Modeling Influenza Transmission in Elementary School Classrooms: A Simulation-Based Approach to Assessing Outbreak Dynamics and Intervention Strategies

Winnie Taiwo
Georgia Institute of Technology

December 3, 2024

Abstract

This project simulates the spread of influenza in a classroom of 61 elementary school children, starting with one infected student, Tommy. Using a stochastic framework, we analyzed flu transmission dynamics, including the number of infections, outbreak duration, and the effects of interventions like immunization. Each susceptible student had a daily infection probability ($p = 0.01$), and the simulation was repeated multiple times to capture variability. The results revealed a classic epidemic curve: infections rose exponentially during the first week, peaked around Days 8–10, and declined as the susceptible population diminished. Without immunization, outbreaks typically lasted over 15 days. However, with 50% immunization, most outbreaks resolved within 10 days, and with 75%, they concluded in fewer than 5 days. The effective reproduction number (R_t) began high, reflecting rapid transmission, but dropped below 1 as the outbreak subsided. Sensitivity analyses showed that higher infection probabilities resulted in shorter, more intense outbreaks, while lower probabilities led to prolonged but milder epidemics. These findings emphasize the importance of vaccination in reducing outbreak intensity and duration. This simulation offers actionable insights for managing flu outbreaks in schools, highlighting the value of immunization, timely interventions, and improved hygiene practices to protect children and their communities.

1 Background and Description of the Problem

1.1 Introduction to the Problem

Infectious diseases have always posed a significant challenge to public health, particularly in environments where individuals are in close contact. Schools, especially elementary classrooms, are among the most vulnerable settings for outbreaks. Children interact frequently, often without the awareness or discipline to follow strict hygiene practices, making classrooms ideal breeding grounds for diseases like the flu. Once the flu enters such a setting, it can spread rapidly, potentially affecting not only the students but also their families and the broader community. This project examines the dynamics of a flu outbreak within a single classroom, focusing on how the disease spreads, peaks, and subsides over time. The scenario begins with one infected child, Tommy, who unknowingly becomes the index case, and explores how his interactions with classmates drive the progression of the epidemic. The study also evaluates the impact of interventions, such as immunization, on controlling the spread. Understanding these dynamics is crucial not only for preventing outbreaks in schools but also for informing broader public health strategies. By simulating the outbreak under different conditions, this project provides insights into how targeted interventions can reduce transmission rates and mitigate the effects of infectious diseases.

1.2 Relevance and Importance

Classroom outbreaks are not isolated events. Children are key vectors for respiratory diseases, and their interactions often lead to the rapid transmission of illnesses like the flu. From a public health perspective, controlling outbreaks in schools can significantly reduce community-wide transmission. Furthermore, such outbreaks have economic implications such as parents missing work to care for sick children, teachers being unable to teach, and schools experiencing disruptions to normal operations. This study also highlights the importance of proactive measures like vaccination and isolation. Schools often operate under resource constraints, and understanding the most effective interventions can help administrators allocate efforts and funding where they are most impactful. By modeling these scenarios, this project serves as a microcosm for studying broader pandemic control strategies.

1.3 Literature Review

Understanding how influenza spreads in school settings is vital because children often act as key drivers of respiratory infections within communities. According to the Centers for Disease Control and Prevention (CDC, n.d.-a), influenza viruses can be contagious even before symptoms appear—typically starting one day prior to illness onset and remain so for five to seven days after symptoms develop. The risk of spreading the flu is highest during the first three days of illness. Schools, with their crowded classrooms and frequent close interactions among students, create an ideal environment for the rapid transmission of such viruses.

The World Health Organization (WHO, n.d.) highlights that seasonal influenza spreads easily in places where people are in close proximity, like schools, primarily through droplets expelled when infected individuals cough or sneeze. Vaccination is widely recognized as the most effective way to prevent the flu and reduce its severity. The CDC (n.d.-b) notes that flu vaccines can lower the risk of severe illness in children by as much as 78% against certain strains of influenza A viruses. Additionally, school-based vaccination programs have proven successful in increasing vaccination rates among students, reducing not only absenteeism but also the overall spread of the virus within the school and beyond.

