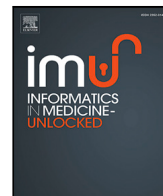




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School Virus Infection Simulator for customizing school schedules during COVID-19

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ABSTRACT

Even as the COVID-19 pandemic raged worldwide, schools strived to provide consistent education to their students. In such situations, schools require customized schedules that can address the health concerns and safety of the students to safely reopen and remain open. School schedules can be customized in many ways, and different approaches' impact on education and effectiveness in reducing infectious risks are different. To address this issue, we developed the School Virus Infection Simulation-Model (SVISM) for teachers and education policymakers. By taking into account the students' lesson schedules, classroom volume, air circulation rates in the classrooms, and infectability of the students, SVISM simulates the spread of infection at a school. We demonstrate the impact of several school schedules in self-contained and departmentalized classrooms and evaluate them in terms of the maximum number of students infected simultaneously, and the percentage of face-to-face lessons. The results show that the impact of increasing the classroom ventilation rate is not as stable as that of customizing school schedules. In addition, school schedules can differently impact the maximum number of students infected simultaneously, depending on whether classrooms are self-contained or departmentalized. We found that the maximum number of students infected simultaneously under a certain schedule with 50 percentage of face-to-face lessons in self-contained classrooms is higher than the maximum number of students infected simultaneously having schedules with a higher percentage of face-to-face lessons; this phenomenon was not found in departmentalized classrooms. These results show that the SVISM can help teachers and education policymakers plan school schedules appropriately to reduce the maximum number of students infected simultaneously, while also maintaining a certain rate of face-to-face lessons.

1. Introduction

During COVID-19, schools have continuously strived to provide consistent education. Teachers and education policymakers are seeking ways to re-open schools, which is necessary for community and economic development.

The World Health Organization (WHO) states that schools should assess several elements when deciding to re-open for students—for instance, the epidemiology of COVID-19 at the local level, the benefits and risks to children and staff, and the capacity of schools/educational institutions to operate safely [1]. The benefits of re-opening schools include not only educational benefits but also the social and psychological well-being of students and staff, essential services, access to nutrition, child welfare, and freedom for parents to work [1].

To re-open safely, the WHO recommends several measures: wearing a mask, ensuring adequate air supply in classrooms, and maintaining

physical distance between students [1]. However, the actual situation in the schools varies. Some schools, especially schools in developing or cold counties, do not have the budget to improve the total airflow supply. Moreover, not all schools have sufficient classrooms or empty classrooms to maintain physical distance.

Thus, many schools have adopted cohorting and customized school schedules, including creating small groups of staff and teachers. The schools restructure their schedules, divide students into several groups, conduct face-to-face lessons for one group, give homework to the other groups, and conduct online classes. This methodology allows students to maintain physical distance and keeps the air clean, without additional classrooms or air conditioners.

The United Nations Educational, Scientific and Cultural Organization (UNESCO) covers four types of school schedules; students' risk of

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infection; and the pros and cons as regards education effects, school management, parents, and so on [2]. According to the schedule provided by UNESCO, students are divided into two groups, and each group is then scheduled to go to school alternately for half a day, one day, two days, and one week; UNESCO ranks the four schedules by infection risk. However, school schedules can be customized in many ways, and their impacts on education, and effectiveness in reducing infectious risks are different. Teachers and education policymakers have to choose a suitable school schedule from a variety of options, without complete knowledge of the infection risks. For example, there are representative school schedules that include self-contained and departmentalized classrooms, but dividing the students into two groups would not be enough when the total number of students is large. They then mix the self-contained and departmentalized classrooms, and online and face-to-face lesson schedules. Hence, teachers and education policymakers cannot judge the infections' risk based on the UNESCO's ranking.

We propose the School Virus Infection Simulation Model (SVISM) to simulate the spread of virus infection at a school based on the school schedule. The SVISM can simulate airborne infection in several school situations, considering the number of students and classrooms and the performance of air conditioners. It can help teachers and education policymakers customize school schedules with respect to the infection risk and the percentage of face-to-face lessons. In this study, education policymakers are the staff members who are responsible for school scheduling, and not for the social economy. That is, they plan school schedules not considering the effect on the social economy.

In this study, we introduce the SVISM and demonstrate that it can evaluate the impact of several school schedules employing self-contained and departmentalized classrooms from the viewpoint of the maximum number of students infected simultaneously and the percentage of face-to-face lessons.

2. Related work

School closures due to COVID-19 have had a severe negative impact on society, and schools are trying to maintain face-to-face classes. To support school activities, several studies have modeled and simulated the spread of COVID-19 that may be caused by the re-opening of schools. Their targets are classified, roughly, into two categories: outside and inside schools. In addition, several school scheduling models are proposed. This study focuses on a representative school scheduling type with self-contained and departmentalized classrooms, mixed with online and face-to-face lesson schedules.

2.1. Effect of COVID-19 school closures

Several countries have recovered from the initial shock of COVID-19, developed COVID-19 response plans, and reopened schools [3–5]. However, new variants of COVID-19 are still being discovered, and we must be prepared for an ongoing or renewed COVID-19 pandemic [6].

Several studies have shown the impact of COVID-19 closures on education and mental health. It has been estimated that the already existing learning loss for students due to COVID-19 closure could be several months and the achievement gap with students in the same grade whose schools did not close or reopened sooner could increase up to 1.5 years [7–10]. Schools are attempting to provide education through online courses; however, the effectiveness of online courses depends on the level of students and their Internet access, parental support, and school support [11–13]. In addition, socioeconomic status has an impact on academic achievement even in a normal situation [14], and socioeconomically disadvantaged students are more likely to have inadequate Internet access, parental support, and school support. The closure due to COVID-19 also caused emotional damage to students, their families, and even school administrators [15–18]. Students experienced significant stress, isolation, anxiety, and depression [15,19], and school administrators experienced COVID-19 phobia [16].

