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Is compulsory home quarantine less effective than centralized quarantine in controlling the COVID-19 outbreak? Evidence from Hong Kong

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ABSTRACT

Faced with the global spread of COVID-19, the Hong Kong government imposed compulsory home quarantine on all overseas arrivals, while cities in mainland China and Macau adopted a more stringent centralized quarantine approach. This study evaluates the effectiveness of compulsory home quarantine as a means of pandemic control. Combining epidemiological data with traditional socioeconomic and meteorological data from over 250 cities, we employ the Synthetic Control Method (SCM) to construct a counterfactual "synthetic Hong Kong". This model simulates the infection trends for a hypothetical situation in which HK adopts centralized quarantine measures, and compares them to actual infection numbers.

Results suggest that home quarantine would have been less effective than centralized quarantine initially. However, the infection rate under home quarantine later converges with the counterfactual estimate under centralized quarantine (0.136% vs. 0.174%), suggesting similar efficacy in the later phase of implementation. Considering its minimal reliance on public resources, home quarantine with heightened enforcement may therefore be preferable to centralized quarantine in countries with limited public health resources. Home quarantine as a quarantine alternative balances public protection and individual freedom, while conserving resources, making it a more sustainable option for many cities.

1. Introduction

The highly contagious, fast-moving novel coronavirus disease COVID-19 has deteriorated into the most serious pandemic in human history. Confronted with the pandemic, countries around the world have imposed a series of control measures to contain the spread of the disease. COVID-19 has shown that it is imperative for governments to enhance the efficacy of epidemic prevention and control measures, to improve the capacity of the public health system, and to heighten risk management to strengthen city resilience. Quarantine measures are among the most widely used anti-pandemic non-pharmaceutical interventions (NPIs) and are an important tool in the prevention and control of novel infectious diseases (NIDs). However, quarantine also has high economic, societal, and psychological costs, with potential restrictions on individual freedoms (Nicola et al., 2020; Brooks et al., 2020; Parmet & Sinha, 2020). The necessity of wide-scale non-discriminate quarantine is also questioned since the number of individuals placed in quarantine who eventually test positive is perceived as being low (Ashcroft et al., 2021). Nevertheless, with the global scope of the pandemic, quarantine on inbound travelers has become an essential component in pandemic control measures. The implementation of quarantine varies across different jurisdictions, and home quarantine or household isolation is now commonplace in many countries (Zhu et al., 2020a). It is important for the government to evaluate and compare the effectiveness of different quarantine approaches, and to identify the best alternative for balancing public protection and individual freedom. Doing so will help to rebuild the resilience of our cities in the face of current and future epidemics.

As an international transportation hub, Hong Kong has been heavily impacted by the COVID-19 pandemic. The city confirmed its first case of

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COVID-19 on January 23[1], 2020. After tightening its border restrictions to control the spread of the virus from the mainland[2], Hong Kong had almost curbed the first wave of the outbreak by late February 2020, with only 3 cases confirmed on average per day[1]. However, as the disease proliferated globally and the World Health Organization (WHO) declared the COVID-19 outbreak a pandemic on March 11, Hong Kong was hit hard by a wave of new cases—mostly imported from overseas. As of April 30, 2020, Hong Kong had 1037 confirmed cases and four deaths. To prevent COVID-19 importations from foreign countries and control potential transmission in local communities, the Hong Kong (HK) government implemented compulsory home quarantine measures for all overseas arrivals since March 19. This is in contrast to the centralized quarantine approach adopted by Macau and many mainland cities during the same time period. These cities required inbound travelers to stay at designated hotels or quarantine centers for 14 days, and to undergo nucleic acid testing during their quarantine period. While mainland China has been quite successful in containing imported cases using the centralized quarantine approach, many countries and regions today are still taking the more flexible home-quarantine/self-quarantine approach, because of concerns about violations of freedom and public sentiments. Yet to date, whether home quarantine is as effective as centralized quarantine remains inconclusive in the literature. In fact, at the time of revising this paper, the HK government has decided to switch to the centralized quarantine approach, fully implementing the Designated Quarantine Hotel Scheme from 22 December 2020 onwards[3]. Our retrospective analysis evaluating the effectiveness of home quarantine for overseas arrivals helps to review Hong Kong's anti-pandemic policy decisions. Given that many countries are still faced with severe pandemic situations and waiting for vaccination programs to unfold, quarantine measures for international travelers are likely to continue for some time globally. Thus, this study should have immediate policy implications for the international community. Furthermore, it can provide empirical evidence for implementing effective quarantine measures for future infectious disease control.

Throughout the pandemic's development, the Hong Kong government gradually enhanced measures to prevent and control COVID-19 transmission from overseas. A detailed timeline of the implementation of relevant containment measures is provided in Fig. 1. The Hong Kong government first issued a Red Outbound Travel Alert (OTA) to all overseas countries/territories on March 17, urging the public to avoid all non-essential travel.[4] Following the Red OTA, the Department of Health expanded and strengthened quarantine measures for travelers arriving from certain countries.[5] On March 19, the government imposed 14-day compulsory quarantine measures for all international arrivals.[6] From March 19 onwards, while centralized facilities have been used to quarantine close contacts of confirmed cases and those arriving from a small number of high-risk areas,[7] for the majority of overseas arrivals, Hong Kong has relied on home quarantine. In contrast, many cities in mainland China adopted a centralized quarantine approach for citizens returning from overseas. Chinese citizens and foreigners undergo strict screening en route and upon arrival and are admitted to centralized observation facilities for a two-week quarantine (Normile, 2020).

The objective of this study is to evaluate whether home quarantine for overseas arrivals was as effective as the more stringent centralized quarantine approach. Although there have been multiple violations of home quarantine, which relies heavily on self-discipline, the obvious advantage of home quarantine over centralized quarantine is its minimal reliance on public resources. In this paper, we apply the synthetic control method (SCM) to construct a counterfactual model (a hypothetical reality that contradicts the observed facts), supposing Hong Kong had instead adopted a centralized quarantine approach for overseas arrivals. Traditional policy evaluation studies often use the Difference in Difference (DID) method to evaluate the effects of policy intervention (e.g., Dimick & Ryan, 2014; Neureiter, 2019; Zhu & Guo, 2021). The DID method estimates an outcome at an average level by comparing the average change over time for the treatment group and the control group. This method requires the fulfillment of parallel trend assumptions that the difference between the treatment and control groups is constant over time in the absence of the intervention. When we only have one city in the treatment group (i.e., Hong Kong), we are not able to use this DID method for averaging the treatment effects. A matching approach is also often used to identify a matched control unit based on both pre-treatment outcomes and other covariates (Diamond & Sekhon, 2013; Hainmueller, 2012). However, it is difficult and even not possible to find an existing city that shares, in every respect, very similar epidemiological trends and city characteristics to Hong Kong for comparison. The SCM approach combines elements of DID and matching techniques and offers a more systematic way to assign weights to the comparison group. SCM accounts for the effects of confounders changing over time and the dynamics of pre-treatment outcomes to construct a synthetic control unit that better approximates the characteristics of the real subject before the intervention (Kreif et al., 2016). Using a set of over 250 prefecture-level cities as donor units, our synthetic control unit is composed of multiple mainland cities with different weights, aiming to match many aspects of Hong Kong in the pre-treatment period, including Covid-19 case numbers, demographic and socioeconomic characteristics, and natural meteorological factors. After obtaining such a synthetic control unit, we then simulate the infection trends in this counterfactual model and compare the real infection numbers to the simulated trends. In this way, we systematically assess the effectiveness of compulsory home quarantine measures as compared to the centralized quarantine approach. Our results show that compulsory home quarantine, accompanied by strict penalties and supervision, can achieve infection control outcomes similar to the more stringent centralized quarantine approach. Previous occurrences of emerging infectious diseases have not stimulated studies addressing city health management (Junior et al., 2021). Our methodology using the data-driven SCM model to simulate counterfactual epidemic trends will contribute to the advancement of research methods for analyzing control measures against infectious diseases.

