Urban Public Spaces and Pandemic Resilience: A Simulative Infection Assessment to Aid Crowd Management

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ABSTRACT

The management of public spaces has become increasingly important as infectious diseases such as COVID-19 continue to shape urban life. Extended lockdowns have underscored the crucial role of accessible outdoor recreational areas, underscoring the importance of maintaining these spaces while minimizing infection risks and enhancing pandemic resilience. This study examines the potential for disease transmission in an urban park by simulating multiple activity-based scenarios using an integrated modelling approach that couples agent-based modelling with system dynamics. The agent-based model captures proximity-based interactions among park users, which in turn feed into the system dynamics model to track changes in infection rates over time. Two primary sets of scenarios were evaluated: those reflecting current park conditions and those incorporating social distancing interventions. The results show that a combination of staggered visitation time slots and at least 75% compliance with safety measures produces the most favourable outcomes, significantly reducing transmission risk while maintaining park usability. These findings demonstrate that strategic, scenario-based interventions can help avoid the need for complete closures of public spaces during health crises. Overall, the study provides evidence that integrated simulation models can support data-driven, transparent, and adaptable public space management strategies. By helping authorities anticipate how behavioural patterns and policy measures influence disease spread, such models can guide decisions that preserve public access to essential urban spaces while safeguarding public health. This approach can be replicated in other urban contexts to enhance preparedness and minimize disruptions during future pandemics.

Keywords: COVID-19; Pandemics; Crowd Management; Urban Parks; Agent-Based Modeling; System Dynamics

INTRODUCTION

COVID-19 is a respiratory illness caused by the SARS-CoV-2 virus, which is very contagious and spreads quickly (Harvard Medical School, 2023). The detrimental consequences of the COVID-19 pandemic have prompted us to explore optimal methods of infection control to achieve social resilience during future pandemics. Human mobility often exacerbates outbreaks caused by infectious respiratory pathogens (Bajardi et al., 2011), as movements increase the contact probability between infected and healthy individuals (Mao, 2014). Such an influence has prompted many countries and their governments to implement measures restricting movements and spatial interactions to curb the spread of the virus. People often perceive urban public spaces as hubs of social interaction and potential disease transmission, so they were closed off during the pandemic. However, prolonged lockdowns limit access to public spaces, disrupting the economy, health, and urban environment (Dilnashin et al., 2021; Nguyen et al., 2021; Wang & Li, 2022).

Recent research indicates that more severe lockdown policies are not associated with lower mortality, suggesting that lockdowns have not achieved their intended effect (Bjørnskov, 2021). Apart from mortality, other collateral damages of the lockdown included unemployment, poverty, food insecurity, interrupted preventive, diagnostic, and therapeutic healthcare, interrupted education, loneliness, and deterioration of mental health (Joffe, 2021; Onyeaka et al., 2021). The ramifications prompt a need for balance in controlling the spread of the disease and allowing daily activities while formulating containment strategies. The strategies formed should be able to control the infection with minimal impact on daily lives, allowing economic activities while containing the spread without compromising the health and well-being of the people. The pandemic response protocol needs an analytical framework to foresee and control the spread of disease, especially in public spaces. Assessing the infection risk posed by these public spaces can help effectively manage them to minimize the risk of infection while allowing activities to be conducted in a regulated manner.

The process of contagion movement in the case of any respiratory infectious disease is essentially spatial (Merler et al., 2020), so researchers need to address the measurement of infection risk spatially. However, our understanding of spatial dynamics of infectious disease spread is rudimentary; fortunately, modeling techniques can potentially probe the intractable complexity of infectious disease dynamics (Heesterbeek et al., 2015). The Infectious Disease Dynamics (IDD) approach, a mathematical simulation technique, is driven by the desire for a fundamental understanding and the need to apply that understanding to inform public health decision-making (Zhou et al., 2021). One such compartment model that employs the IDD approach is the SEIR model, where the main idea is to divide the population into several compartments, which respectively represent agents in different disease states. Dynamic equations for related variables are then established using mathematical techniques (Zhou et al., 2021).

Simulation of similar mathematical models tracks the dynamic trajectory of a system based on a set of rules that dictate how the system evolves from its current state to a future one (Ilya Grigoryev, 2021). The researchers can assess the risk of infection by simulating the dynamics of people interacting in public spaces. Currently, simulation modeling uses three methods: system dynamics, which assumes very high abstraction for strategic modeling; discrete event modeling, which supports medium and medium-low abstraction; and agent-based models, which can vary from very detailed models where agents represent physical objects to highly abstract models where agents represent competing companies or governments (Ilya Grigoryev, 2021). The models are selected solely or as a mix of these methods based on the requirements of the problem at hand.