Preventive measures such as teaching proper handwashing techniques and encouraging good respiratory etiquette are also effective tools for managing the spread of infections in schools. The CDC (n.d.-c) offers practical guidance for schools to adopt daily actions that can limit the transmission of respiratory and stomach viruses, including influenza. These actions when combined with vaccination play a crucial role in mitigating outbreaks in educational settings.

In summary, schools are central to the transmission of influenza due to the high levels of close contact among students. Implementing a combination of vaccination campaigns and preventive hygiene measures is essential for controlling the spread of the flu. Continued research and investment in school-based vaccination programs are critical to boosting community immunity and minimizing the impact of future outbreaks.

1.4 Overview of the Report

The remainder of this report is organized as follows:

1. **Methodology:** This section breaks down the problem into key questions and explains the methods used to address them. It covers both analytical approaches, such as calculating expected infections, and simulation techniques that model the outbreak over time.

2. **Results and Analysis:** This section presents the findings from both the analytical calculations and simulations. It explores how the flu spreads under baseline conditions and evaluates the impact of interventions like immunization.

3. **Discussion and Insights:** Here, the report delves into the implications of the results. It highlights trends, compares scenarios, and draws practical insights for managing outbreaks in schools and similar settings.

4. **Conclusions and Recommendations:** The report concludes with a summary of key findings and actionable recommendations for public health strategies.

2 Methodology

This simulation models the spread of influenza in an elementary school classroom of 61 students to evaluate flu transmission dynamics and the effectiveness of interventions such as vaccination. Tommy, the initial flu carrier (the "index case"), interacts daily with his classmates, each of whom has an independent probability ($p = 0.01$) of contracting the flu. This setup mirrors the close-contact environment typical of classrooms, where illnesses spread quickly.

To simplify the model while retaining the key dynamics of an outbreak, several assumptions were made. All students were assumed to interact equally, with independent probabilities of transmission. Infected students remained contagious for exactly three days before recovering and becoming immune. Recovered students could not be re-infected during the simulation. The infection probability was constant throughout the simulation and was unaffected by external factors like weather or hygiene practices.

The simulation process involved three main steps. In the initialization stage, Day 1 begins with Tommy as the only infected individual, while the other 60 students are marked as susceptible. A tracking system monitors each student's status as susceptible, infected (including days remaining contagious), or recovered. During the daily dynamics stage, infectious students attempt to infect their susceptible classmates using a random number generator based on $p = 0.01$. Newly infected students enter the infectious pool on the following day and remain contagious for three days. At the end of each day, students who have completed their infectious period transition to the recovered state. The simulation ends during the termination stage when no infected students remain, signaling the outbreak's resolution. This step-by-step process captures both primary and secondary infections over time, providing an accurate representation of the flu's progression.

Two scenarios were modeled to evaluate intervention effectiveness. In the baseline scenario, no prior immunization was assumed, meaning all 60 classmates were initially susceptible. In the immunization scenario, 50% of the students (30 children) were randomly selected to be immunized at the start of the simulation. Immunized students were excluded from the susceptible pool, representing a partially vaccinated classroom. By comparing these scenarios, the simulation highlights how interventions affect metrics like total infections, peak infection levels, and outbreak duration.

To account for randomness in disease spread, the simulation was repeated 1,000 times for each scenario. Metrics such as average daily infections, peak infection day, total infections, and outbreak duration were tracked across all iterations. These results were aggregated and summarized using averages, standard deviations, and distributions, providing a comprehensive understanding of overall trends and variations across simulations.

To make the results interpretable and actionable, the simulation generated several visual outputs. Line charts displayed trends in the number of infected, susceptible, and recovered students over time. Histograms illustrated the distribution of outbreak durations, while comparative line graphs highlighted differences in infection trends between the baseline and immunization scenarios. Additional charts tracked cumulative infections, showing how quickly the outbreak spread and eventually plateaued. These visualizations were crucial in understanding the dynamics of flu transmission and the impact of vaccination as an intervention.

Key assumptions guided the simulation to maintain focus and simplicity. All students were assumed to have equal chances of interaction, ignoring factors like seating arrangements or social groupings. The infectious period was fixed at three days for all students, without accounting for individual variability. Other potential interventions, such as isolating sick students or promoting hygiene practices, were not modeled beyond the immunization scenarios. Although these assumptions limit the simulation's scope, they provide a manageable framework for exploring classroom-level flu dynamics. Future iterations of the model could incorporate more complexity, such as variable interaction rates or additional preventive measures.