These studies show that the closure due to COVID-19 has had serious negative effects on society. Therefore, a school schedule plan that maintains a certain percentage of face-to-face classes is needed.

2.2. Outside the school model

Cruz et al. [20] simulated school re-opening strategies in the São Paulo Metropolitan Area. These included two scenarios: re-opening schools with all the students at once, following the São Paulo government's plan, and re-opening only when a vaccine becomes available. They used a stochastic compartmental model that included a heterogeneous, dynamic network. Gharakhanlou and Hooshangi [21] simulated the spatio-temporal outbreak of COVID-19 with an agent-based model. They investigated the impact of various strategies of school and educational center closure, with special attention to social distancing and office closures, on the COVID-19 outbreak in Urmia, Iran. Lee et al. [22] simulated the outbreaks in the greater Seattle area, and evaluated the effect of the combination of non-pharmaceutical interventions, such as social distancing, use of face mask, school closure, testing, and contact tracing. Kim et al. [23] modeled the COVID-19 transmission dynamic in Korea with the susceptible–exposed–infectious–recovered model. Their model considered two age groups, children and adults, because social behaviors are different between these groups. They estimated the effect of delay in school re-opening in Korea. Chin et al. [24] developed a national- and county-level simulation model, considering school closures and unmet childcare needs in the US, and estimated the projected rate of unmet childcare needs for healthcare worker households.

2.3. Inside the school model

Zafarnejad and Griffin [25] assessed school policy actions for COVID-19 using an agent-based simulation. They modeled a classroom with two-dimensional tiles and simulated the spread of COVID-19 quanta in a closed classroom environment. They compared the infection risks among several non-pharmaceutical interventions, including class schedules, social distancing, ventilation, air filtration, surveillance testing, and contact tracing. Brom et al. [26] modeled the interactions among pupils and teachers in Prague as a multi-graph structure with an agent-based simulation. They investigated the impact of several school schedule types and of antigen and PCR test schedule types on reducing the spread. Ghaffarzadegan [27] developed a hypothetical university model of 25,000 students, and 3000 faculty/staff in a U.S. college town with a mathematical and compartmental model. He simulated several combinations of policies and evaluated the impact of COVID-19. The policies tested included proactive and quick testing, high mask adoption, better risk communication with students, and remote work for high-risk individuals. Bilinski et al. [28] developed an agent-based network model to simulate transmission in elementary and middle school communities. They built three screening strategies weekly or bi-weekly screening of all students and teachers, and a 24-hour test turnaround time. They then compared these screening scenarios with three school scenarios: five-day in-person attendance, a hybrid model in which 50% of students attended class on Monday and Tuesday, and the other 50% on Thursday and Friday, and complete remote learning. McPeck and Magori [29] built an agent-based model in which students moved and interacted on a dormitory floor of Eastern Washington University. They simulated multiple scenarios with a combination of vaccination and masking rates.

2.4. School scheduling

Schools consider teachers' cost and students' learning effect when making school schedules. One such representative school scheduling type includes self-contained and departmentalized classrooms (Fig. 1). Students in self-contained classrooms took the same lesson in the same classroom. This could be regarded as a type of cohorting. In contrast,

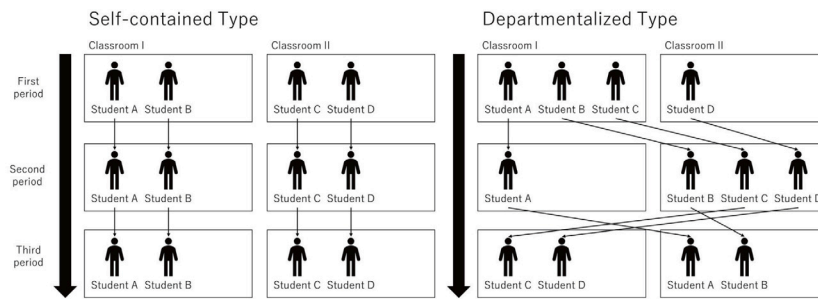


Fig. 1. Classroom type. Students of self-contained classrooms took the same lesson in the same classroom. Students in departmentalized classrooms took individual lessons in different classrooms.

students in departmentalized classrooms took individual lessons in different classrooms. Self-contained classrooms required teachers to specialize in multiple subjects [30], whereas teachers of departmentalized classrooms focused on only one subject. Students studying in lower grades, or those with low-incidence disabilities, need learning support. The teachers of self-contained classrooms can observe these students continuously, whereas the teachers of departmentalized classrooms can observe them once a day, or once in two days. Therefore, schools tend to adopt self-contained classrooms for lower grades and departmentalized classrooms for higher grades. However, some high schools have recently mandated self-contained classrooms to reduce student interactions [31].

2.5. Summary

Our simulation model was classified into the inside school model. Previous studies assumed that all students' behavior was the same and targeted only one type of school system. Despite this, we focused on the varied effect of school schedules during COVID-19 on different school types.

Previous studies that considered external factors did not simulate and analyze the details of internal school factors. However, UNESCO pointed out that the effect of internal school factors was very important [2]. Tupper and Colin [32], and Leng et al. [33] pointed out the risk of COVID-19 clusters inside schools. We focused on the inside of schools. We assumed that the external factors could be replaced by the number of students infected outside a school per unit time. In the experiment sections of this study, we simulated the effect of one infected student. This student is the first infected person in the school, and no students have antibodies against COVID-19. It is noted that our model can simulate scenarios where multiple students get infected at various times.

Furthermore, schools are caught in a dilemma between self-contained and departmentalized classrooms, considering teachers' cost, students' learning effect, and reduction in infection. Self-contained and departmentalized classrooms would react differently to school schedule interventions. In this study, we shed light on the infection phenomena of self-contained and departmentalized classrooms.

