to ensure that potential carriers did not infect domestic volunteers and/or service staff in China. Meanwhile, the frequency of nucleic acid testing for volunteers and service staff was increased. A semi-closed-loop form of management was carried out to protect the volunteers and service staff from getting infected by potential carriers and effectively prevent them from spreading the epidemic in China once they were affected. There was no spread of cases during the Winter Olympics, as depicted in Fig. 6. The management strategy is shown in Fig. 7, which is quoted from the playbook [37] of the 2021 International Olympic Committee.

![Fig. 5. New confirmed cases in Japan during the Tokyo Olympics.](image1)

![Fig. 6. New confirmed cases in Beijing, Tianjin, and Hebei during the Beijing Winter Olympics.](image2)
5. Conclusions

A division method of a pandemic life cycle containing 23 phases is proposed based on the six-phase division method to portray the varied characteristics of different pandemic phases over time, considering that the present methods merely provide approximations and are unable to describe the details. A country-city-community-individual system containing 86 strategies was developed to be applied to the corresponding phases of the pandemic life cycle. The conclusions of this study are presented as follows.

First, the study reveals that the current division methods of the pandemic propagation process are not infeasible because of the prolonged life cycle of the pandemic and the complexity of the characteristics originating from virus mutation. Second, the 23-phase division method is proposed, and it captures more details of the spread of a pandemic. Third, strategies applied to prevent and control pandemics should not be constant. It is suggested that corresponding and matching strategies be applied in phases for the different characteristics of the pandemic evolution process. Fourth, applications of matching epidemic prevention and control strategies to the phased characteristics for two cases, including the city level and significant events, prove that the mismatching strategies are unable to prevent the spread of the outbreak to other regions and usually ensue heavy losses.

This 23-phase method is meant to characterize more phases of the pandemic, whereafter appropriate strategies can be selected to match the varied characteristics of different phases in the pandemic life cycle. It should also be noted that further studies on the quantitative assessment of the effectiveness of the matching method are required to improve the findings presented herein.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work is supported by National Key R&D Program of China (No. 2021ZD0111200), National Science Foundation of China (Grant No. 72174099), High-tech Discipline Construction Fundings for Universities in Beijing (Safety Science and Engineering).

References

[1] A.D. Kaye, C.N. Okeagwu, A.D. Pham, R.A. Silva, J.J. Hurley, B.L. Arron, N. Sarfraz, H.N. Lee, G.E. Ghali, J.W. Gamble, H. Liu, R.D. Urman, E.M. Cornett, Economic impact of COVID-19 pandemic on healthcare facilities and systems: International perspectives, Best Practice & Research-Clinical Anaesthesiology 35 (3) (2021) 293–306.
[2] M. Vildirim, F. Solmaz, COVID-19 burnout, COVID-19 stress and resilience: Initial psychometric properties of COVID-19 Burnout Scale, Death Stud. 46 (3) (2022) 524–532.
[3] K.B. Habersat, C. Betsch, M. Danchin, C.R. Sunstein, R. Böhm, A. Falk, N.T. Brewer, S.B. Omer, M. Scherzer, S. Sah, E.F. Fischer, A.E. Scheel, D. Faccourt, S. Kitayama, E. Dubé, J. Leask, M. Dutta, N.E. MacDonald, A. Temkina, A. Lieberoth, M. Jackson, S. Lewandowsky, H. Seale, N. Friel, P. Schmid, M. Gelfand, L. Korn, S. Eitzes, L. Flenedreff, P. Sprengholz, G. Salvi, R. Butler, Ten considerations for effectively managing the COVID-19 transition, Nature Human Behaviour 4 (7) (2020) 677–687.

[4] L. Kou, X. Wang, Y. Li, X. Guo, H. Zhang, A multi-scale agent-based model of infectious disease transmission to assess the impact of vaccination and non-pharmacological interventions: the covid-19 case, Journal of Safety Science and Resilience 2 (4) (2021) 199–207.

[5] Y. Mohamadou, A. Halidou, P.T. Kpe, A review of mathematical modeling, artificial intelligence and datasets used in the study, prediction and management of COVID-19, Applied Intelligence 15 (11) (2020) 3913–3925.

[6] S. Han, C. Lei, Global stability of equilibria of a diffusive SEIR epidemic model with nonlinear incidence, Appl. Math. Lett. 98 (2019) 114–120.

[7] D. Ivanov, Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case, Transportation Research Part E-Logistics and Transportation Review 136 (2020) 101922.

[8] C.S.M. Carrie, J.W. Fowler, K. Kotiadis, T. Monk, B.S. Onggo, D.A. Robertson, A.A. Tako, How simulation modelling can help reduce the impact of COVID-19, Journal of Simulation 14 (2) (2020) 83–97.

[9] Z. Wang, Q. Guo, S. Sun, C. Xia, The impact of awareness diffusion on SIR-like epidemics in multiple networks, Appl. Math. Comput. 349 (2019) 134–147.

[10] S. He, Y. Peng, K. Sun, SEIR modeling of the COVID-19 and its dynamics, Nonlinear Dyn. 101 (3) (2020) 1667–1680.

[11] K. Rus, V. Kilar, D. Koren, Resilience assessment of complex urban systems to natural disasters: A new literature review, International Journal of Disaster Risk Reduction 31 (2018) 311–330.

[12] X. Guo, X. Zhou, F. Tian, H. Zhang, Identification of the high-risk residence communities and possible risk factor of covid-19 in Wuhan, China. Journal of Safety Science and Resilience 2 (2) (2021) 31–39.

