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The SEIR model incorporating asymptomatic cases, behavioral measures, and lockdowns: Lesson learned from the COVID-19 flow in Sweden

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ABSTRACT

The Sweden approach is unique in handling the COVID-19 flow, compared to other European countries. While other countries have practiced the full lockdowns, Sweden has practiced the lighter lockdowns or the partial lockdowns as public spaces such as cafes and restaurants are allowed to serve their customers subject to government recommendations. This study aims to develop an SEIR model for Sweden capturing important issues such as the roles of behavioral measures, partial lockdowns, and undocumented cases. The suggested SEIR model is probably the first SEIR model capturing the roles of behavioral measures, partial lockdowns, hospital preparedness, and asymptomatic cases for Sweden. The SEIR model can successfully reproduce similar main observed outputs, namely documented infected cases and documented death cases. This study finds that the effects of partial lockdowns effectively start 52 days after the first confirmed case. Again, behavioral measures and partial lockdowns reduce possible infected cases about 22% and 70% respectively. This study also suggests that the Sweden government should step up to the full lockdowns by conducting public closures so COVID-19 flow can be curtailed significantly. Likewise, owing to airborne transmission, protecting vulnerable people such as senior citizens should be prioritised.

1. Introduction

From Wuhan, China in 2019, the coronavirus (SARS-CoV-2) relates to the COVID-19 has spread across the world, being the greatest pandemic in the last decade. As the COVID-19 pandemic has impacted almost all sectors [5,10,17,18], affected countries have struggled to hamper the COVID-19 flow. In general, there are two types of measures to hinder the COVID-19 flow namely, behavioral measures and lockdowns [14;21]. The behavioral measures relate to humankind acts such as physical distancing, face mask(s), and handwashing. In the case of Sweden, the public health authority [29] asked people to do voluntary acts such as staying at home (if they feel relevant symptoms), physical distancing, and working from home (WFH).

As the COVID-19 has been spread through human interaction, lockdowns have been practiced in containing the SARS-CoV-2. Generally, lockdowns mean limiting the human interactions to slow the flow of COVID-19. Since human interaction is the main reason of the COVID-19 transmission [17,26], almost all affected countries have practiced lockdowns.

In practice, there are two types of lockdowns. The first one is the full lockdown which means all types of human interaction are prohibited in public spaces, except for human interaction in fulfilling basic needs. To date, almost all affected countries such as Germany, France, and Singapore have ever practiced the full lockdown. The full lockdown has successfully slashed the COVID-19 flow across the world [32]. However, due to the negative impacts of the full lockdown, many countries have refused to apply the full lockdown. For instance, Sweden [2,32] and Indonesia [30] have practiced partial lockdowns. The partial lockdown is the lighter version of the full lockdown. In Sweden, there are no public closures as schools, universities, and other public spaces are not closed. However, in the middle of 2020, Sweden has banned any gathering of 50 people or more, but Sweden has still allowed public spaces such as restaurants, schools, and pubs to publicly open.

As its approach is relatively different, some studies have investigated a Sweden case study. A study [11] used the agent-based modeling approach to elucidate the COVID-19 flow in Sweden. Many studies [24,32] compared the impacts of the COVID-19 in Nordic countries such as Denmark and Sweden, stating that Sweden has experienced a higher infected rate and a higher mortality rate than other Nordic countries. Other existing focused on the analysis of the herd immunity [22] and containment strategy [21,23,25] in Sweden.

Due to limited capability of the basic SEIR model [13] and limited

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Table 1
Parameter values of the SEIR model.

No	Names	Values	References
1	The first confirmed case (s)	January 31st, 2020	[20]
2	Ro (basic reproduction number)	(2–3.8)	[31]
3	Incubation time	5 (2–14) daysmedian (min–max)	[31]
4	Infection duration	(5–22) days	[27,28]
5	Recovery time	(5–22) days	[27,28]
6	Behavioral reaction time The behavioral reduction time is measured between the first infection case and the beginning of the behavioral risk reduction actions. This time measurement also applies to other time measurements.	In earlier March 2020, there were announcements of the COVID-19 threats by public health agency (PHA) led to appropriate acts such as physical distancing and WFH This study sets this variable from the first confirmed cases and lockdowns.	[25]
7	Behavioral risk reduction	This is about individual behavior such as physical distancing. This is assumed to be between 10% and 50%	
8	Lockdown reaction time (This is measured from the first confirmed cases) .	On March 11th, 2020, the government banned the gathering of 500 people or more (about 40 days from the first date of lockdowns)	[2]
9	Lockdown risk reduction	The lockdowns are very strict and enforced by law, so the efficacy is relatively high (50%-95%)	Existing studies [4,14–16] pointed out the beneficial impacts of lockdowns
10	Fraction of asymptomatic cases	(40–62) %	[19]
11	Lockdown time for senior citizens. Another study stated that protecting senior citizens is important [25]	March 16th, 2020 (45 days after the first confirmed case)	[20]
12	Lockdown reduction for senior citizens	This is assumed to be between 10% and 50%	–
13	Public spaces are open	Sweden allows public spaces such as pubs and restaurants to serve their customers subject to the public health agency recommendations [25].	

