Effectiveness of Interventions for Controlling COVID-19 Transmission between Construction Workers and Their Close Contacts

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ABSTRACT

The insufficiency of continued non-pharmaceutical interventions (NPIs) and ongoing vaccination programs continue to pose challenges in recovering from the coronavirus disease 2019 (COVID-19) pandemic. Before herd immunity, controlling at-risk and vulnerable groups in combination with vaccination plans is strongly recommended. The construction industry is especially vulnerable to the negative impacts of COVID-19 as illustrated by frequent relevant clusters globally and given the manual labor performed by construction workers in close physical proximity. It increases the likelihood of exposure. To gain insights into the transmission dynamics COVID-19 to inform the establishment of effective, and targeted NPIs in the construction industry, a dual-community model was developed that includes the Susceptible-Exposed-Infectious/Asymptomatic-Hospitalized-Recovered-Pathogen (SEI/AHR-P) model for construction workers and the Susceptible-Exposed-Infectious/Asymptomatic-Hospitalized-Recovered (SEIAHR) model for their close contacts. The results of our sensitivity analysis corroborate previous findings that close contacts are significant participants in the spread of the infection. However, the contributions of indirect transmission pathways at a construction site were found to be weak, suggesting the need for further study given conflicting results in other research. Based on the parameters identified as significant in the sensitivity analyses, 28 NPI scenarios were devised to analyze the total attack rate (TAR) and duration of an outbreak (DO). The scenario in which exposed individuals are controlled in terms of close contacts performs best, reducing the TAR with 25% absolute efficiency (AE) and decreasing the DO in the whole population by 1.8 days. In addition to NPIs, both construction workers and their close contacts are suggested to get vaccinated. Vaccination of all construction workers would lead to a lower TAR compared to vaccination of only 15% of both construction workers and their close contacts. Vaccination of all construction workers along with at least 67% of their close contacts can extinguish an ongoing wave.

Keywords:

COVID-19 transmission dynamic, construction workers, epidemic model

INTRODUCTION

Since the initial coronavirus disease 2019 (COVID-19) outbreak in December 2019 (Li et al. 2020), this pandemic has spread globally, causing unprecedented fatalities. COVID-19 vaccines offer hope in ending this pandemic if enough of the population (i.e. at least 75–90%) gets vaccinated to attain the basic reproduction number $\mathcal{R}_0$ (2.5-3.5) (Anderson et al. 2020)), in turn achieving herd immunity. More than six vaccines have been approved for emergency or full use by the World Health Organization (WHO) (World Health Organization 2021b). As of August 30 2021, a total of 5,019,907,027 vaccine doses have been administered (World Health Organization 2021a), which accounts for around 60% of the global population. This implies that there is still a long journey ahead in achieving herd immunity. Even if all eligible people have been vaccinated (assumed vaccine efficacy: 88%), the $\mathcal{R}_0$ may not be reduced to below one (Moore et al. 2021) because the effect of a given vaccine on severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is highly contingent on the apecific properties of each vaccnine and the degree of population uptake. Meanwhile, the frequent mutations of SARS-CoV-2 also pose challenges to vaccines' continual efficacy (Bartsch et al. 2020). For example, the SARS-CoV-2 Delta variant has increased the secondary attack rate by 42 to 55% higher than the Alpha variant (Campbell et al. 2021). Therefore, vaccination alone may not be sufficient to contain the outbreak. A combination of vaccination and non-pharmaceutical interventions (NPIs) is probably necessary to control the transmission risks.

NPIs, including mask wearing, lockdowns, and social distancing , have been widely used at the city and country level since the beginning of the pandemic, which did achieve some great successes in containing the virus (Eikenberry et al. 2020; Lin et al. 2020; Wu et al. 2020). In addition, the majority of these macroscopic NPIs were studied using well-established compartment models (e.g., Susceptible-Infectious-Susceptible(SIS), Susceptible-Infectious-Recovered (SIR), and Susceptible-Exposed-Infectious-Recovered(SEIR)). The fundamental assumption of these models is that the macroscopic NPIs are circumscribed by well-mixed and homogeneous populations, which is an assumption that may oversimplify the reality. Meanwhile, as the pandemic has continued to persist over a prolonged period, the public has shown signs of pandemic fatigue in relation to macroscopic NPIs (World Health Organization and others 2020) since the second half of 2020 , meaning that the public has become demotivated in following these NPIs. To reinvigorate public support, many governments and researchers have shifted from advocating and implementing macroscopic NPIs to promoting microscopic NPIs at individual levels, such as indoor pedestrians (Xiao et al. 2021), students in universities (Weeden and Cornwell 2020), consumers in restaurants (Li et al. 2021), and passengers in cruise ships (Azimi et al. 2021). At this a smaller scale of intervention, microscopic NPIs are generally easier to implement. Moreover, studies on microscopic NPIs overcome the limitations of macroscopic NPI' studies because the former ones could be more effectively considering transmission heterogeneity and the characteristics of people in a specific scenario (Xiao et al. 2021; Weeden and Cornwell 2020; Li et al. 2021; Azimi et al. 2021). Furthermore, as an infected individual may participant in both work and non-work scenarios, focusing solely on one setting is likely to not account for the entire transmission process, and thus leading to increased transmission risks. To address this methodological limitation, it is essential to analyze the effectiveness of microscopic NPIs in different settings with consideration of vaccination rates.

Construction sites are characterized by heterogeneous work types, changeable work environments, and tiers in the labor force. Such complexities could make the implementation of microscopic NPIs on sites together with vaccination a challenging task. It is not surprising that numerous construction site-associated COVID-19 clusters have been recorded globally (Biswas et al. 2021) (e.g., Singapore (Leclerc et al. 2020; World Health Organization et al. 2020), the United States (Kelly Outram 2020; Alsharef et al. 2021), and Hong Kong (Department of Health 2021)). However, the most of COVID-19 related studies in the construction literature concentrate on the severity of the economic losses and health crises brought about by this pandemic (Alsharef et al. 2021) or the efficacy of NPIs (e.g., social distancing, PPE, and sanitization) by collecting feedback from construction companies (Simpeh and Amoah 2021) or employees (del Rio-Chanona et al. 2020). Few studies have depicted the transmission dynamics of SARS-CoV-2 on the construction site, which form the basis of enhancing anti-epidemic strategies. To narrow such knowledge gaps and address methodological hurdles in predicting transmission risks, this study investigates how different combinations of microscopic NPIs and vaccination plans could affect the transmission dynamics of SARS-CoV-2 among construction workers and their close contacts so as to predict the effectiveness of various interventions. A dual-community compartment model was developed, including a Susceptible-Exposed-Infectious/Asymptomatic-Hospitalized-Recovered-Pathogen (SEI/AHR-P) model for construction workers and a Susceptible-Exposed-Infectious/Asymptomatic-Hospitalized-Recovered (SEIAHR) model for their close contacts. Mathematical modeling approaches were chosen because they offer insights into the importance of multiple transmission routes of SARS-CoV-2 and how different intervention scenarios can reduce transmissibility through comparison of the respective attack rate (AR) with absolute/relative effectiveness (AE/RE) and the duration of the outbreak (DO) associated with each scenario.

LITERATURE REVIEW

Epidemic models (e.g., the compartment model (Kermack and McKendrick 1927)) have been applied to describe the transmission dynamics of infectious diseases and have been widely used during the COVID-19 pandemic (Xiang et al. 2021). During the early phase of COVID-19, the compartment model was used for calculating the reproduction number $\mathcal{R}_0$ of COVID-19 base on disease-free equilibrium (Van den Driessche and Watmough 2002). When $\mathcal{R}_0$ is larger than one, the disease is proven to spread out. Given the equation of $\mathcal{R}_0$, the at-risk group who contributes the most to $\mathcal{R}_0$ should be prioritized for infection control. Wu et al. (2020) validated an SEIR metapopulation model by the number of cases exported from Wuhan and found that the $\mathcal{R}_0$ (2.68) in China was larger than one (Wu et al. 2020). The $\mathcal{R}_0$ in Italy ranged from 2.43 to 3.10 based on a SIR model (D'Arienzo and Coniglio 2020). In addition to some basic properties (e.g., disease-free and endemic equilibria), the compartment model can also provide important information for generating epidemic prevention and control strategies, such as travel restrictions, lockdowns, and quarantines (Lin et al. 2020). In light of the global implementation of various NPIs and noticing the transmissibility of asymptomatic infectious individuals (Rothe et al. 2020), some researchers modified the SEIR model by adding asymptomatic, hospitalized, and quarantined individuals (Tang et al. 2020).

