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Research Article

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Proposal for Teaching Mathematical Modelling Using COVID-19 as an Example of an Infectious Disease Epidemic: The Case of Japan in the Corona Vortex

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ABSTRACT

Someone with a mathematical background can understand that if a virus such as COVID-19 enters a country, it will increase exponentially and cause a pandemic. Are students watching daily news reports with this level of sensibility? It is not difficult for students already familiar with differential and integral calculus to use the susceptible-infected-recovered or removed model to predict the number of new infections and determine the effect of self-restraint. Current education practices emphasize the memorization of concepts. When confronted with unknown difficulties such as COVID-19, it is important to develop teaching materials that, rather than frightening and emotionally discouraging students, enable them to utilize their previous knowledge, confront the difficulties, and explore the significance of mathematics education. This study provides example mathematical modelling material. Students learned mathematical modelling using the example of the number of new infections in Japan's first wave of COVID-19. A survey was conducted before and after instruction which revealed that students in Japan are not being taught how to build mathematical models, and teaching using mathematical models can be used successfully to help students learn construction of mathematical disease models and also about exponential change.

Keywords: mathematical modelling, SIR model, differential equation, COVID-19

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INTRODUCTION

The first case of novel coronavirus disease 2019 (COVID-19) was identified in Wuhan City, Hubei Province, China, on 31 December 2019 (Kuniya, 2020a; WHO, 2020). The first case of COVID-19 was confirmed in Japan on 15 January 2020 (WHO, 2020), and a state of emergency was declared on 7 April. The typical symptoms of COVID-19 are fever, cough, and malaise (The University of Tokyo Health Service Center, 2020), and person-to-person transmission occurs through droplets or airborne infection (Tang et al., 2020). Social distancing measures in Europe and the US–such as lockdowns and travel restrictions–were implemented (Inaba, 2020). In Japan, all schools were closed on 27 February, and the closures had a substantial influence on students' daily lives and learning. When this paper was being drafted, the pandemic had taken its toll on human lives and many restrictions were imposed.

As the pandemic has spread across the world with devastating consequences, mathematics has been gaining face and is currently in the spotlight. News media, such as papers and websites all over the world, use graphs and charts as never before. Everybody is talking about exponential growth as the number of cases doubles and about how one infected individual can lead to unexpectedly large numbers of COVID-19 patients (Engelbrecht et al., 2020).

Despite historical records revealing that infectious diseases have been a major cause of death, many people still suffer from infections because of their apathy, as they do not consider themselves to be in danger of infection. This crisis offers an opportunity for students to focus their attention on prevention and control of the disease by applying their mathematical knowledge rather than just accepting it.

PROBLEMS

Difficulties in Introducing Mathematical Modelling Education

Mathematical modelling is now part of mathematics curricula worldwide (Hankeln, 2020). In many countries, however, only a few studies are available that explore the application of modelling in mathematics education (Arseven, 2015). Methods for mathematical modelling are yet to be determined, and to the best of my knowledge, there are rarely any studies on mathematical modelling (e.g., Arseven, 2015; Bora & Ahmed, 2019; Lingefjärd, 2007). In Japanese high schools, physics and mathematics are considered separate disciplines (Aoki, n. d.), and Japanese students are not blessed with the experience of generating mathematical models from real models (Kota, 1981). In addition to the faculty's poor insight into mathematical modelling, mathematical modelling is not a precise mathematical body of knowledge, like calculus or linear algebra, by nature as an interdisciplinary discipline, and the sense that it is not 'real mathematics' (Lingefjärd, 2007) is certainly a factor for why it is rarely taught. Currently, the level of mathematics taught in high schools mostly reinforces mathematical concepts and skills that the students have already attained. Watanabe (2018) argues that in the early Meiji period, the idea was to catch up with Western science and technology rather than to advance mathematics. Burghes and Borrie (1981) point out that out of the seven steps (i.e., (1) drafting a model of reality; (2) formulating a hypothesis for the model; (3) formulating a mathematical problem; (4) solving the mathematical problem; (5) explaining the meaning of the solution; (6) testing the validity of the model; and (7) using the model to explain, predict, decide and plan) for problem solving, most mathematics education is only concerned with the fourth step, 'solving mathematical problems,' and does not proceed to the other steps, especially 5-7. If step 3 is ignored, it may make generation of models (steps 1 and 2) and examination of the meaning and validity of solutions (steps 5 and 6) impossible. Furthermore, students entering Japanese universities are obsessed with inputting knowledge and solving problems to pass university entrance examinations. If the concepts are understood, there is little need to focus on memorization. Education in Japanese high schools and preparatory schools often ignores understanding of concepts and focuses on memorization or a particular methodology, which is often seen as a problem. This leaves them with little time to develop other mathematical skills, such as generating models or examining the meaning of the figures obtained as answers and the appropriateness and validity of the solutions. Yanagimoto (2008) raises the concern that although the number of modelling materials should increase as the grade level increases, there is no room for modelling materials in high school mathematics classes, where students are preparing for entrance examinations. Even if this could be incorporated, delayed implementation of IT in elementary and secondary education is likely to serve as an obstacle. Interpretation of a real-life problem as a mathematical model requires processing it and analyzing the results. In some cases, the students are either unable to formulate the equation, are unable to apply it to arrive at the solution, or they apply it partially, making it difficult to ascertain whether the teaching materials were effective or not. If this is the case, students will not be able to understand and implement the sequence of mathematical modelling, and the significance of the teaching materials will decrease.

