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Research article

A dynamic model for elevator operation-induced spread of a respiratory infectious disease in an apartment building

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ABSTRACT

Residents have to use elevators to leave and enter their high-rise apartments frequently. An elevator car can easily spread respiratory infectious diseases, as it has a confined and small space. Therefore, studying how elevator operations promote epidemic transmission is of importance to public health. We developed an infectious disease dynamics model. First, we used homemade codes to simulate the operating state of an elevator and the dynamic process of infectious disease transmission in an apartment building due to elevator operations. Second, we analysed the temporal distribution patterns of infected individuals and patients. Finally, we validated the reliability of the model by performing continuous-time sensitivity analysis on important model parameters. We found that elevator operations can cause rapid spread of infectious diseases within an apartment building. Therefore, it is necessary to enhance elevator ventilation and disinfection mechanisms to prevent the outbreak of respiratory infections. Moreover, residents should reduce elevator use and wear masks.

1. Introduction

The pathogens of respiratory infectious diseases such as influenza, severe acute respiratory syndrome (SARS), and coronavirus disease 2019 (COVID-19) usually spread in the population through airborne transmission and often cause outbreaks (or even worldwide pandemics) [1, 2, 3]. Superspreading events or the rapid spread of epidemics often occur in hospitals, gatherings, subways, and other places with high population density and mobility [4-7]. In particular, elevator cars are characterised by small spaces, a closed environment, and high passenger mobility. Therefore, if multiple individuals use the elevator at the same time while one of them is infected, all others are exposed to the risk of infection. In fact, pathogenic infections of passengers in an elevator car may result in an epidemic [8,9]. In the course of urbanisation, China has built a large number of residential high-rise apartments that are equipped with elevators, with most residents opting to use elevators rather than stairs. Although elevators make it convenient for residents to travel, they also pose a potential risk for the spread of infectious diseases. During an outbreak, a respiratory disease can spread easily within an apartment building via the elevator due to two reasons: (1) when using elevators, especially during the rush hours, several residents living on different floors are usually crowded in one elevator car; and (2) the residential population that uses elevators at the

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same time changes constantly. Therefore, using theoretical models to study the mechanism of elevator operation-induced transmission of infectious diseases not only broadens our understanding of the dynamics of infectious diseases, but also has important public health implications. Although a number of models have been developed to study the spread of viral aerosols in elevators [10,11] and queuing systems have been proposed for elevator rides [12], there has been little research on the dynamics of infectious diseases in this context.

At present, most widely used infectious disease dynamic models rely on ordinary differential equations to analyse the dynamic characteristics of susceptible, exposed, infectious, and recovered populations. For example, during the COVID-19 pandemic, Chen FY et al. estimated the association between meteorological factors and the epidemic [13]; Asamoah JKK et al. analysed the optimal control and comprehensive cost-effectiveness [14]; Dangerfield CE et al. proposed how to coordinate mathematical modelling research to support a pandemic [15]; and Ma X et al. evaluated the influence of mask use [16]. However, such models are not applicable in the present study, as it is impossible to establish a mathematical equation to describe elevator operation owing to the random nature of elevator use by residents. To overcome this obstacle, we used homemade codes and developed a computer-based model to describe the daily elevator-use behaviour of residents and the spread of the COVID-19 epidemic. Studies based on such models do not involve any mathematical equations but rely entirely on a computer program to ensure the randomness of elevator rides under various modelling scenarios.

Such a computer-based model has been used by our research group to accurately analyse the transmission characteristics of epidemics in a variety of scenarios in previous studies [17–20]. The model has the advantage of being able to randomly simulate specific behaviours of individuals—such as the use of public transportation, attending dinner with family and friends, and going on trips among cities. Therefore, compared with the dynamic model of differential equations, this model can not only accurately simulate the complex behaviour of each individual at the micro level, but can also reflect the regularity of epidemics caused by the behaviour of the group at the macro level. In the present study, the first working step of the model is to identify the passengers in a given elevator every time it is used based on the residents' schedules of elevator use. If the passengers include both infectious and susceptible individuals, transmission of the infectious disease may occur. Moreover, if a member of a given household becomes infectious in the daytime, all other susceptible members of the same household will be infected during the night. Therefore, epidemic transmission occurs both in the elevator and in the household. The moments of the two types of transmission events are combined to depict the full course of epidemic transmission.

2. Methods

2.1. Constraints on the model

This is a computational model study and does not involve human trials; therefore, there is no institutional review board statement.