The COVID-19 pandemic poses challenges to many industries, such as coronavirus-driven supply chain disruptions (Ivanov 2020), vulnerable transit systems (Qian et al. 2021b), project delays, and labor shortages (Assaad and El-adaway 2021). Each industry has carried out efforts to rebound from this pandemic by in part exploring its cross-cutting transmission dynamics. The dynamic physical distance changes between pedestrians (Xiao et al. 2021) and weighted metro contact networks (Mo et al. 2021; Qian et al. 2021b) have been considered to better describe the transmission dynamics in public transit systems. Educational institutions have attempted to use transcript data to map out transmission dynamics among students (Weeden and Cornwell 2020). To find a trade-off between protecting populations from the infection of SARS-CoV-2 and curbing and economic losses caused by suspending projects, the construction industry has also explored many strategies, such as adding disinfection processes (Kim et al. 2021), suspending nonessential projects (Assaad and El-adaway 2021), accelerating the construction of essential projects (e.g., emergency hospitals (Wang et al. 2021; Tan et al. 2021; Luo et al. 2020)), and working from home on alternate weeks (Pirzadeh and Lingard 2021). Yet, current studies rarely examine the core principle of transmission dynamics of SARS-CoV-2 in the construction industry. The uncertainties associated with transmission dynamics can simplify the severity and duration of ongoing outbreaks and delay projects. It is essential to gain a more thorough understanding of the problems generated by the pandemic before implementing any intervention (Assaad and El-adaway 2021).

METHODS

Model Structure

This study modified the SEIR model by incorporating direct and indirect transmission routes to simulate SARS-CoV-2 transmission dynamics at a construction site, within its connected community, and between each of these. All those designated in this study as close contacts of construction workers in the connected community are not employed by the construction site. All construction employees working on the construction site are designated construction workers. The total human population at time t, denoted as $N(t)$, has been split into ten mutually exclusive compartments as follows: susceptible individuals (who can get infected) on the construction site $S_{hi}(t)$, susceptible individuals in its connected community $S_{ho}(t)$, exposed individuals (who are under incubation period) on the construction site $E_{hi}(t)$, exposed individuals in its connected community $E_{ho}(t)$, asymptomatic infectious individuals (who get infected and show no symptom) on the construction site $A_{hi}(t)$, asymptomatic infectious individuals in its connected community $A_{ho}(t)$, symptomatic infectious individuals (who get infected and show symptoms) on the construction site $I_{hi}(t)$, symptomatic infectious individuals in its connected community $I_{ho}(t)$, hospitalized infectious individuals $H_h(t)$ (who are hospitalized) and recovered individuals $R_h(t)$ (who are recovered or die). The pathogen concentration inhaled/infected per person on the construction site is represented as $P_a(t)$. The model is given by nonlinear ordinary differential equations (ODEs) as Eqs. (1) and depicted in Fig. 1. All variables and parameters are described in Table 1.

$$
\begin{cases}
\frac{dS_{ho}}{dt} = \theta_2\, S_{hi} - (\lambda^c_{hh} + \theta_1)\, S_{ho}, \\
\frac{dS_{hi}}{dt} = \theta_1\, S_{ho} - (\lambda^s_{hh} + \lambda^s_{ha} + \theta_2)\, S_{hi}, \\
\frac{dE_{ho}}{dt} = \lambda^c_{hh}\, S_{ho} + \theta_3\, E_{hi} - \alpha_1\, E_{ho}, \\
\frac{dE_{hi}}{dt} = (\lambda^s_{hh} + \lambda^s_{ha})\, S_{hi} + \theta_4\, E_{ho} - \alpha_2\, E_{hi}, \\
\frac{dI_{ho}}{dt} = \sigma_2\, E_{ho} - \alpha_3\, I_{ho}, \\
\frac{dI_{hi}}{dt} = \sigma_1\, E_{hi} - \alpha_4\, I_{hi}, \\
\frac{dA_{ho}}{dt} = \sigma_4\, E_{ho} - \epsilon_4\, A_{ho}, \\
\frac{dA_{hi}}{dt} = \sigma_3\, E_{hi} - \epsilon_3\, A_{hi}, \\
\frac{dH_h}{dt} = \epsilon_1\, I_{hi} + \epsilon_2\, I_{ho} + \epsilon_3\, A_{hi} + \epsilon_4\, A_{ho} - \alpha_5\, H_h, \\
\frac{dR_h}{dt} = \gamma\, H_h - \delta_r\, R_h, \\
\frac{dP_a}{dt} = \eta_1\, E_{hi} + \eta_2\, I_{hi} + \eta_3\, A_{hi} - \mu\, P_a,
\end{cases} \tag{1}
$$

The force of infection is written as:

$$
\begin{aligned}
\lambda^c_{hh} &= \frac{C_{11}E_{ho} + C_{12}I_{ho} + C_{13}A_{ho} + C_{14}E_{hi} + C_{15}I_{hi} + C_{16}A_{hi}}{N^c}, \\
\lambda^s_{hh} &= \frac{C_{21}E_{ho} + C_{22}I_{ho} + C_{23}A_{ho} + C_{24}E_{hi} + C_{25}I_{hi} + C_{26}A_{hi}}{N^s}, \\
\lambda^s_{ha} &= \frac{\beta_3 P_a}{N^s},
\end{aligned} \tag{2}
$$

where

$$
\begin{aligned}
&\alpha_1 = \theta_4 + \sigma_2 + \sigma_4, \quad \alpha_2 = \theta_3 + \sigma_1 + \sigma_3, \quad \alpha_3 = \epsilon_2 + \delta_i, \quad \alpha_4 = \epsilon_1 + \delta_i \quad \alpha_5 = \gamma + \delta_h. \\
&C_{11} = \beta_1 a_{11}, \quad C_{12} = \beta_1 a_{12} \quad C_{12} = \beta_1 a_{13}, \quad C_{12} = \beta_1 a_{14}, \quad C_{12} = \beta_1 a_{15}, \quad C_{12} = \beta_1 a_{16}, \\
&C_{21} = \beta_2 a_{21}, \quad C_{22} = \beta_2 a_{22} \quad C_{22} = \beta_2 a_{23}, \quad C_{22} = \beta_2 a_{24}, \quad C_{22} = \beta_2 a_{25}, \quad C_{22} = \beta_2 a_{26},
\end{aligned} \tag{3}
$$

with N^s and N^c representing the total population at time t within the construction site and its connected community formulated as $N^s(t) = S_{hi}(t) + E_{hi}(t) + A_{hi}(t) + I_{hi}(t)$, $N^c(t) = S_{ho}(t) +$

$E_{ho}(t) + A_{ho}(t) + I_{ho}(t) + H_h(t) + R_h(t)$ and $N(t) = N^s(t) + N^c(t)$.

Basic Reproduction Number

First of all, we consider solutions of Eqs. (1), formulated as

$$\Omega = \{(S_{hi}, E_{hi}, A_{hi}, I_{hi}, P_a, S_{ho}, E_{ho}, A_{ho}, I_{ho}, H_h, R_h) \in \mathbb{Z}_+^{11} : N > 0\}.$$

All solutions of the model that start in Ω will remain in Ω for all $t \geq 0$. The existence, uniqueness, and continuation results hold provided restricted solutions in Ω hold (Musa et al. 2019). The basic reproduction number $\mathcal{R}_0$ is defined as the average number of secondary infections caused by an individual in an entirely susceptible population (Mwalili et al. 2020). The Disease-free Equilibrium (DFE) is a state in which a disease is absent from a population ahd locally asymptotically stable (Van den Driessche and Watmough 2002): only $S_{hi}(0)$ and $S_{ho}(0)$ are not equal to zero, other variables should equal zero or much less than $S_{hi}(0)$ and $S_{ho}(0)$ as shown in Ω_1.

$$\begin{aligned}\Omega_1 =&[S_{hi}(0), E_{hi}(0), A_{hi}(0), I_{hi}(0), P_a(0), S_{ho}(0), E_{ho}(0), A_{ho}(0), I_{ho}(0), H_h(0), R_h(0)]\\ =&[S_{hi}(0), 0, 0, 0, 0, S_{ho}(0), 0, 0, 0, 0, 0].\end{aligned}$$

Based on a next generation matrix (Van den Driessche and Watmough 2002), let $x = (E_{ho}, E_{hi}, I_{ho}, I_{hi}, A_{ho}, A_{hi}, H_h, P_a)^T$, the model (1) can be represented as $\frac{dx}{dt} = F(x) - V(x)$.

$$F(x) = \begin{pmatrix} \frac{C_{11}E_{ho}+C_{12}I_{ho}+C_{13}A_{ho}+C_{14}E_{hi}+C_{15}I_{hi}+C_{16}A_{hi}}{N^c} \\ \frac{C_{21}E_{ho}+C_{22}I_{ho}+C_{23}A_{ho}+C_{24}E_{hi}+C_{25}I_{hi}+C_{26}A_{hi}}{N^s} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \eta_1 E_{hi} + \eta_2 I_{hi} + \eta_3 A_{hi} \end{pmatrix} \tag{4}$$

and

$$V(x) = \begin{pmatrix} \alpha_1 \, E_{ho} - \theta_3 \, E_{hi} \\ \alpha_2 \, E_{hi} - \theta_4 \, E_{ho} \\ \alpha_3 \, I_{ho} - \sigma_2 \, E_{ho} \\ \alpha_4 \, I_{hi} - \sigma_1 \, E_{hi} \\ \epsilon_4 \, A_{ho} - \sigma_4 \, E_{ho} \\ \epsilon_3 \, A_{hi} - \sigma_3 \, E_{hi} \\ \alpha_5 \, H_h - \epsilon_1 \, I_{hi} - \epsilon_2 \, I_{ho} - \epsilon_3 \, A_{hi} - \epsilon_4 \, A_{ho} \\ \mu \, P_a \end{pmatrix}. \tag{5}$$