Previous literature mainly studies quarantine measures for COVID-19 cases and their close contacts. There is currently limited research available on the impacts of quarantine measures for inbound travelers in controlling the transmission of COVID-19. As the disease continues to proliferate in some parts of the globe, this stream of research is of great significance, especially in providing implications for government

[1] The statistics and situation of cases of COVID-19 are reported by the Centre for Health Protection. Department of Health, the Government of the Hong Kong SAR, see https://www.chp.gov.hk/files/pdf/local_situation_covid19_en.pdf

[2] The Hong Kong government had incrementally tightened its border control with mainland China by banning visitors from Hubei from entry, hauling the issuance of travel/entry permits and mandatory quarantine during the period from January 27 to February 8. For more details, see https://www.coronavirus.gov.hk/eng/inbound-travel.html

[3] Compulsory quarantine arrangement in Designated Quarantine Hotels for travelers who stayed in countries outside China, https://www.coronavirus.gov.hk/eng/designated-hotel.html

[4] Government issues Red Outbound Travel Alert on all overseas countries/territories, http://www.info.gov.hk/gia/general/202003/17/P2020031700577.htm

[5] DH to further extend and adjust health quarantine arrangements on inbound travelers from overseas, https://www.info.gov.hk/gia/general/202003/13/P2020031300832.htm

[6] DH to further extend health quarantine arrangements on inbound travelers from overseas https://www.info.gov.hk/gia/general/202003/17/P2020031700754.htm

[7] DH to further extend and adjust health quarantine arrangements on inbound travelers from overseas https://www.info.gov.hk/gia/general/202003/13/P2020031300832.htm

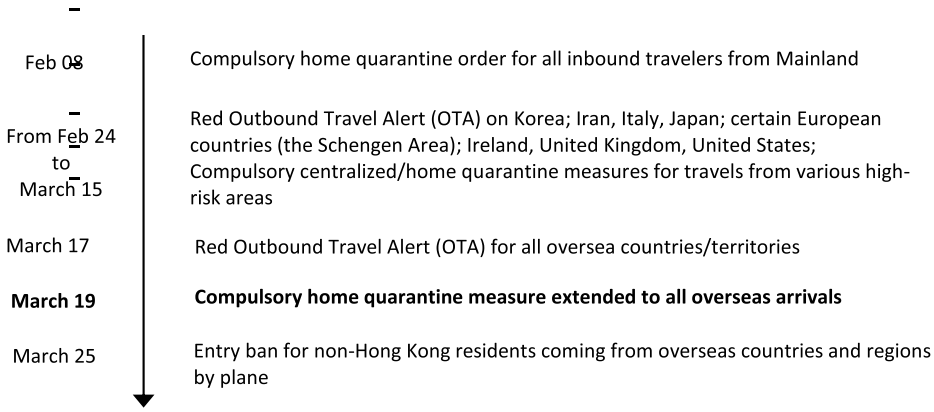

Fig. 1. Timeline of government containment measures to control COVID-19 transmission from overseas.

policymaking on pandemic control. More importantly, there is currently little empirical evidence on the effectiveness of home quarantine which is now becoming commonplace in many countries. This research will fill this gap in the literature by providing data-driven analysis of the effectiveness of different quarantine approaches (i.e., home-based quarantine and centralized quarantine). While our study focuses on Hong Kong, as the COVID-19 pandemic envelops the globe, many other cities also face similar challenges and utilize similar methods of pandemic control. Some, like Hong Kong, are cities where the virus is relatively well-controlled, attempting to prevent an imported wave. The success of home quarantine in Hong Kong suggests it may be a viable and cost-saving solution for these cities. Although Hong Kong is unique in many ways, not only in the great diversity and internationalization of the city itself, but also in its location and legal status as compared to mainland China, these characteristics do not directly relate to the effectiveness of compulsory home quarantine measures for overseas arrivals. Though we focus on compulsory home quarantine for inbound travelers, our findings also have implications for local home quarantine practices applied to control community transmission, including the Shelter-In-Place initiatives implemented in the U.S. and the Stay-At-Home order adopted in the U.K. The success of home quarantine in Hong Kong suggests that given appropriate implementation, Stay-At-Home or similar practices may also significantly lower infection rates and thus can be an effective tool for many cities and communities.

2. Literature review

The high transmissibility of COVID-19 is attributed to its unique epidemiological characteristics. Early patterns of human-to-human transmission of COVID-19 in China involved family-based and hospital-based clusters; however, outbreaks have been observed in settings as diverse as slaughterhouses, migrant worker communities, and meatpacking plants (Chan et al., 2020; Chen et al., 2020, 2020; Middleton et al., 2020; Joob & Wiwanitkit, 2020). It is generally accepted that COVID-19 is more transmissible than SARS-CoV and MERS-CoV (Hu, Guo, Zhou, & Shi, 2021; Li et al., 2020). A growing body of medical and clinical research suggests that people of all ages are susceptible to COVID-19 infection, while the median age of infection is approximately 50 (Guan et al., 2020; Huang et al., 2020; Wu & McGoogan, 2020). A notable characteristic of COVID-19 is its long incubation period, commonly cited as lasting up to 14 days, with some researchers even claiming an incubation period of up to 21 days (Alimohamadi et al., 2020; Leung, 2020; Koff et al., 2020). This has necessitated relatively long periods of quarantine for pandemic control, making quarantine more socially disruptive and potentially fiscally burdensome than in the case of many other infectious diseases. With the spread of the COVID-19 outbreak globally, virus importation has become a severe concern for governments all over the world. In jurisdictions that have managed to control infections relatively well locally, or in some cases have even reduced local cases to zero, preventing case importation and isolating incoming travelers has become an important juncture to control new sources of infection from places where infection rates are higher. The effectiveness of quarantine is also critical for a gradual opening up of movement without increase of transmission risks.