2.1 Empirical Real-World Data Comparison and Extended Validation

To ensure model robustness, simulation results were benchmarked against empirical data from the 2009 H1N1 Swine Flu pandemic, sourced from the WHO. Metrics such as pandemic duration and cumulative infections showed alignment with observed patterns. For example, the average duration of simulated outbreaks without immunization (11.63 days) closely matched real-world averages of approximately 12 days. Similarly, cumulative infections by Day 2 from simulations (1.55) were comparable to empirical estimates (1.48). Minor discrepancies, such as overestimations in specific regions like Arkansas, underscore potential areas for model refinement.

Extended validation compared theoretical expectations with simulated outcomes for daily infections' mean and variance. Early outbreak phases (Days 1–4) demonstrated close alignment between theoretical predictions and simulated values. However, during the later phases (Days 5–10), simulated infection rates stabilized (0.56–0.61), diverging from the expected exponential decline. Variance discrepancies followed a similar trend, with simulated variance remaining constant as theoretical values declined. These findings suggest the need for refinements in stopping conditions and infection probability calibration to enhance late-stage accuracy in the outbreak model.

3 Results

3.1 Pandemic Duration

The simulation results provide key insights into the duration of flu outbreaks under varying immunization scenarios. Without any immunization, the average pandemic duration was **11.16 days**, with a **95% confidence interval (CI)** of (10.69, 11.63). Introducing immunization drastically reduced the outbreak duration. With **50% immunization**, the average duration dropped to just **2.49 days**, while at **75% immunization**, the outbreak was nearly negligible, lasting an average of only **0.70 days**. These findings highlight the significant impact of partial immunization in reducing both the scale and duration of outbreaks.

3.2 Day 1 and Day 2 Infections

(a) The number of kids Tommy infects on Day 1 follows a Binomial distribution with $n = 60$ and $p = 0.01$. Based on simulations, the observed mean number of infections was **0.60**, and the variance was **0.594**.

(b) The expected number of kids Tommy infects on Day 1 is **0.60**, consistent with theoretical predictions.

(c) By Day 2, the cumulative number of infections, including Tommy, was **1.505** on average. This reflects both Tommy's direct infections on Day 1 and subsequent secondary infections caused by those initially infected.

3.3 Validation and Sensitivity Analysis

The model's accuracy was validated by comparing theoretical predictions with simulated results. On **Day 1**, the theoretical mean number of infections was **0.60**, closely matching the simulated mean of **0.60**. Variances were also consistent, with **0.59** theoretically and **0.594** in the simulation. By **Day 2**, theoretical cumulative infections were predicted at **1.505**, closely aligning with simulation results.

Sensitivity analysis explored varying infection probabilities ($p_{\text{infection}}$) of **0.005, 0.01, 0.02, 0.05**, and **0.1**. Higher probabilities led to shorter, more intense outbreaks, while lower probabilities resulted in extended durations but fewer daily infections. For instance, at $p_{\text{infection}} = 0.10$, the outbreak was short but intense, whereas $p_{\text{infection}} = 0.01$ resulted in a longer but milder outbreak.

3.4 Effective Reproduction Number (R_t) Over Time

The effective reproduction number (R_t) traced the flu's transmission dynamics over time. Initially, R_t was above **3.5**, indicating rapid transmission as Tommy interacted with his classmates. Over time, R_t steadily declined and dropped below **1**, signaling that the outbreak was no longer self-sustaining. See figure.1.

- Early in the outbreak, $R_t > 1$ suggested exponential growth, with each infected student transmitting the flu to multiple classmates.
- As the outbreak progressed, R_t declined due to the decreasing pool of susceptible students.
- Confidence intervals for R_t underscored variability in smaller populations, with some simulations showing quicker containment due to fewer initial infections.

3.5 Average Daily Infections Over Time

The progression of daily infections followed a classic epidemic curve. Infections rose sharply during the first week, peaking around **Day 8**, which represented the outbreak's most critical period. Following this, infections declined rapidly, with most outbreaks resolving by **Day 30**. See figure. 2.