The basic reproduction number $\mathcal{R}_0$ is represented as follows:

$$\mathcal{R}_0 = \rho(FV^{-1}) = \frac{1}{6}\sqrt[3]{g_1 + 12\sqrt{g_2}} - 6\,\frac{g_3}{\sqrt[3]{g_1 + 12\sqrt{g_2}}} + \frac{D_8}{3} + \frac{D_1}{3}. \tag{6}$$

where

$$g_1 = 8\,{D_1}^3 - 12\,{D_1}^2 D_8 + 36\,D_1 D_2 D_7 - 12\,D_1 {D_8}^2 - 72\,D_{15} D_{13} D_1 + 36\,D_2 D_7 D_8 + 108\,D_{14} D_2 D_{13} + 8\,{D_8}^3$$
$$+\,36\,D_{15} D_8 D_{13},$$

$$g_2 = -12\,{D_{13}}^3 {D_{15}}^3 + [24\,{D_1}^2 {D_{15}}^2 + (-108\,D_2 D_{14} D_{15} - 24\,D_8 {D_{15}}^2) D_1 + 81\,{D_2}^2 {D_{14}}^2 + (-36\,D_7 {D_{15}}^2 +$$
$$54\,D_8 D_{14} D_{15}) D_2 - 3\,{D_8}^2 {D_{15}}^2] {D_{13}}^2 + [-12\,{D_1}^4 D_{15} + (12\,D_2 D_{14} + 24\,D_8 D_{15}) {D_1}^3 + ((-60\,D_7 D_{15} - 18\,D_8$$
$$D_{14}) D_2 - 6\,{D_8}^2 D_{15}) {D_1}^2 + (54\,{D_2}^2 D_7 D_{14} + (6\,D_7 D_8 D_{15} - 18\,{D_8}^2 D_{14}) D_2 - 6\,{D_8}^3 D_{15}) D_1 + (-36\,{D_7}^2 D_{15}$$
$$+\,54\,D_7 D_8 D_{14}) {D_2}^2 + (-6\,D_7 {D_8}^2 D_{15} + 12\,{D_8}^3 D_{14}) D_2] D_{13} - 3\,({D_1}^2 - 2\,D_8 D_1 + 4\,D_7 D_2 + {D_8}^2)$$
$$(D_8 D_1 - D_7 D_2)^2,$$

$$g_3 = \frac{D_8 D_1}{9} - \frac{D_7 D_2}{3} - \frac{D_{15} D_{13}}{3} - \frac{{D_1}^2}{9} - \frac{{D_8}^2}{9},$$

$$D_1 = \frac{C_{11}\alpha_2}{\alpha_6} + \frac{C_{14}\theta_4}{\alpha_6} + \frac{C_{12}\sigma_2\alpha_2}{\alpha_6\alpha_3} + \frac{C_{15}\sigma_1\theta_4}{\alpha_6\alpha_4} + \frac{C_{13}\sigma_4\alpha_2}{\alpha_6\epsilon_4} + \frac{C_{16}\sigma_3\theta_4}{\alpha_6\epsilon_3}$$

$$D_2 = \frac{C_{11}\theta_3}{\alpha_6} + \frac{C_{14}\alpha_1}{\alpha_6} + \frac{C_{12}\sigma_2\theta_3}{\alpha_6\alpha_3} + \frac{C_{15}\sigma_1\alpha_1}{\alpha_6\alpha_4} + \frac{C_{13}\sigma_4\theta_3}{\alpha_6\epsilon_4} + \frac{C_{16}\sigma_3\alpha_1}{\alpha_6\epsilon_3}$$

$$D_7 = \frac{C_{21}\alpha_2}{\alpha_6} + \frac{C_{24}\theta_4}{\alpha_6} + \frac{C_{22}\sigma_2\alpha_2}{\alpha_6\alpha_3} + \frac{C_{25}\sigma_1\theta_4}{\alpha_6\alpha_4} + \frac{C_{23}\sigma_4\alpha_2}{\alpha_6\epsilon_4} + \frac{C_{26}\sigma_3\theta_4}{\alpha_6\epsilon_3}$$

$$D_8 = \frac{C_{21}\theta_3}{\alpha_6} + \frac{C_{24}\alpha_1}{\alpha_6} + \frac{C_{22}\sigma_2\theta_3}{\alpha_6\alpha_3} + \frac{C_{25}\sigma_1\alpha_1}{\alpha_6\alpha_4} + \frac{C_{23}\sigma_4\theta_3}{\alpha_6\epsilon_4} + \frac{C_{26}\sigma_3\alpha_1}{\alpha_6\epsilon_3}$$

$$D_{14} = \frac{\eta_1\theta_4}{\alpha_6} + \frac{\eta_2\sigma_1\theta_4}{\alpha_6\alpha_4} + \frac{\eta_3\sigma_3\theta_4}{\alpha_6\epsilon_3}, \quad D_{15} = \frac{\eta_1\alpha_1}{\alpha_6} + \frac{\eta_2\sigma_1\alpha_1}{\alpha_6\alpha_4} + \frac{\eta_3\sigma_3\alpha_1}{\alpha_6\epsilon_3},$$

$$D_{13} = \frac{\beta_3}{\mu}, \quad \text{and} \quad \alpha_6 = \alpha_2\alpha_1 - \theta_4\theta_3.$$

$\mathcal{R}_0$ is determined by human-related factors (D_1, D_2, D_7 and D_8) and pathogen-related factors (D_{13}, D_{14} and D_{15}), representing two modes of transmission of this disease as shown in Table 2.

SENSITIVITY ANALYSIS

Both global and local sensitivity analyses are conducted in this study. As Eqs. (1) are nonlinear ODEs with non-monotonic input-output relationships, global sensitivity analysis by the Sobol method (Zhang et al. 2015) can reveal the influences of parameter interaction. Local sensitivity is designed to explore the effects of every single parameter in response to the outputs when other parameters are constant, which directly provides insights on the efficacy of various control strategies.

Global Sensitivity Analysis

The Sobol method was performed using **SimBiology** via **Matlab** software version **R2021a** (The MathWorks, Inc. 2021). First-order and total-order sensitivity indices are intended to show how every single parameter and the interaction between parameters contribute to the output variance over a full range of parameter space (Sobol 2001). According to the basic reproduction number $\mathcal{R}_0$ and previous studies (Liu et al. 2021; Liang et al. 2018), the inputs include human-to-human transmission rates (β_1, β_2), transition rate between the construction site and its connected community (θ_1 - θ_4) and effective contact ratio (a_{11} - a_{26}). This section excludes transmission rate from pathogens β_3 owing to the model complexity, which will be discussed in the following subsection. Since symptomatic and asymptomatic infectious individuals are generated in the latency period by exposed individuals (Van den Driessche and Watmough 2002), the exposed individuals within the connected community $x(1)$ and the exposed individuals within the construction site $x(2)$ contribute the most to determining $\mathcal{R}_0$. Hence, the output includes exposed individuals on the construction site ($[constructionsite].E_{hi}$) and in its connected community ($community.E_{ho}$) as shown in Fig. 2 and 3.

Local Sensitivity Analysis

Given the results found of previous studies described above, this section sets 0.1 as the interval and tests transmission rate, effective contact ratio and transition rate ranging from 0 to 1, as shown in Fig. 4. The transmission rates are assumed to be equal: $\beta_1 = \beta_2 = \beta_3 = \beta$. The outputs include total attack rate (TAR) and attack rate (AR) in each area. TAR is defined as the proportion of being infected (including pre-symptomatic, asymptomatic and symptomatic) among the whole susceptible population during the simulation period (Liu et al. 2021). Attack rate on the construction site (AR^s) and in its connected community (AR^c) reflect the severity of the outbreak in each area respectively. Another criterion is the duration of an outbreak (DO). All results are shown in Fig. 4.