3. School virus infection simulation model

The SVISM is a model used to simulate the spread of virus infection at a school. It simulates students' behavior based on their lesson schedule, classroom volume, classroom air change rate, and infectability of the virus. The SVISM is based on an extended version of the susceptible–exposed–infectious–removed model, and agent-based model [34–43].

3.1. School scheduling model

SVISM is based on an agent-based model where every student (agent) attends lessons based on their individual schedules; the SVISM can simulate a wide variety of school scheduling. In one instance, all students come to school for two to three weeks, after which they stay at home for a week. WHO states that “the average time from exposure to COVID-19 to the onset of the symptoms is 5–6 days” [44]. Hence, when students are infected, their symptoms will appear during the home week, and they can take the following weeks off. This decreases the risk of infection. In another instance, students are divided into four groups. These groups come to school during alternate weeks so that they can interact with more peers. Teachers and education policymakers have to choose a school schedule from the available options without prior knowledge of the infection risk of the schedule.

Fig. 2 shows an example of school scheduling. Students are divided into two groups, Group A and Group B. Each group goes to school for half a day, alternatively. This schedule corresponds to UNESCO's school schedule option 1 [2]. In addition, the classroom type is departmentalized. For example, student A takes first and second period lessons in classroom I and the third period lesson in classroom II, and then the student takes the day off for the fourth, fifth, and sixth periods.

3.2. Infection model

Students' status consists of susceptible, exposed, infectious–exposed, infectious, asymptomatic, and recovered (Fig. 3). Exposed individuals do not pose the risk of infecting others, while infectious–exposed can infect other people. Susceptible students become exposed according to the infection probability. Exposed students become infectious–exposed after a certain period. Infectious–exposed students become infectious or asymptomatic, probabilistically, after a certain period. Infectious and asymptomatic students recover after a specific period. Infectious–exposed and asymptomatic students infect susceptible students according to the infection probability. Infectious components are the students who develop symptoms and take the day off or take online lessons. Asymptomatic students are those who do not develop symptoms and continue attending school.

Infection probability is calculated based on Dai's extended edition of Wells–Riley equation [45–47].

$$P = \frac{C}{S} = 1 - e^{-Iqp(1-n_I)(1-n_S)/Q} \quad (1)$$

P is the probability of infection, C is the number of new infection cases, S is the number of susceptible people, I is the number of infectors (infectious exposed and asymptomatic students), q is the quanta generation rate, p is the pulmonary ventilation rate of a student, t is the lesson time interval, n_I is the exhalation filtration efficiency, n_S is the respiration filtration efficiency, and Q is the classroom ventilation rate with clean air.

A student takes lessons based on their schedule, and the infection probability is calculated using Eq (1). Fig. 4 shows the calculation

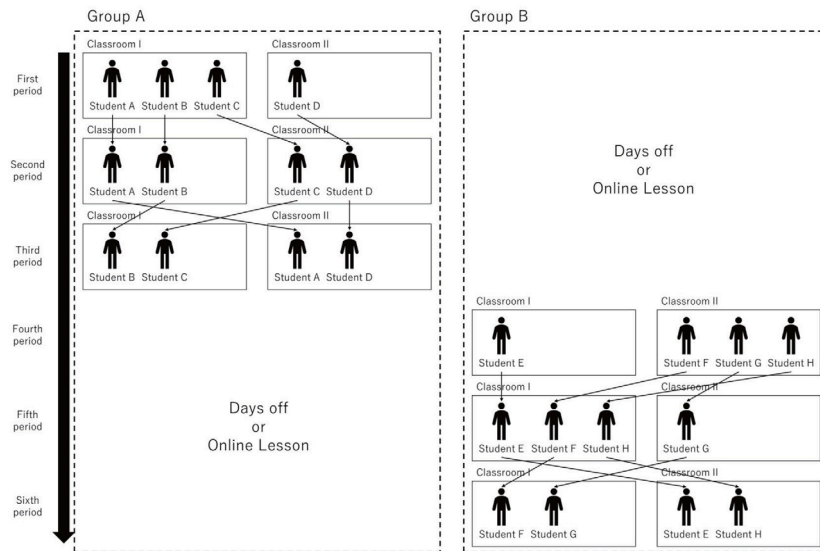


Fig. 2. School scheduling model example. This schedule corresponds to UNESCO's school schedule option 1 [2].

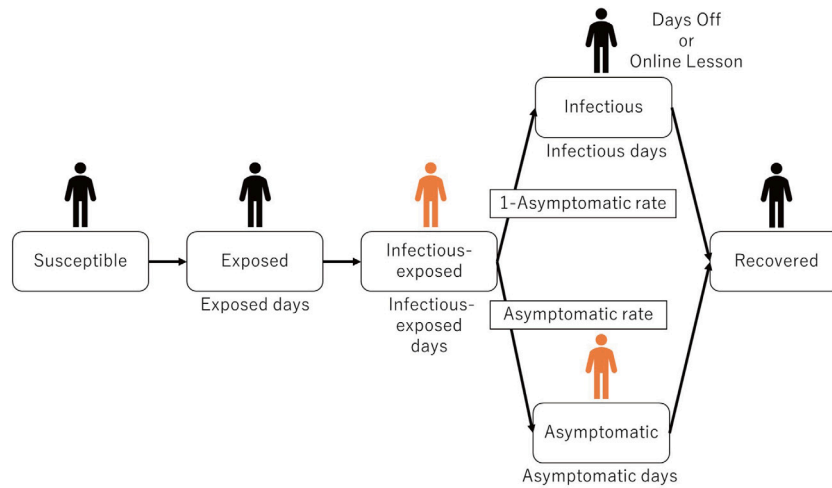


Fig. 3. Infection model. Students' status comprises susceptible, exposed, infectious-exposed, infectious, asymptomatic, and recovered.

of new infection cases. The Wells–Riley equation is generally used to calculate the basic reproduction number of the infection (C/I). Therefore, we should calculate the new infection cases as the number of susceptible students multiplied by Eq (1). However, the number of students in the classroom is often less than 100, and the probability of infection is generally less than 0.01. Thus, the new infection cases become less than one student. Therefore, we used Eq (1) as the probability of infection for each susceptible student. The expectation value of the new infection cases fits the basic reproduction number, using multiple simulations. In Fig. 4, one hundred susceptible students, five infectious exposed students, and three asymptomatic students take lessons in the same classroom. Then, I in Eq (1) becomes eight, and each susceptible student becomes exposed with the probability of infection $(1 - e^{-8qp(1-n_j)(1-n_s)/Q})$.

