

Understanding the Spread of COVID-19 in Japan: Preliminary Results from a System Dynamics Model

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Abstract

This study developed a system dynamics model to understand the spread of coronavirus disease (COVID-19) in Japan. The model is built on the generic SEIR (Susceptible, Exposed, Infected, and Recovered) framework adopted by Ghaffarzadegan and Rahmandad (2020) to build a system dynamics model for the spread of COVID-19 in Iran. Japan seems to be successful in containing the spread compared with other countries, and its first peak has passed. However, because this also leaves a large population still susceptible to the virus, it could cause a second and potentially higher peak of infection after the state of emergency aimed at reducing contact rate is lifted. As the government has proposed the “New Lifestyle,” it is critical to behave cautiously so as not to be infected. While the model focuses on the SEIR structure, the reflection of other sub-structures such as economy and hospital capacity that have tradeoffs with reducing contact rate should be beneficial. However, before extending the model, it is also critical to conduct estimates using confidence intervals rather than point estimates to better reflect uncertainties.

Keywords

COVID-19; SARS-CoV-2; System dynamics; Japan; SEIR

1. Introduction

This study adopts a modeling-in-real-time approach to understand the spread of coronavirus disease (COVID-19) in Japan, how it has spread, and what changes influence the spread. Although there is great uncertainty in estimating parameters given the limitation of data available, we cannot wait for the sufficient data to be available. Rather, it is critical to keep making decisions by updating the model and our understanding of the issue as we obtain more data.

This study adopts a system dynamics model built on the generic SEIR (Susceptible, Exposed, Infected, and Recovered) framework developed by Ghaffarzadegan and Rahmandad [1]. Their model was developed and parameterized in Iran. As explained below, this study adjusted their model by changing parameters and structures to fit Japan.

It should be noted that the purpose of this preprint is not to provide reliable point estimates. Rather, it intends to share the complete model information for its replicability and make it extendable or polishable by other scholars, address the potential uniqueness of the Japanese situation with corresponding implications for tackling the spread in Japan, and identifying the aspects of the model that need further investigation.

2. Materials and Methods

2.1 COVID-19 in Japan

COVID-19 has spread around the globe, and Japan is no exception [2]. The first case was reported on January 15, 2020, and the patient returned from Wuhan in China [3]. Since then, the number of people infected has increased, and thus far, 714 cases have tested positive using the polymerase chain reaction (PCR) test on April 12, 2020, was the peak of the outbreak [4]. The Japanese government established New Coronavirus Infectious Disease Control Headquarters on January 30,

2020, and implemented measures to tackle the outbreak of the disease [5]. Measures include the declaration of a state of emergency, to the delivery of masks to households, to subsidiaries to companies suspending their operations. The relative mortality has been smaller than that in other countries (5 per million people in Japan, 58 per million in the US, 94 per million in Germany, and 584 per million in Spain), although it is not clear why Japan has been successful in keeping the number of deaths relatively low [6].

2.2 Key Model Structure

Figure 1 shows the stock-and-flow diagram built on the model developed by Ghaffarzadegan and Rahmandad [1]. The model development and its simulation used Vensim Professional for Windows 8.0.9 Double Precision x64 (Ventana Systems, Inc., www.vensim.com). Details of the model can be found in the supplementary material in [1]. The full model in the Vensim format is provided as part of the supplementary materials. The key stocks are expressed by the following integral equations [1]:

$$S = \int_0^t (-i_E) dt + S_0 \quad (1)$$

$$I_E = \int_0^t (i_E + i_F - i_L) dt + I_{E,0} \quad (2)$$

$$I_L = \int_0^t (i_L - O_R - O_D) dt + I_{L,0} \quad (3)$$

$$R = \int_0^t O_R dt + R_{E,0} \quad (4)$$

$$D = \int_0^t O_D dt + D_0 \quad (5)$$

where, S Susceptible Population [individual]; i_E : Exposure [individual/day]; S_0 : Initial value for S [individual]; I_E : Early infected [individual]; i_F : Infected arriving from abroad at time t_0 [individual/day]; i_L : Onset [individual/day]; $I_{E,0}$: Initial value for I_E [individual]; I_L : Late infected [individual]; O_R : Recovery rate [individual/day]; O_D : Death rate [individual/day]; $I_{L,0}$: Initial value for I_L ; R : Cumulative recovered [individual]; $R_{E,0}$: Initial value for R [individual]; D : Cumulative death [individual]; D_0 : Initial value for D .