In addition to this current state of affairs, English (2017) points out that mathematics (M) and engineering (E) have been undervalued in STEM education. In most schools, science and mathematics are taught in isolation from each other, and engineering is not included in the curriculum (English, 2017). In Japan's ancient capital of Kyoto, KYOTO STEAM, a festival of art (A), science (S), and technology (T), is held, where are M and E?

Mathematical modelling is seen as an important tool for creating opportunities to engage students in STEM activities (Muhammed et al., 2019). English et al. (2013) pointed out that in mathematics classrooms, modelling activities can be used to implement a context-integrated model of STEM education, and Lyon and Magana (2020) noted that mathematical modelling activities are becoming an important part of engineering education classrooms. In recent years, modelling has been considered a fundamental aspect of STEM education, and research needs to be conducted to explore how modelling can be developed to establish connections between the STEM disciplines in a meaningful way (Hallström & Schönborn, 2019). In short, mathematical modelling is a powerful teaching tool for connecting mathematics education with other disciplines. Modelling activities can integrate mathematics, physics, and other STEM concepts concurrently (Kertil & Gurel, 2016); however, increasing the curriculum by broadly incorporating mathematical modelling into the classroom may mean that some existing topics will have to be deleted (Lyon & Magana, 2020).

Handling Exponential Functions

Although 'exponential and logarithmic functions' are part of the mathematics II curriculum in traditional Japanese high schools, I have sometimes found that the teacher in charge of the subject does not cover it at all, and a teacher of a different subject (mathematics B) teaches it instead. The reason for this is that this component is often ignored in Japanese university entrance examinations. For example, in the case of the University of Tokyo, in the past 40 years, out of 375 questions (1980-2019), only two questions pertained to 'exponential and logarithmic functions,' which is quite uncommon compared to other fields. For students who are not good at mathematics, it is difficult to ascertain whether they can distinguish the difference between the graph of an exponential function and the graph of a quadratic function and between exponential increase and linear increase.

The anecdot[1] of Sorori Shinzaemon from the 16th century is passed down in Japan. Still, after witnessing the discrepancy between the timing of experts' warnings of a crisis and political decisions in the COVID-19 epidemic, one wonders if Japanese politicians and citizens are aware that the number of infected people increases exponentially.

If the component 'exponential functions' is neglected because of one aspect of evaluation, such as university entrance examinations, this creates a problem, and I believe that it is important to link exponential functions (mathematics) to other disciplines and to incorporate material into modelling activities to engage students and teachers.