The following constraints were imposed on the model in order to make the model design concise yet representative of true situations: (1) the apartment building had 15 floors, and each floor was inhabited by four households sharing one elevator. The reason for this setting was that if the floor was too high, then it required at least two elevators, while if the floor was too low, there would be few residents. All residents above the second floor chose to use the elevator instead of the stairs; (2) the number of members of each household was set randomly according to the Household Population Distribution in China; (3) none of the residents in the apartment building visited any of the other households; i.e., residents from different households could only meet in the elevator; (4) the seven days of a week were divided into weekdays (Monday to Friday) as working days and weekends (Saturday and Sunday) as non-working days, with each one-member household having one worker and each multi-member household having two workers. The commute for work on working days started between 6 a.m. and 8 a.m., and the workers returned to the elevator from work between 5 p.m. and 7 p.m. All residents (workers and non-workers) were back home by 10 p.m. each day; (5) for a given worker, the start time of the commute for work on a given working day (i.e., the moment of pushing the elevator button) was randomly selected within a time interval of 0.5 h. The position of the time interval was fixed for the worker on each working day, but was different for a different worker. The worker's time of return to the elevator after work was also designed in the same way; (6) the number of times that a non-worker left home on each working and non-working day, as well as the number of times that a worker left home on each non-working day, was randomly selected from a Poisson distribution with a mean of 2.5 times per 24 h. There was a separation of at least 10 min between the current moment when the individual left home and the previous moment when the same individual returned home. On each working day, the number of times that a worker left home again after returning from work was also randomly selected from a Poisson distribution with a mean of 2.5 times per 24 h; (7) the time for an elevator to pass each floor was set at 3 s, and it stopped at a floor for 10 s if residents needed to enter and/or leave the elevator on that floor; and (8) each infected individual experienced a susceptibility period, an incubation period (where they were referred to as an infected individual), an infectious period with symptoms (where they were referred to as a patient), an in-patient treatment period, and a recovery period in sequence. In particular, it was assumed that hospitalised patients did not take the elevator and that recovered patients had lasting immunity.

2.2. The framework of the model

The model parameters were initialised, including the number of floors, the incubation period, the number of members in each household, and the maximum iteration time T (days), etc. Next, the model iterated from the first day until the T-th day, with each iteration for a given day (e.g., the n-th day) involving steps 1–3. In step 4, the iteration was terminated and data were analysed.

The first step was to set the moments of each resident leaving and returning home. Specifically, the number of departures and the moments of each departure and arrival (i.e., the moments of pushing the elevator buttons upon departure and arrival) on the n-th day were set for each resident of the apartment building. The moments of departure and arrival of each resident (with corresponding serial numbers) were stored in the data frames Timeout and Timeback, respectively. Based on the moments of hospitalisation and discharge of infected residents (stored in data frame D), the serial numbers of hospitalised patients and their moments of departure and arrival were removed from the two data frames.

In the second step, the moment of each operation of the elevator and the serial numbers of the passengers in the elevator car were determined. According to the elevator operation rules in Methods 2.3, the serial numbers of passengers carried alone or together in each operation and the operation time of the elevator were calculated, and the calculation results were stored in a data frame named Passengers. In Passengers, each row represented one operation of the elevator, and the first element of each row represented the operation time of the elevator, with the subsequent elements being the serial numbers of passengers (residents). The operation of an elevator in this study refers to the process of the elevator transporting a resident to the first floor in the downward direction or to the home floor in the upward direction after departing or arriving residents press the elevator buttons. The operation moment of an elevator refers to the moment when the elevator with departing residents reaches the first floor, or the moment when returning residents start to enter the elevator at the first floor. Since the number of intra-elevator passengers was highest at these moments, they were also referred to as the moments when susceptible passengers were infected in the elevator. Simultaneously, a data frame named State (corresponding to Passengers) was generated to record the infection status of each passenger, with 0 denoting the susceptibility period, 1 the incubation period, 2 the infectious period, 3 the in-patient treatment period, and 4 the recovery period. State and Statef (the data frame recording the infection statuses of household members) were updated daily according to the recorded moments in data frame D when passengers started to enter various infection statuses (latency, infectious, in-patient treatment, and recovery periods). The order of rows in Passengers and State were re-sorted according to the operation moments of the elevator.