During the COVID-19 pandemic, most city authorities closed down or restricted access to urban public spaces to minimize the risk of disease transmission (Geneletti et al., 2022). One such public space is the urban park, which is often closed and left inaccessible to the general public. Urban parks are public spaces that can be both a potential zone for virus transmission and a keystone of general public health (Yue et al., 2021a). The restrictions on accessing urban parks impeded people's social interaction, leisure activities, and business activities, with negative consequences on their mental health and subjective well-being (F. Wang & Boros, 2021). The movement restrictions also reduce alternatives for visiting green spaces, forcing people to visit overcrowded areas (Geneletti et al., 2022). The study examines the dynamics of spatial interaction in an urban park to assess the infection risk and support authorities in developing optimal infection control strategies.

Previous research addresses policy scenarios for restricting access to urban green spaces (L. K. N. Nguyen et al., 2020) and park capacities during social distancing in urban parks (Yue et al., 2021b) during the COVID-19 pandemic. However, the studies concentrate on managing access and visitor behavior during physical distancing without directly addressing disease transmission dynamics or specific interventions. The study aims to simulate the daily activities of an urban park to calculate the risk of infection under various scenarios. Simulation models enable the authors to estimate the rates of susceptible, infected, and exposed users by applying different rules of possible infection to the crowd and their activities. The simulation assessed the spatial infection risk posed by the urban park, providing a basis for managing visitor movement effectively and minimizing disease spread, thereby helping to achieve social resilience during pandemics. The paper proposes strategies for crowd management based on the risk of infection simulated in different scenarios. An urban park from Andhra Pradesh, India, is used as a case study to demonstrate the approach and to discuss the outcomes.

METHODS

Study Area

To demonstrate the risk of infection posed by an urban park, the Chitturi Memorial Park, located in Tanuku, Andhra Pradesh, India, was selected for the study. The park is located on the campus of SCIM Government College in Tanuku and is accessible to both students and the public. Users utilize the park for various physical

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activities, including exercise, jogging, and yoga. The authors selected the park based on its accessible location in the urban area and the presence of varying activities that take place in the area.

Model

The study employs the SEIR model for COVID-19 infection, a widely used technique due to its predictive effectiveness. The model divides the total population into four chambers, namely the susceptible population (S), the exposed population (E), the infected population (I), and the recovered population (R). Specifically, the individuals in chamber S are not infected but are susceptible to infection. Individuals in chamber E are infected but not yet contagious. In chamber I, the individuals are infected and contagious. The individuals in the R chamber have been cured or disease-free and are immune. (J. Wang, 2023) The authors developed the SEIR model for COVID-19 based on the flow chart in Figure 1. Table 1 defines the variables and parameters of the SEIR model used for the spread of the virus.

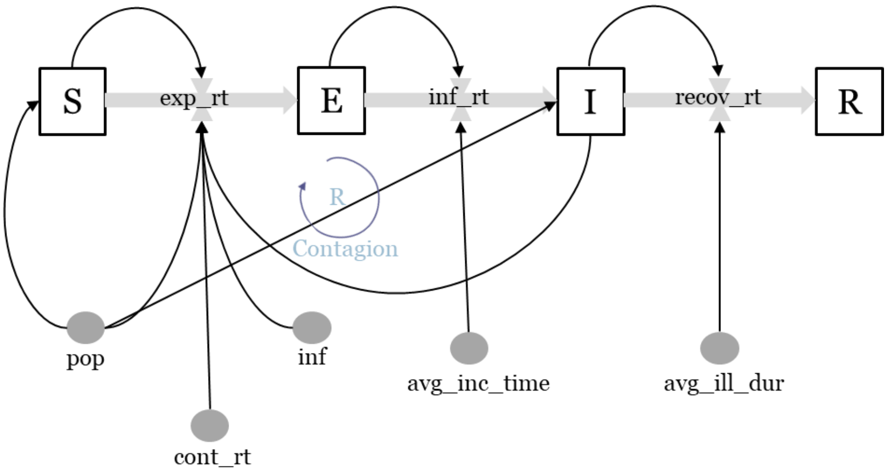

Figure 1. SEIR Model Transfer Diagram for COVID-19 Infection

Table 1. Variables and Parameters in the SEIR Model

Variable	Definition
S	The number of people susceptible to the COVID-19 virus infection
E	The number of people exposed to the COVID-19 virus
I	The number of people infected with the COVID-19 virus
R	The number of people recovered from the COVID-19 virus infection
Parameter	
exp_rt	Disease transmission rate from susceptible to exposed
inf_rt	Disease transmission rate from exposed to infected
recov_rt	Disease transmission rate from infected to recovered
pop	Total number of people using the park
cont_rt	Rate of contact
inf	Infectivity

avg_inc_time	Average incubation time from infection to onset of symptoms
avg_ill_dur	Average duration of illness