Mathematics Education During COVID-19

With the ongoing threat of the coronavirus, an invisible virus, 2020 was a life-changing year for many people. New infections continued to be reported every day, and experts suggested a 'reduction of contact between people by 80% people.' On the contrary, some documents suggest it to be 70% (Nishiura, 2020); this discrepancy may be attributed to the fears associated with the disruption of economic activities. Some students raised the following questions: 'with an 80% reduction in contact, I cannot go out with my friends; would it not be easier to get the public's cooperation with a 60% reduction?' In other words, 'Is 60% reduction not good enough?' I responded, 'No!' but have been left wondering how to explain why 60% is not 'safe enough' so that students

[1] When Sorori Shinzaemon, who served as an attendant to the emperor TOYOTOMI Hideyoshi, was offered a reward by Hideyoshi, Shinzaemon replied, 'I would like to receive one grain of rice on the first day, two grains of rice on the second day, four grains of rice on the third day, and so on for thirty days, doubling the amount of rice from the previous day. Hideyoshi thought it was a humble offer and readily agreed to it on the spot, but later realised that it would be a huge amount and changed the reward (there are various theories as to how many days he promised to receive the rice).

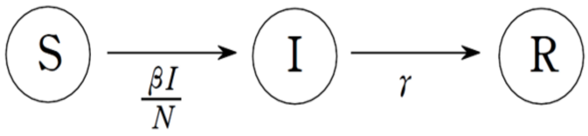

Figure 1. SIR model transition diagram

and others can fully understand the difference between what would happen if 60% was the goal rather than 80%.

Experts' recommendations should not be accepted without critical evaluation, but a distinction must be made between these recommendations and self-centered decision-making, and individuals should be able to justify their decisions. Mathematical models are used to predict the spread and end of infectious diseases. While the plague, an infectious disease that may have had the greatest impact on human beings, is now history, the current emerging infectious disease, COVID-19, is still a threat. Although the lack of integration of mathematical modelling into education is an inherent problem in Japan, infectious diseases, including COVID-19, are universal. According to Sun and Weng (2020), 'The model predictions indicated that asymptomatic cases are a more serious threat compared with importation.' Sun and Weng (2020) argued that strict interventions should be continuously implemented and that unravelling the asymptomatic pool is critically important compared to preventive strategies such as vaccines. However, the author believes that behavioral restrictions are limited in time.

For high school and first-year college students who are already familiar with differential and integral calculus, modelling these issues on their own, correctly understanding the daily news reports, and thus, adopting the appropriate level of fear and caution seems to have high potential as teaching material that is likely to help students develop interest.

Yanagimoto (2008) lists 40 mathematical modelling education materials reported so far, but most of them are for grades up to the first year of high school, and only two are for the second year of high school or higher grades. In addition, only a few reports on modelling education in infectious disease epidemiology are available, such as Handel (2017). The objectives of teaching the same subject matter will change depending on whether it is taught as infectious disease epidemiology or as mathematics. Furthermore, most of the studies conducted on mathematical modelling to date have focused on creating mathematical models from real-life models, and only a few reports pertain to the development of skills related to the transition from real-life situations to real-life models and their effects (Yoshimura & Akita, 2021). The aim of this paper is to show that the teaching of mathematical modelling can be successfully used to construct mathematical disease models and to learn about exponential change.

Research Questions

This paper explores the following research questions:

Does mathematical modelling material on infectious diseases within a mathematics lesson for students who have already studied calculus, based on the number of new infections in the first wave of COVID-19 in Japan, influence students' sense of exponential increase (or decrease)?