The contact rate is one of the key characteristics that stipulates the dynamics of pandemic and characterizes Ghaffarzadegan and Rahmandad's [1] model. It is a combination of policy intervention exogenously given and endogenously changing public perception of recent deaths.

$$c = \rho c_{max} \left(1 - \frac{1}{1 + e^{s(O_D^* - \overline{O_D})}} \right) \quad (6)$$

where ρ is the impact of other policy measures beyond the public perception of recent deaths, $\overline{O_D}$ is the public perception of death rate, O_D^* is a threshold for the public perception of recent deaths, at which contact rate endogenously declines to half of the maximum contact rate, c_{max} , and s is the sensitivity of public behavior to recent deaths.

The diagram is a slight modification of that by Ghaffarzadegan and Rahmandad [1]. The parameters in blue are estimated through calibration to fit the historical data of Japan; parameters in pink are from other studies and best guesses used in Ghaffarzadegan and Rahmandad [1]. Parameters in green are policy variables that change exogenously.

2.3 Model Adjustments

2.3.1 Model Structure

Except for the treatment of fatalities, no major changes were made to Ghaffarzadegan and Rahmandad's [1] model for Iran. Due to the potential gap between official reports and actual deaths in Iran, their model embedded the structure to reflect the gap (see Supplementary material to accompany [1]). However, the official report of deaths due to COVID-19 seems to be accurate [7], and this study assumes no gap between them.

2.3.2 Parameter Value Estimates

There are three types of parameters: those taken from other sources and best guesses (pink in Figure 1), those estimated through calibration (blue in Figure 1), and those exogenously given (green in Figure 1).

Parameters taken from other sources and best guesses are the same as those in Ghaffarzadegan and Rahmandad [1] because at this moment, there are no better values fitting Japan available. As more data are reported, they are updated accordingly.

The parameters in blue were estimated through calibration using Powell, which is an optimization method available in Vensim [8]. The parameters were optimized such that the set of parameter choices produced the dynamics of infected, recovered, and dead as close as possible to the actual data available up to May 15, 2020. In the calibration, in contrast to Ghaffarzadegan and Rahmandad [1], policy changes were induced in its effect because the historical data are a reflection of the policies. For model fit, the actual data were measured by root-mean-square error (RMSE) and root-mean-square-percentage error (RMSPE), as shown below.

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum (X_m - X_d)^2} \quad (7)$$

$$\text{RMSPE} = \sqrt{\frac{100}{n} \sum \left(\frac{X_m - X_d}{X_d} \right)^2} \quad (8)$$

where X_d is the data series and X_m is the model output.

There are two types of parameters in green: policies and seasonal effects. This study assumes that there is no seasonal effect, as there has been no indication of its effect thus far. The Japanese government has implemented measures to tackle the outbreak of the COVID-19 pandemic [5]. Among others, the government declared a state of emergency effective on April 7, 2020, and applied it to seven prefectures (Saitama, Chiba, Tokyo, Kanagawa, Osaka, and Hyogo); this was later expanded to all prefectures on April 16, 2020 [5]. The state of emergency is not a lockdown but a request to businesses and citizens to reduce the contact rate by 70% or 80% if possible [9]. The state of emergency was lifted on May 14 in 39 prefectures after a decline in the number of new infections.