Data Collection

A one-day primary observational survey provided the necessary input data for the simulation model. The data collected included user statistics, activities, and timings. Observational surveys recorded the total population using the park for a day and their movements from entry to exit. The activities and times that take place in the park on a given day were collected through an observational survey. The primary activities included yoga, walking, jogging, badminton, and open-gym exercise.

The activities began with yoga at 4:30 a.m. and continued until 8:00 a.m. The park allowed yoga without instructors, according to the convenience of the visitors. A maximum of 25 visitors, aged 25 to 30 years, engaged in the activity for an average of one hour per person. The next activity was badminton, in which a maximum of 30 users aged 20 to 30 years participated for an average of 1.5 hours per individual. The primary activities in the park are walking and jogging, which are done by around 150 people on a typical day. At any instant, a minimum of 30 people use the walking or jogging track. Users aged 8 to 60 years used the track for an average of two hours per individual. A maximum of 20 people used the open gym immediately, with ages ranging from 19 to 25 years. The average duration spent by an individual is around one hour for the open gym area and around 20 minutes at the exercise bars.

Simulation

The authors selected a hybrid simulation model to execute the SEIR model by coupling the Agent-based and System Dynamics models. The authors used AnyLogic software (https://www.anylogic.com/) to execute the hybrid model. The model utilized the collected data to simulate both existing and social distancing scenarios, analyzing the impact on disease spread in various scenarios. Table 2 presents the four scenarios simulated to determine the change in the potential for infection. Scenario 1 represents the typical activities with the existing population and lower infectivity. However, Scenario 2 indicates the same, with double the population and slightly higher infectivity. Scenarios 3 and 4 accommodate social distancing conditions with 50% and 75% compliance, respectively.

Table 2. Conditions Used for Scenarios

Parameters	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Total Population	200	400	200	200
Infectivity (%)	0.5	1	0.5	0.5
Contact Rate (ppl/hr)	75	126	30	12
Average Incubation (hr)	144			

Agent-based Model

The authors implemented the agent-based model, which provided the contact rate among users in various scenarios. The process began with defining spaces and the corresponding activities to scale. The addition and definition of agents followed this. The agent, in general, is the basic unit that moves in the main environment, replicating the movements of the park users. So, the authors named the agent a pedestrian and described its characteristics and movements, as recorded during the primary survey. The paths of movement of people are defined using target lines to reach the activity areas.

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The study employs the SEIR (Susceptible, Exposed, Infected, and Recovered) model, a compartmental differential-equation model that categorizes the infected population by age of infection, utilizing simple compartments for individuals who are susceptible, exposed, infected, and recovered (Zhou et al., 2021). The authors defined a state chart for the agent, detailing the various states of susceptibility, exposure, infection, and recovery that the agent undergoes in the SEIR model. The model removed the state of recovery as the simulation extended for a day. Susceptible people move to the exposed state once they come into contact. The exposed people move to the infectious state after the disease's latency period. Finally, the authors executed the simulation to determine the number of contacts per hour per individual for each scenario, based on the number of proximity interactions identified.

System Dynamics Model

After obtaining contact rates for various scenarios from the agent-based model, the authors used the System Dynamics model to estimate potential infections for each scenario. The SEIR model employed the stocks and flows method, with formulas and flow rates defined within the model, and adjusted parameters to generate results across various scenarios. The stocks in the model represent susceptible, exposed, infectious, and recovered individuals, while the flows correspond to the rates of exposure, infection, and recovery. These flows are defined for each scenario using the parameters outlined in the model, as detailed in Tables 1 and 2. The parameters include total population, infectivity, contact rate, average incubation time, and average illness duration. The authors incorporated a time flow chart into the model, assigning parameter values based on the agent-based model data. Finally, they simulated to calculate the number of susceptible, infected, and exposed individuals in various scenarios, which informed the development of crowd management strategies.

RESULTS

Scenario 1

In scenario 1, the authors simulated the disease spread according to the actual activities recorded in the park. Based on the ABM model, the contact rate is 75 people per hour. Table 2 presents the parameters and corresponding values for the existing conditions. The simulation results (Figure 2) showed that eight people were infected and 47 were exposed after one hour. After two hours, the results showed that 48 people were infected and 138 were exposed.