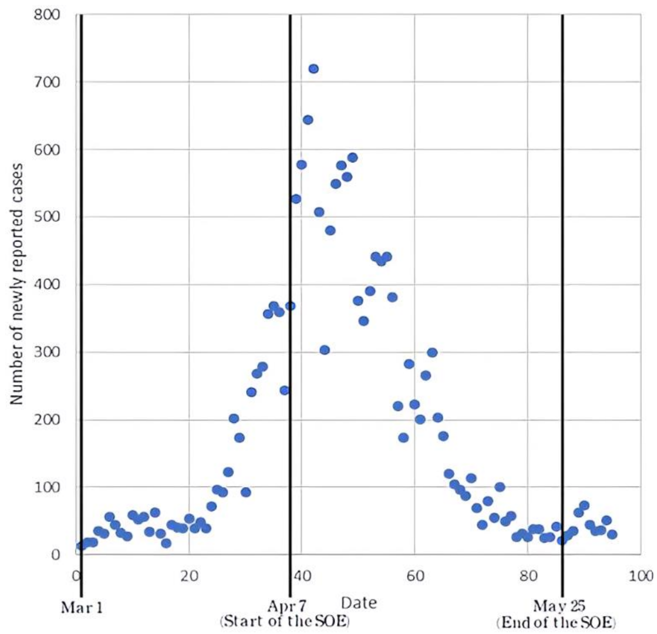

Figure 2. Number of newly infected people before and after the issuance of the state of emergency (SOE) based on NHK News (2020)

MATERIALS AND METHODS

Preparation

Modelling using the example of a pandemic uses the SIR model, as shown in **Figure 1**. The SEIR model is a tool used to predict the epidemiology of the infectious disease (cf. Inaba, 2020; Kuniya, 2020b). However, in this article, I use the SIR model for its simplicity and ease of use.

If we divide the host population into three states: susceptible, infectious, and recovered (immune), and denote the respective population densities of each state as $S(t)$, $I(t)$, and $R(t)$, then in a closed system,

$$\frac{dS(t)}{dt} = -\frac{\beta S(t)I(t)}{N}, \frac{dI(t)}{dt} = \frac{\beta S(t)I(t)}{N} - \gamma I(t), \frac{dR(t)}{dt} = \gamma I(t).$$

Here, $\beta I(t)$ is the infection rate, γ is the recovery rate, and $S(t) + I(t) + R(t) = N$(total population). During early days of infection, if time $t = 0$ and $S_0 = S(0) > 0$, then

$$I(t) = I(0)e^{(\frac{\beta S_0}{\gamma N}-1)\gamma t}.$$

$R_t = \beta S_0/\gamma N$ is called the effective reproduction number,

$$I(t) = I(0)e^{(R_t-1)\gamma t}.$$

Specific Method Using the Number of Infected People in Japan

In Japan, the R_t at the time of the declaration of a state of emergency (7 April 2020) was $t = 14, I(0) = 72, I(14) = 368$ (NHK News, 2020), and $\gamma = 0.1$ (Anderson et al., 2020).

$$R_t = 2.14$$

(in fact, $R_t = 2.5$ [Nishiura, 2020]).

Figure 2 shows the scatter plot of the number of newly infected people before and after the issuance of the state of emergency (SOE) based on NHK News (2020).

Reducing the contact by 80%: $\beta \rightarrow \beta/5$ results in $R_t \rightarrow R_t/5$,

$$I(t) = I(0)e^{-0.057t}.$$

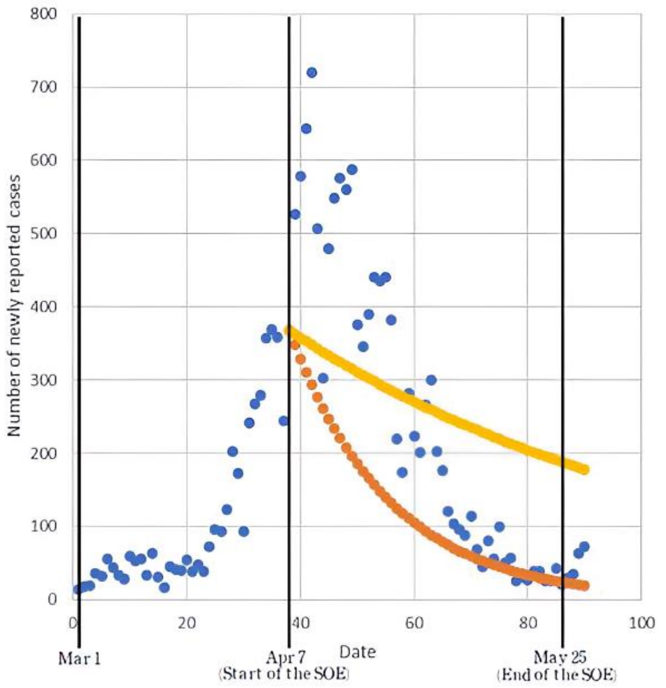

Figure 3. When not considering the time lag (80% reduction in orange dots, 60% reduction in yellow dots)