3.3. Summary

The SVISM enables teachers and education policymakers to simulate the effects of their school policies in specific situations. Every school's policy might be different. The lesson schedule and classroom volume vary according to school, country, and state. Moreover, the budget is different. Even if teachers and education policymakers in

developing countries know that a high ventilation rate with clean air is effective, they would not have enough funding to change the air conditioners. The SVISM can consider these problems and help them plan lesson schedules to reduce infection probability without replacing air conditioners.

4. Experiment design

First, we show the effects of changing classroom volumes and classroom air change rates during COVID-19. This experiment is a kind of bench mark. Later, we discuss the effects between changing classroom volumes, classroom air change rates, and several school schedules. Next, we demonstrate the impact of several school schedules in self-contained and departmentalized classrooms, and evaluate those schedules for the maximum number of students infected simultaneously and the percentage of face-to-face lessons. The former is an essential indicator for controlling COVID-19 because hospitals must accommodate isolated beds and medical equipment (e.g., extracorporeal membrane oxygenation) for infected people [48]. The percentage of face-to-face lessons is also essential for understanding educational effect and students' motivation, and building classroom community [1].

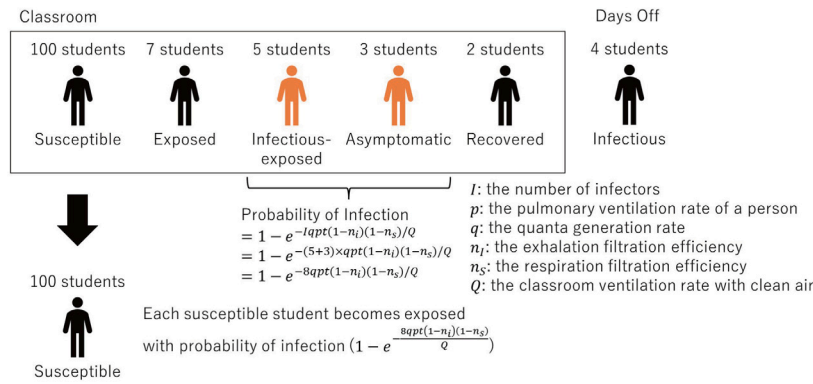


Fig. 4. Infection example. One hundred susceptible students, five infectious–exposed students, and three asymptomatic students take lessons in the same classroom.

Table 1

Basic parameters.

Item	Value
p : the pulmonary ventilation rate of a person	0.54 (m ³ /h)
q : the quanta generation rate	48
n_e : the exhalation filtration efficiency	0.5
n_s : the respiration filtration efficiency	0.5
Asymptomatic rate	0.3
Exposed days	Three days
Infectious–exposed days	Two days
Infectious days	14 days
Asymptomatic days	Eight days

Table 2

Self-contained classrooms and departmentalized classrooms parameters.

Item	Self-contained	Departmentalized
Classroom volume	150 m ³	
Classroom air change rate	Three time/h	
Classroom ventilation rate with clean air ^a	450 m ³ /h	
Lesson time	50 min	
Total number of students	24 students	480 students
Number of classrooms per lesson	One classroom	20 classrooms
Lesson weeks ^b	12 weeks	
Number of lessons per day	7 lessons	

^aClassroom volume multiplied by classroom air change rate.

^bFive days are lesson days and two days are days off in a week.

4.1. Basic parameters

Table 1 lists the basic parameters in all the experiments. Buonanno et al. estimated the pulmonary ventilation rate of sedentary activity as 0.54 (m³/h) [49,50]. Dai and Zhao calculated the quanta generation rate of COVID-19 as 14–48 in 2020 [45]. We adopt 48 as q because the Delta and Omicron variants are spreading worldwide, and the infectabilities are estimated to be stronger than the original [51]. Dai and Zhao estimated the exhalation filtration efficiency, and the respiration filtration efficiency as 0.5 when all students wear a mask [45]. The CDC says, “isolation, and precautions can be discontinued 10 days after symptom onset, and after resolution of fever for at least 24 h, and improvement of other symptoms” [52]. Thus, we roughly estimated 14 infected days. Dai and Zhao estimated that infectability is at a peak two days before and one day after symptom onset. WHO states, “the time from exposure to COVID-19 to the moment when symptoms start to show, on average, is 5 to 6 days”. Hence, we adopted three days and two days as exposed days and infectious–exposed days, respectively [44,53]. Bullard et al. estimated that SARS-CoV-2-infected Vero cell infectivity is observed only eight days after symptom onset [54]. Hence, we adopted eight days as asymptomatic days. Also, we considered the CDC estimate of asymptomatic infection percentage as 30% (the current best) [55].

4.2. School schedules

We designed several school schedules (Tables 2, 3, and 4). A school chooses self-contained or departmentalized classrooms and divides students into several groups: some groups take face-to-face lessons, and the other groups do homework or take online classes for several periods. The groups take face-to-face lessons alternatively.