EFFECTIVENESS OF INTERVENTIONS

Non-pharmaceutical Interventions (NPIs)

"Scenario 1" is set as a baseline with all effective contact ratios kept as one and $\beta_1 = \beta_2 = \beta_3 = 0.54$ as depicted in Fig. 5, representing no intervention in the whole population. Globally, the average household size is 4.0 (Population Reference Bureau 2020). The close contact size is assumed to be 5 which is larger than 4. The initial population N^s is assumed to be 40 which is one-fifth of the population in its connected community N^c. Absolute effectiveness (AE) and relative effectiveness (RE) (Liu et al. 2021) are defined to assess the efficiency of different interventions.

$$\begin{aligned} TAR &= \frac{\text{the number of confirmed cases}}{\text{the total population}}, \\ AE_i &= TAR_i - TAR_{baseline}, \\ RE_i &= AE_i / TAR_i. \end{aligned} \tag{7}$$

Scenario Design The transmissibility between populations and transmission pathways in under varying scopes of reducing effective contact is investigated in this section. Parameters elicited in the sensitivity analyses were organized into 28 scenarios of interventions and TAR and DO were constructed to quantitatively evaluate each of these scenarios. The effective contact ratio $a_{ij}, (i = 1, 2$ and $j = 1, 2, ..., 6)$ between different populations, human-related (i.e., direct) transmission rate (β_1, β_2), pathogen-related (indirect) transmission rate β_3 and transition rate θ_k, $(k = 1, 2, 3, 4)$, which are considered as key elements in designing different NPIs, has a range from 0 to 1. The interval is set as 0.1 following the conditions in local sensitivity analysis. As mentioned, Scenario 1 is the baseline without any intervention. Scenario 2 is intended to prevent pathogen-related transmission. Scenarios 4 – 15 are single parameter targeted. Scenarios 16 – 21 aim to control two parameters from the same infectious resources in one community. Scenarios 22 – 24 consider four parameters from the same origins in both communities. Scenarios 3, 27, and 28 represent interventions for different scopes for controlling effective contact. Scenario 25 prohibits physical interaction between these two communities. Scenario 26 protects the whole population from risks through a more complete control of both effective contact and connection between the two communities. All scenarios are described in Table 3. The three criteria for evaluating the performance of all scenarios are AE, RE and DO. All 28 scenarios are ranked by their DO as shown in Fig. 6. Scenario 16 was identified to be the best one.

Vaccination

Pharmacological intervention measures include effective medical treatments and available vaccinations. Many industries have encouraged their personnel to get vaccinated. For example, in Hong Kong's construction industry, construction workers have been asked to take regular PC-RTC tests for COVID-19 since September 2020 (HK Government 2020) and encouraged to get vaccinated since May 2021 (HK Government 2021). In this section, the vaccine efficacy is assumed as at least 60% (Bartsch et al. 2020). This study simulates the effectiveness of different vaccination rates under different scenarios (Bartsch et al. 2020) and aims to identify how to best extinguish an ongoing wave of infection by reducing the attack rate on the construction site as shown in Fig. 7.

RESULTS AND DISCUSSION

Sensitivity Analysis Comparing the results for first-order, total-order, fraction of unexplained variance, and total variance, this study analyzed the relationships between different parameters. The fraction of unexplained variance represents the amount of variance that is not captured by the proposed model, which is both close to zero in Figs. 2 and 3. Their total variances tend to increase but do not exceed 0.005 or 0.0001, meaning that the unexplained variance could be insignificant.

A local virus mutation represents more sensitivity than an imported virus mutation as indicated in Fig.2a. Transmission rate β_1 is more sensitive in the connected community and so is β_2 on the construction site. Generally, when the Sobol indices of one parameter exceed 0.05 that implies an important input to the outputs. The contribution to the variance of E_{hi} from the interaction between β_1 and β_2 increases smoothly and becomes significant when β_1 and β_2 are larger than 0.8. Hence, due to the greater number of susceptible people in a larger community, virus mutations are especially impactful in such a population. Unexpected variances appear to increase as shown in Fig. 2a. While this suggests that excluded factors do not have a significant impact, additional research could clarify potential relationships involving such factors.

In Fig. 2b, transition rate θ_4 represents the most sensitivity indicating that intermingling of a higher percentage of contagious individuals with a wholly susceptible population increases the possibility of triggering an outbreak. Theoretically, the mobility of susceptible individuals cannot accelerate infection since only pre-symptomatic, asymptomatic, and symptomatic infectious individuals participate in transmitting SARS-CoV-2. The Sobol indices of θ_1 and θ_2 from susceptible individuals demonstrate increases over time, indicating that fully unrestricted population mobility is not feasible before herd immunity.

As shown in Fig. 3, the results within the construction site and its connected community exhibit similarities due to their analogous transmission dynamics. Sobol indices of a_{12} (0.55 - 0.756)/a_{22} (0.43 - 0.75), a_{11} (0.12 - 0.26)/a_{21} (0.12 - 0.22) and a_{14} (0.03 - 0.217)/a_{24} (0.03 - 0.2) rank as the top three to which I_{ho}, E_{ho} and E_{hi} especially contribute. Compared their impacts on the construction site and its connected community, higher effective contact ratios will contribute more to a large population. Although symptomatic individuals (a_{12}, a_{22}) is more sensitive to the variance of E_{hi} and E_{ho}, exposed people may more freely between different locations in the absence of symptoms and should be wll controlled owing to the high sensitivity of θ_3 and θ_4. Nevertheless, controlling exposed individuals is difficult due to the period of asymptomatic presentation that precedes and sometimes continues during infection, so vaccination remains a critical practice. For example, the Hong Kong government has encouraged more construction employees to get vaccinated and has exempted them from regular COVID-19 testing after 14 days upon his or her completion of the necessary doses of vaccine (HK Government 2021). To help make optimal vaccination plans for the construction industry, the following section discusses their effectiveness.

In Fig. 4, the maximum AR (from 0.05 to 0.5) and average DO (from 120 to 50) changed sharply when the transmission rate β was less than 0.3. When β equals 0.7, AR and DO tend to be stable at 0.85 and 30 respectively due to a small proportion of the remaining susceptible people. Similarly as a_{ij} ($i = 1, 2; j = 1, 2, 4$ in Fig. 3 indicates high sensitivity. In Figs 4d-4g, when θ_1, θ_3

and θ_4 exceed 0.5 and/or θ_2 exceeds 0.8, AR^s will be larger than 1, which may be attributable to human mobility leading to overall population increased on the construction site while the original number of construction workers remains unchanged.

Effectiveness of NPIs Scenario 1 is the baseline (TAR: 51.55%, DO in the whole population: 42.93 days). Of all the 28 scenarios, Scenario 3 displays the greatest efficiency by reducing the attack rate up to 14 times RE but increasing DO by 18.75 days. Scenario 14 reduces DO the most, by 28% with a low RE of 1.305%. When controlling the effective contact ratio with wide-ranging restrictions, the AR can be reduced by at least 17% but will increase DO (Scenario 3, 19, 22, 23, and 27) in most cases. Hence, aiming for high-sensitivity effective contact ratios will lead to more significant efficiency. According to the sensitivity analysis, a_{ij} ($i = 1, 2$; $j = 1, 2, 4$) are the targeted elements. Compared to Scenario 4, 10, and 16, controlling both a_{11} and a_{21} from E_{ho} shows a better comprehensive performance than separate controlling. Controlling I_{ho} extends DO with moderate effectiveness (around 5%). In terms of E_{hi}, Scenario 19 performed better than Scenarios 7 and 13 while increasing DO by three days. To reduce both TAR and DO, Scenario 16 demonstrates the best performance (25% AE and around 1.8 days DO reduction).

In terms of the pathogen, controlling indirect contacts can decrease the AR, though with low efficiency. Due to the limitation of this case study, the risk from indirect transmission pathways calls for more investigation. A visiting ban between the construction site and its connected community can only reduce AR by around 17.3% RE. The relationship between the pathogen in the environment and the severity of a pandemic in the construction industry was minimal and more empirical research is needed.

Effectiveness of Vaccination A comparison of the results shown in Figs. 7a and 7b reveals that even if 100% of construction workers get vaccinated, the attack rates will still increase sharply within 10 days. Vaccination of all construction workers would lead to lower TAR in comparison to vaccination of merely 15% of both construction workers and their close contacts. Attack rates decreased as an outcome of vaccination during the simulation for a vaccine assumed to have at least a 60% vaccine efficacy in preventing infection compared to no vaccination, varying with a vaccination rate among close contacts shown in Figs. 7c-7f. When 30%, 50%, 70%, and 100% of construction workers get vaccinated, 79%, 76%, 72%, and 67% respectively of their close contacts should be encouraged to also get vaccinated. Therefore, not only should construction workers be urged to get vaccinated but also their close contacts.