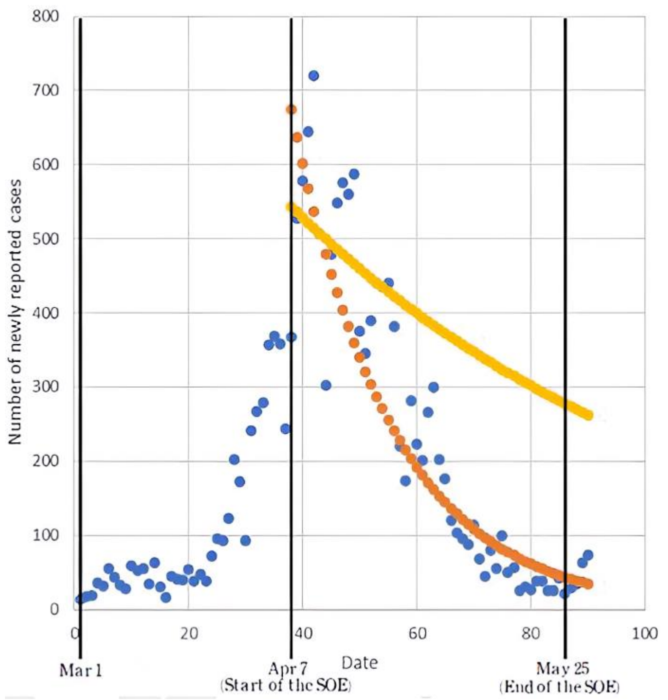

Figure 4. When considering the time lag (80% reduction in orange dots, 60% reduction in yellow dots)

Thus, it will take 23 days to reduce the number of infected people from 368 to less than 100, and it will take 94 days to reduce the number of infected people by 60%, through reduction of contact, as shown in **Figure 3**; the discrepancy appears to be large. As the model suggests an incubation period, it is unrealistic to expect the effect of self-restraint to appear the next day. Therefore, an incubation period is considered to be five days (Anderson et al., 2020). In other words, when recalculated based on when the effect of self-restraint was first reflected (i.e., on 12 April 2020 (507 new infections)), the following result was obtained for an 80% reduction:

$$100 > 507e^{-0.057t},$$
$$e^{0.057t} > \frac{507}{100},$$

$0.057t > log_e 5.07 = 1.623\cdots$ Therefore, $t > 28.47\cdots$. Thus, it is easy to understand that it takes 34 days after the declaration of a state emergency for the number of infected people to drop below 100. This has been illustrated in **Figure 4**. In this model, in the latter half of the period after the declaration of the state of emergency in Japan, it was found that the number of contacts was successfully reduced by 80%[2], and it is possible to estimate the change in the number of infected people in the case of a 60% reduction.

On 7 April 2020, it was concluded that in Japan, it would take 34 days to reduce the number of infected people to 100 or fewer when contact was reduced by 80%, and 121 days when contact was reduced by 60%, which indicated a clear difference of 3.5 times. This estimation revealed that the experts thought that the limit of self-restraint would be about one month and 80%, but I will not discuss this in detail because it may be used as a political criticism inside and outside the classroom, or vice versa. In my daily teaching, I have observed that many students do not understand the exponential nature of the rates of increase and decrease for most of the natural phenomena, such as an increase in the prevalence of a virus. In other words, they may lack clear understanding, thinking that the increase or decrease is simply linear (a linear function). However, the author assumed that sharing the results with the students would help them develop a sense of exponentiation.

RESULTS

In January 2021, the SIR model was taught to first- and second-year university students who have already studied calculus in a classroom setting; owing to the ongoing COVID-19 pandemic, both lectures were conducted online. The lecture followed the content of the previous section. In the first lecture, the students were asked to submit a descriptive report explaining the case where contact is reduced by 80%, and **Figure 3** and **Figure 4**, where the 80% reduction is drawn, were completed. They reported on the following points:

(1) how many days it would take to reduce the number of new infections to less than 100 when contact is reduced by 60%, and

(2) what condition they would add to the model. In the following week's lecture, the students began by reporting the results after applying the mathematical modelling; they also created **Figure 4** and practised formulating differential equations using some of the models they had considered while writing the report.