2.1. Impacts of quarantine measures on COVID-19 control

Quarantine is one traditional prevention measure deployed to control the outbreak of infectious diseases (Peak et al., 2020). Over a year has passed since the outbreak of COVID-19, and researchers from a wide range of disciplines have started to pay attention to the implementation of quarantine measures as a means to contain the spread of the virus. Most of these studies focus on domestic quarantine, such as quarantine for confirmed and suspected patients as well as their close contacts, community-level self-quarantine order, and city-level lockdown. Nussbaumer-Streit et al. (2020) conducted a comprehensive review of a number of observation and modeling studies on different infectious diseases and concluded that quarantine measures for individuals who were in close contact with a confirmed or suspected COVID-19 case were consistently found to have significant benefits. The positive effects are observed, especially when quarantine measures are combined with other prevention and control measures (e.g., travel restrictions, social distancing, and school closures). Quarantine measures were found to significantly reduce the COVID-19 infection rate in 10 highly infected countries; this is mediated by individual, cultural, demographic, and ethnic habits (Thu et al., 2020). Concerning quarantine for individuals, Dandekar & Barbastathis, 2020 used machine learning to quantify the effects of quarantine and found that countries implementing strict quarantine measures were successful in preventing the outbreak from exploding exponentially. With case numbers controlled at a relatively low level, the use of quarantine and cordon sanitaire to isolate potential cases has been an important measure for containing the pandemic in the final phase of the current outbreak in China (Tang et al., 2020), although Dandekar et al. (2020) suggested that random testing is a very close substitute for quarantine and can substantially reduce the need for indiscriminate quarantines to stop the diffusion of the disease. Some existing studies based in mainland China investigate the city lockdown in Wuhan and the use of cordon sanitaire as a relatively extreme form of mobility/travel restriction to influence the geographical transmission of COVID-19 (Fang et al., 2020; Tian et al., 2020; Kraemer et al., 2020). It was concluded that mobility restrictions in China during the COVID-19 pandemic were useful in the early stage of the outbreak to contain the virus within certain areas; however, its effectiveness may have decreased once the virus had spread out of certain boundaries (Tian et al., 2020; Kraemer et al., 2020). In terms of community quarantine measures, a study in Italy suggests that quarantine adherence has a

notable impact on reducing the outbreak, while less strict community quarantine can still flatten the curve of an outbreak compared to no quarantine (Sjödin et al., 2020).

There is limited research focusing on the effectiveness of home-based or centralized quarantine in the context of COVID-19 containment. Sehgal et al. (2021) are among the few to investigate the feasibility of home quarantine; they find that more than 1 in 5 U.S. homes lack sufficient space and plumbing facilities to comply with recommendations to isolate or quarantine to limit the household spread of COVID-19. Zhu et al. (2020a) argue that, compared with home quarantine, centralized quarantine for COVID-19 patients is not only more convenient for timely treatment and intervention but also helps to cut off transmission effectively.

In addition to its implications for virus transmission, psychology and health science scholars have also expressed concern about the psychological and physical impacts of quarantine measures. Many studies suggest that quarantine orders may impose negative impacts on people's mental health and cause anxiety and depression-related disorders, especially for children and the elderly (Saurabh and Ranjan, 2020; Zhu et al., 2020b; Khodabakhshi-koolaee, 2020; Luo et al., 2020). Others suggest that home quarantine could affect diet and physical activity and thereby increase the risks of other diseases (Goethals et al., 2020; Mattioli et al., 2020).

The existing literature covers evidence about the effects of domestic quarantine measures in containing COVID-19 transmission. There is also evidence suggesting that non-pharmaceutical interventions (NPIs) such as social distancing, suspending intra-city public transport, closing entertainment venues, and banning public gatherings contributed to the overall containment of COVID-19, while the effectiveness of isolating suspected and confirmed patients is not yet clear (Sun & Zhai, 2020; Tian et al., 2020; Ahmed et al., 2021). Previous studies have mainly focused on quarantine measures for confirmed cases and their close contacts but have seldom paid attention to quarantine for inbound travelers or overseas arrivals. As the COVID-19 pandemic continues to proliferate in some hotspot areas in the world, quarantine for overseas arrivals has been widely used in many countries to manage the risks of virus importation and prevent the resurgence of a local outbreak. It is thus important to investigate its impact on the overall performance of pandemic control. Furthermore, there has been limited evidence on the effectiveness of home quarantine, an increasingly common practice for both domestic quarantine and quarantine for overseas arrivals, in controlling the transmission of COVID-19. This study will fill this gap in the literature by examining the effectiveness of compulsory home quarantine for overseas arrivals as compared to the more stringent centralized quarantine approach. During the pandemic era, it is important to evaluate and review the implementation of quarantine measures to prevent virus importation. In addition, this Hong Kong-based study contributes to providing valuable lessons to many other cities that face similar threats of virus transmission from overseas hotspots to their local communities.

2.2. Other factors influencing the transmission of pandemic diseases

Previous literature on epidemics and pandemics suggests that regional socioeconomic characteristics and natural meteorological conditions also affect the transmissibility and severity of contagious diseases.

Socioeconomic status, social environment, and government response are important factors for the emergence of infectious diseases (Kim, 2021). Ethnicity, income, crime rate, and migration factors exhibit strong associations with COVID-19 cases and deaths (Maiti et al., 2021). Sociodemographic and healthcare factors, including population density and proportion of the elderly population aged 65 and above, as well as hospital beds and diabetes rates, are significant determinants of COVID-19 incidence rates (Mansour et al., 2021). Furthermore, per capita income, population with disabilities, the proportion of the population aged 17 or below, poverty, automobile ownership, and educational level are found to significantly impact stay-at-home behavior in the U.S. (Fu & Zhai, 2021). Living environment and housing quality can also be important predictors for the number of COVID-19 infections and death count (Hu et al., 2021; Das et al., 2021). Since high-speed rail connections alter the time–space relationships between cities (Cao & Zhu, 2017; Zhu 2021; Zhu et al., 2015), it is also proven to be a major facilitator that increases risks of virus transmission between connected cities (Zhu & Guo, 2021). Rail connectivity is the most influential regional built environment attribute that increases COVID-19 infection rates in a city (Li, Ma, & Zhang, 2021; Zhu, 2012, 2013). High-speed rail and air connectivity with Wuhan are significantly associated with increases in COVID-19 case numbers (Zhu & Guo, 2021). Research on other pandemic diseases found that the transmissibility and severity of the 1918-19 influenza pandemic were associated with regional socioeconomic situations, such as population density, illiteracy, unemployment, access to health care, and access to trade (Grantz et al., 2016; Tuckel et al., 2006, 2006; Clay et al., 2019; Mamelund et al., 2013; Adda, 2016).

Weather conditions may also play a vital role in the variance of a pandemic since airborne transmission is an important mode of infectious respiratory disease transmission (Guo et al., 2021). Some studies have investigated the role of meteorological conditions in the development of COVID-19. They use aggregated data from multiple countries to examine the relationship between meteorological variables (i.e., air temperature, relative humidity, wind speed, and visibility) and the severity of the outbreak on a global scale. They find that for all countries in general, the transmission of COVID-19 is significantly associated with weather conditions (Chen et al., 2020, 2020; Bannister-Tyrrell et al., 2020; Wang et al., 2020a, 2020b). Consistent with their findings, regional studies in Mainland China and Jakarta, Indonesia, also confirm the strong correlation between weather conditions and the spread of COVID-19 within a country (Shi et al., 2020; Tosepu et al., 2020). They suggest that daily mean temperature was one of the key factors determining the spread of the virus. Jia et al. (2020) show that a higher relative humidity helped to control the spread of COVID-19 in China. Similarly, studies of Severe Acute Respiratory Syndrome (SARS), the virus that shares high genetic homology with COVID-19, provide evidence that supports the claims that weather conditions influence the transmission of epidemic diseases (Tan et al., 2015; Bi, Wang and Hiller, 2007). Tan et al. (2005) find that the fluctuation of SARS cases in Beijing and Hong Kong during the peak of the outbreak in 2003 was negatively related to the daily maximum temperature, minimum temperature, daily temperature range, and sunshine hours. In addition, air quality could also affect the spread of a pandemic. Jia et al. (2020) confirmed the effect of air quality on the transmission rate of COVID-19, but such effects differ across regions with different levels of population movement. Studies of the 1918-19 Influenza Pandemic also provided unanimous conclusions about the impact of air quality on the severity of the pandemic. It was found that air pollution caused higher mortality among infected patients during the 1918-19 Influenza Pandemic (Clay et al., 2015; Clay et al., 2019).