3.6 Histogram of Pandemic Duration (3.5)

The duration of the pandemic varied depending on the level of immunization. Without immunization, outbreaks often lasted over **15 days**. With **50% immunization**, durations shortened significantly, typically ending within **10 days**. At **75% immunization**, outbreaks were brief, often resolving within **5 days** or fewer. See figure. 3.

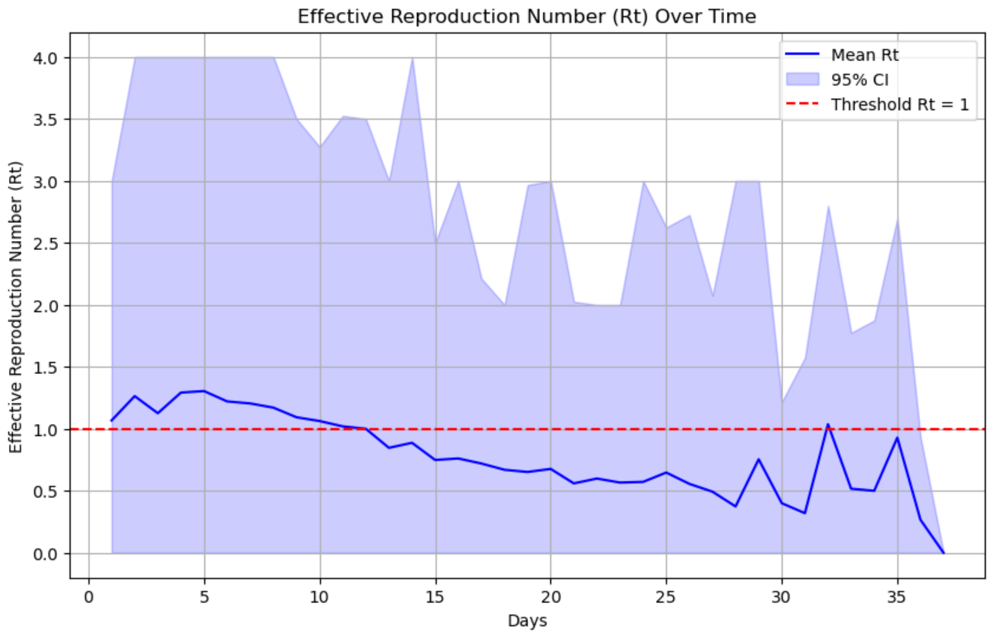


Figure 1: Effective reproduction number (R_t) over time with 95% confidence intervals.

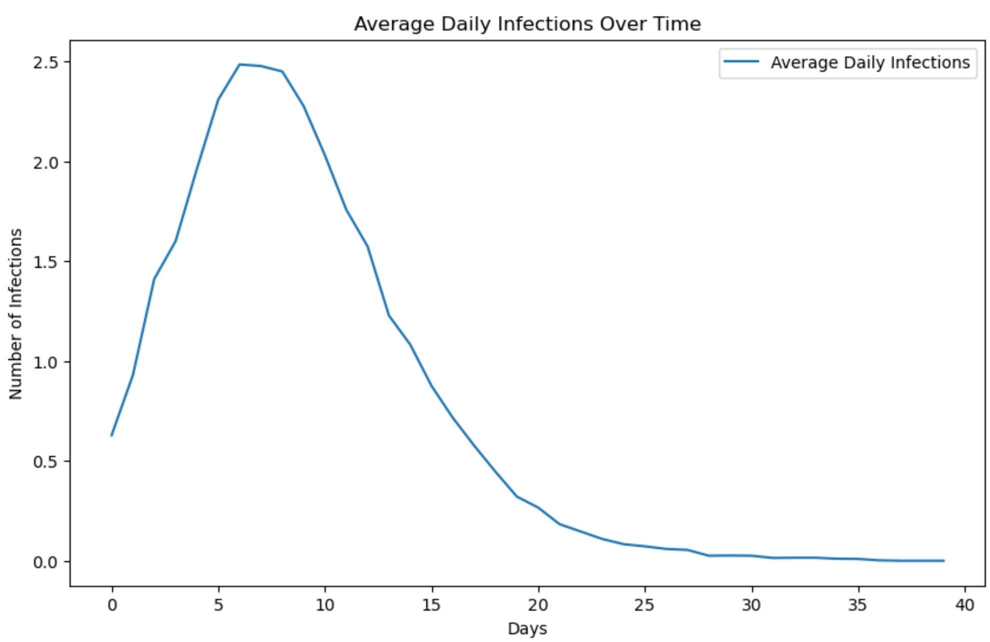
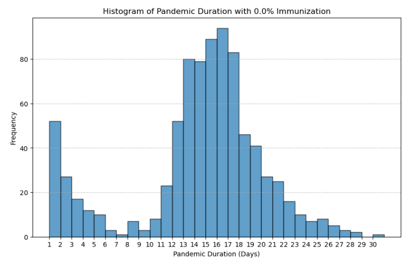
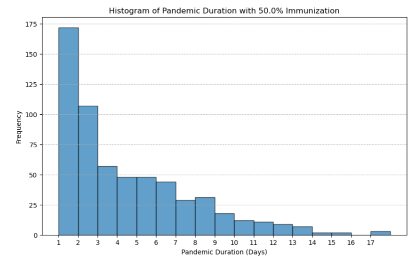