After that, the students were asked to submit a final report in which they formulated differential equations based on their own report (2) based on the previous session by incorporating their own additional status.

[2] Inaba (2020) and Kuniya (2020a) reported that an 80% reduction in the number of contacts was achieved. However, Mikami (2020) reported a 70% reduction even in Umeda, the area with the greatest reduction. Moreover, Kurita (2020) pointed out that this reduction was never achieved.

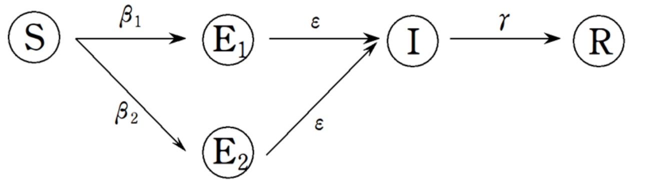

Figure 5. Example of infection rate with or without a mask (E: exposed)

When the question 'If the population of a village with 1,000 people increases by 10% every year, how many people will there be in 10 years?' was asked to 37 students before providing instruction, only 18 students (48.7%) answered it correctly. However, after two classes discussed herein, the questionnaire was re-administered, and the number of students who answered a similar question correctly increased to 28 (75.7%). Therefore, Wilcoxon's signed-rank test (one-sided) was performed, which was significant at z=5.545, and asymptotic significance probability was determined at p<.001. This indicates that students who had completed multiple studies on mathematical models of infectious diseases tended to have a significantly higher understanding of exponential increase and decrease than those who had not completed their studies.

DISCUSSION

Benefits of Thinking About SIR Model

The second section illustrates how the SIR model was applied to the case of Japan to predict the number of infected people. Modelling a similar simulation using data from the target student's country may interest students, as the content is relevant to their own lives. Students will learn to fear the speed of divergence of exponential functions. Even though the construction of simple models may be easy, by doing so, students can become aware of their interest in daily news and their own surroundings. As a result of modelling, if there is a discrepancy pertaining to reality, the students can freely add the factors that need to be included, and this provides them the opportunity to think.

In fact, the most frequent comment after this lecture (free description) was "difficult" (17 students). This was mainly an assertion that it was difficult to think. On the other hand, as for the reasons given by the 9 students who wrote that they "enjoyed" the lecture, three students wrote that they enjoyed thinking, and three students wrote that learning itself was enjoyable. The remaining three students gave as their reason that they learned that mathematics is useful in the real world. It seems that there is a difference in whether the content related to their lives is perceived positively or negatively by the students.

In addition, according to the reports of the 37 first- and second-year university students mentioned above, the most common factor added to the SIR model was death (23 students), followed by incubation period (14 students) and reinfection (13 students). There was also a branching model (**Figure 5**) because the infection rate varied depending on the presence or absence of a mask, the effectiveness of the vaccine, and the severity of the cases (mild or severe). An example considering births, deaths, and reinfections is shown in **Figure 6**.

The university only allowed attendance to classes once a week, but it seemed that the students actively exchanged their views with each other outside the class pertaining to the elements that could be added to the model. The students also considered the following factors:

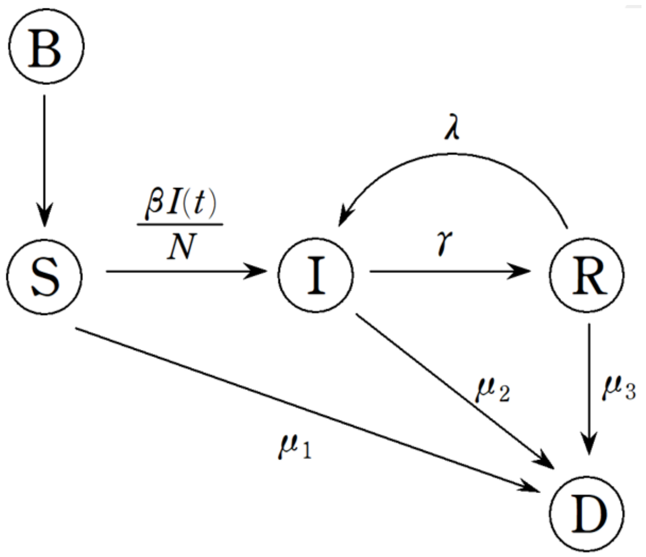

Figure 6. Example of birth (B), death (M), and re-infection (λ: reinfection rate & μ: mortality)

examination errors, asymptomatic states, entry or exit from the country, presence of underlying disease, displaced individuals, age, and gender. Thus, it was possible to understand which factors each student believed would result in an increase or decrease in the infection rate.