While the data directly describing contract rate are not available, there are several proxy data available. For example, the number of people in Tokyo station at 15:00 on Friday, May 22 has declined by 69.7% compared with the average between January 18 and February 14, that is, before the pandemic, and 41.5% compared with the day before the declaration of the state of emergency (April 7) [10]. Google COVID-19 Community Mobility Reports reported that mobility at "Retail & recreation" sites (e.g., restaurants, cafes, shopping centers, theme parks, museums, libraries, and movie theaters) and "Train stations" (e.g., subway, bus, and train stations) on Friday, May 15 has reduced by 32% and 44%, respectively, compared with the baseline data that are the mean values during January 3 and February 6, 2020 [11].

The impact of the declarations of the state of emergency was reflected ρ in Eq. (1), which was set to 1 when there was no policy impacting the contact rate implemented. The state of emergency was first declared on April 7 ($t = 68$) and applied to seven prefectures, it was then expanded to all prefectures on April 16 ($t=77$). The key target of the declaration was to reduce the contact rate by 70% or 80%, if possible, through social distancing [9]. To reflect this 2-step process of declaration and corresponding target contact rates, ρ was set to 0.65 (35% reduction) at $t = 68$ by applying a weighted average according to the targeted population and then 0.2 (80% reduction) at $t = 77$.

3. Results

3.1 Simulation Results

Figure 2 (a) – (c) show the fitness of the model in terms of historical data from December 31, 2019 to May 15, 2020. The RMSPE varies from 5.9% to 7.8%.