existing studies investigating the COVID-19 flow in Sweden, this study aims to develop an SEIR model based on the system dynamics approach. Likewise, this study contributes to the computer model of the SEIR model, enabling policymakers to simulate different effects of lockdowns, social distancing, and asymptomatic cases. This is important as another study [1] neglected the impacts of asymptomatic cases that lead to overrate the impacts of lockdowns and social distancing. It is hoped that this study can be a basis and a gauge to understand previously mentioned important issues such as asymptomatic cases, social/physical distancing, and partial lockdowns in Sweden.

2. Data and methods

The main source of data is https://ourworldindata.org/coronavirus/country/sweden. From this link, two available data including infected cases and death cases were collected. Data from January 2020 to October 2020 were collected. Other data such as average infection and recovery time were collected from available existing studies as seen in Table 1.

Like other studies [3,9;14], this study develops the SEIR model based on the system dynamics approach. Similar to other studies [8;14,16,15], this study conducts the Markov Chain Monte Carlo (MCMC) calibration to obtain the best values for variables without unknown parameter values.

This study runs multiple calibrations such as the Markov Chain Monte Carlo (MCMC) and the Powell calibration schemes. The calibrations were also carried by 10,000 runs to obtain the best-estimated values. This study also separates two types of measures during the pandemic including social behavior and lockdowns. They are separated as the first measure or behavior acts such as physical distancing were voluntary acts, while the second measure or partial lockdowns are usually accompanied by law enforcement.

Other main issues such as undocumented cases and hospital preparedness are also embedded into the SEIR model. Undocumented cases, so-called asymptomatic cases, have roles in spreading the COVID-19 flow [19]. Again, hospital preparedness aims to measure the quality of healthcare in handling infected cases. This simplified variable aims to elucidate the quality of hospital preparedness as it leads to low fatality rates and higher recoveries. Hospital preparedness is an important factor as other studies [4,12;14] claimed that owing to better hospital preparedness, Singapore is more advanced and more successful in handling the COVID-19 flow, leading to low death rates.

3. Discussion and results

Human interaction is the main reason for the COVID-19 [17,26]. As such, more human interaction leads to more infected droplets or more infected surfaces. Afterward, infected droplets lead to asymptomatic and symptomatic cases. In some cases, symptomatic cases will increase the number of inpatient or hospitalized cases. It is also possible that symptomatic cases lead to deaths without hospitalization. A simplified causal loop diagram (CLD) depicting dynamic interactions between behavioral measures, asymptomatic cases, and other factors is described in Fig. 1.

After a recovery time, hospitalized patients will be recovered and unfortunately, after an infection duration time, symptomatic cases may lead to deaths. Recovery time is defined as the average time between the symptom onset and recoveries. Similarly, infection duration is measured between the symptom onset and death. In general, better preparedness such as trained healthcare workers and bed capacities can decrease fatalities. Due to limited data, parameters such as infection duration and recovery time are unknown. Owing to this, the calibration process, so-called the MCMC calibration is conducted.

The CLD is converted into a stock-flow model using Vensim© as seen in Fig. 2. As previously mentioned, the MCMC calibration process was conducted to obtain the best parameter values. To obtain the best parameter values, ranges of possible values for each unknown parameter are collected based on existing studies (Table 1). To do the calibration, range values for each unknown parameter are inserted during the calibration stages. For instance, Table 1 shows that the fraction of undocumented cases is (40–62) % (Table 1, point 10). So, during the calibration stage, the fraction of undocumented cases is set between 40% and 62% as suggested by another study [19]. This means the MCMC calibration will find the best-estimated value of the fraction of undocumented cases between 40% and 62% subject to observed documented infected cases.

The main equations of the SEIR model that capture critical factors such as undocumented cases, behavioral measures, and lockdowns are explained. Undocumented cases (asymptomatic cases) are defined as a multiplication between a fraction of undocumented cases and infected cases. Respectively, the number of infected cases, deaths, and recoveries are a division between each respective cumulative case and its respective time as seen in Eqs. (1)–(3) as follows:

$$infected\ rates = "exposed\ cases"/incubation\ time \quad (1)$$

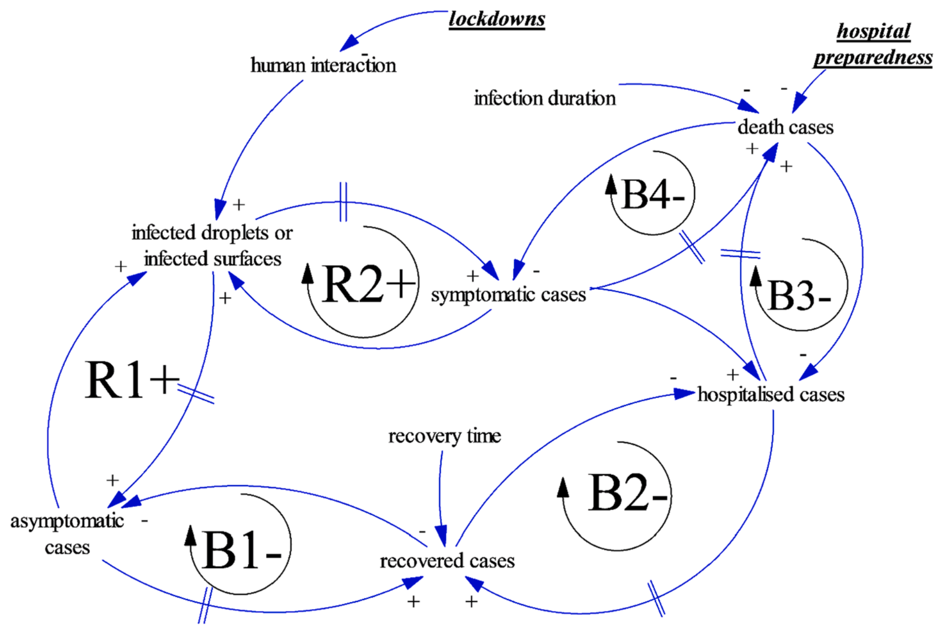

Fig. 1. A simplified CLD of the SEIR model [17].

$$dying\ rates = "infected\ cases"/infection\ duration \quad (2)$$

$$recovery\ rates = "infected\ cases"/recovery\ time \quad (3)$$

The transmission rate measures a conversion of susceptible people to be exposed people [7]. The first policy (behavioral measures) is a combination of "behavioral risk reduction" (the effects of behavioral measures) and" behavioral reaction time" (the occurring time of the effects of behavioral measures). So, once the first policy is active, the transmission rate will be decreased properly. Eqs. (4) and (5) define the first policy and the transmission rate respectively. Please note that "import time" is the time once the coronavirus comes into Sweden.

$$the\ impacts\ of\ behavioral\ risk\ reduction = IF\ THEN\ ELSE(Time >= import\ time + ''behavioral\ reaction\ time'', ``behavioral\ risk\ reduction'', 0) \quad (4)$$

workers tend to minimize death cases. Eq. (7) as follows elucidates the role of the hospital treatment quality:

$$dying\ rates = infected\ cases/infection\ duration^{*} (1 - the\ hospital\ treatment\ quality) \quad (7)$$

Eq. (7) is modified further to include another variable, namely, lockdown reduction for senior citizens as Eq. (8) below:

$$dying\ rates = Infected\ cases/infection\ duration^{*} (1 - hospital\ preparedness) * IF\ THEN\ ELSE(Time > = lockdown\ time\ for\ older\ people, lockdown\ reduction\ for\ older\ people, 1) \quad (8)$$

While Fig. 1 shows the capability of the SEIR model to reproduce similar patterns of the cumulative death and infected cases, Table 2 highlights the best-estimated value for each given parameter (the SEIR

$$Transmissionrate = (Ro/recoverytime + infectionduration)^{*}fractionofsusceptible^{*}(1 - theimpactsofbehavioralriskreduction) \quad (5)$$

model is available as a supplementary material). It appears that the best-estimated values are between suggested ranges as seen in Table 1. For example, the basic reproduction number (Ro) is about 3.15 which is corresponding with the WHO recommendation (2–3.8) [31]. The SEIR model also has similar values compared with other studies. The first instance is infection duration is about 20 days which is a similar range by another study [27]. The second instance is a fraction of asymptomatic cases (60%) which is similar to another study [19].

The second policy i.e., lockdowns is calculated similarly to Eq. (4). Eqs. (6a) and (6b) show the number of exposed cases decreases after the second policy starts at "lockdown reduction time".

$$the\ expected\ impacts\ of\ lockdown\ risk\ reduction = IF\ THEN\ ELSE(Time> =import\ time+'lockdown\ risk\ reduction\ time',' lockdown\ risk\ reduction', 0) \quad (6a)$$

$$the\ actual\ impacts\ of\ lockdown\ risk\ reduction = DELAY3I(\ the\ expected\ impacts\ of\ lockdown\ risk\ reduction,\ delaytime,\ the\ expected\ impacts\ of\ lockdown\ risk\ reductionx) \quad (6b)$$

The hospital preparedness aims to measure each country's performance in handling infected cases, so the number of deaths is minimized. Intuitively, the higher capability of available hospitals and the better healthcare systems lead to minimum death cases or low case fatality rates (CFR). Better hospital treatment and high-skilled healthcare workers tend to minimize death cases.