CONCLUSIONS AND IMPLICATIONS

The dual-community compartment model in this study is intended to examine how different combinations of targeted NPIs and vaccination plans could affect the transmission dynamics of SARS-CoV-2 among construction workers and their close contacts. The findings show that when the index case of SARS-CoV-2 is introduced to the construction industry, in the absence of any intervention, infection rapidly spreads among both construction workers and their close contacts, reaching its peak within 10 days. In addition, the SARS-CoV-2 in each community follows different transmissibility danamics. The construction site is impacted by both direct and indirect transmission pathways. Designed according to the sensitivity of significant parameters (i.e., effective contact ratios between different groups, transmission rates, etc.) from model (1), 28 customized NPI scenarios helped reduce the TAR and DO. In particular, controlling exposed individuals among their close contacts (Scenario 16) is recommended given the estimated ability of such control to reduce DO by 1.8 days and TAR with 25% AE as the primary measures. Limited by the insufficiency of screening technologies and frequent virus mutations, the NPIs combined with COVID-19 vaccines are strongly supported particularly in light of the diminishing public adherence to some existing NPIs. The results indicate the efficacy of having both construction workers and their close contacts become vaccinated. Otherwise, the vacination of only construction workers will not be able to curb an outbreak. Around 67–79% of the close contacts of vaccinated construction workers should also be given a vaccine.This study supplements the limited literature addressing the epidemic spread of SARS-CoV-2 in the construction industry considering the virus's transmission dynamics at the industry level. The macroscopic compartment model has been used to describe transmission dynamics at a city or country scale, but this model is hampered by its well-mixed and heterogeneous population assumptions. Designing an individual-based anti-epidemic strategy may prompt a discussion on transmission heterogeneity but cannot optimize misses the effectiveness of containing the epidemic explicitly. This study treats construction workers and their close contacts as part of the whole population in the construction industry due to their social activities. Thus, it balances the challenges faced in considering heterogeneous transmissibility microscopically and intervention planning macroscopically.

Targeted NPIs in combination with sufficient vaccination are recommended for implementation on construction sites. The vulnerability of construction workers is evident through their close physical proximity and the manual labor required. Given the objective of prioritizing the protection of construction worker health, controlling at-risk people (i.e. exposed individuals among their close contacts) and encouraging both construction workers and their close contacts to get vaccinated are the two most effective methods identified through this study.

LIMITATIONS AND DIRECTIONS FOR FUTURE RESEARCH

This study did not distinguish indoor or outdoor construction sites. The majority of scenarios in prior studies are indoor settings since sharing indoor spaces with infected individuals has been confirmed to be the major infection risk origin of SARS-CoV-2 by many retrospective analyses (Qian et al. 2021a). However, there are significant gaps in our understanding of indoor and outdoor settings due to their vague definition (Bulfone et al. 2021). Many outdoor risk sources (aerosolized particles emitted during wastewater treatment (Senatore et al. 2021), respiratory droplets shedding from infected patients when gathering outside (Leclerc et al. 2020), etc.) can act as virus carriers as well. The significance of indirect pathogen transmission calls for more investigation and, will be influenced by whether the construction site is indoors or outdoors.

Theoretically, indirect pathogen transmission has been confirmed to be not as significant as human-related direct transmission, although the force of infections as shown in Eqs. (1) and the interpretation of $\mathcal{R}_0$ both point to a certain plausibility to the significance of pathogen-related transmission. Empirical and experimental evidence indicates that indirect transmission of the virus has occurred (Alsharef et al. 2021; Xie et al. 2020; Richard et al. 2020). As for the construction industry, more empirical and observation studies are needed, which may include examining the possibility of construction workers shedding the virus into the environment or differing pathogen concentrations in indoor or outdoor construction sites.

A longitudinal study to prevent other respiratory diseases is also needed for further researches, e.g., establishing a social-contact network (Weeden and Cornwell 2020). The epidemiological justification for suspending face-to-face construction projects is that infected construction workers can spread a virus to others when sharing the same space through work or non-work activities. Co-working on the same construction site with someone who might shed the virus does not necessarily lead to an infection as workers may stand some distance away from each other or wear masks properly, but there can remain an increased risk. Management can facilitate responsibly resuming or continuing a construction project during an epidemic outbreak by supporting co-working networks for contact-tracing. Future research can further explore this topic by collecting construction workers' activity trajectories.

DATA AVAILABILITY STATEMENT

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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List of Tables

TABLE 1. Notation

Notation	Description
Variables	
S_{hi}	the number of susceptible individuals on the construction site
E_{hi}	the number of exposed individuals on the construction site
A_{hi}	the number of asymptomatic infectious individuals on the construction site
I_{hi}	the number of symptomatic infectious individuals on the construction site
P_a	the pathogen concentration inhaled/infected per person on the construction site
S_{ho}	the number of susceptible individuals in its connected community
E_{ho}	the number of exposed individuals in its connected community
A_{ho}	the number of asymptomatic infectious individuals in its connected community
I_{ho}	the number of symptomatic infectious individuals in its connected community
H_h	the number of hospitalized infectious individuals
R_h	the number of recovered individuals
Parameters	
θ_1	the transition rate from S_{ho} to S_{hi}
θ_2	the transition rate from S_{hi} to S_{ho}
θ_3	the transition rate from E_{hi} to E_{ho}
θ_4	the transition rate from E_{ho} to E_{hi}
σ_1	the transition rate from E_{hi} to I_{hi}
σ_2	the transition rate from E_{ho} to I_{ho}
σ_3	the transition rate from E_{hi} to A_{hi}
σ_4	the transition rate from E_{ho} to A_{ho}
ϵ_1	the hospitalized rate of I_{hi}
ϵ_2	the hospitalized rate of I_{ho}
ϵ_3	the hospitalized rate of A_{hi}
ϵ_4	the hospitalized rate of A_{ho}
γ	the recovery rate of hospitalized individuals H_h
δ_i	the rate of death among symptomatic infectious individuals
δ_h	the rate of death among hospitalized population
δ_r	the rate of death among recovered individuals
η_1	the rate of virus spread to environment by E_{hi}
η_2	the rate of virus spread to environment by I_{hi}
η_3	the rate of virus spread to environment by A_{hi}
μ	natural death rate of pathogens in the environment
β_1	the transmission rate between human to human in its connected community
β_2	the transmission rate between human to human on the construction site
β_3	the transmission rate between pathogen to human on the construction site
a_{11}	effective contact ratio between E_{ho} and S_{ho}
a_{12}	effective contact ratio between I_{ho} and S_{ho}
a_{13}	effective contact ratio between A_{ho} and S_{ho}
a_{14}	effective contact ratio between E_{hi} and S_{ho}
a_{15}	effective contact ratio between I_{hi} and S_{ho}
a_{16}	effective contact ratio between A_{hi} and S_{ho}
a_{21}	effective contact ratio between E_{ho} and S_{hi}
a_{22}	effective contact ratio between I_{ho} and S_{hi}
a_{23}	effective contact ratio between A_{ho} and S_{hi}
a_{24}	effective contact ratio between E_{hi} and S_{hi}
a_{25}	effective contact ratio between I_{hi} and S_{hi}
a_{26}	effective contact ratio between A_{hi} and S_{hi}

TABLE 2. Interpretation of the basic reproduction number $\mathcal{R}_0$

Term	Interpretation
$\alpha_6 = \alpha_2\alpha_1 - \theta_4\theta_3$	the remaining exposed individuals in the whole system.
D_n $(n = 1, 2, 7, 8)$	D_n has six terms representing the contributions to $\mathcal{R}_0$ from E_{ho},E_{hi},I_{ho},I_{hi},A_{ho} and A_{hi} respectively.
D_{13}	β_3 is the infectious rate transmitting from pathogen to human and μ shows the emigration rate of pathogens. Hence, D_{13} represents the remaining pathogens.
D_{14} $(m = 14, 15)$	D_m has three terms representing contributions to $\mathcal{R}_0$ from E_{hi},I_{hi} and A_{hi} respectively.

TABLE 3. Scenario

Scenario No.	**Conditions**	**Description**
Scenario 1	$a_{11} = ... = a_{16} = 1$ $a_{21} = ... = a_{26} = 1$	Baseline: No intervention.
Scenario 2	β_3	Controlling pathogen on the construction site.
Scenario 3	$a_{11}, ..., a_{16}$ $a_{21}, ..., a_{26}$	Controlling effective contact among the whole population.
Scenario 4	a_{11}	Controlling effective contact between E_{ho} and S_{ho}.
Scenario 5	a_{12}	Controlling effective contact between I_{ho} and S_{ho}.
Scenario 6	a_{13}	Controlling effective contact between A_{ho} and S_{ho}.
Scenario 7	a_{14}	Controlling effective contact between E_{hi} and S_{ho}.
Scenario 8	a_{15}	Controlling effective contact between I_{hi} and S_{ho}.
Scenario 9	a_{16}	Controlling effective contact between A_{hi} and S_{ho}.
Scenario 10	a_{21}	Controlling effective contact between E_{ho} and S_{hi}.
Scenario 11	a_{22}	Controlling effective contact between I_{ho} and S_{hi}.
Scenario 12	a_{23}	Controlling effective contact between A_{ho} and S_{hi}.
Scenario 13	a_{24}	Controlling effective contact between E_{hi} and S_{hi}.
Scenario 14	a_{25}	Controlling effective contact between I_{hi} and S_{hi}.
Scenario 15	a_{26}	Controlling effective contact between A_{hi} and S_{hi}.
Scenario 16	a_{11}, a_{21}	Controlling effective contact between E_{ho} and S in both construction site and its close contact community.
Scenario 17	a_{12}, a_{22}	Controlling effective contact between I_{ho} and S in both construction site and its close contact community.
Scenario 18	a_{13}, a_{23}	Controlling effective contact between A_{ho} and S in both construction site and its close contact community.
Scenario 19	a_{14}, a_{24}	Controlling effective contact between E_{hi} and S in both construction site and its close contact community.
Scenario 20	a_{15}, a_{25}	Controlling effective contact between I_{hi} and S in both construction site and its close contact community.
Scenario 21	a_{16}, a_{26}	Controlling effective contact between A_{hi} and S in both construction site and its close contact community.
Scenario 22	$a_{11}, a_{14}, a_{21}, a_{24}$	Controlling effective contact between all E and S.
Scenario 23	$a_{12}, a_{15}, a_{22}, a_{25}$	Controlling effective contact between all I and S.
Scenario 24	$a_{13}, a_{16}, a_{23}, a_{26}$	Controlling effective contact between all A and S.
Scenario 25	$\theta_1, ..., \theta_4$	Controlling connection between construction site and its connected community.
Scenario 26	$a_{11}, ..., a_{26}$ $\theta_1, ..., \theta_5$	Controlling effective contact and connection among the whole population.
Scenario 27	$a_{11}, ..., a_{16}$	Controlling effective contact in community.
Scenario 28	$a_{21}, ..., a_{26}$	Controlling effective contact on the construction site.