In summary, the relevant literature demonstrates that social and economic factors, including the level of economic development, population density, illiteracy, unemployment, access to medical services, and transportation development, could affect the speed and scope of transmission of a virus. Another stream of the literature suggests that meteorological conditions such as air temperature, relative humidity, and air quality significantly influence the spread and severity of pandemics. Therefore, data on these factors will be collected and included as predictors in our simulation models.

3. Synthetic control method for simulating the counterfactual condition under centralized quarantine

To address the research question proposed, we apply the Synthetic

Control Method (SCM) to simulate the counterfactual trajectory of infections in a synthetic control unit, and then compare the simulated trend to the actual trend observed in Hong Kong. The SCM approach was proposed by Abadie and Gardeazabal (2003). This method has been broadly applied to evaluate the impacts of various economic policies and political reforms (Abadie et al., 2010; Billmeier & Nannicini, 2013; Adhikari et al., 2018; Marrazzo and Terzi, 2017; Barlow et al., 2017; Pieters et al., 2016). In terms of disease modeling, Mitze et al. (2020) has used the SCM as a key methodology to analyze the effect of face mask mandates on the spread of COVID-19 in Germany. The rationale behind SCM is that, although it is impossible to find a perfect control region to compare with Hong Kong, it is possible to make an appropriate combination of several major cities in mainland China to construct a fitted "synthetic control unit" which has similar characteristics and epidemic situation to Hong Kong. A major advantage of SCM is that the optimal weighted combination for the synthetic control unit is selected based on the data, which avoids the arbitrariness involved in a researcher's subjective selection of the control group. Instead of picking an existing city as the comparison unit, the SCM approach incorporates multiple potential donor units (i.e., over 250 mainland cities and Macau), calculates the optimal weighted combination of these donor units based on the data, and construct a "synthetic Hong Kong" with approximately the same pre-intervention characteristics as the real Hong Kong. SCM provides a data-driven approach to finding the best-suited synthetic control unit for comparison, thereby eliminating self-selection biases, ambiguity, and endogeneity issues that are often associated with policy interventions. Empirical research usually uses an instrumental variable approach to address the endogeneity issue and investigate potential causal effects (Zhu et al., 2018; Zhu et al., 2017).

Using such synthetic controls, we simulate COVID-19 transmission trends for the counterfactual situation that a centralized quarantine measure was adopted for overseas arrivals. Specifically, we will estimate the trends of daily new confirmed cases and cumulative confirmed cases in these counterfactual situations based on the aggregated epidemiological data from selected cities (i.e., donor units). By comparing the real case numbers in Hong Kong with the simulated trends, we can evaluate the effectiveness of compulsory home quarantine measures in terms of COVID-19 control.

3.1. Model specification

Our SCM model is illustrated as follows: we defined the number of confirmed COVID-19 cases for city j at time t as Y_{jt}. Suppose we have $J+1$ cities, where the first city ($j = 1$) (i.e., Hong Kong) is influenced by compulsory home quarantine after time T_0, and the remaining J cities (selected mainland cities which adopted centralized quarantine approach) constitute the donor pool of potential controls. Set Y^I_{jt} as the number of confirmed COVID-19 cases for city j with compulsory home quarantine measures for overseas arrivals and Y^N_{jt} as the simulated number of cases in the synthetic control unit where centralized quarantine measures were implemented at time $t \in [T_0 + 1, T]$. Then, the observed outcome Y^I_{jt} can be written as

$$Y^I_{jt} = Y^N_{jt} + \tau_{jt} D_{jt} \tag{1}$$

where τ_{jt} is the effect of policy intervention for city j at time t. Since we define that only the first city ($j = 1$) is influenced by compulsory home quarantine, the indicator D_{jt} takes the following form:

$$D_{jt} = \begin{matrix} 1 & for j = 1, t > T_0 \\ 0 & otherwise \end{matrix}$$

Our goal is to estimate $\tau_{1T_0+1}, \tau_{1T_0+2}, \ldots, \tau_{1T}$.

Following the notation of Abadie et al. (2003), we assume that Y^N_{jt} is given by a factor model

$$Y^N_{jt} = \delta_t + \theta_t Z_j + \lambda_t \mu_j + \varepsilon_{jt} \tag{2}$$

where $Z_j = [Z_{j1}, \ldots, Z_{jr}]'$ is a $(r \times 1)$ vector of observed predictors that are not affected by the policy intervention (i.e., compulsory home quarantine for overseas arrivals), as listed in Table 1. $\theta_t = [\theta_{1t}, \ldots, \theta_{rt}]$ is a $(1 \times r)$ vector of coefficients. $\lambda_t = [\lambda_{1t}, \ldots, \lambda_{kt}]$ is a $(1 \times k)$ vector of unobserved common factors. $\mu_j = [\mu_{j1}, \ldots, \mu_{jk}]'$ is a $(k \times 1)$ vector of unknown factor loadings. The error terms $\varepsilon_{jt}$are unobserved transitory shocks with zero mean, and δ_t is an unknown common factor with constant factor loadings.

In our analysis (T_0= March 19), D_{jt} indicates whether city j has imposed compulsory home quarantine or centralized quarantine for overseas arrivals at time t. If home quarantine was implemented, then $D = 1$. If centralized quarantine was implemented, then $D = 0$. For $t > T_0$, $\tau_{1t} = Y^I_{1t} - Y^N_{1t}$ calculates the effectiveness of compulsory home quarantine measures for overseas arrivals in Hong Kong, as compared with a centralized quarantine approach.

The real number of confirmed cases can be observed in Hong Kong; thus, we have $Y^I_{jt} = Y_{1t}$. However, Y^N_{1t}, the number of confirmed COVID-19 cases in the synthetic control unit, is not observed between $T_0 + 1$ and T. To estimate Y^N_{1t}, Abadie and Gardeazabal (2003) consider a $(J \times 1)$ vector of weights $W = [w_2, \ldots, w_{J+1}]'$ such that $w_j \geq 0$ for $j = 2, \ldots, J+1$ and $\sum_{j=2}^{J+1} w_j = 1$.