Table 2 also proves that behavioral measures such as physical distancing and handwashing started their effective effects about 45 days (around March 10th, 2020) after the first confirmed case on January 31st, 2020. Moreover, the partial lockdowns such as a ban of people gatherings more than 50 people started their effective effects about 52 days after the first confirmed case (around March 23th, 2020). Please notice that the Sweden government ordered the ban of people gatherings and the campaigns of the COVID-19 flow on March 11th, 2020, and early February 2020 respectively. This finding means that the partial lockdowns have an immediate effect.

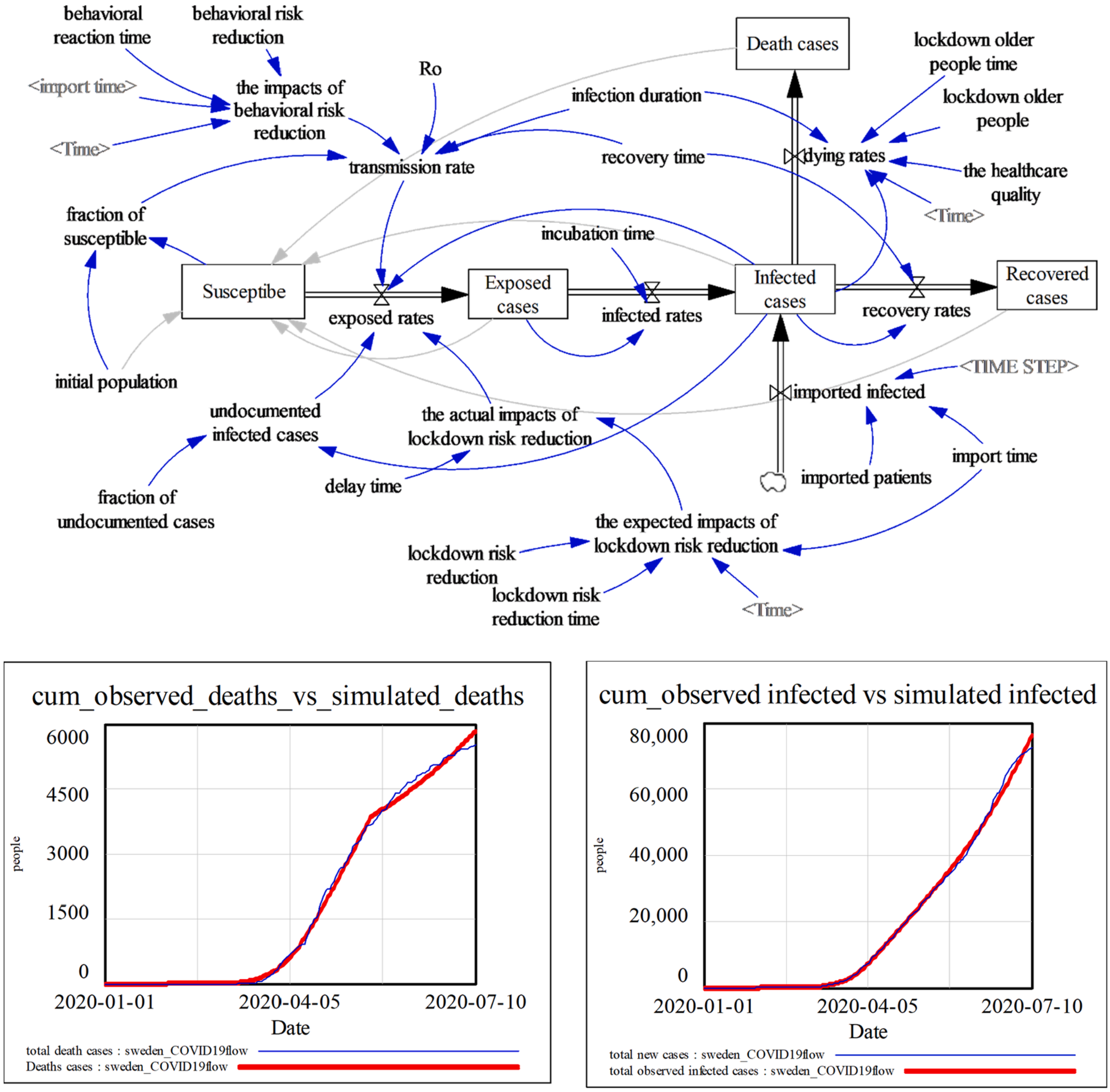

Fig. 2. The SEIR model for Sweden and simulated outputs (cumulative infected and death cases) (In the SEIR model, hospital preparedness is represented as the healthcare quality).