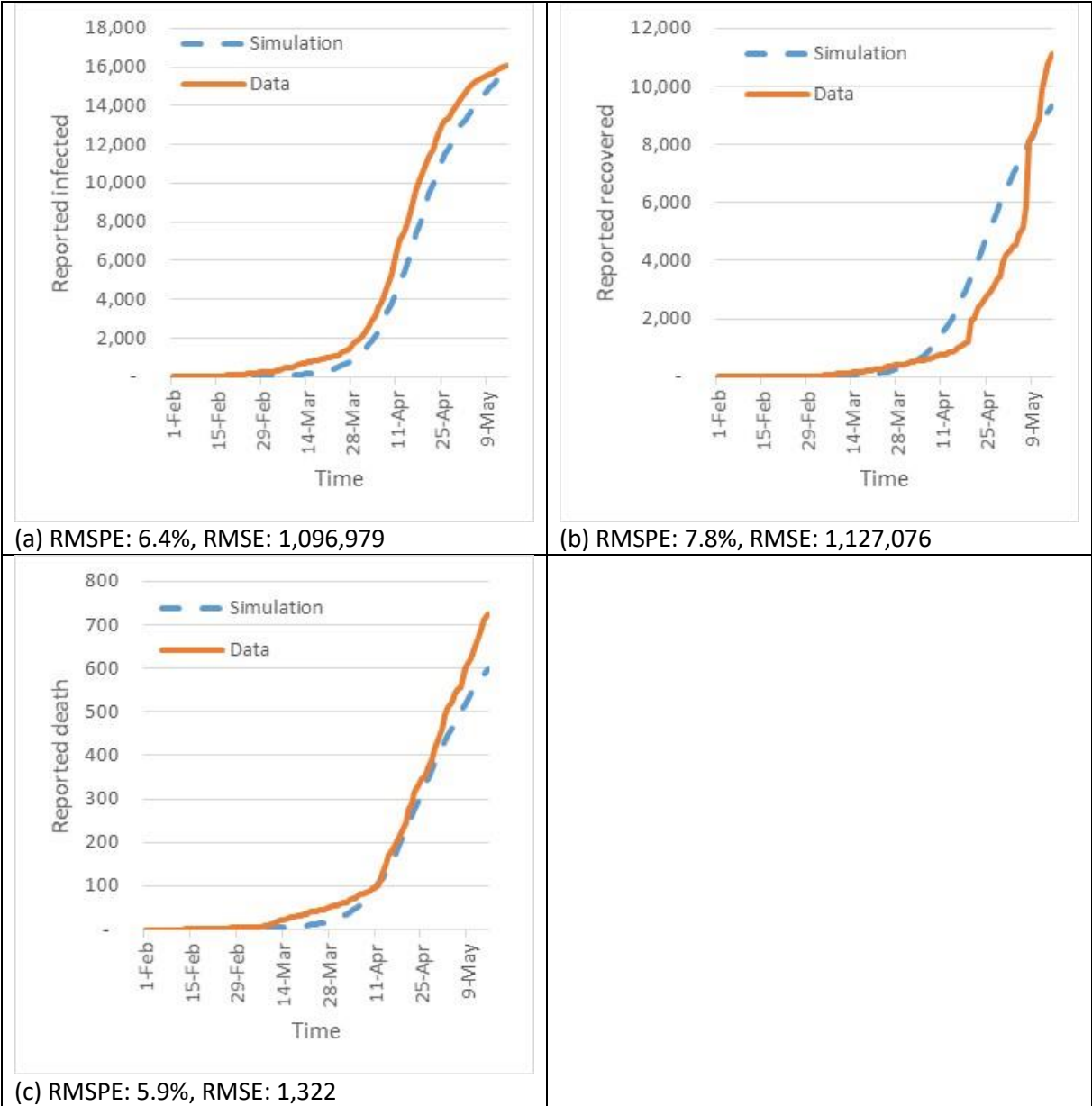


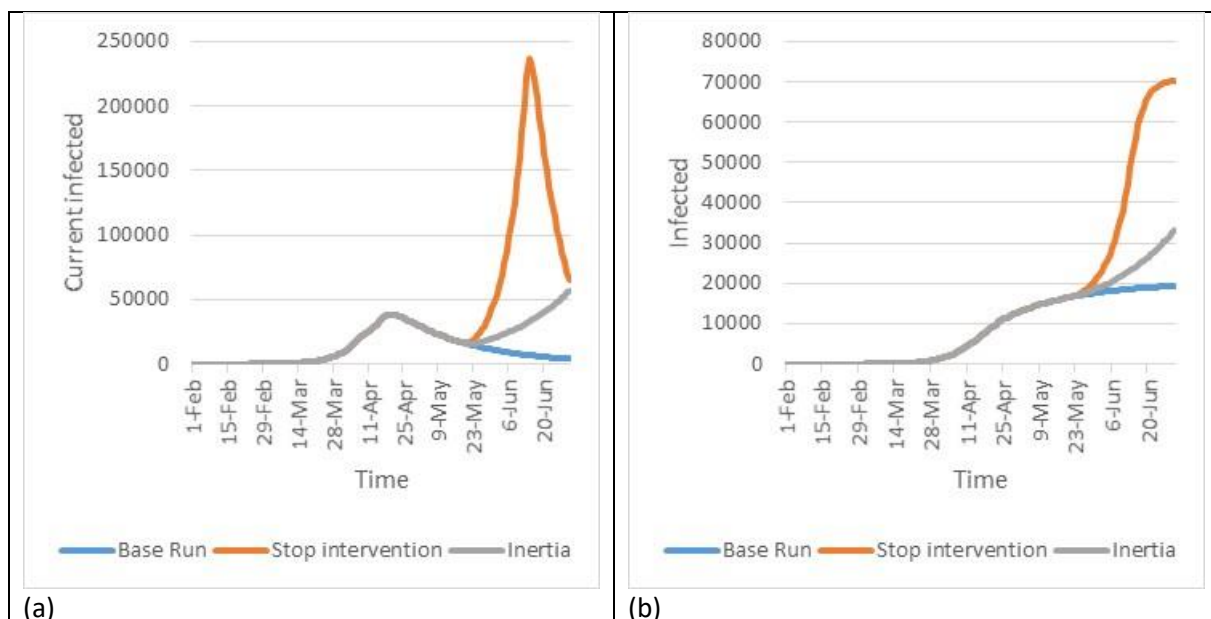
Figure 2. Comparison of key simulation results with data. The model was calibrated through December 31, 2019 to May 15, 2020.