List of Figures

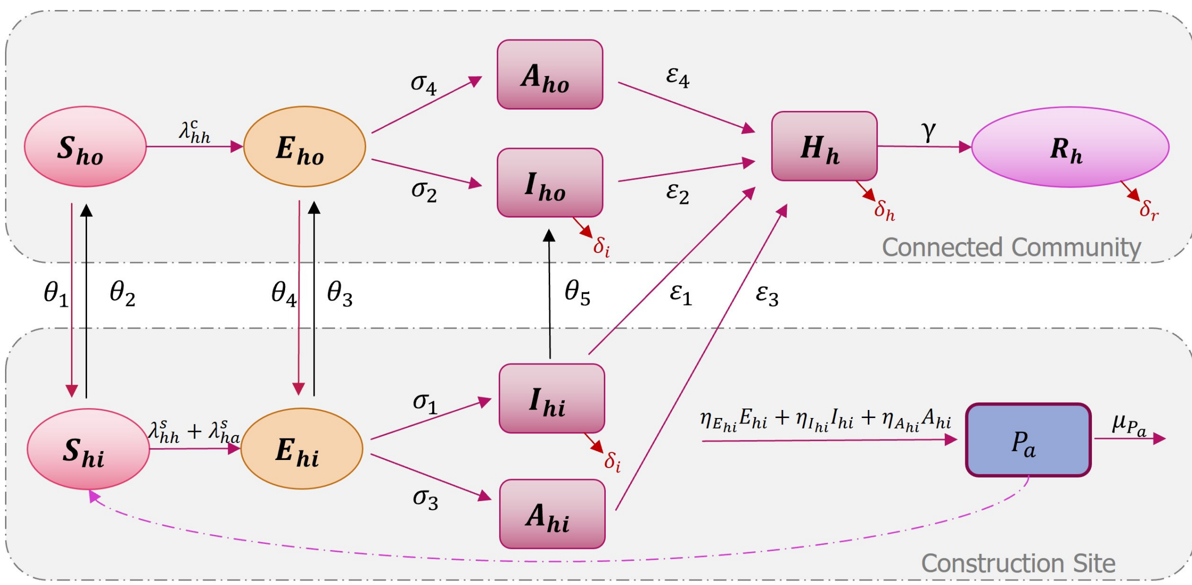
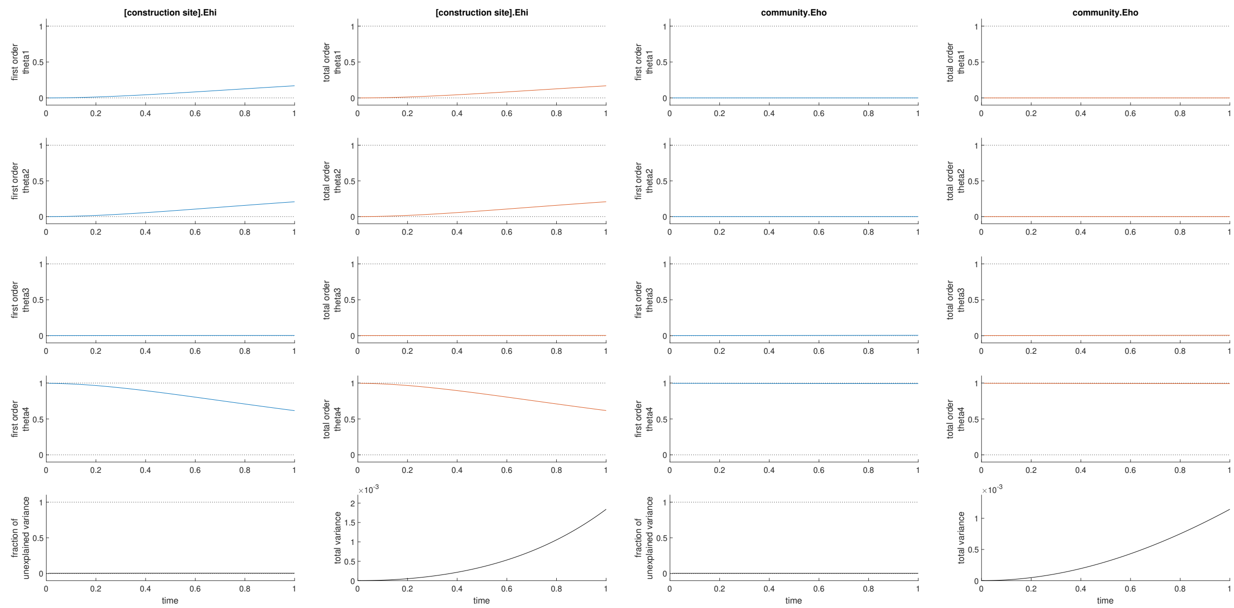
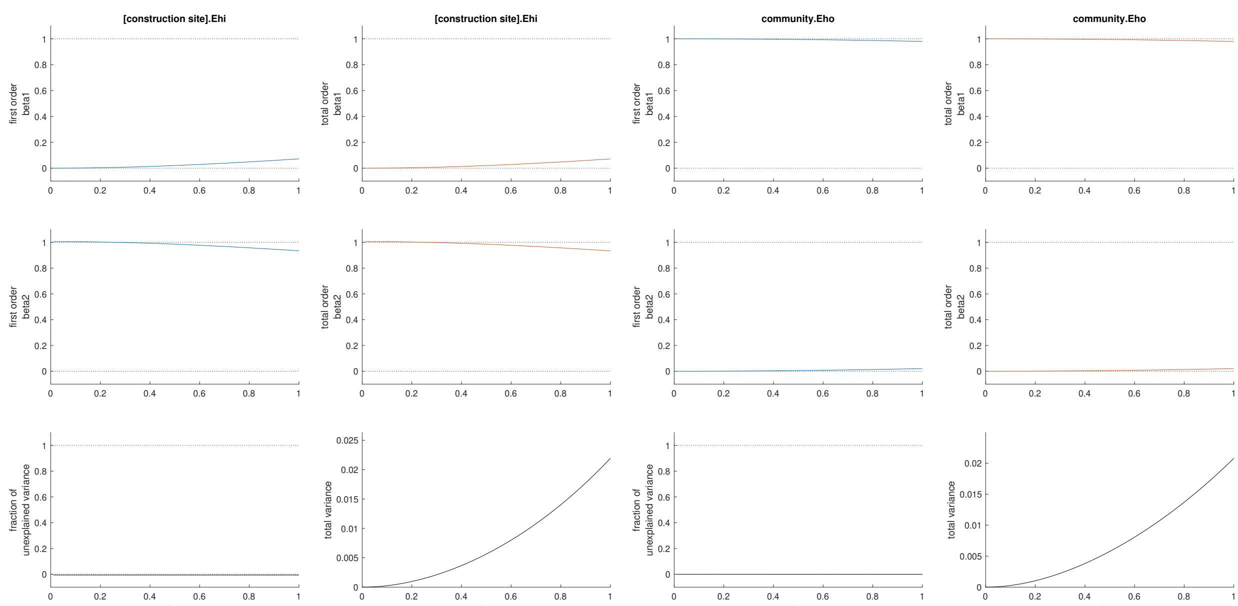