The third step was to describe disease transmission within the elevator and households. The Passengers data frame was searched row by row for the residents' serial numbers at each operation moment of the elevator (and possibly at the moment of intra-household infection) in chronological order while searching State for the infection statuses of the residents. Disease transmission could occur when both infectious and susceptible individuals were among the residents in the elevator. Based on the transmission rate *p*, the information of all newly infected individuals was stored in vector d, which was added into D as the last row. The elements in d were, from left to right, the individual's serial number, their status as a worker (1) or a non-worker (2), the serial number of the household, the floor on which the household was located, the moment of infection, the moment of onset, the moment of treatment, and the moment of discharge. Next, State was updated again based on the time information in d. According to the records in Statef, when the

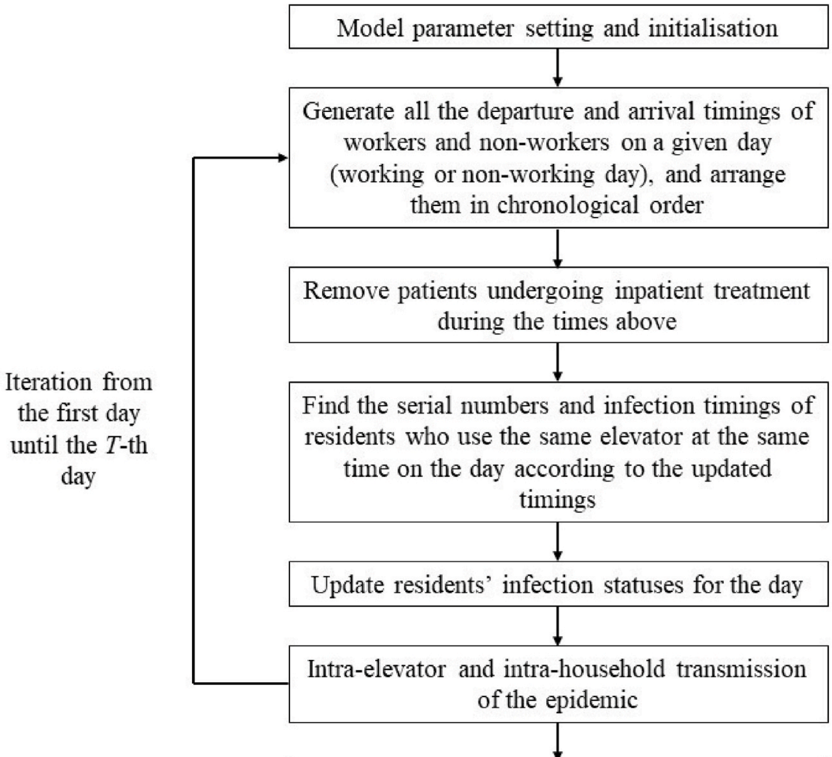

Fig. 1. Basic framework of the model design.

first individual of a household became infectious on day *n,* all susceptible individuals in that household were randomly infected over the period from 10 p.m. to 6 a.m. of the following day. The moments of intra-household infections, the sources of infections, and the susceptible individuals in households were added into Passengers while adding their infection statuses into State.

In the fourth step, the iteration of steps 1–3 was terminated on day *T*. Based on the information in **D**, the time distribution of new and cumulative infected individuals as well as patients was calculated. The framework of the model is shown in Fig. 1, and the program code is shown in the appendix (Figure S1).

2.3. *Operating rules of the elevator*

The elevator was designed to operate in a manner consistent with real scenarios, as briefly described below.

Rule 1. If a resident pressed the elevator button to leave the apartment building when the elevator was stationary at the *f*-th floor above that resident, the elevator started to descend. During the descent, if someone at the *g*-th floor below the (*f*-1)-th floor pressed the elevator button before the elevator reached the ($g + 1$)-th floor, the elevator stopped at the *g*-th floor. The elevator operated in accordance with this rule until it reached the first floor.

Rule 2. If a resident at the *g*-th floor pressed the elevator button to leave the apartment building when the elevator was stationary at the lower *f*-th floor, the elevator started to ascend. If at least one resident above the (*f*+1)-th floor pressed the button before the elevator reached the (*g*-1)-th floor, the elevator ascended without stopping until it reached the highest floor among the residents who pressed the button. Afterwards, the elevator started to descend in accordance with **Rule 1**.

Rule 3. If the elevator was stationary on the *f*-th floor when a resident pressed the elevator button on the first floor, the elevator would descend from the *f*-th floor towards the first floor. During the downward movement, the elevator would bring all the residents below the (*f*-1)-th floor who pressed the button to the first floor in accordance with **Rule 1**. Afterwards, all the residents waiting on the first floor to go home would be sent to their respective floors in turn. See lines 257–394 in the appendix for the code details.