UNESCO proposes four types of school schedules [2] (Fig. 5). Option 1 is an hour-based model, Options 2A and 2B are day-based models, and Option 3 is a week-based model. UNESCO states that infection risk decreases in this order [2]. These models have different advantages and disadvantages. For example, in Option 1, “students constantly

interact with peers, improving their emotional connection”. However, it is “logistically demanding for parents as the face-to-face instruction time is short”. We made 12 school schedule types (see Tables 1 and 2 in Supplementary material). School schedule type (i) is the basic schedule. In type (i), five days are active school days and two days are off every week, with seven lessons every day from the first day to the fifth day. School schedule type (ii) is a shortened schedule compared to type (i). In type (ii), six days are active school days and one day is off every week, with six lessons every day from the first day to the fifth day, and five lessons on the sixth day. School schedule types (ix), (viii), (vii), and (vi) correspond to UNESCO’s options 1, 2A, 2B, and 3, respectively. An example of generating a school schedule type (x) and simulating it in departmentalized classrooms is shown below.

- step(1) We accumulated students from 1 to 480.
- step(2) We divided the students into four groups: Group A included students 1 to 120, Group B included students 121 to 240, Group C included students 241 to 360, and Group D included 361 to 480.
- step(3) We generated six combinations of the two groups, who took face-to-face lessons together. The combinations were (A, B), (A, C), (A, D), (B, C), (B, D), and (C, D).
- step(4) We assigned the groups for face-to-face lesson schedules for six weeks. We generated their patterns in every combination under two limiting conditions: Group A was permanently set for face-to-face lessons in the first week, and no group took face-to-face lessons for three weeks straight. We found 48 patterns that fulfilled the conditions.
- step(5) After the first six weeks, the school would repeat the schedule of the first six weeks (Fig. 6).
- step(6) We adjusted the number of simulations in each case by considering that the total number of simulations of type (x) was close to the other types’ total number of simulations.

School schedule type (x) included all the combinations of the two groups, and students could meet all the members in face-to-face lessons.

Table 3
School schedules (a).

Schedule name	Type (i) Pre-COVID-19	Type (ii)	Type (iii)	Type (iv)	Type (v)	Type (vi) UNESCO 3
Schedule category	Basic	Shortened	Weeks	Weeks	Weeks	Weeks
Number of groups	1	1	2	4	1	2
Number of face-to-face lesson groups at one time	1	1	1	3	1	1
A continuous period of face-to-face lesson for each group	Always	Always	Three weeks	Three weeks	One week	One week
A continuous period of not going to a school for each group	No	No	One week	One week	One week	One week
Percentage of face-to-face lessons	100%	100%	75%	75%	50%	50%
Percentage of class members that the students meet in face-to-face lessons	100%	100%	100%	100%	100%	50%

Table 4
School schedules (b).

Schedule name	Type (vii) UNESCO 2B	Type (viii) UNESCO 2A	Type (ix) UNESCO 1	Type (x)	Type (xi)	Type (xii)
Schedule type	Days	Days	Days	Weeks	Weeks	Weeks
Number of groups	2	2	2	4	1	4
Number of face-to-face lesson groups at one time	1	1	1	2	1	1
A continuous period of face-to-face lesson for each group	Two and a half days	One day	A half-day	Depends on groups	One week	One week
A continuous period of not going to a school for each group	Two and a half days	One day	A half-day	Depends on groups	Three weeks	Three weeks
Percentage of face-to-face lessons	50%	50%	50%	50%	25%	25%
Percentage of class members that the students meet in face-to-face lessons	50%	50%	50%	100%	100%	25%

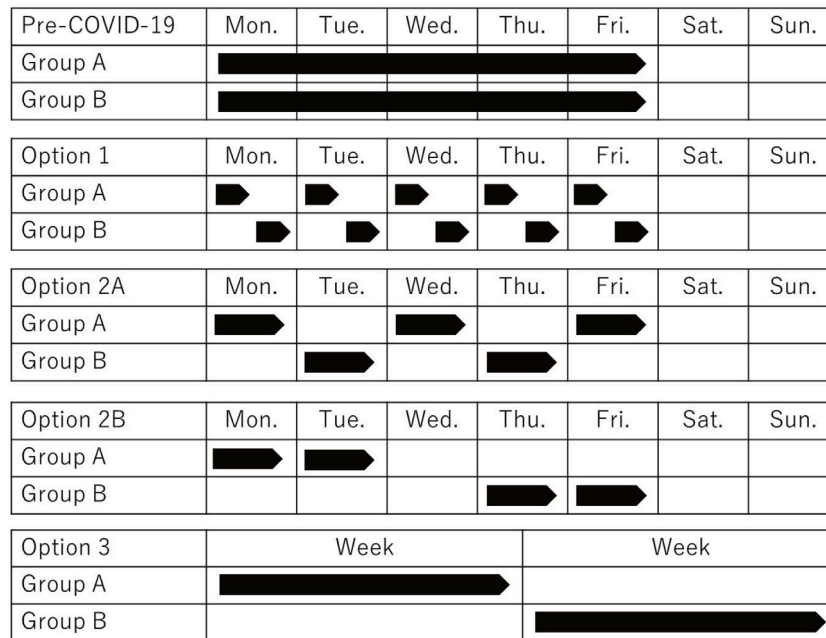


Fig. 5. UNESCO school schedule [2]. Option 1 is an hour-based model, Option 2A and 2B are day-based models, and Option 3 is a week-based model. UNESCO states that infection risk decreases in this order.

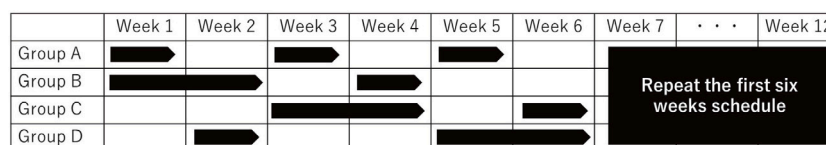


Fig. 6. Example of school schedule type (x). School schedule type (x) included all the combinations of the two groups, and students could meet all the members in face-to-face lessons.