Fig. 1. Diagram

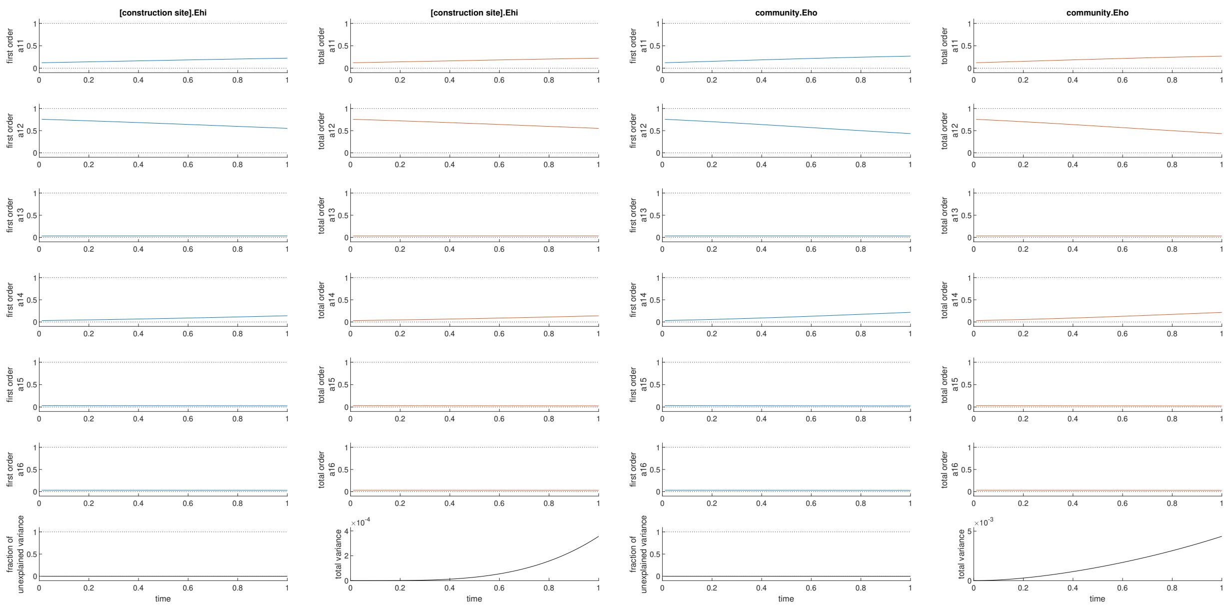


(a)

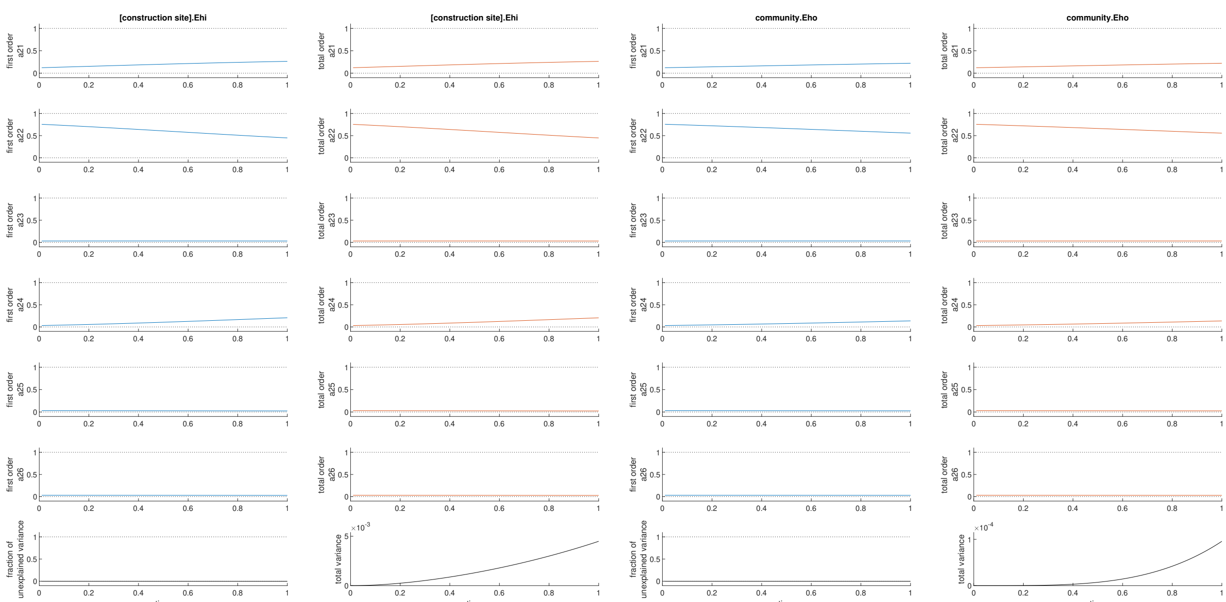


(b)

Fig. 2. Sobol indices of (a) transmission rate β_1 and β_2; and (b) transition rate between construction site and its connected community.



(a)



(b)

Fig. 3. Sobol indices of (a) effective contact ratio a_{11} - a_{16}; and (b) effective contact ratio a_{21} - a_{26}.

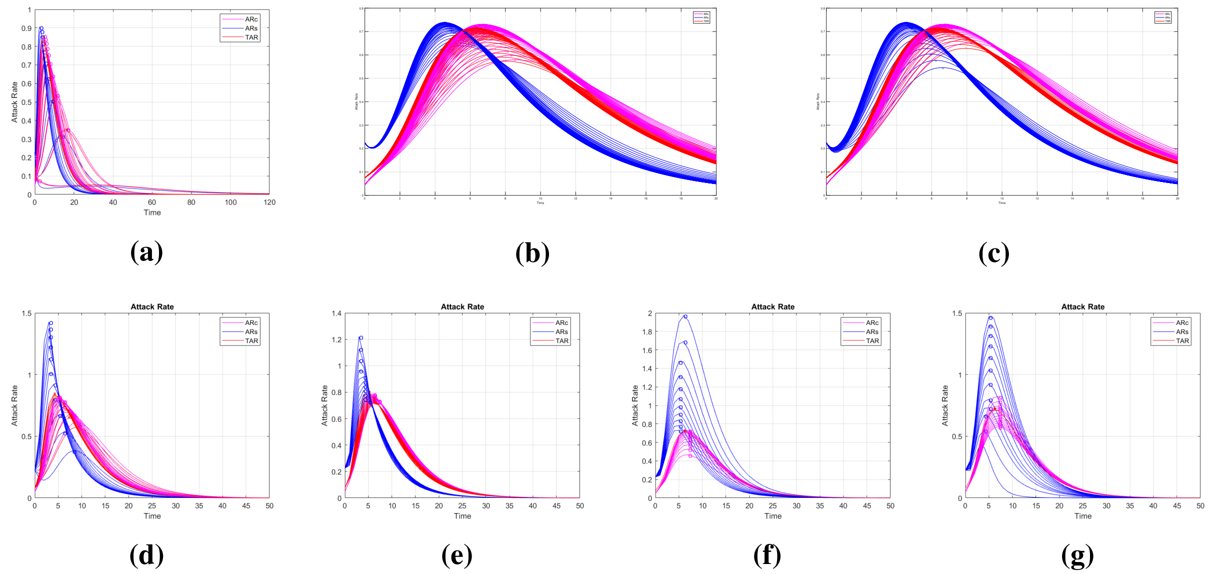


Fig. 4. Sensitivity analysis of (a) transmission rate β; (b) effective contact ratio a_{11} to a_{16}; (c) effective contact ratio a_{21} to a_{26}; (d) transition rate θ_1; (e) transition rate θ_2; (f) transition rate θ_3; and (g) transition rate θ_4 ranging from 0 to 1.