However, the more complex the model, the more difficult it becomes to formulate differential equations and the more difficult it becomes to solve them algebraically.

Suggestions for Future Research

In some cases, when the criterion for assessment is an exam that is scored, the only solution that can be determined in a certain way is preferred. In January 2022, when I taught the same content in an engineering class, I found that students who were good at calculus had a challenging time creating a model. Conversely, we found that in some cases, in the face-to-face classes, students with low computational proficiency were able to actively generate models. In an educational environment where paper tests are used as an indicator of achievement, there is a possibility that students may not prefer engaging in mathematical modelling. However, the question which arises is, in an age of unpredictability, how long can we teach only predictable things? As we move from an era of mass production and mass consumption to one of variety and quantity, it is imperative that teachers expand the possibilities of what they can teach in the classroom. Although there is no established method of evaluating abilities that cannot be measured by paper tests, this does not mean that the value of teaching mathematical modelling of infectious diseases using the number of new COVID-19 infections as the material is lessened because of this very reason. In the Japanese case introduced here, face-to-face classes could not be held because of COVID-19, and even if face-to-face classes could be held, students could not engage in active group work owing to social distancing norms. Inclusion of group activities may not only lead to a better understanding of the sensitivities of students pertaining to each other in this unstable daily life but may also give rise to hesitancy in the students to engage in group work. This is likely to impact the modelling results. In addition, the results of the modelling do not fit the pattern because students' interests will change depending on which period of the year it was implemented. For example, in the case of awareness that the virus has a low mortality rate existed at the time of implementation of the model, students would not be overly aware of the status of mortality as in this paper. This will lead to an increased need for the teachers to conduct extensive research on teaching materials. However, as teachers cannot be expected to learn by transmission, it must be included in the mandatory courses of teacher education, which has not been possible till now (Blum, 2015). Kawakami et al. (2019) point out that it is not easy for teachers, who are novices in modelling instruction, to develop new modelling materials, and sufficient explanation is not yet available. The contents of this paper could equally well be covered in Japanese high school classes, but there is a difficulty in calculating specific values without a natural logarithm table at hand. However, owing to the impact of COVID-19, in Japan, the schedule for implementation of the GIGA school concept has been moved forward earlier than the originally planned schedule (Ministry of Education, Culture, Sports, Science and Technology, Bureau of Elementary and Secondary Education, Educational Support and Teaching Materials Division, 2022). Many elderly teachers do not have smartphones or computers, but applications will become more commonplace in the educational field. Furthermore, in Japan, programming education will begin in the first year of high school in 2022. The problem of having to write computer codes, which has been a barrier for students (Handel, 2017), will be remediated, and students will be able to examine approximate solutions to differential equations by themselves, as revealed in the results of the study. Therefore, the scope of mathematical modelling materials will be expanded, and their necessity will be realized.

CONCLUSIONS

In a post-lesson survey of 37 Japanese students, all said they had never built such a model, and 26 (70.3%) said there was a need for its incorporation in their mathematics education curriculum. It is likely that there will be students in classrooms directly affected by the first wave of COVID-19 for the next decade or so, and hence, it will be easy to draw their attention to the identity of the changes to their lifestyle. Even for viral outbreaks with less of an overall global impact than the outbreak of COVID-19, the twenty-first century alone has seen a succession of viral threats, including SARS, H5N1 influenza, MERS, and H1N1 influenza. Additionally, it is important for students to learn to respond courageously and never stop learning; educational materials such as the mathematical model of COVID-19 can be applied to similar infectious diseases on a case-by-case basis.

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