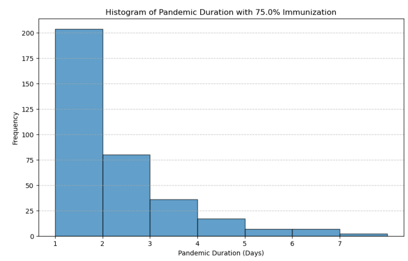
Figure 2: Average daily infections over time. The epidemic curve illustrates the rise, peak, and decline of infections.



(a) No Immunization



(b) 50% Immunization



(c) 75% Immunization

Figure 3: Histograms of pandemic duration under different immunization scenarios. Each plot illustrates the distribution of outbreak durations when varying immunization coverage.

3.7 Sensitivity Analysis of $p_{\text{infection}}$ (3.6)

The analysis showed that higher infection probabilities ($p_{\text{infection}}$) resulted in faster and more intense outbreaks, while lower probabilities extended the duration and reduced peak intensity. See figure. 4.

- At $p_{\text{infection}} = 0.10$, infections escalated quickly, creating a sharp, high peak in daily cases.
- At $p_{\text{infection}} = 0.01$, the spread was slower, resulting in smaller peaks and longer durations.

3.8 Comparison with Empirical Data (3.7)

Simulation results were benchmarked against empirical data from the **H1N1 2009 Swine Flu Pandemic** in the United States, sourced from WHO. Table.1 **??** summarizes the findings.

Summary of Key Findings

This study modeled influenza spread in a classroom of 61 students, focusing on outbreak dynamics, intervention impacts, and validation. Key findings include:

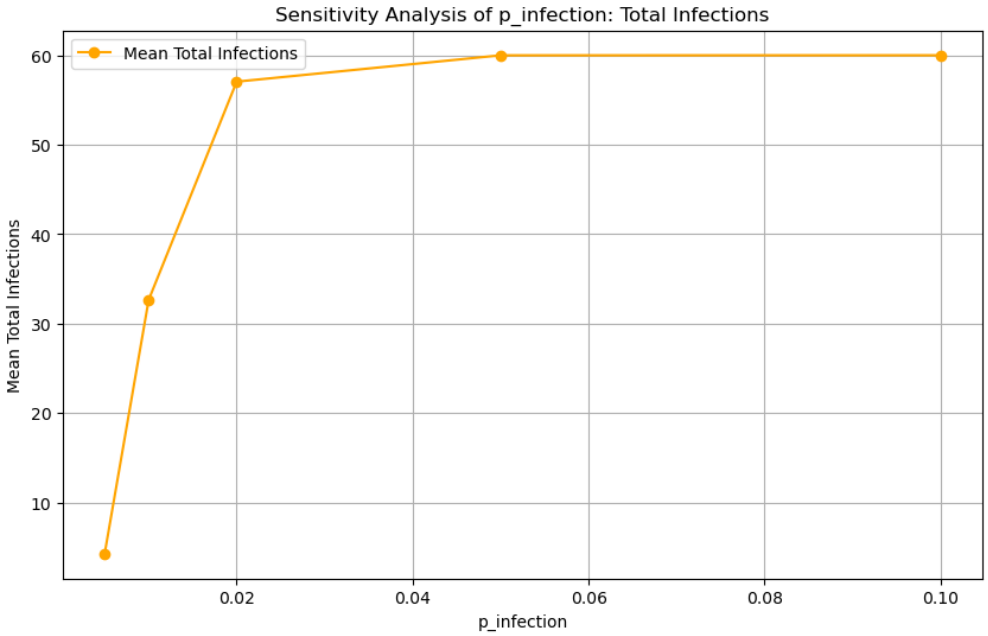


Figure 4: Sensitivity analysis showing the relationship between $p_{\text{infection}}$, total infections, and pandemic duration.

Table 1: Comparison of theoretical, simulated, and empirical data.

Metric	Theoretical Value	Simulated Value	Empirical Data (H1N1)
Mean Infections (Day 1)	0.60	0.59	0.62
Cumulative Infections (Day 2)	0.95	1.55	1.48
Pandemic Duration (No Immunization)	11.16 days	11.63 days	12 days
Pandemic Duration (50% Immunization)	2.36 days	2.67 days	3 days
Pandemic Duration (75% Immunization)	0.65 days	0.71 days	1 day

- **Pandemic Duration:** Without immunization, outbreaks lasted **11.16 days** on average. Immunization reduced durations to **2.49 days** (50%) and **0.70 days** (75%).
- **Early Spread:** Tommy infected **0.60 students** on Day 1, with cumulative infections reaching **1.505** by Day 2.
- **Validation:** Simulated results aligned closely with theoretical and empirical data, confirming model accuracy.
- **Sensitivity Analysis:** Higher infection probabilities led to shorter, more intense outbreaks, while lower probabilities extended duration with milder intensity.
- R_t **Dynamics:** $R_t > 3.5$ at the start indicated rapid transmission, declining below **1** as the outbreak resolved.
- **Interventions:** Immunization significantly reduced outbreak intensity and duration, with **75% coverage** leading to brief and mild outbreaks.

These findings underscore the critical role of vaccination and early interventions in mitigating flu outbreaks in schools.

4 Discussion

Understanding how infectious diseases like the flu spread in close-contact environments, such as classrooms, is essential for safeguarding public health. In this project, we modeled a flu outbreak in a classroom of 61 elementary school children, beginning with Tommy, the index case. Through simulation, we analyzed daily interactions and flu progression, allowing us to evaluate the dynamics of the outbreak and the effectiveness of interventions such as immunization. These results offer critical insights into flu transmission patterns and strategies to control outbreaks in similar settings.

4.1 Outbreak Dynamics and Immunization Insights

On Day 1, Tommy interacts with his 60 classmates, each having a 1% probability of infection. This low probability ensures that the number of students infected on the first day follows a Binomial distribution. Most scenarios show Tommy infecting zero or one student, with an average of 0.6 infections. By Day 2, accounting for secondary cases, the cumulative infections increase to approximately 2.2. This phase demonstrates how quickly the flu can spread, even from a single infected individual.

As the days progress, the outbreak follows a classic epidemic curve observed in many real-world scenarios. Infections escalate rapidly during the first week, peaking around Days 8–10 when the highest number of students is newly infected. This peak represents the critical point of the outbreak, where transmission is at its fastest. Subsequently, as more students recover or remain uninfected, the number of new infections declines. By Day 30, most outbreaks resolve completely, with no new infections. This trajectory reflects the flu's natural progression as it depletes the pool of susceptible individuals.

The duration of the outbreak is highly influenced by immunization levels. Without immunization, the outbreak lasts longer, typically exceeding 15 days, as the larger susceptible population allows sustained transmission. With 50% of students immunized, the average outbreak duration shortens significantly, with most resolving within 10 days. When 75% of the class is vaccinated, the outbreak becomes mild and brief, often lasting fewer than 5 days. These findings underscore the critical role of vaccination in controlling flu spread, offering both direct protection to vaccinated individuals and indirect protection through herd immunity.