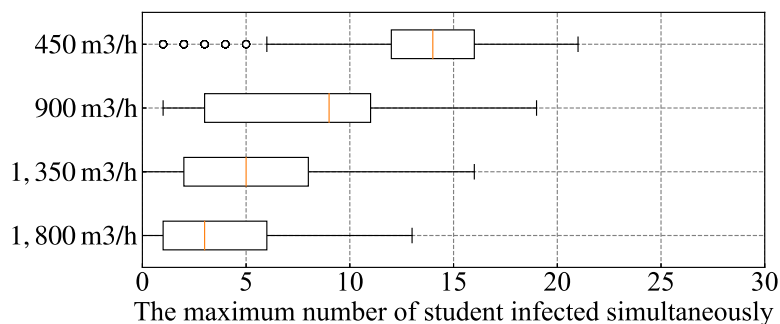


Fig. 7. Experiment 1: The maximum number of students infected simultaneously in self-contained classrooms and the classroom ventilation rate. The maximum number of students infected simultaneously decreased as the classroom ventilation rate increased. The variance of 450 m³/h results is the lowest among the variance of the lower classroom ventilation rates' results.

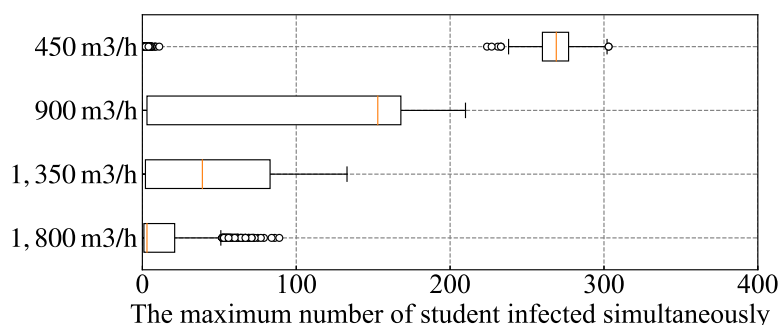


Fig. 8. Experiment 1: The maximum number of students infected simultaneously in departmentalized classrooms and the classroom ventilation rate. The maximum number of students infected simultaneously decreased as the classroom ventilation rate increased. The variance of 450 m³/h results is the lowest among the variance of the lower classroom ventilation rates' results.

The percentage of class members that the students met in face-to-face lessons was 100%.

Under every school schedule, we made only the student 1 in Group A infectious, exposed on Day 0 (Monday), and simulated virus infection spread for 12 weeks.

5. Experiment 1

To evaluate the effects of classroom volumes, and classroom air change rates, we used type (i) as a basic school schedule, and changed the classroom ventilation rate with clean air (Q in Eq. (1)) to 450 m³/h, 900 m³/h, 1350 m³/h, and 1800 m³/h. This experimental design corresponded to a change in the volume or air rate as the basic parameter, doubled, tripled, and quadrupled. Figs. 7 and 8 present the results. The maximum number of students infected simultaneously decreased as the classroom ventilation rate increased. The variance of 450 m³/h results is the lowest among the variance of the lower classroom ventilation rates' results. These results show that increasing classroom ventilation effectively decreases the spread of COVID-19 and the impact of increasing classroom ventilation is not stable.

6. Experiment 2

We simulated school schedules to evaluate the impact of varied school schedules in self-contained and departmentalized classrooms. Figs. 9 and 10 present the results. As a general tendency, the maximum number of students infected simultaneously decreases as the percentage of face-to-face lessons increases.

6.1. Effect of shortened school schedule

The maximum number of type (ii) is slightly higher than that of type (i) in self-contained and departmentalized classrooms. The total lesson time per day is shorter, and the infection risk per day decreases.

However, the continuous period of face-to-face lessons was one day longer. An additional day would increase the maximum number of students infected simultaneously.

6.2. Effect of 75% face-to-face lesson school schedules

The results of the effect of 75% face-to-face lessons in the school schedules (type (iii) and type (iv)) in self-contained and departmentalized classrooms do not correspond. All students went to school for three weeks and then took one week off in type (iii). SARS-CoV-2 would spread like type (i) during the face-to-face lesson week.

The maximum number of type (iv) was slightly lower than that of types (i) and (iii). Three of the four groups went to school alternatively, and each group took face-to-face lessons for three weeks in type (iv). The period of these was the same as that of type (iii), and the number of students who took face-to-face lessons simultaneously was lower than that of types (i) and (iii). Thus, the reduction in class size would decrease the maximum number of students infected simultaneously.

6.3. Effect of 50% face-to-face lesson school schedules

The 50% face-to-face school schedules (types (v), (vi), (vii), (viii), (ix), and (x)) are effective in self-contained and departmentalized classrooms. The decrease in type (v) was smaller than that in types (vi), (vii), (viii), (ix), and (x). All the students go to school for one week, after which they take one week off in type (v). In contrast, half of the students attended school simultaneously in types (vi), (vii), (viii), (ix), and (x). Thus, the maximum number of students infected simultaneously correlates with the reduction in class size.