2.4. *Spread of the epidemic*

The spread of an epidemic in an elevator car can only occur when there are multiple passengers, including both infectious and susceptible individuals. Assuming that the probability of a susceptible individual being infected when riding in an elevator with an infectious individual is p (the transmission rate), the probability of being infected when there are n infectious individuals in the elevator car is $1-(1-p)^n$. In addition to the elevator, the household space was also a relatively small, confined space. It was assumed in this study that as soon as one household member was infected during the infectious period, all other susceptible members of the household were infected at a random moment during the night (from 10 p.m. to 6 a.m. of the following day). The transmission moments of the epidemic in the elevator and in the household, as well as the individuals involved and their infection statuses, were considered comprehensively to identify the newly added infected individuals in the order of transmission moments. See lines 402–572 in the appendix for the details of the algorithm.

Some parameters of the model were obtained from previous reports, such as the incubation period, the infectious period, and the in-patient treatment period for the disease. The remaining parameters—for example, the average number of departures per day for each resident, the moments of departure, and the transmission rate *p*—were set according to basic facts and principles. The meaning and value of each parameter are listed in Table 1.

Table 1
Model parameters.

Description	Distribution characteristics	Numerical values	Sources (References)
Incubation period	Lognormal distribution	$\mu = 5.2$ $\sigma = 0.87$	[28]
Infectious period (mean duration from onset to hospital admission estimated as 12.5 days, 95% CI, 10.3–14.8 days)	Weibull distribution	Shape parameter $m = 1.66$ Scale parameter $\eta = 8.73$	[28]
Duration of hospitalisation	Uniform distribution	12–20 days	[29]
Transmission rate (p) indicates the probability that a susceptible individual will be infected when using an elevator simultaneously with a patient in the infectious period	Bernoulli distribution	0.3, 0.4, 0.5	Assumed
Number of times each non-worker leaves the apartment building per day	Poisson distribution	2.5 times per day on average	Assumed
Distribution of Chinese family sizes	Bernoulli distribution	Probabilities that the family size is 1, 2, 3, and 4 are 0.2, 0.33, 0.28, and 0.19, respectively	[30]
The time it takes for the elevator to pass a floor during operation	Constants	3 s	Assumed
The time it takes for the elevator to stay on a floor when passengers are entering or exiting it	Constants	10 s	Assumed

2.5. Sensitivity analysis

Partial rank correlation coefficients (PRCC) and Latin hypercube sampling (LHS) is a classic and widely used sampling-based sensitivity analysis method. This method was used to calculate correlations between a set of parameters and the model outputs after removing the linear effects of the target parameter [21]. Continuous time PRCC-LHS was used to conduct sensitivity analyses for the six main parameters in this model. We divided each parameter interval into N smaller equal intervals, then randomly selected one sample from each interval. After that, all parameter samples were included in the model to calculate the outputs at each time point [21, 22]. Finally, standard coefficients were calculated denoting the correlation between each parameter and the model output. All analyses were conducted using MATLAB R2019a software (MathWorks, Natick, Massachusetts, USA).

3. Results

3.1. Operating characteristics of the elevator

Fig. 2a shows the proportions of elevator operations grouped by the number of passengers in each operation on a day when the epidemic is absent. On non-working days, the proportion of elevator operations with only one passenger in each operation was as high as 0.85, which was higher than the corresponding proportion of 0.75 on working days. However, the proportion of elevator operations with two passengers in each operation markedly decreased to approximately 0.15 on working and non-working days, and further decreased to below 0.1 with three passengers. Because the transmission of the epidemic could only occur in the presence of more than one passenger, there was an approximately 80% probability that transmission was absent during the elevator operation in this scenario.

Fig. 2b shows the number of elevator operations at different times from 6 a.m. to 10 p.m. There were two primary operation peaks on each working day: one in the morning and the other in the evening, with a secondary operation peak after 8 p.m. On each non-working day, the number of elevator operations increased slowly from morning to evening.

Fig. 2c shows the temporal distribution of the proportions of elevator operations with more than one person in each operation on a given day, revealing the periods wherein intra-elevator transmission of the infectious disease can occur. The pattern presented here is similar to that in Fig. 2b, with the transmission on working days mostly occurring during the elevator's peak operation hours in the morning and evening. In contrast, intra-elevator transmission on non-working days mostly occurred after 4 p.m.