Note: RMSPE: Root-mean-square percentage error, RMSE: Root-mean-square error

3.2 Policy analyses

To explore the potential impact of policy intervention, the impacts of two scenarios were compared with the base run as shown in Figure 3; “Stop intervention” and “Inertia.” The only difference made to the model is the policy intervention (that is, ρ in Eq. (6)), as shown in Figure 3 (f). For the base run, policy intervention remains the same until the end of June. “Stop intervention” assumes that policy intervention is lifted on May 14 as the government actually implemented [12]. However, “Inertia” assumes that the impact of policy intervention lasts to some degree even after it was lifted. The “Inertia” scenario seems to be more plausible. For example, Google COVID-19 Community Mobility Reports showed that people are still restraining their movements even after the state of emergency lifted [11]. The mobility trends for retail and recreation Japan were -31% (May 13), -30% (May 14), -32% (May 15), and -40% (May 16) compared with the baseline [11]. The ρ for “Inertia” was chosen arbitrarily because of the limited information available at this moment.

Figure 3 (a) to (d) show the key dynamics of the pandemic. The contact rate (Fig. 3 (e)), which is influenced by policy intervention (Fig. 3 (f)), is key to explaining the differences in Fig. (a) – (d) across different scenarios. The current infection rate continues to decline if the policy intervention continues (blue curves in Fig. 3). However, if the policy intervention is lifted, there may be a second peak of infections, which is higher than the first, peak that occurred on April 12, 2020. When the impact of policy intervention lingers after the intervention is lifted, there may be a second peak but slower and lower than the case without the inertia.