6.4. Effect of 25% face-to-face lesson school schedules

The type (xii) school schedule is effective for self-contained and departmentalized classrooms. Each of the four groups went to school

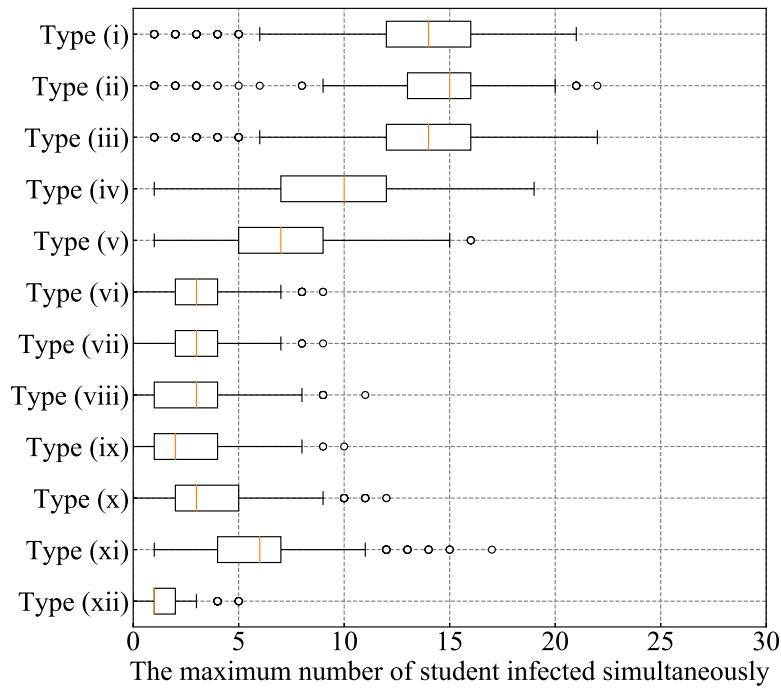


Fig. 9. Experiment 2: The maximum number of students infected simultaneously in self-contained classrooms and school schedule types. The type (xi) school schedule is not effective compared to departmentalized classrooms. In addition, the maximum number in type (xi) in self-contained classrooms is nearly the same as that in type (v) and higher than that of the other 50% face-to-face school schedules.

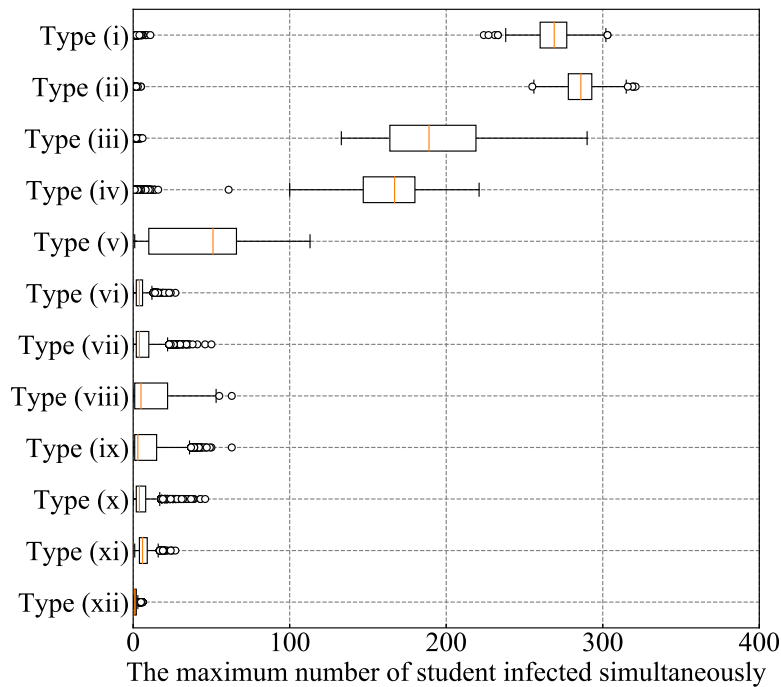


Fig. 10. Experiment 2: The maximum number of students infected simultaneously in departmentalized classrooms and school schedule types. The type (xi) school schedule is effective compared to self-contained classrooms.

for one week, and took leave for three weeks. When students were infected during the face-to-face lesson week, symptoms appear in class online while staying at home, and they skipped the next face-to-face lesson week. This reduces the maximum number of infected individuals.

The effects of type (xi) were opposite between self-contained and departmentalized classrooms. All students went to school for one week, after which they took leave for three weeks. Type (xi) school schedule was effective in departmentalized classrooms; however, it was not as

effective in self-contained classrooms. The maximum number of type (xi) in self-contained classrooms is nearly the same as that from type (v), and higher than that of the other 50% face-to-face school schedules.

Tables 5 and 6 show the classroom percentages associated with infection probability of type (xi) in each classroom in self-contained and departmentalized classrooms for 3600 simulation cases. In type (xi), students go to school for a week and then stay at home for three weeks. Day 0 (Monday), all students of the self-contained school schedule take

Table 5

Classroom percentages associated with infection probability of type (xi) in each classroom in self-contained classrooms. The infection probability increased on Day 4 and was higher than that of departmentalized classrooms. Consequently, all students take the day off on Days 5 and 6, and all rooms' infection probabilities become zero.

Infection probability	Day						
	0	1	2	3	4	5	6
0	0%	0%	70.3%	70.3%	9.50%	100.0%	100%
0%–2%	100%	100%	29.7%	29.7%	24.3%	0%	0%
2%–4%	0%	0%	0%	0%	51.0%	0%	0%
4%–6%	0%	0%	0%	0%	14.1%	0%	0%
6%–8%	0%	0%	0%	0%	0.80%	0%	0%
8%–10%	0%	0%	0%	0%	0.30%	0%	0%
10%–12%	0%	0%	0%	0%	0%	0%	0%

Table 6

Classroom percentages associated with infection probability of type (xi) in each classroom in departmentalized classrooms. The infection probability increased on Day 4 and was lower than that of self-contained classrooms. Consequently, all students take the day off on Days 5 and 6, and all rooms' infection probabilities become zero.