Figure 2. Simulation Results of Scenario 1

Scenario 2

Scenario 2 simulates the same activities in the park, but with twice the population and a different infectiousness rate. Thus, the contact rate has increased, as per the ABM model. The values of other parameters remain unchanged, as shown in Table 2. The simulation results (Figure 3) showed that 19 people were infected and 143 were exposed after one hour. After two hours, the results showed that 128 people were infected and 272 were exposed.

Figure 3. Simulation Results of Scenario 2

Scenario 3

This scenario simulates the park's activities with 50% compliance with social distancing measures, with the same population. Based on the agent-based model, the contact rate is 30 people per hour with an infectivity of 0.5%. The simulation results (Figure 4) showed that three people were infected and 11 were exposed after one hour. After two hours, the results showed that 14 people were infected and 49 were exposed.

Figure 4. Simulation Results of Scenario 3

Scenario 4

This scenario explains the same conditions as the previous scenario, but with 75% compliance with social distancing measures. Based on the agent-based model, the contact rate is 30 people per hour with an infectivity of 0.5%. The simulation results (Figure 5) showed that one person was infected and four people were exposed after one hour. After two hours, the results showed that three people were infected and eight were exposed.

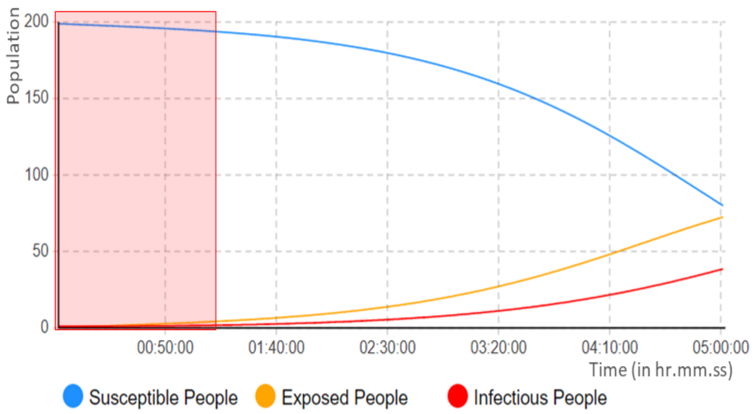

Figure 5. Simulation Results of Scenario 4

DISCUSSION

The results of this study highlight the critical role that activity patterns, population density, and social distancing measures play in the transmission of infectious diseases within public spaces, such as urban parks. In analyzing four different scenarios, we can observe how varying these factors impacts the infection dynamics and inform potential management strategies. Scenario 1 serves as the control case, reflecting actual behaviors and movement patterns in the park. The infection grows exponentially in the first two hours due to a high contact rate and lack of interventions. The steep decline of the blue curve (susceptible) and the sharp rise in the orange and red curves (exposed and infectious, respectively) in Figure 2 reflect the rapid transmission dynamics in an unrestricted environment. This scenario underscores the vulnerability of public spaces when no mitigation strategies are applied, highlighting the urgency for intervention.

In Scenario 2, doubling the population and increasing infectivity result in a dramatic rise in both the number of exposed and infected individuals. This is evident in Figure 3, where all three population curves shift steeply: susceptible individuals decline more rapidly, and the peak of the exposed population occurs earlier and at a higher level than in Scenario 1. The infectious curve (red) also rises sharply. This scenario illustrates how increased crowding and disease transmissibility can exponentially exacerbate outbreaks, underscoring the importance of managing population density in public spaces. In Scenario 3, applying moderate social distancing measures significantly reduces the transmission of the disease. The graphs in Figure 4 depict a slower decline in the susceptible population and a more gradual increase in exposed and infected individuals. The epidemic curve flattens compared to Scenarios 1 and 2, showing the effectiveness of even partial compliance. However, infections still accumulate over time, indicating that 50% compliance alone is not sufficient to halt transmission completely but does help mitigate the outbreak.

Scenario 4 demonstrates the most effective intervention. With 75% compliance to social distancing, the infection curve in Figure 5 remains flat, and the exposed population remains low. The blue curve (susceptible) shows minimal decline, indicating low transmission. This scenario confirms that higher compliance with preventive measures, such as social distancing, significantly curbs disease spread, even when contact rates are moderately high. It presents a compelling case for public health campaigns to promote high adherence to non-pharmaceutical interventions. Doubling the population size showed a disproportionate effect on disease spread. However, social distancing effectively reduced both exposure and infection, with higher compliance offering exponentially better results. These findings can inform policy decisions related to park access and management during crises, helping balance public health concerns with the need for outdoor spaces. Additionally, they stress the importance of controlling crowd size and enforcing physical distancing to minimize the risk of widespread infection in public spaces.