Table 2
The best parameter values.

No	Variables	Sweden
1	Ro (basic reproduction number)	3.74
2	Incubation time (days)	5.79
3	Infection duration (days)	21
4	Recovery time (days)	5
5	Fraction of asymptomatic cases	42%
6	Behavioral reaction time (days)	45
7	Behavioral risk reduction	22%
8	Lockdown risk reduction time (days)	52
9	Lockdown risk reduction	70%
10	Delay time (days)	7
11	Hospital preparedness quality	40%
12	Lockdown time for older people (days)	143
13	Lockdown reduction for older people	30%

This study also finds that the effects of the partial lockdowns (70%) are relatively higher than those of behavioral measures (22%). This finding is in line with other case studies in Italy [15], Southeast Asian countries [14], and Germany [16], stating that lockdowns have a higher impact than behavioral measures. This finding also is supported by other previous studies [17,26], stating that human interaction is the main cause of the COVID-19 flow.

On the other hand, the lockdown of senior citizens has the effects on about 143 days (the second week of June 2020) after the first confirmed case. Since the government ordered the lockdown of senior citizens on March 16th, 2020, this study shows that the effects of the lockdown of senior citizens did not have immediate effects. The main possible reason is although senior citizens is asked to stay at home, young people may visit them, leading to possible infections among the senior citizens.

4. Sensitivity analysis

Many variables have uncertain values such as incubation time, Ro, and recovery time. Another study [15] found that these uncertain variables are also highly sensitive variables as small changes of these parameters lead to large changes of infected and death cases. This study conducts sensitivity analysis by varying these highly sensitive

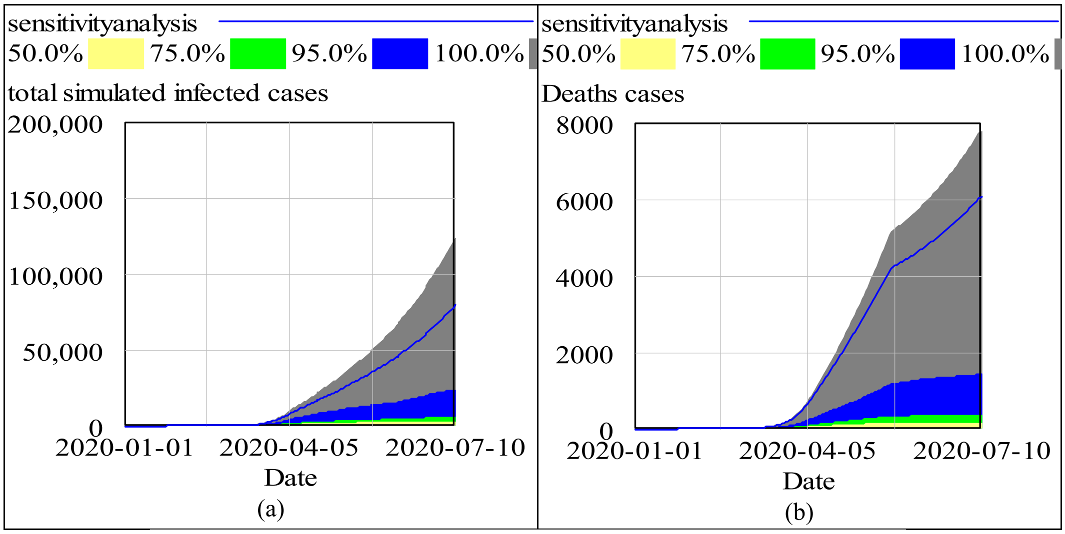

Fig. 3. Results of sensitivity analysis. Infected cases (a). Death cases (b).

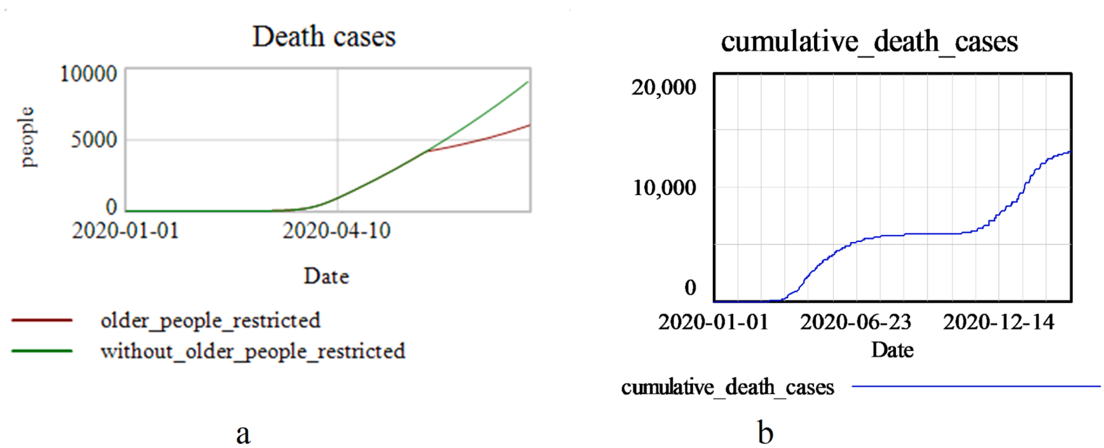

Fig. 4. Higher death cases in the absence of the movement restriction of senior citizens and group gathering bans (a). Higher infected cases beyond October 2020 after relaxing the old-people restriction and group meeting bans (b). (Death cases are simulated death cases and total death cases are observed death cases).