[13] P.P. Wang, X. Zheng, J. Li, B. Zhu, Prediction of epidemic trends in COVID-19 with logistic model and machine learning technics, Chaos Solitons & Fractals 139 (2020) 110058.

[14] T. Asselah, D. Durante, E. Pasmant, G. Lau, R.R. Schinazi, COVID-19: Discovery, diagnostics and drug development, J. Hepatol. 74 (1) (2021) 168–184.

[15] E.N. Muratov, R. Amarho, C.H. Andrade, N. Brown, S. Ekins, D. Fourches, O. Iasyev, D. Konakov, J.L. Medina-Franco, K.M. Mera, T.I. Oprea, V. Poroikov, G. Schneider, M.H. Todd, A. Varnek, D.A. Winkler, A.V. Zakharov, A. Cherkesov, A. Trophsa, A critical overview of computational approaches employed for COVID-19 drug discovery, Chem. Soc. Rev. 50 (16) (2021) 9121–9151.

[16] M. Jakovljevic, S. Bjerlov, N. Jaksic, I. Jakovljevic, COVID-19 pandemia and public and global mental health from the perspective of global health security, Psychiatria Danubina 32 (1) (2020) 6–14.

[17] O. Kokach, O.M. Kokach, M.Z. Younis, The Psychological Consequences of COVID-19 Fear and the Moderator Effects of Individuals’ Underlying Illness and Witnessing Infected Friends and Family, Int. J. Environ. Res. Public Health 18 (4) (2021) 1836.

[18] M.M. Afzal, G.W. Payrijo, Z.S. Lassi, B.Perry H, Community health workers at the dawn of a new era: 2. Planning, coordination, and partnerships, Health Research Policy and Systems 19 (SUPPL 3) (2021) 163.

[19] S.-F. Tsao, H. Chen, T. Tsieveronisighe, Y. Yang, L. Li, Z. Butt, What social media told us in the time of COVID-19: a scoping review, Lancet Digital Health 3 (3) (2021) E175–E194.

[20] E.W. Hedima, M.S. Adeyemi, N.Y. Ikumakaye, Community Pharmacist: On the front-line of health service against COVID-19 in LMICs, Research in Social & Administrative Pharmacy 17 (1) (2021) 1964–1966.

[21] W. Lyu, G.L. Wehby, Community Use Of Face Masks And COVID-19: Evidence From A Natural Experiment Of State Mandates In The US, Health Aff. 39 (8) (2020) 1419–1425.

[22] J. Budd, B.S. Miller, E.M. Manning, V. Lamos, M. Zhusang, M. Edelstein, G. Rees, V.C. Emery, M.M. Stevens, N. Stevens, M.I. Short, D. Short, E. Short, L.J. Short, D. Heymann, A.M. Johnson, R.A. McKendry, Digital technologies in the public-health response to COVID-19, Nat. Med. 26 (8) (2020) 1183–1192.

[23] A. Wilder-Smith, C.J. Chiew, V.J. Lee, Can we contain the COVID-19 outbreak with the same measures as for SARS? Lancet Infectious Diseases 20 (5) (2020) E102–E107.

[24] K. Gikotialitis, O. Cats, Public transport planning adaptation under the COVID-19 pandemic crisis: literature review of research needs and directions, Transport Reviews 41 (3) (2021) 374–392.

[25] C. Wang, H. Zhang, Y. Guo, Q. Deng, Comparative Study of Government Response Measures and Epidemic Trends for COVID-19 Global Pandemic, Risk Anal. 42 (1) (2022) 40–45.

[26] L. McLaren, Successful Societies: How Institutions and Culture Affect Health, Canadian Public Policy-Analyse De Politiques 36(3) (2010) 404-406.

[27] S. Meewor, J.P. Newell, M. Stul, Defining urban resilience: A review, Landec. Urban Plan. 147 (2016) 38–49.

[28] D. Koren, K. Rus, The Potential of Open Space for Enhancing Urban Seismic Resilience: A literature Review, Sustainability 11 (21) (2019) 5942.

[29] R. Francis, B. Bekeza, A metric and frameworks for resilience analysis of engineered and infrastructure systems, Reliab. Eng. Syst. Saf. 121 (2014) 90–103.

[30] A.E. Junco, Resilience as the new EU foreign policy paradigm: a pragmatist turn? European Security 26 (1) (2017) 1–18.

[31] D. Bailey, Social Resilience in the Neoliberal Era, Perspectives on Politics 13 (1) (2015) 160–161.

[32] R.D. Kusumastuti, V. Viverita, Z. Husodo, S. Suardi, Developing a resilience index towards natural disasters in Indonesia, International Journal of Disaster Risk Reduction 10 (2014) 327–340.

[33] D. Koren, V. Kilar, K. Rus, Proposal for holistic assessment of urban system resilience to natural disasters, World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium (WMCAS), 2017.

[34] S.A. Argryoudis, S.A. Mitoulis, L. Hofer, A. Zanini, E. Tubaldi, D.M. Frangopol, Resilience assessment framework for critical infrastructure in a multi-hazard environment: Case study on transport assets, Sci. Total Environ. 714 (2020) 136854.

[35] A. Tiwari, Modelling and analysis of covid-19 epidemic in India, Journal of Safety Science and Resilience 1 (2) (2020) 135–140.

[36] F.M. Khan, A. Kumar, H. Puppala, G. Kumar, R. Gupta, Projecting the criticality of COVID-19 transmission in India using GIS and machine learning methods, Journal of Safety Science and Resilience 2 (2) (2021) 50–62.

[37] International Olympic Committee, The Beijing 2022 Playbooks, (2021)https://olympics.com/ioc/beijing-2022-playbooks.