We try to approximate Z_1 and Y_{1t} for $t \leq T_0$ by a weighted average of donor units taking into account their observed covariates and outcomes during the pre-intervention period. Hence, for $t \in [1, T_0]$, $W = (w_2, \ldots, w_{j+1})$ is determined such that

$$Y_{1t} = \sum_{j=2}^{J+1} w_j Y_{jt} \tag{3}$$

$$Z_1 = \sum_{j=2}^{J+1} w_j Z_j \tag{4}$$

We use February 27 - March 18, the 21 days immediately prior to the extension of compulsory home quarantine measures to all overseas arrivals in Hong Kong, as the pre-intervention control period. Once W is determined, the effect of policy intervention at $t = T_0 + 1, T_0 + 2, \ldots$ is estimated as

$$\tau_{1t} = Y_{1t} - \sum_{j=2}^{J+1} w_j Y_{jt} \tag{5}$$

The optimal weights W should minimize the differences in pre-intervention characteristics between the real Hong Kong and the synthetic control unit. To obtain them, we use the optimization procedure proposed in Abadie et al. (2003), which technically minimizes the mean squared prediction error (RMSPE) to match the trend of the outcome variable between Hong Kong and the synthetic control during the pre-intervention period. RMSPE measures model fit and can be interpreted as the average difference in the outcome between the concerned research unit and the synthetic control unit (Abadie et al., 2015; Abadie

Table 1
Donor cities and weights for synthetic control units.

Synthetic HK 1 in Model 1 (Fig. 2) Outcome variable: cumulative cases		Synthetic HK 2 in Model 2 (Fig. 3) Outcome variable: daily new cases	
City	Weight	City	Weight
Shanghai	0.344	Shanghai	0.609
Macau	0.275	Macau	0.239
Jinan	0.176	Beijing	0.092
Yangjiang	0.132	Jinan	0.06
Qinzhou	0.047		
Panjin	0.026		

et al., 2010). Mathematically, the pre-intervention RMSPE in this study is defined as

$$RMSPE = \left(\frac{1}{T} \sum_{t=1}^{T_0} \left(Y_{1t} - \sum_{j=2}^{J+1} w_j Y_{jt} \right)^2 \right)^{\frac{1}{2}} \quad (6)$$

3.2. Handling potential confounding factors

As the quarantine intervention we study is targeted at overseas arrivals, we need to carefully consider how to incorporate the influx of overseas travelers in our analysis. However, including the number of overseas arrivals as a specific control variable in the SCM model would cause problems in evaluating the efficacy of quarantine measures. This is because quarantine measures reduce virus transmission from overseas travelers via two mechanisms: i) they help to prevent transmission and identify virus carriers by keeping potential carriers isolated during the incubation period; ii) they impose inconvenience and restrictions on overseas travelers and thus reduce the number of travelers who are willing to enter the city/country. Compared to home quarantine, centralized quarantine is a stricter policy measure that imposes more restrictions on freedom, and hence discourages more overseas travelers from entering. These two mechanisms make it unnecessary or even erroneous to include the number of overseas arrivals as a control variable in our model, because that would exclude the second mechanism and only reflect the partial impact of quarantine measures. If the number of overseas arrivals is added into the model as a control variable, then the model essentially assumes the synthetic Hong Kong (with centralized quarantine) and the real Hong Kong (with home quarantine) would continue to have approximately the same amount of overseas arrivals after the implementation of quarantine measures. This is problematic because the second mechanism of quarantine measures' impact on case numbers (i.e., via reducing the influx of overseas arrivals) is quite influential, as people are much less likely to travel to destinations with centralized quarantine requirements as compared to destinations with home quarantine measures. In sum, the number of overseas arrivals is part of the effects of quarantine measures (for both home quarantine and centralized quarantine). Controlling for this variable in the model would make the estimated impact of quarantine measures incomplete, hence making the comparison between the two quarantine measures incorrect.

Rather than specifically using the number of overseas arrivals in the model, we apply another approach to incorporate the influence from the influx of international travelers by ensuring that all donor cities composing the synthetic control unit have ports of entry (i.e., international airports, road, and rail border-crossing ports, or seaports) operating during the investigation period. The establishment and status of ports in each Chinese city were verified using the National Immigration Administration website (www.nia.gov.cn/n794014/n1050176/n1077211/n1215569/n1215581/index.html). There are around 100 cities with at least one port of entry operating during the period were identified. In practice, we use a "leave out" procedure in the SCM modeling. We do the SCM simulation with the complete set of 250 cities from the donor pool and obtain a synthetic control unit. Then, we check whether all selected donor cities have ports of entry operating during the investigation period; if not, we will drop the invalid donor cities from the pool and re-run the SCM until we obtain a synthetic control unit composed of cities with operating international ports. In this way, we can ensure that all donor cities that construct the synthetic control unit have a certain influx of people from overseas, and thus, the simulated synthetic control unit should be face risks of virus importation from overseas similar to Hong Kong.

Another concern might be provoked by the changes in immigration policies toward inbound travel. In fact, Mainland China and Hong Kong implemented similar entry restrictions on foreigners in a fairly close time period. Mainland China imposed travel bans on foreigners with visa or residential permits on March 28[8], and Hong Kong restricted all non-Hong Kong residents from entering the city on March 25, as previously mentioned. These immigration policies are essentially the same; neither mainland cities nor Hong Kong modified their entry bans during our investigation period. Therefore, changes in immigration policies toward inbound travel should not be a major confounding factor in our estimation.

4. Data and Variables

This study combines epidemiological data with natural meteorological data and census data from more than 250 cities in China and Macau to construct synthetic control units for counterfactual analysis of Hong Kong's policy interventions. We use the number of daily cumulative confirmed cases and the number of daily new confirmed cases as the outcome variables to represent the level of outbreak. A variety of city-level variables are used as major predictors in our SCM models, including demographic and socioeconomic variables, and natural meteorological variables (e.g., daily average temperature, relative humidity, wind speed, and air quality index). To rule out any confounding effects derived from the systematic differences other than the disparity in quarantine measures (i.e., home vs. centralized) between Hong Kong and the synthetic control unit,[9] we incorporate two epidemiological variables that measure pre-intervention infection trends as additional predictor variables. They are the mean of daily cumulative case numbers for the 14-day pre-intervention control period and the mean of daily cumulative case numbers per 10,000 people for the same period (which takes into account population size). Our city-level data are obtained from a variety of sources.

Prefecture-level COVID-19 epidemiological data. We utilize prefecture-level daily epidemiological data in our SCM analysis. Daily epidemiological data for February to April 2020 were drawn from an open-source project called the COVID-19 Epidemic Spatial-Temporal Dataset (https://github.com/Estelle0217/COVID-19-Epidemic-Dataset).

Demographic and socioeconomic data. Regional social and economic factors, including the level of economic development, population density, illiteracy, unemployment, access to medical services, and transportation development, could affect the speed and scope of transmission of a contagious disease (Clay et al., 2019; Adda, 2016; Grantz et al., 2016; Mamelund et al. 2013; Tuckel et al., 2006, 2006). In this study, demographic and socioeconomic data for each city were obtained from the 2019 China City Statistical Yearbook (data for the year 2018), and the Statistical Yearbooks provided by Hong Kong and Macau's Census and Statistics Departments.