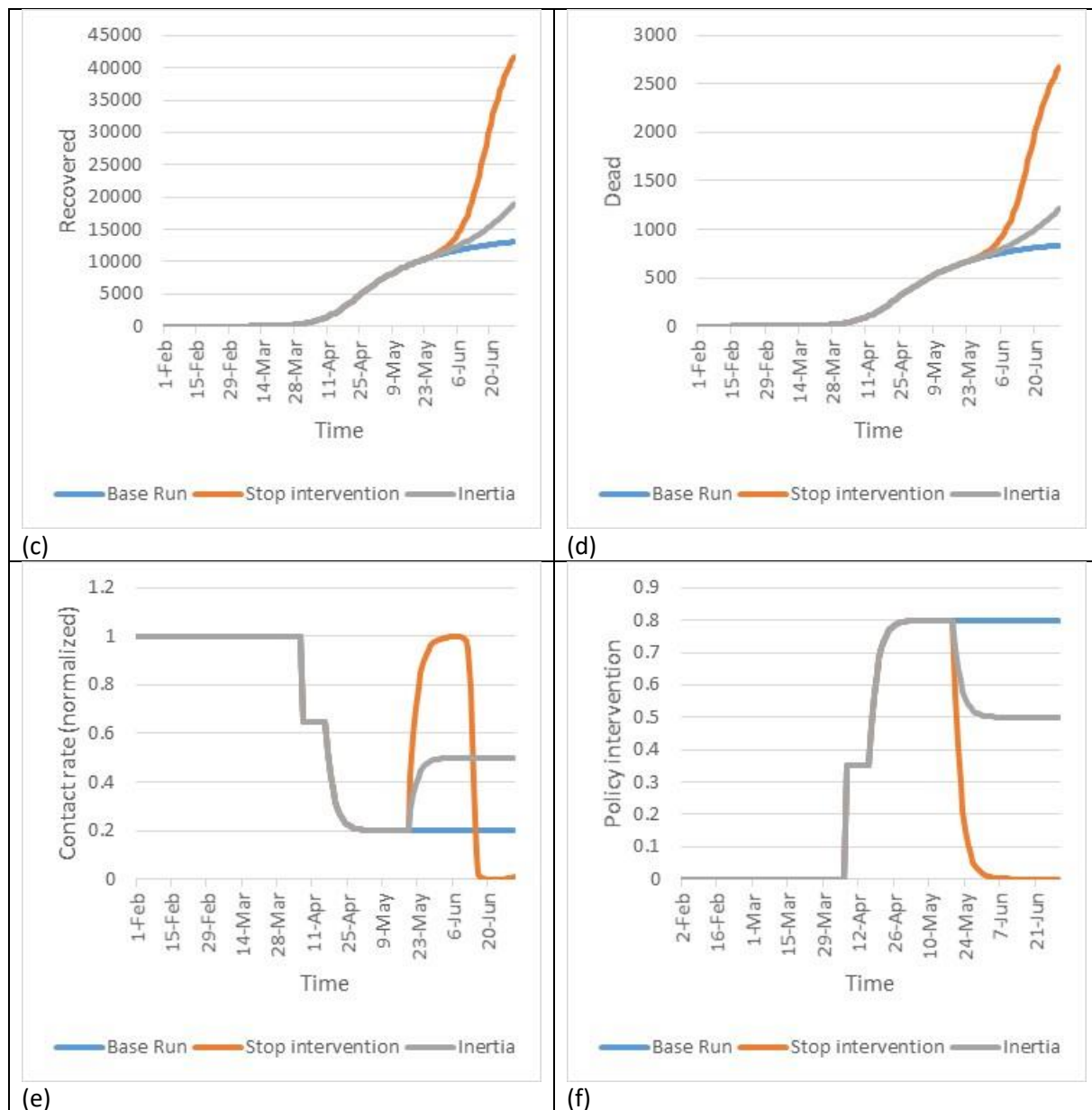


Figure 3. Key results of policy analyses

4. Discussion and Conclusion

It is critical to begin this section with the limitation of this study to avoid misusing the simulation results. First, in addition to commonly used model tests [13], it is highly recommended to improve the model parameter by applying more sophisticated techniques. This study employed point estimates commonly employed for model parameters, but it provides very limited insights [14]. Instead, it would be desirable to adopt a method that could further reflect uncertainty such as conventional Monte Carlo (MC) or Markov Chain Monte Carlo (MCMC) [15]. MCMC generates samples from the posterior distribution [14]. For example, Ghaffarzadegan and Rahmandad [1] adopted MCMC to calibrate their model and show their estimates with confidence intervals. Wu et al. [16] used a similar method to examine the COVID-19 epidemic in and beyond China.

Using the Powell calibration technique, the model fits the historical data up to May 15, 2020; RMSPE ranges from 5.9% to 7.8% (Figure 2). However due to the aforementioned limitations of this study, it

would be better to restrict our discussion on qualitative changes, especially regarding what will happen up to the end of June 2020 (Figure 3).

A primary implication we could obtain from this study is to help us understand how to avoid a second peak to occurring (“Stop intervention” in Figure 3. (a)). The scenario analysis indicates that the second peak may be higher than the first peak on April 12. There are two points that deserve discussion regarding this. First, the second peak could be higher because there is a large population susceptible to COVID-19. Japan has been said to be successful in constraining the spread of the coronavirus [6] It is a good thing, but at the same time, it leaves a large population susceptible unless Japan has already established the herd immunity against a virulent type G SARS-CoV-2 [17]. Until an effective treatment or vaccine is found, there is a possibility of another, even higher peak. Second, “Stop intervention” may not be realistic as unlikely to change their behavior even when the intervention is lifted. The Japanese government has suggested the adoption of a “new lifestyle” [18], which presents various practices in daily life to avoid infection: keeping distance, wearing masks, washing hands with soap, speaking more quietly, playing outside rather than inside, and conducting telework (see Figure 4 for more examples). If people implement such a new lifestyle, the infection can be constrained even after the intervention is lifted; the data also substantiated this point [11].