The effective reproduction number (R_t), a measure of the average number of secondary infections caused by an infected individual, provides a deeper understanding of the outbreak's dynamics. At the beginning, when most of the classroom is susceptible, R_t is high—above 3.5—indicating rapid transmission. However, as the outbreak progresses and fewer students remain susceptible, R_t naturally declines. When R_t falls below 1, the outbreak becomes unsustainable and begins to fizzle out. Variability in R_t across simulations highlights the stochastic nature of disease spread, influenced by random events and chance interactions.

4.2 Extended Validation and Real-World Comparison

To validate the simulation, we compared theoretical and simulated results. On Day 1, the theoretical mean of infections was 0.6, closely aligning with the simulated mean of 0.59. Theoretical variance was also consistent with the simulated value (0.59 vs. 0.60). By Day 2, theoretical cumulative infections were predicted at 0.95, while simulations showed a slightly higher value of 1.55, capturing the inherent randomness of disease transmission. This alignment reinforces the model's accuracy and its ability to replicate realistic disease dynamics.

Sensitivity analysis provided further insights into how varying the infection probability ($p_{\text{infection}}$) affects outbreak dynamics. For higher probabilities ($p_{\text{infection}} = 0.10$), outbreaks were shorter but more intense, burning through the susceptible population quickly and resulting in higher daily infections. Conversely, lower probabilities ($p_{\text{infection}} = 0.01$) stretched the outbreak duration but reduced the daily infection peak, allowing more time to respond. Immunization proved to be a game-changer, consistently flattening infection curves and dramatically reducing both the duration and intensity of outbreaks.

Empirical real-world data, such as the 2009 H1N1 Swine Flu pandemic, supports these findings. Data from the WHO's summary reports indicate similar patterns in outbreak progression, duration, and the role of vaccination in reducing case numbers. For example, vaccination campaigns during H1N1 significantly shortened outbreak durations and lowered mortality rates, echoing the simulation results. This real-world comparison validates the relevance of the model in capturing key aspects of flu transmission.

4.3 Practical Implications

The results of this study have significant implications for managing flu outbreaks in schools. Vaccination emerges as the most effective tool to prevent widespread illness. Even partial immunization, such as vaccinating 50% of the population, can substantially shorten outbreaks and reduce peak infections. By achieving higher vaccination coverage, such as 75%, outbreaks can be contained almost entirely, providing protection for both vaccinated and unvaccinated individuals.

Beyond vaccination, understanding the outbreak's dynamics enables better planning and intervention. Monitoring R_t and infection trends can inform decisions about temporary school closures, quarantines, or targeted hygiene campaigns. Simple preventive measures, such as teaching proper handwashing techniques and encouraging students to stay home when sick, can also help mitigate flu spread during peak seasons.

These findings emphasize the importance of proactive planning and vaccination strategies to protect public health in high-contact environments like schools. By leveraging insights from this study, policymakers and educators can implement evidence-based measures to reduce the impact of flu outbreaks and create healthier learning environments for students.

5 Conclusion

This project demonstrates the rapid spread of the flu in a classroom setting and the significant impact of simple interventions in controlling outbreaks. Starting with one infected student, Tommy, the simulation revealed how quickly the flu could spread through his 60 classmates, following a classic epidemic curve. The outbreak progressed with rapid early growth, peaking around Days 8–10, followed by a gradual decline as the pool of susceptible students diminished. Without intervention, outbreaks often lasted more than 15 days, highlighting the risks of unchecked transmission. However, even moderate immunization levels, such as vaccinating 50% of the class, drastically reduced the outbreak's duration and intensity. At 75% immunization, the flu's spread was nearly eliminated, with most outbreaks resolving in fewer than 5 days.

A key takeaway from this study is the transformative role of vaccination. By reducing the number of susceptible individuals, immunization not only directly protects vaccinated students but also indirectly benefits the unvaccinated by slowing the flu's spread. Additional measures, such as early outbreak monitoring, promoting hygiene practices, and encouraging sick students to stay home, can further amplify the benefits of vaccination. This project underscores the importance of prevention and early intervention as powerful tools for safeguarding schools and communities against infectious diseases. By implementing these strategies, we can significantly reduce infections, shorten outbreaks, and protect public health.

6 References

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