3.2. Temporal distribution of the spread of the epidemic

As shown in Fig. 3a, 3c, and 3e, the number of newly infected individuals showed an overall trend of first increasing and then decreasing. There were two obvious peaks on days 10–15 and a decrease on day 6, indicating that intra-elevator transmission was more severe on working days than on non-working days. When $p = 0.3$, 0.4, and 0.5, the median number of newly infected individuals reached the maximum on days 15 (n = 16.5), 12 (n = 17), and 11 (n = 20), respectively. This indicates that the greater the transmission rate p, the faster the rate of growth of newly infected individuals. On day 35, the cumulative number of infected individuals reached 158; that is, all residents above the second floor of the apartment had been infected.

As shown in Fig. 3b, 3d, and 3f, when $p = 0.3$, 0.4, and 0.5, the temporal distribution of the number of new patients was not bimodal. The lack of a bimodal pattern was due to the incubation period between the onset of infection and the onset of disease. The incubation period of each infected individual was randomly set, which alleviated the uneven temporal distribution of infection events. The median number of new patients reached the maximum on days 17 (n = 12), 16 (n = 13), and 15 (n = 14) for the three p-values, respectively. The cumulative number of patients reached 158 on day 35; that is, all residents above the second floor of the apartment had been infected.

As shown in Fig. 4a, 4c, and 4e, the number of newly intra-elevator-infected individuals was significantly higher than that of newly intra-household-infected individuals. When $p = 0.3$, 0.4, and 0.5, the median number of new intra-elevator-infected individuals

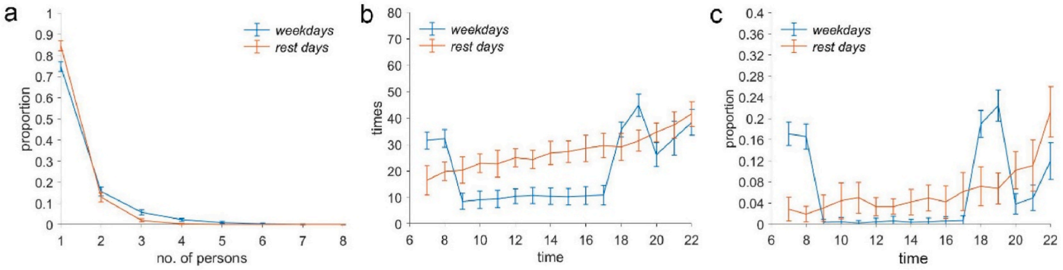

Fig. 2. Characterisation of elevator operation in the absence of the epidemic. a: distribution of the number of passengers using the elevator simultaneously, with the abscissa representing the number and the ordinate representing the corresponding proportion of elevator operations relative to total elevator operations. b: the temporal distribution of the number of elevator operations in a day. c: the temporal distribution of the proportion of elevator operations with more than one passenger in a day.

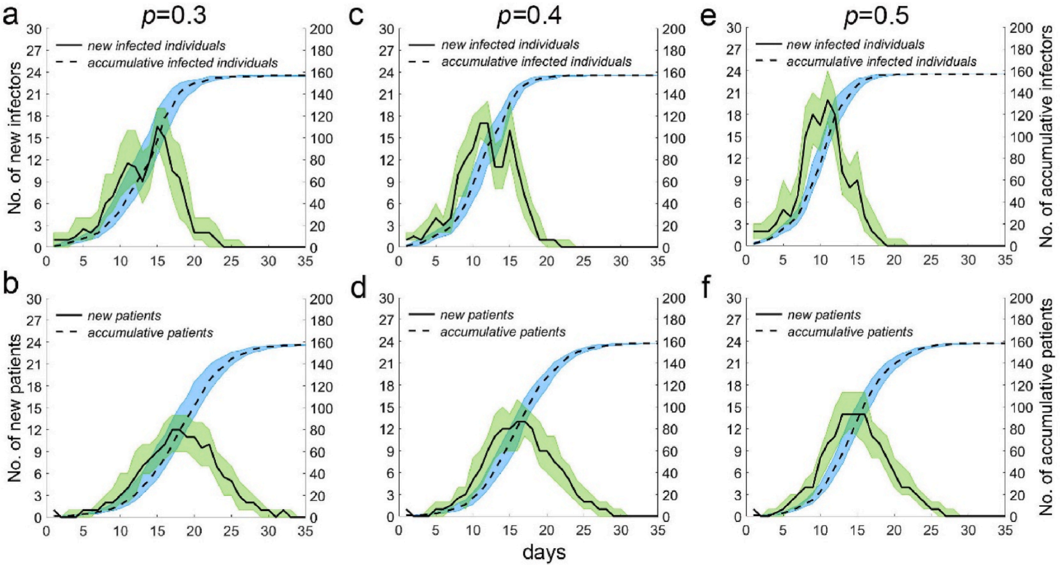

Fig. 3. Temporal distribution of infected individuals and patients. a, c, and e: temporal distribution of new infected individuals and cumulative infected individuals when $p = 0.3$, 0.4, and 0.5, respectively. b, d, and f: temporal distribution of the number of new and cumulative patients when $p = 0.3$, 0.4, and 0.5, respectively. The blue and green areas represent the 25%–75% percentiles of the values.