Natural meteorological data. Weather conditions and air quality have all been proven to influence the transmission of COVID-19 (Chen et al., 2020, 2020; Bannister-Tyrrell et al., 2020; Wang et al., 2020a, 2020b;

[8] The Chinese Ministry of Foreign Affairs, 2020. Announcement on the temporary suspension of entry by foreigners holding valid Chinese visas and residence permits. available at https://www.fmprc.gov.cn/web/wjbxw_673019/t1761858.shtml

[9] These systematic differences may include any 'human elements' – social context and the fundamental differences between people in Hong Kong versus Macau and mainland in terms of their behaviors (e.g. public compliance), other available containment policies (e.g., use of health bar codes and big data to facilitate the contact tracking in mainland cities, community checkpoints, etc.), and the strictness of policy enforcement (e.g., manpower and penalty). These systematic differences would have been embedded and reflected in their own pre-intervention infection trends and remained mostly unchanged during the intervention period.

Shi et al., 2020; Tosepu et al., 2020; Jia et al., 2020) and other epidemics (Clay et al., 2019; Clay et al., 2015; Bi et al., 2007; Tan et al., 2005; Ye et al., 2004). Thus, our model incorporates various city-level natural meteorological factors based on the literature, including daily average temperature, relative humidity, wind speed, and air quality index (AQI). With our SCM model, we ensure that the meteorological environment of the constructed synthetic control unit (where centralized quarantine is hypothetically implemented) is similar to Hong Kong. Meteorological data were obtained through the China Meteorological Data Service Centre (http://data.cma.cn/), the Hong Kong Observatory (www.hko.gov.hk), and the Macao Meteorological and Geophysical Bureau (www.smg.gov.mo). For each city, the values of daily average temperature, relative humidity, and wind speed are calculated using Empirical Bayesian Kriging interpolation in ArcGIS Desktop. Kriging is a statistical technique for optimal spatial prediction. Compared with classical Kriging methods, the Empirical Bayesian Kriging is more robust as it accounts for the error introduced by estimating the semivariogram model (Krivoruchko, 2012). AQI data for each city in mainland China are collected from Harvard Dataverse (https://doi.org/10.7910/DVN/XETLSS), while daily AQI data for Hong Kong and Macao are collected from the World Air Quality Index (WAQI) project (https://aqicn.org).

By accounting for these influencing factors, the SCM model ensures that trends in the pre-treatment period capture the non-linear nature of disease transmission. We also acknowledge that other non-pharmaceutical interventions (NPIs) not restricted to overseas arrivals, such as rapid testing, contact tracing, and the self-quarantine of local residents, influence the number of confirmed cases. However, there were no major changes in these domestic interventions in either mainland cities or Hong Kong during the pre-treatment and treatment periods (March–April). For example, rapid testing and contact tracing have been broadly adopted in both HK and Mainland China, and self-quarantine of local residents (close contacts of confirmed cases) were enforced in both places throughout the study period. Therefore, other interventions are not likely to be responsible for any significant differences between the real HK and our synthetic HK during the investigation period.

5. Results

In our SCM models, we tested the effectiveness of compulsory home quarantine measures for overseas arrivals to Hong Kong, as compared to the compulsory centralized quarantine measures implemented in most mainland cities. After data cleaning, the donor pool contains 282 cities. For the pre-intervention control period, we select the 14-days immediately prior to the implementation of compulsory home quarantine measures to all overseas arrivals. This choice of control period covers the 14-day long incubation period of the disease. Since the outbreak evolved quickly during the sampling period, this relatively shorter control period, therefore, better captures the variance in infections and the dynamics of city environments. Table 1 indicates the weights of the donor cities that constitute the synthetic control units used in the simulations for the trends of cumulative cases and daily new cases. Our SCM incorporates several important covariates to simulate the synthetic control unit and to predict the infection trends under it. The selected donor cities are chosen based on similarity to Hong Kong in terms of outbreak situation as well as socioeconomic, demographic, and natural meteorological conditions during the pre-intervention period. This selection method results in some cities close to Hong Kong, such as Guangzhou, not being selected while others less intuitively related to Hong Kong are included because of their similarity in infection numbers, socioeconomic conditions, and meteorological conditions. Table 2 shows the pre-treatment balance of predictors for Hong Kong and the synthetic controls. The modeling results for cumulative and new case trends are shown in Figs. 2 and 3.

Fig. 2 demonstrates that implementing home quarantine for overseas arrivals in Hong Kong resulted in a higher number of cumulative cases, as compared to the counterfactual model of infection trends if centralized quarantine measures had been imposed for all overseas arrivals. Our model suggests that if Hong Kong had hypothetically quarantined overseas arrivals at centralized quarantine sites, the outbreak situation would have been contained at a moderate level, with no more than 250 cumulative cases (246.07 cases in total, as of April 30), while the actual infections reached 1037 cases during the study period. During the first three weeks of intervention, the gap between the actual number of cases and the corresponding counterfactual estimates in our synthetic control widens. However, Hong Kong later observed a slowdown in the growth of infections (as represented by the flatter slope of the actual case numbers line). The two lines become almost parallel after mid-April, meaning that the growth rate of infections became very similar under the two quarantine scenarios. In fact, the average daily growth rate of cumulative infections[10] after April 15th (until the end of April) is even lower in the actual data (0.136%, with home quarantine measure) than in the synthetic control (0.174%, with centralized quarantine measure). Taking into account the long incubation period of COVID-19 and the reporting lag of 2–3 days, our results suggest that, less than one month after the intervention, compulsory home quarantine measure for overseas arrivals was as effective as a centralized quarantine approach in terms of slowing down the transmission of COVID-19 in Hong Kong.

Fig. 3 compares the actual and simulated daily new confirmed cases and indicates that implementing home quarantine for overseas arrivals resulted in more daily new cases than if a centralized quarantine approach had been adopted. During the early stage of intervention, the number of daily new cases estimated under the centralized quarantine scenario slightly increases and then gradually decreases until April 9, while actual infection patterns fluctuated widely. However, the hypothetical infection trend surges to 35.1 new cases on April 11, far more than the actual infection numbers (11 new cases) recorded in Hong Kong. This unusual surge in the estimated trend is largely due to the

Table 2
Balance of predictor variables. [12]

Outcome Variable		# of cumulative cases (Fig. 2)	# of daily new cases (Fig. 3)
Predictors	Real HK	Synthetic HK 1	Synthetic HK 2
Pre-intervention 14-day mean of daily cumulative case numbers	133.64	133.64	238.79
Pre-intervention 14-day mean of cumulative cases per 10,000 people	0.15	0.16	0.21
City-level GDP (million yuan)	2,398,046	1,365,708	2,322,997
Population Density (# of persons per sq.km)	6,736.89	7,034.94	6,722.28
# of Hospital Beds per 10,000 persons	54.27	62.24	67.50
# of Doctors per 10,000 persons	19.66	40.19	43.22
Average Temperature (℃)	20.62	14.74	13.71
Relative Humidity (%)	81.50	81.82	85.33
Wind Speed (m/s)	6.67	3.15	3.00
Air Quality Index (AQI)	71.50	61.22	53.18
RMSPE		**21.411**	**6.296**

[12] Though the simulated number of doctors per 10,000 people in synthetic Hong Kong is higher than the real number in Hong Kong, it would not result in a significant deviation in the results since Hong Kong mobilized a considerable number of civil servants and police officers to work on the pandemic frontline.