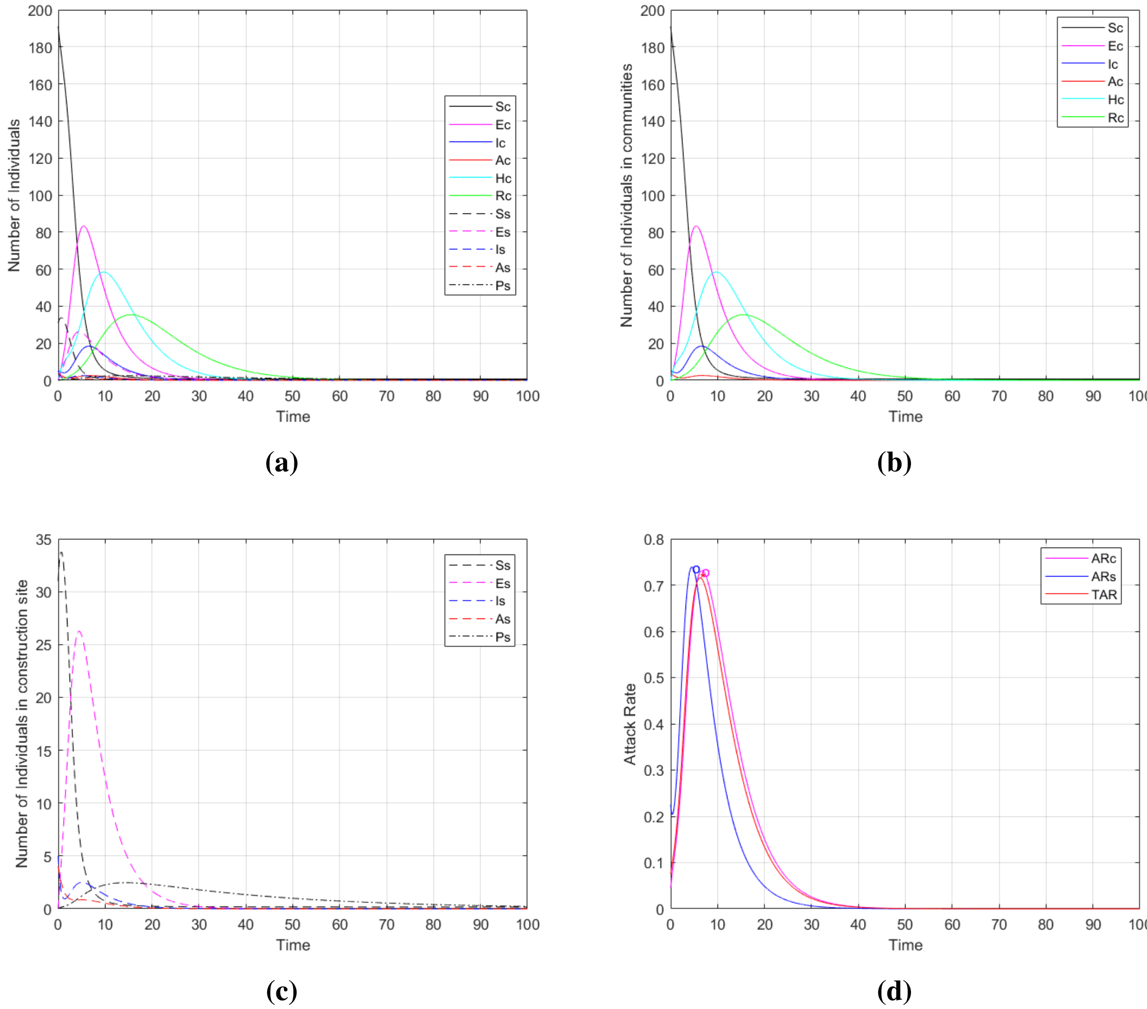


Fig. 5. Scenario 1: baseline of (*a*) SEIARP model; (*b*) within the community; (*c*) on the construction site; and (*d*) attack rate.

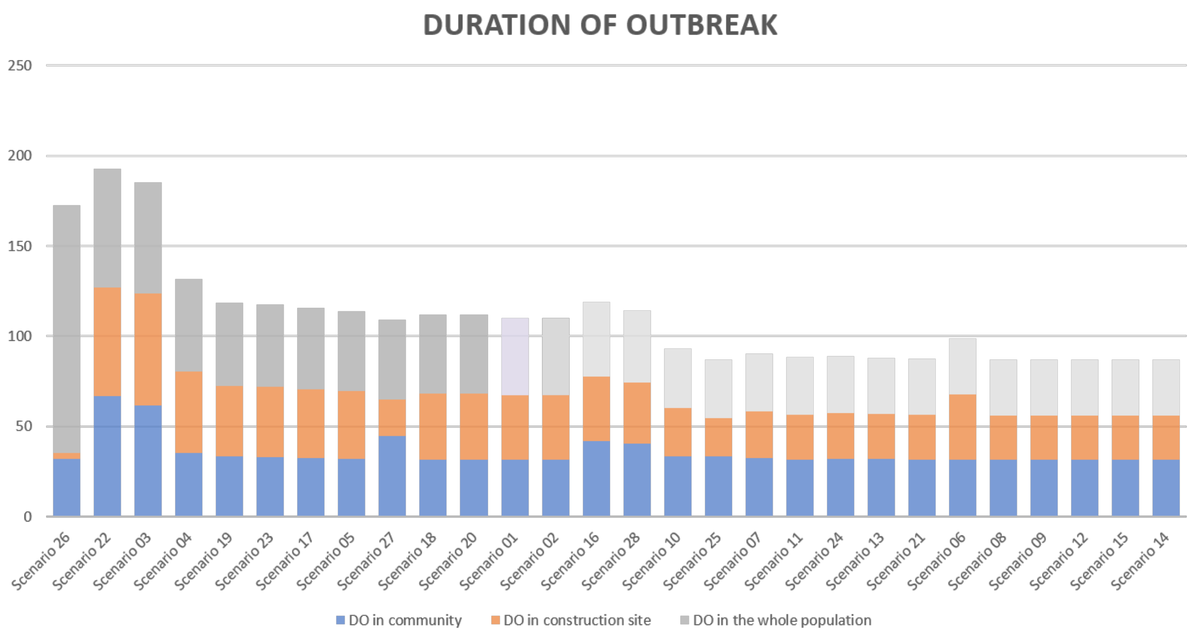


Fig. 6. Duration of Outbreak.

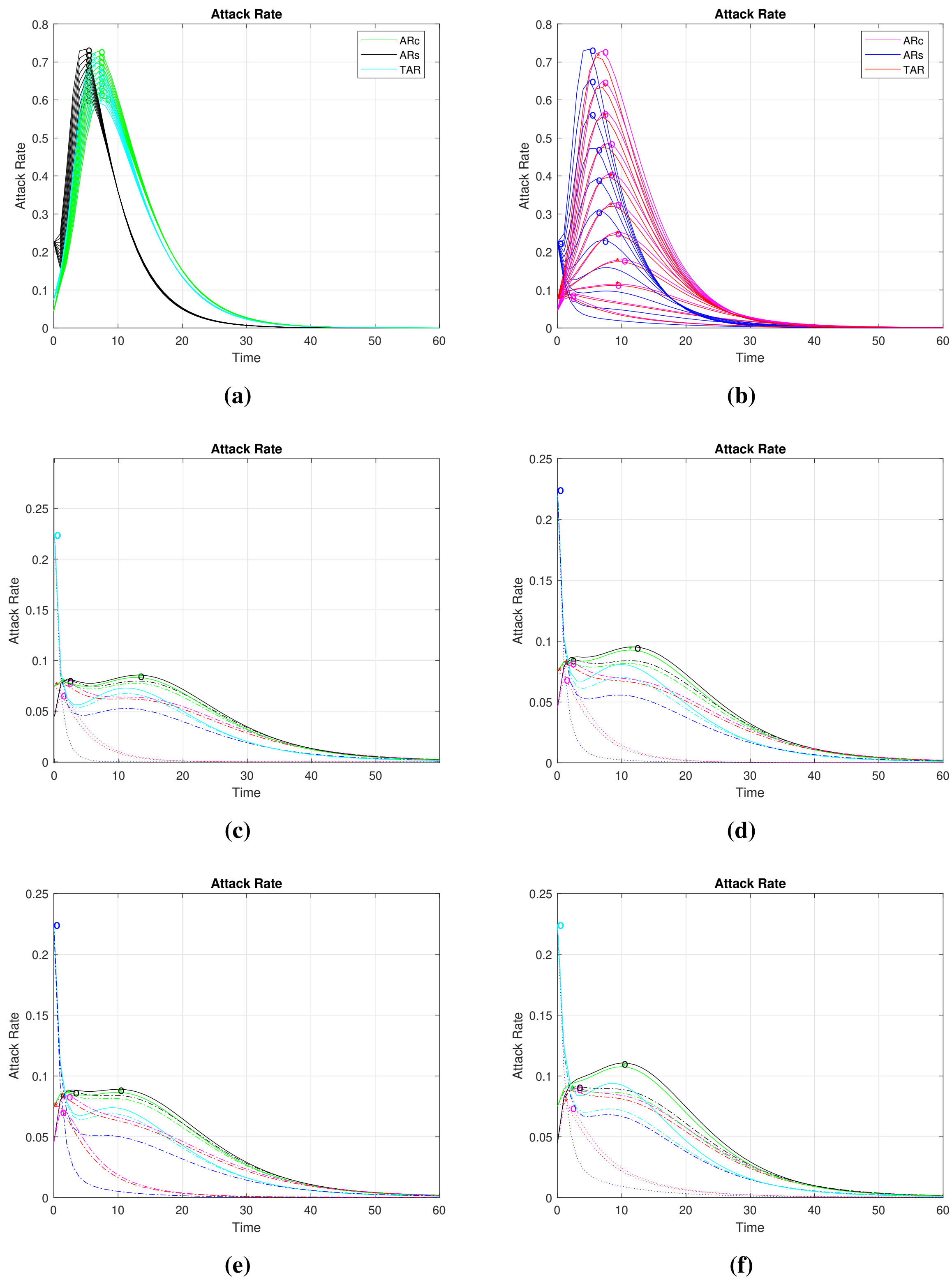


Fig. 7. Vaccination effectiveness (a) when only construction workers vaccinated; (b) when only close contacts vaccinated; (c) when 100% construction workers vaccinated; (d) when 70% construction workers vaccinated; (e) when 50% construction workers vaccinated; and (f) when 30% construction workers vaccinated.