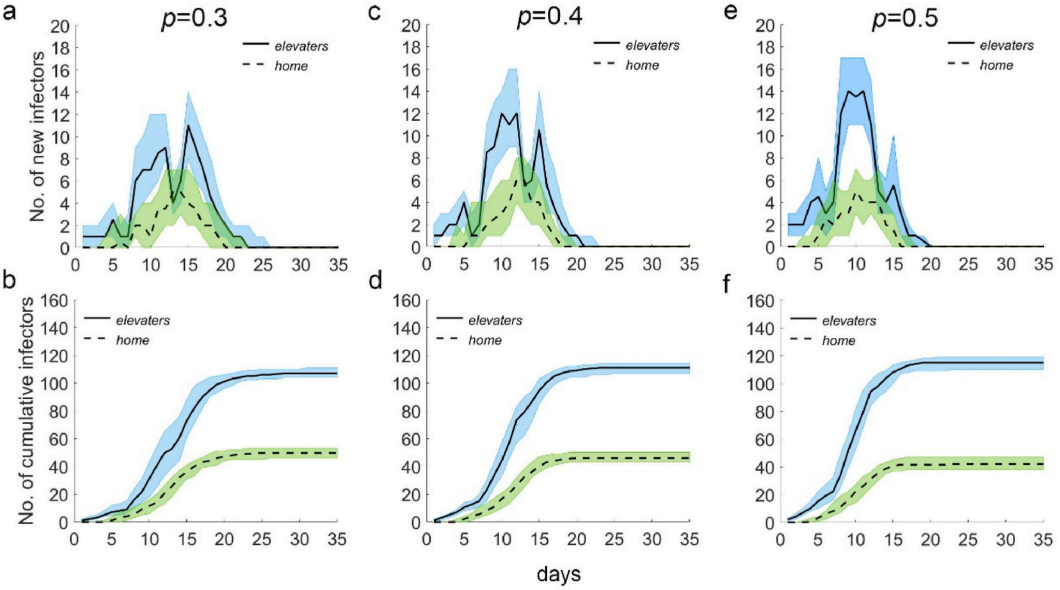

Fig. 4. Temporal distribution of intra-elevator and intra-household infected individuals. a, c, and e: temporal distribution of new infected individuals when $p = 0.3$, 0.4, and 0.5, respectively. b, d, and f: temporal distribution of cumulative infected individuals when $p = 0.3$, 0.4, and 0.5, respectively. The blue and green areas represent the 25%–75% percentiles of the values.

reached the maximum on days 15 (n = 11), 10 (n = 12), and 9 (n = 14), respectively. The median number of new intra-household-infected individuals reached the maximum on days 13 (n = 5), 12 (n = 6), and 10 (n = 5) for the three *p*-values, respectively. As shown in Fig. 4b, d, and 4f, when $p = 0.3$, 0.4, and 0.5, the median cumulative number of intra-elevator-infected individuals reached the maximum of 107, 111, and 115, respectively, whereas the number of intra-household-infected individuals reached 49.5, 46, and 42, respectively. This indicates that the greater the transmission rate *p,* the greater the number of individuals infected in the elevator compared to those infected in households. It can be concluded from these results that the main reason for the epidemic spread in the apartment was people taking the elevator compared to within-household spread.

3.3. Sensitivity analysis

In this study, six parameters (*p, n*, infectious period, incubation period, hospitalisation period, and time interval) were selected to conduct sensitivity analyses. The model output was a continuous time series of the cumulative number of infected individuals. We took 100 samples from a uniform distribution of each parameter interquartile range. PRCCs near 1 or −1 indicated that the parameter had a strong positive or negative impact on the output, whereas those closer to 0 had less effect on the output result (Fig. 5). The results indicated that *p*, *n*, and infectious period were positively correlated with the cumulative number of infected persons. The correlation of hospitalisation period and the time interval was not significant; however, there was a negative correlation with incubation period.