parameters such as Ro, recovery time, and incubation time. The results of sensitivity analysis of 300 runs can be seen in Fig. 3.

The confidence bounds of the sensitivity analysis are described into four bands (50%, 75%, 95%, and 100%) and a blue line expresses the baseline or mean of the sensitivity analysis results. As seen in Fig. 3, the intervals are not evenly spaced, and uncertainty grows over time. The uncertainty grows over time is due to natural values of cumulative numbers: cumulative infected cases and cumulative death cases.

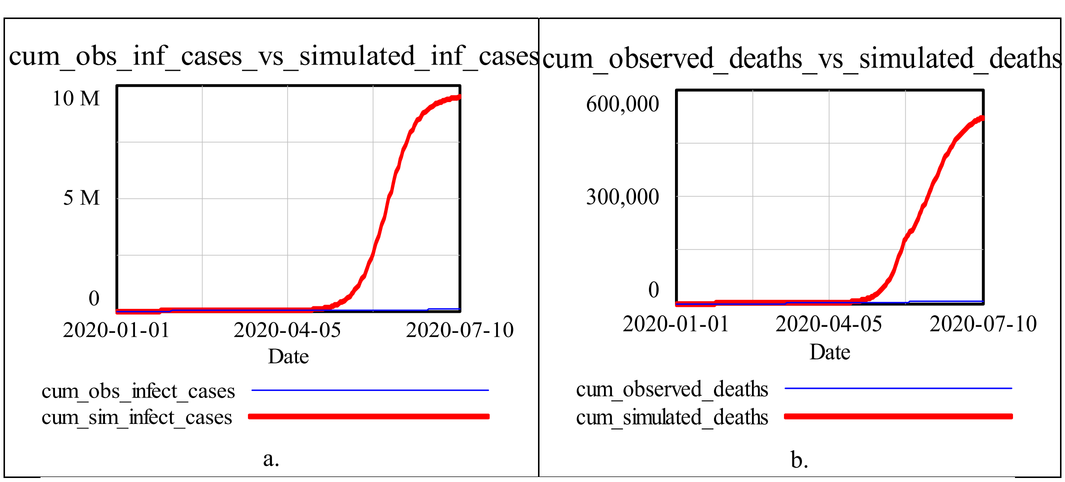

Fig. 5. Simulation results for the first policy (behavioral reduction policy without lockdowns). Cumulative infected cases (a). Cumulative death cases (b).

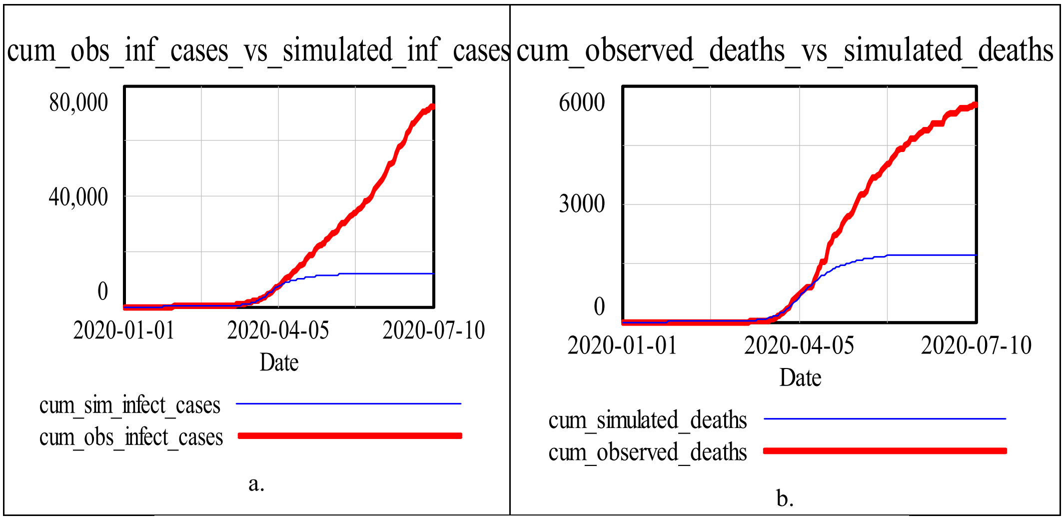

Fig. 6. Simulation results for the second policy (the full lockdown policy) Cumulative infected cases (a). Cumulative death cases (b).