[10] Calculating the average daily growth rate of cumulative infections: Hong Kong has 1016 cumulative cases on April 15 compared to an estimated number of 239.72 cumulative cases in the synthetic control unit. On April 30, Hong Kong counts 1037 cases while the synthetic control unit has 246.07 cases, in total. The average daily growth rate in Hong Kong is denoted by r and can be computed from $1016\ (1+r)^{15}=1037$. Similarly, the average daily growth rate in the synthetic unit r_c can be computed from $239.72(1+r_c)^{15}=246.07$.

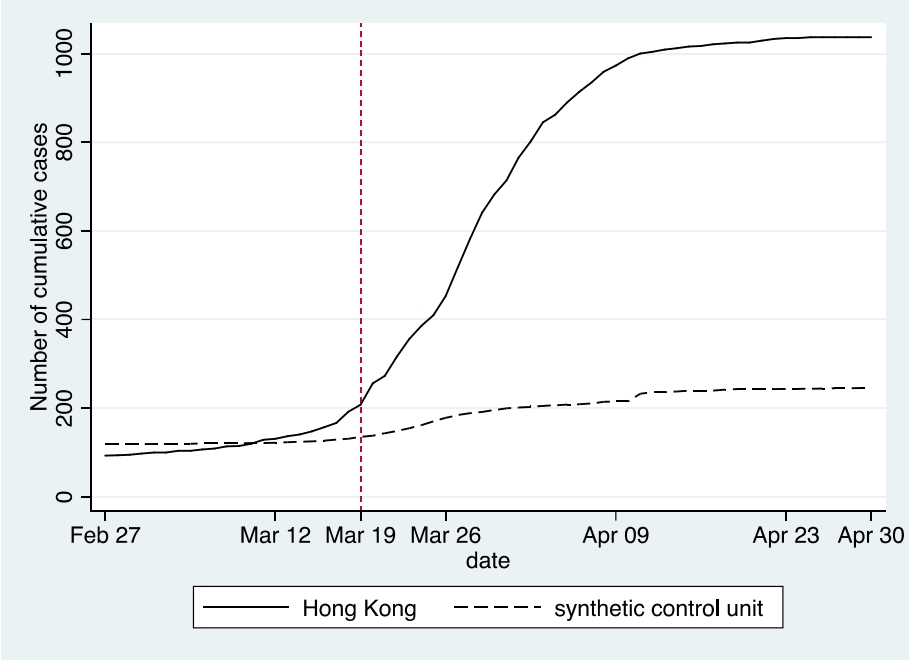

Fig. 2. Number of Cumulative Cases (Hong Kong vs. Synthetic control unit).

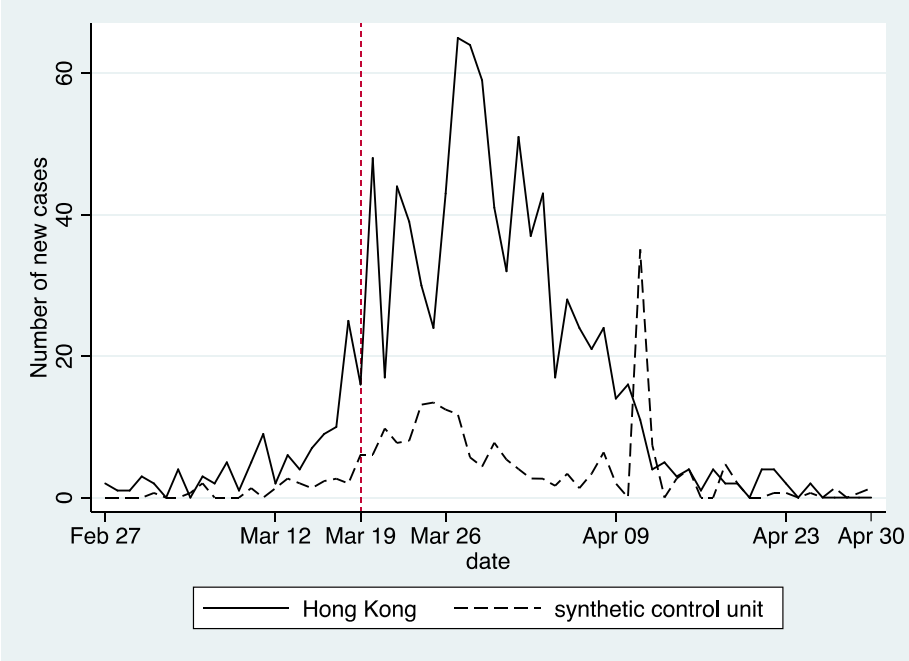

Fig. 3. Number of daily new confirmed cases (Hong Kong vs. Synthetic control unit).

sudden rise of imported cases in Shanghai, which is a major donor city and contributor to our synthetic control unit (see Table 1). Shanghai reported 52 cases and 11 cases on April 11 and 12, all of them imported cases from overseas[11]. This indicates that centralized quarantine for overseas arrivals still faces uncertainties in terms of controlling the number of new infections and might not curb the transmission entirely.

After April 11, the numbers of new confirmed cases both in Hong Kong and the synthetic control unit remain stable at a lower level in late April. Fig. 4 shows more intuitively the gap between new confirmed cases in Hong Kong and the synthetic control unit. In fact, Hong Kong demonstrated a gradual reduction in the number of new confirmed cases after reaching a peak of 65 new cases on March 27, reflected in the downward convergence of actual trends with the synthetic control in April. On April 11, Hong Kong even observed a much lower number of new cases as compared to the centralized quarantine scenario. The entry ban on non-HK residents and the suspension of all international transfers at the Hong Kong International Airport as of March 25 may have contributed

[11] Shanghai Municipal Health Commission and Administrator of Traditional Chinese Medicine, 2020, Shanghai reported imported cases from overseas. Available at http://wsjkw.sh.gov.cn/xwfb/20200412/e90b4f8f7baf4cf39b9bc7eaddc14c60.html

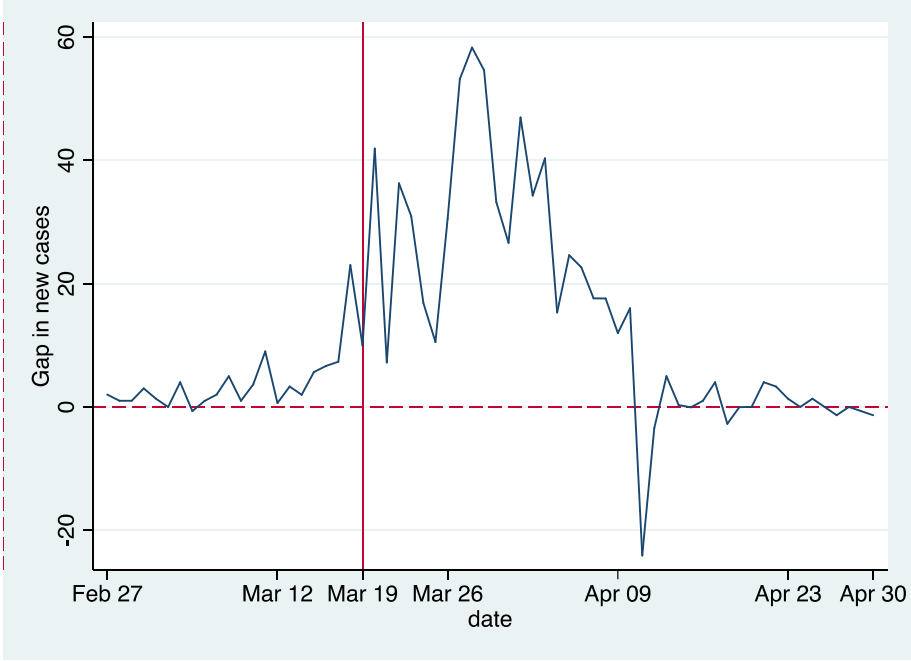

Fig. 4. Gap of daily new confirmed case in Hong Kong and the synthetic control unit.