Example of practicing "New Lifestyle"

(1) Basic infection prevention measures for each person

Three basics for preventing infection:

① Keeping physical distance, ② wearing a mask, ③ washing hands

- ☐ Keep a distance of two meters as much as possible, or at least one meter, between two persons
- ☐ Chose outside rather than inside if you are to play
- ☐ Avoid standing right in front of each other during conversation as much as possible
- ☐ Wear a mask when you go out or talk inside even without any symptoms
- ☐ Wash your hands and face first when you get back home, followed by changing clothes and taking a shower as soon as possible
- ☐ Carefully wash your hands with water and a soap for approximately 30 seconds (also possibly with hand sanitizer)

※ Pay more attention to your health, especially when meeting those who may have a high risk of serious symptoms, such as the elderly or people with chronic diseases.

Infection prevention related to traveling

- ☐ Refrain from traveling to and from where the infection is prevailing
- ☐ Refrain from traveling upcountry or for leisure. Business trips only when it is unavoidable
- ☐ Keep a record of the people you meet and the time of meeting in case you get infected
- ☐ Carefully follow how the infection is prevailing locally

(2) Basic lifestyle for daily life

- ☐ Wash and sanitize hands frequently
 - ☐ Make sure to observe coughing etiquette (by covering your mouth)
 - ☐ Ventilate frequently
 - ☐ Keep physical distance
 - ☐ Avoid gatherings in crowded places, close contact settings and closed spaces
 - ☐ Check your health condition and measure body temperature every morning
- Do not force yourself to go out, and stay home if you have symptoms of fever or cold



(3) Lifestyle for each scene of daily life

Shopping

- ☐ Use online shopping
- ☐ Shop by yourself or in a small group, at off-peak hours
- ☐ Use electronic payment
- ☐ Plan your shopping in advance and shop quickly
- ☐ Refrain from touching displays like samples
- ☐ Keep a distance while lining up at the cashier

Leisure, Sports etc.

- ☐ Select places like parks at off-peak time
- ☐ Refer to videos for home muscle training or yoga
- ☐ Jog in a small group
- ☐ Keep a distance as etiquette when passing others
- ☐ Utilize booking systems for leisure
- ☐ Do not stay long in small rooms
- ☐ Keep a distance or stay online for singing or cheering others

Public Transports

- ☐ Refrain from chatting
- ☐ Avoid peak-hours
- ☐ Take a walk or ride a bike if possible

Meals

- ☐ Take away or delivery
- ☐ Enjoy meals at outside spaces
- ☐ Serve individually, avoid sharing plates
- ☐ Do not sit face-to-face, rather besides
- ☐ Concentrate on eating, refrain from chatting
- ☐ Avoid pouring drinks for others, sharing glasses or sake cups

Family ceremonial occasions

- ☐ Avoid banquets or meetings with large numbers
- ☐ Decline participation when you have symptoms of fever or cold

(4) New working style

- ☐ Work remotely and rotate commuting shifts
- ☐ Keeping a distance while commuting during different working hours
- ☐ Open and widen working spaces
- ☐ Use online meetings
- ☐ Exchange business cards online
- ☐ Wear a mask and ventilate venues in case of a face-to-face meeting

※ Infection prevention guidelines for each business sectors will be prepared by relevant organizations.

Figure 4. Examples of practicing "New Lifestyle" adopted from the Ministry of Health, Labour, and Welfare [19].

In addition to improving the reliability of the simulation results through further model testing, it is critical for future studies to reflect tradeoffs in the model by tackling epidemics. While it seems to be evident that the simplest and most effective measure to stop the spread is to reduce the contact rate to zero, such an approach could greatly influence economic activities. A research institute projected that the growth rate of GDP in Japan may decline by 6.3% to 9.0% [20]. Because the impact of lockdown may not be even across industries, it would be desirable to extend the model such that it can simulate the economic impact on an individual industry level. For example, the model can be coupled with an input-output model [21,22]. For example, while sales at grocery stores have increased by 10.7% in April compared with April last year, sales at department stores dropped by 75.2% in April compared with April last year [23,24]. Due to the huge economic impacts of lockdown, some countries such as Sweden have opted against a lockdown to contain the spread of the coronavirus [25]. However, such an approach could lead to a higher number of deaths [25]. Another problem is that the number of patients needing to be hospitalized outweighs hospital capacity [26].

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