Likewise, simulated outputs (cumulative infected cases and cumulative death cases) fall within the 100% interval of the results of sensitivity analysis. In general, this means that the sensitivity analysis reproduces similar patterns of the SEIR model outputs as seen in Fig. 2.

As another study [15] explained that many parameters of the SEIR model such as Ro, infection duration, and recovery time are highly sensitive parameters, the results of sensitivity analysis show that a relatively larger spread of cumulative infected cases and cumulative death cases. Highly sensitive parameters also mean that society should manage these sensitive parameters to contain the coronavirus. For instance, applying lockdowns to hamper the COVID-19 flow. Another example is to prepare the healthcare systems so that the number of deaths can be minimized.

5. Restriction movement of senior citizens

This study also elucidates the importance of restriction movement of senior citizens and group gatherings (starting from March 16th, 2020). It seems that the restriction movement has the best effect starting around early June 2020. If the government did not impose the restriction movement of senior citizens, death cases may be higher as seen in Fig. 4a. Fig. 4a shows that without the restriction movement of senior citizens and group gathering bans, death cases could have peaked at about 9,000 death cases by October 2020.

The implication of the restriction movement of senior citizens has been seen in the next wave of the COVID-19 in Sweden (Fig. 4b). Fig. 4b shows that Sweden flattened death cases (especially among senior citizens) from March 2020 until September 2020. But, Sweden experienced higher death cases after the government has relaxed the restriction movement of senior citizens starting from October 2020 [2].

6. Modeling other policies

Two possible policies are simulated using the SEIR model. The first policy is to apply a behavioral reduction policy without lockdowns. The second policy is to apply the full lockdown. In the first policy, the behavioral reduction policy has the effectiveness of about 22% (Table 2) and the lockdown policy effectiveness is nil. Of the second policy, the impacts of the full lockdowns are set similar to that in Germany (85%) [16]. Fig. 5 show that projected infected and death cases in Sweden upon the first policy are about 10 million and 0.6 million cases respectively by October 2020. This means that the behavioral reduction policy has very limited capability to slash the COVID-19 flow.

Differing from the first policy, infected and death cases upon the second policy (the full lockdown) are very low compared with observed cases respectively (Fig. 6). Under the second policy, the SEIR model shows that infected and death cases are about 10,000 cases and 1,500 cases by October 2020. Effectivenesss of the full lockdown is very high, so a lot of countries have applied the full lockdown [6]. The high impacts of the full lockdown are also are confirmed by other studies [4;16,15,14].

7. Conclusion

This study develops the SEIR model for Sweden, replicating cumulative observed infected and cumulative death cases. The SEIR also captures the importance of asymptomatic cases (undocumented cases), behavioral measures, and partial lockdowns. This means that the SEIR model elucidates the important issues relate to the COVID-19 such as undocumented cases, behavioral measures, healthcare preparedness, and the restriction movement.

Behavioural reduction acts such as physical distancing are important, but the full lockdown measures are far better in slashing the COVID-19 flow. Likewise, the partial lockdown should be step up into the national or the full lockdown to significantly curtail infected and death cases Next, the better healthcare preparedness such as appropriate bed capacities and trained healthcare workers is important to respond to the pandemic.

The low significance of the behavioral measures in tackling the COVID-19 transmission supports airborne precautions to protect healthcare workers, especially when they are treating infected patients. Likewise, protecting vulnerable groups such as senior citizens should be encouraged to decrease the number of infected and death cases among vulnerable groups.

As that study [14], this study also suggests that the management of pandemic should focus on dealing with sensitive parameters such as incubation time, and infection duration so the flow of pandemic can be managed properly, leading to low infected and death cases. For instance, the length of the isolation people coming from infected areas should be similar to observed incubation time. Next, the bed capacities should conform with the length of infection duration and recovery time.

The SEIR model developed in this study can be a basis to investigate more major issues such as undocumented cases, the quality of the healthcare system, and lockdown efficacy in other regions. In the next avenue, general comparisons between Sweden and other countries will be investigated. Moreover, comparisons between multiple waves of the COVID-19 flow and the effects of vaccination in Sweden and other countries will be analyzed.

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.

Appendix A. The alternative model

In the alternative SEIR model, asymptomatic cases are a stock as seen in Fig. A1. Through the same calibration stage, optimum values for each variable are given in Table A1. As seen in Table A1. Both models have relatively similar values. Especially, for highly sensitive parameters such as Ro, infection duration, and reccovery time. This is an indication that each model is a good representation of the COVID-19 flow in Sweden.