to this decline, as well as the fact that the tide of international returnees was coming to an end by early April. More importantly, the government took pains to strengthen virus detection for overseas arrivals and to improve tracking to ensure compliance with home quarantine measures. After this, the trend in actual new confirmed cases converged with the counterfactual trend in our synthetic control unit. This corroborates the finding that home quarantine and centralized quarantine have similar efficacy in the later stage of intervention.

At the beginning of the intervention, it is unlikely that the implementation of compulsory quarantine would have immediately stopped the spread of COVID-19. Given that the global outbreak had already begun at the time of intervention, and that COVID-19 has a 14-day incubation period, it is likely there were cases already in the community that quarantine on arrival could not address. Moreover, policy announcement effects may have contributed to a large influx of people returning to Hong Kong from overseas before March 19 to avoid compulsory quarantine, leading to the surge in imported cases and raising the risks of community transmission. Since such compulsory quarantine measures are without precedent in Hong Kong, supervision to ensure compliance was insufficient in the early stages of enforcement, reducing the effectiveness of the measures. However, in the latter stages of policy implementation, advanced technology (e.g., electronic wrist bands with geolocation services enabled) and severe punishment have increased the effectiveness of home quarantine and made its advantages apparent.

As mentioned previously, the value of RMSPE represents how well the pre-intervention trend of the outcome variable in the synthetic control unit matches the actual trend in Hong Kong. It is important to note that the value of RMSPE is affected by the scale of the outcome variable, as shown in Eq. (6). Therefore, a direct comparison of RMSPE values between models with different outcome variables is inappropriate. In this paper, we model two outcome variables: the number of cumulative cases and the number of daily new cases. A much higher RMSPE in the cumulative case model as compared to the daily new case model is therefore reasonable. The estimated RMSPE values in Table 2 indicate that the average difference in the number of cumulative cases between Hong Kong and the synthetic control unit in Fig. 2 is 21.411, while the average difference in the number of daily new cases between Hong Kong and the synthetic control unit in Fig. 3 is 6.296.

6. Discussion

While there have been doubts about the efficacy of home quarantine given its strong reliance on self-discipline, the results of this study suggest that home quarantine can potentially be as effective as centralized quarantine for containing infectious diseases. In the early stages of the intervention, infection trends under home quarantine were found to be higher than in the counterfactual model with centralized quarantine. However, these high numbers in the real-world infection trends might be the result of a large influx of residents returning to Hong Kong from overseas, as well as the long incubation period of COVID-19. In the later stages of implementation, the effectiveness of home quarantine became more apparent. The actual number of daily new confirmed cases in Hong Kong started to decrease and converged with the trends in our synthetic control unit with centralized quarantine. This could be because, in the later stage of implementation, enhanced surveillance measures such as using wristbands and Bluetooth location information for tracking, as well as legislation against breaching the compulsory quarantine orders, have collectively improved the effectiveness and benefits of home quarantine. The results suggest that compulsory home quarantine measures with enhanced enforcement can be as effective as centralized quarantine while minimizing reliance on public resources. Therefore, we believe that Hong Kong's compulsory home quarantine for inbound travelers has the potential to realize its goals of reducing transmission from overseas, when supervision and legal punishment mechanisms are strengthened. In this regard, the recent amendment of the policy to change home quarantine to centralized quarantine at designated hotels from December, 2020 might be overcautious as well as less cost-effective, because it significantly increased the quarantine costs (e.g., monetary and psychological) for travelers. The results suggest that as long as the epidemic does not significantly intensify, cities/countries can consider relaxing centralized quarantine requirements for overseas arrivals. Those who come from non-hotspot areas could be allowed to home quarantine. The resources saved by choosing home quarantine measures could instead be utilized to enhance testing for earlier diagnosis and treatment, and thus to block virus transmission more effectively. For countries with very fragile public health systems and limited public health resources, compulsory home quarantine could be adopted as an alternative to manage the risks of imported cases. Supervision and

punishment mechanisms should be set up to guarantee compliance with compulsory quarantine guidelines in order to achieve optimal suppression effects.

With Hong Kong still amid its third wave of COVID-19, our findings may help the Hong Kong government to make timely amendments to current anti-pandemic policies, to improve its precautionary governance for managing future Novel Infectious Diseases (NIDs), and to expand its policy capacity with predicament thinking under big uncertainties and complexities of those hard-to-tackle wicked problems. These findings may also be useful to policymakers in other parts of the world as they continue to develop policy interventions to control the spread of COVID-19 while seeking to minimize the costs of such interventions. Empirical evidence of the effectiveness of a more flexible and lower-cost quarantine measure (e.g., home-based quarantine) allows policymakers worldwide to make more informed decisions for their cities or countries when seeking to balance both cost and safety considerations. These findings are not only important for policymakers responding to the current COVID-19 pandemic, but they will also be relevant to policymakers handling future novel infectious disease outbreaks.

Furthermore, this timely research provides a generalizable analytical framework for evidence-based decision-making in managing infectious diseases and protecting public health; our methodology can be generalized and applied to other cities or regions to inform their policymaking. The results of this research may also be used as inputs for cost-effectiveness comparisons of multiple policy alternatives via other larger research projects. Nonetheless, we acknowledge that this study may bear some limitations. Hong Kong and cities in mainland China are different in terms of citizen compliance, social and cultural environment, political regimes and institutions, and the power of governing authorities (e.g., the rule of law in Hong Kong vs. rule by law in China). These inherent differences may possibly influence the effectiveness of their respective control policies. The best strategy would be to explicitly control them when constructing the synthetic control unit. However, these factors cannot be included in our model because they are time-invariant variables. Alternatively, we use a long pre-treatment period in our SCM model and match a wide range of epidemiological, socio-economic, and meteorological factors through simulation for this period. Arguably, our well-fit simulation results for all outcome and explanatory variables suggest that those unobserved factors (e.g., political system, social context) have also been implicitly controlled.

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.

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N/A

Author Contributions

P.Z. conceptualized the study and carried out initial planning. P.Z. supervised a research assistant to retrieve and construct the dataset. X.T. carried out the statistical analysis under P.Z.'s supervision. P.Z. and X.T. both drafted the paper, which was later finalized by P.Z. Both authors reviewed and approved the final draft.

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