3.4. Basic reproduction number R_0

R_0 represents the average number of secondary cases generated by a typical primary case when taking the elevator in an entirely susceptible population. At the beginning of the epidemic, because an No. 0 infector could not only infect their entire family (the total number of family members is n_f) at night but could also infect other residents in the elevator according to the constraints of the model, we assume that if the total number of infected individuals caused by No. 0 infector and his/her infectious family members through the elevator during their infectious period was greater than 1, the epidemic would spread, and if it was less than 1, the epidemic would end. Assuming that the average number of susceptible individuals that an infector encountered when taking the elevator is m, the transmission rate is p, the average times each infector took the elevator each day is λ, and the infectious period is τ, then the approximate expression of R_0 is:

$$R_0 \approx mp\lambda\tau \tag{1}$$

$mp\lambda$ is the average number of newly infected individuals due to the infector taking the elevator each day. Therefore, the number of newly infected individuals caused by No. 0 infector and his/her family members during the infectious period N is:

$$N = R_0 n_f \tag{2}$$

If $N > 1$, that is, $R_0 > 1/n_f$, the epidemic spreads; if $N < 1$, that is, $R_0 < 1/n_f$, the epidemic ends. Among these parameters, p and λ represent the infectivity of the pathogen and the frequency of taking an elevator, which are the main factors affecting the epidemic; therefore, if $p\lambda > 1/m\tau n_f$, the epidemic spreads.

4. Discussion

4.1. Innovation in this study

This study had several novel features. First, it developed a model to investigate intra-elevator transmission of an infectious disease that can lead to an epidemic. This is a unique research perspective rarely explored in existing studies on infectious disease dynamics but has important public health implications. Second, the model incorporates the daily activities of residents, elevator operations, and the disease transmission process in a chronological order, thereby allowing better reproduction of real-life scenarios. Third, the computer-based model allows us to randomly design the behaviour of each resident as well as the processes of infection, symptom onset, and treatment. This not only ensures the randomness of the behaviour of each resident, but also helps achieve overall consistency in these behaviours.

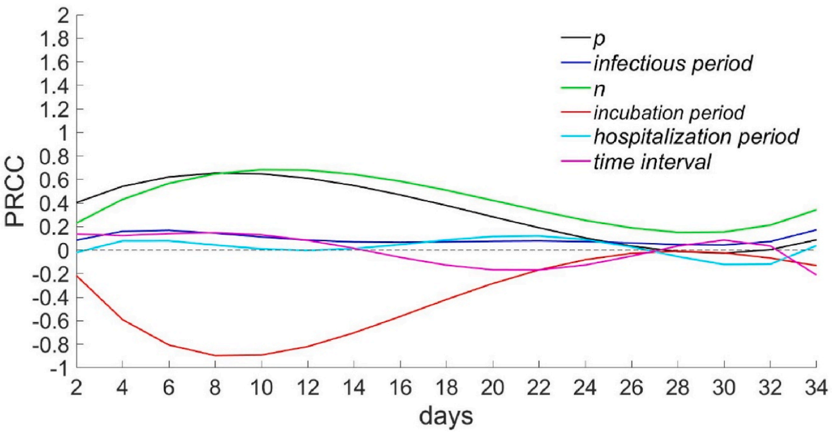

Fig. 5. Continuous-time sensitivity analysis. *p* denotes the transmission rate in the elevator car; *n* indicates the average number of departures from the apartment building per day per resident; time interval indicates the time range for each worker to commute on working days.

4.2. Operation of the elevator

Because infected residents undergo hospitalisation for a period of time, they do not use the elevator during this period. Therefore, hospitalised residents were excluded from consideration when designing the elevator operation procedure. During the temporal iteration of the program, it was necessary to update the daily moments of residents' exit from and entry into the apartment building while considering the timing of hospitalisation of the infected residents. The program code of elevator operation was executed based on the updated moments.

As shown by the elevator operation results in Fig. 2a, although only approximately 20% of the elevator operations were likely to lead to intra-elevator transmission, transmission can occur within households and increase the number of infected individuals, thereby allowing the epidemic to spread rapidly throughout the apartment building via elevator operations. As shown in Fig. 2b, the number of elevator operations on working days increased again to some extent after the high peak at 7 p.m., because some workers choose to go out after returning home from work. As shown in Fig. 2c, the peak operation hours of the elevator in the morning and evening on working days, as well as the hours with an increased number of elevator operations after the evening peak, were the main periods of intra-elevator transmission on working days. This is attributed to the high frequencies of residents leaving and returning during these hours, which leads to a high probability of multiple individuals using the elevator simultaneously.