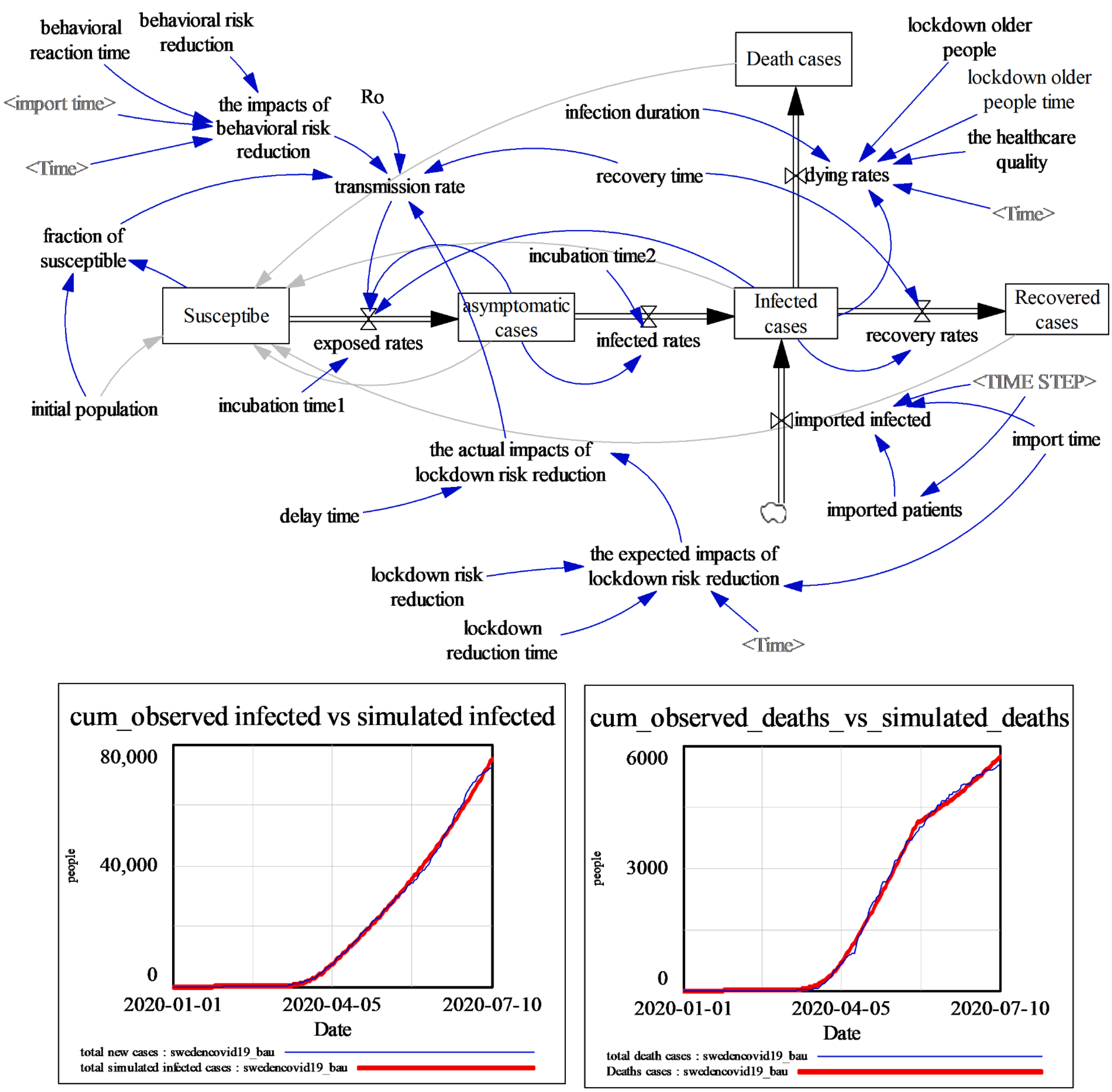

Fig. A1. The alternative SEIR model.

Table A1
A comparison optimum values of the 1st model and the 2nd model (The alternative SEIR model).

No	Variables	The 1st model	The 2nd model
1	Ro (basic reproduction number)	3.74	3.8
2	Incubation time (days) *For the 2nd model, incubation time is an average of needed time to asymptomatic cases and needed time to symptomatic cases	5.79	11
3	Infection duration (days)	21	16
4	Recovery time (days)	5	5
5	Fraction of asymptomatic cases	42%	48%
6	Behavioral reaction time (days)	45	59
7	Behavioral risk reduction	22%	10%
8	Lockdown risk reduction time (days)	52	64
9	Lockdown risk reduction	70%	80%
10	Delay time (days)	7	1
11	Hospital preparedness quality	40%	50%
12	Lockdown time for older people (days)	143	141
13	Lockdown reduction for older people	30%	27%

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