RECOMMENDATIONS

The simulation results clearly demonstrate that spatial design, population distribution, and behavioral management play a crucial role in controlling the transmission of infectious diseases in public spaces. Urban planners and public health officials must work collaboratively to design parks and public spaces that not only serve recreational needs but also function as epidemiologically safe environments during pandemics. The ABM simulations illustrate how changes in population behavior and density can rapidly impact outcomes. Table 3 provides the areas of intervention recommended based on the simulated scenarios.

Table 3. Areas of Intervention Informed by Simulation Scenarios

Areas of Intervention	Evidence and Interventions
Design for Physical Distancing	**Evidence:** Scenarios 3 and 4 demonstrated that reduced contact rates and increased distancing compliance significantly lowered infection and exposure rates.
	• Widen pathways and walkways to a minimum of 3–4 meters to allow bi-directional pedestrian flow while maintaining a safe distance.

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	• Create looped walking circuits with one-way movement signs to reduce face-to-face encounters. • Space out seating areas, exercise stations, and picnic zones by at least 2 meters.
Implement Smart Access and Entry Control	**Evidence:** Scenario 2 highlighted the dangers of overcrowding. Doubling the population led to 128 infections in 2 hours, underscoring the need for access regulation.
	• Use gated or geofenced entry systems to monitor and control the number of people entering a park or public space. • Introduce real-time occupancy tracking apps with visual dashboards available to the public, warning them of crowd levels and suggesting alternate visiting times.
Create Decentralized and Distributed Green Spaces	**Evidence:** Concentrated activity in a single large park increases the risk of infection, as seen in the high transmission rates of Scenarios 1 and 2.
	• Avoid overcrowding by distributing smaller parks and open spaces across neighborhoods, especially in high-density residential zones. • Ensure equitable access to green infrastructure to prevent people from congregating in limited urban green zones.
Temporal Zoning and Activity Scheduling	**Evidence:** Flattening the curve is not just a spatial concept. Temporal spacing helps reduce simultaneous exposure, particularly useful in high-footfall parks.
	• Introduce time-slot-based usage to stagger demand. • Encourage off-peak visits through differential pricing (where applicable) or community coordination.
Integrate Health Infrastructure and Surveillance	**Evidence:** Real-time intervention capability allows authorities to act before the contact rate escalates to critical thresholds, as seen in rapid spread scenarios.
	• Install temperature screening booths, sanitation stations, and mask dispensers at entry points. • Deploy CCTV and drone-based crowd monitoring systems to enforce social distancing in larger or hard-to-monitor parks.
Flexible Re-design of Public Amenities	• Enable modular park layouts with movable benches, shade structures, and activity areas that can be spaced out as needed during outbreaks. • Design “breathable” event spaces with capacity-limited zones, clear markings, and pedestrian flow control.
Promote Active Transport and Dispersed Mobility	• Enhance safe walking and cycling networks to reduce reliance on crowded public transit to access parks. • Integrate linear parks or green corridors along urban mobility routes to encourage dispersed and safe recreation.

CONCLUSION

Identifying public spaces and associated activities that contribute to higher infection risks is essential for formulating effective containment strategies. Assessing these risks requires a detailed understanding of the nature and intensity of human interactions in these areas, given the contagious nature of the disease. Simulation models can play a vital role by replicating real-world activities and estimating the probability of transmission. Such spatial risk assessments provide a robust foundation for policy decisions regarding lockdown priorities, permissible activities, occupancy limits, and other mitigation measures. For instance, in public places such as urban parks, crowd management strategies informed by disease spread simulations can help regulate visitation patterns in alignment with public health objectives.

The case study of an urban park simulated the probability of disease in various scenarios involving the park's activities with and without social distancing norms. The simulations revealed a higher probability of infection with an increase in population. Furthermore, it demonstrated how compliance with social distancing measures can reduce the risk of infection. The results helped identify areas for intervention to reduce the risk of infection in urban parks for future pandemics. The case study demonstrated how simulations can aid in spatial risk assessment, enabling planners and policymakers to prepare effective containment plans. The study has only addressed the case of an urban park. Similar studies should be extended to all other public spaces, forming a solid foundation for crowd management in public spaces during infectious disease outbreaks. Similar simulations for a longer span of days could help identify the influence of infection on people's recovery.

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