4.3. Spread of the epidemic

The present model integrates intra-elevator transmission with intra-household transmission. This is because the household space is also a closed environment where household members are in close contact, which promotes pathogen transmission. Moreover, clustered transmission of COVID-19 in a household environment has been reported extensively [23–25]. In the present model, intra-household infection of any susceptible member is set to occur at a random moment in a time interval from 10 p.m. to 6 a.m. the following day. This is due to the following reasons: (1) all household members are at home in this interval and will be in contact with each other for a long time; (2) this design greatly simplifies the program code. To integrate intra-household transmission with intra-elevator transmission in terms of time, the model stores information as follows: the information on intra-household infection sources, susceptible household members, moment of infection, and intra-elevator transmission is stored in the data frame **Passengers;** and each member's infection status (scored as 2 when the member is an infection source and 0 when they are a susceptible individual) is stored in the data frame **State**.

When $p = 0.3$ and 0.4, the number of new intra-elevator-infected individuals showed a significant decrease on the first two weekends (days 6, 7, 13, and 14), with two high peaks on days 10–15. This was because the probability of multiple individuals using the same elevator at the same time was lower on weekends than on working days; therefore, the number of infected individuals on weekends is less than that on working days. When $p = 0.5$, only one peak appeared on days 10–15 because the large value of p led to a large number of intra-elevator-infected individuals before day 11, thereby causing a sharp decrease in the number of susceptible individuals. Thereafter, the number of newly infected individuals showed a decreasing trend on both working and non-working days. Compared with intra-household infection, more individuals are infected intra-elevator. The reasons are as follows: (1) Persons in each family must be infected intra-elevator first, then may infect other family members; therefore, at least one person in each family is infected intra-elevator; (2) workers account for 73% of the total number of residents. They have a high probability of contacting and infecting each other in the elevator on working days.

4.4. Sensitivity analysis

n, p had more positive effects than the infectious period. This is because the larger the n and the more residents who use the elevator simultaneously, thus the greater the chance of disease transmission. The greater the transmission rate p, the higher the probability of a susceptible individual being infected in the elevator. Both showed a trend of first increasing and then decreasing, which is consistent with the trend of new infected individuals shown in Fig. 3. The infectious period had a moderately and steadily positive correlation in the long term because the extension of the infectious period can lead to a marginal increase in the number of infected individuals so that sufficient infected individuals is generated in the later period compared with p and n. The longer the incubation period, the slower the growth rate of the infected individuals, so it is negatively correlated with the number of infected individuals. The sensitivity analysis not only further confirms the previous findings, but also proves that the model design is scientifically sound and reasonable.

4.5. Limitations of the study

One limitation of this study is that the reliability of the model cannot be evaluated by modelling real data because there are no epidemiological survey data on elevator operation-induced transmission of respiratory infectious diseases in real situations. To solve this problem, we performed continuous-time sensitivity analysis. Second, many constraints were imposed on the model to make it more concise and efficient. These included constraints such as assuming that there were no visits by non-residents to the apartment, that all residents returned home by 10 p.m. each night, and that intra-household transmission of the epidemic occurred only at night. These constraints idealise the model and make it deviate from real situations to some extent. Third, even in the absence of an infection source, the air or buttons inside the elevator car may retain viruses (such as SARS-CoV-2), which can lead to infections in other individuals [26,27]. However, these scenarios were not considered in the model design due to the high number of uncontrollable factors.

In summary, in this study, we developed a computer-based model to simulate the dynamic process of transmission of respiratory infectious diseases through elevator operations in a residential apartment building. The results reveal that the elevator car is an important place and fomite for pathogen transmission, and can lead to the rapid spread of an epidemic in an apartment building. Moreover, the greater the intra-elevator transmission rate, the greater the number of individuals infected during elevator operations, ultimately leading to infections of all residents in the apartment building. To prevent and control the spread of infectious diseases, the number of elevator passengers should be reduced, and residents should be encouraged to use the stairs. Moreover, it is necessary to improve air circulation and disinfection in elevators while encouraging residents to wear masks and touch fewer buttons when using elevators.

Declarations

Author contribution statement

Zuiyuan Guo: Conceived and designed the experiments; Performed the experiments; Analysed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Guangquan Xiao; Jianhong Du; Bing Li; Dan Xiao; Wei Cui: Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data associated with this study has been deposited at https://doi.org/10.5281/zenodo.7014394.

Declaration of interest's statement

The authors declare no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e13612.

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