Infection probability	Day						
	0	1	2	3	4	5	6
0	95.0%	95.0%	98.5%	98.5%	89.6%	100%	100%
0%–2%	5.00%	5.00%	1.49%	1.49%	9.84%	0%	0%
2%–4%	0%	0%	0%	0%	0.52%	0%	0%
4%–6%	0%	0%	0%	0%	0%	0%	0%
6%–8%	0%	0%	0%	0%	0%	0%	0%
8%–10%	0%	0%	0%	0%	0%	0%	0%
10%–12%	0%	0%	0%	0%	0%	0%	0%

lessons in the same class (one classroom) with an infected student (student 1). The infection probability of a classroom is always 0.012. On the other hand, students in a departmentalized school schedule take lessons in 20 classrooms separately, and an infected student (student 1) joins one of the 20 classrooms. The infection probability of one classroom (5%) is always 0.012, and the infection probability of the other 19 rooms (95%) is always zero. The infection probability increased on Day 4, and that of self-contained classrooms was higher than that of departmentalized classrooms. Student 1 comes to school from Day 0 (Monday) to Day 1 (Tuesday) and infects other students. If the student is not asymptomatic, the student becomes infectious and takes a day off from Day 2. If the student is asymptomatic, the student continues to attend school and the newly infected students become exposed. The probability of student 1 becoming infectious is 70% (Table 1). Then, 70% of self-contained classrooms' infection probabilities are zero on Day 2; 30% of 5% (1.5%) of departmentalized classrooms' infection probabilities is not zero and 98.5% (100% - 1.5%) of those is zero on Day 2. The newly infected students on Day 0 become infectious or asymptomatic three days later (Day 4) and start to infect other students. The number then becomes the highest on Day 4 (Friday). These classroom percentages are expected values and slightly different from the simulation results (Tables 5 and 6). All new infectious and asymptomatic students come to the same classroom in self-contained classrooms; meanwhile, the new infectious and asymptomatic students are scattered across several classrooms in departmentalized classrooms. Subsequently, the infection probability of self-contained classrooms is higher than that in departmentalized classrooms. Consequently, all students take the day off on Days 5 and 6; all rooms' infection probabilities become zero.

7. Discussion

Experiment 1 shows that increasing classroom ventilation rate is effective, as also recommended by the CDC [56]. However, it is found

that the impact is not stable when the classroom ventilation rate increases as opposed to customizing school schedules (Experiment 2).

Experiment 2 shows that school schedules can differently impact the maximum number of students infected simultaneously, depending on whether classrooms are self-contained or departmentalized.

UNESCO suggests four types of school schedules – Options 1, 2A, 2B, and 3 – corresponding to school scheduling types (ix), (viii), (vii), and (vi). UNESCO states that infection risk decreases in this order [2]. UNESCO's school schedules actually decrease the maximum number of students infected simultaneously, both in self-contained and departmentalized classrooms. However, we found no significant difference between their effects.

The percentage of class members that the students meet in face-to-face lessons of type (x) is 100%, and that of UNESCO's school schedules is 50%. In addition, type (x) of both self-contained and departmentalized classrooms has the same effect, as compared to UNESCO's school schedules. This means that type (x) of departmentalized classrooms has two advantages: a lower maximum number of students infected simultaneously, and constant interaction with a wide variety of peers.

It was found that type (xi) in self-contained classrooms had a slightly higher maximum number of students infected simultaneously, compared to schedules with a higher percentage of face-to-face lessons. This result is caused by a combination of the school schedule, the exposed days, and the infectious-exposed days.

These results imply that teachers and education policymakers have to consider a combination of school schedules, and their classroom types, not just the percentage of face-to-face lessons. This is a complex phenomenon, and a difficult task.

8. Conclusion

We developed the SVISM for teachers and education policymakers. It simulates the spread of infection at a school, considering the students' lesson schedules, classroom volume, air circulation rates in classrooms, and infectability. We then show the effects of changing classroom volumes, and classroom air change rates, and demonstrate the impact of several school schedules in self-contained and departmentalized classrooms.

The results show that internal school infection is very complex, and we cannot obtain the expected result without appropriate school scheduling. For example, the maximum number of students infected simultaneously of type (xi) in self-contained classrooms is higher than the maximum number of students infected simultaneously having schedules with a higher percentage of face-to-face lessons; This phenomena was not found in departmentalized classrooms. Although, teachers can acquire information such as the ranking of four types of classroom models as per their infection risk [2] or that “self-contained classrooms reduce student interaction” [31], the SVISM and the simulation results can help teachers and education policymakers plan school schedules appropriately and reduce the maximum number of simultaneously infected students, while also conducting face-to-face lessons.

This study focuses on self-contained and departmental classroom schedules. However, there is a wide variety of school scheduling: self-contained and departmental classroom schedules can be mixed; students move to special classrooms like a science room, a music room, and an art room; students with disabilities gather in special small classes; and boys and girls are separated into different classrooms. SVISM can simulate these school scheduling issues with changes to the parameter settings.

However, this study has certain limitations. We set basic parameters as in Table 1 based on previous studies [44,45,49–53]. We did not consider differences in parameters between students' ages. For example, the pulmonary ventilation rate of a person in Table 1 is estimated for a male adolescent, or a young/middle-aged adult and older adult combined group [50]. There are three main transmission routes of COVID-19 [56]: inhalation, deposition, and touching. We focus on

inhalation because the airborne (inhalation and deposition) route is estimated as the dominant route for SARS-CoV-2 transmission [57]. In addition, deposition has a negligible effect compared with the removal effect of ventilation [45]. The Wells–Riley equation can consider deposition by treating the ventilation rate (Q) (Eq. (1)) as the equivalent clean air delivery rate, which is equal to the actual ventilation rate multiplied by filtration efficiency [58]. It is beneficial to give teachers and school policymakers a reliable, convenient, and simple model with demonstrated results. In addition, the SVISM does not consider effective measures in reducing the transmission of COVID-19, such as frequently conducting antigen and PCR tests, contact tracing, cleaning, and disinfecting [27,59]. In the future, the SVISM should consider these factors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The program can be referenced from the following <https://github.com/satoshi-takahashi-lab/school-virus-infection-simulator>.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.imu.2022.101084>.

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