COVID-19 mathematical model reopening scenarios for São Paulo - Brazil

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Abstract

The objective of the current investigation was to produce a generalized computational model to predict consequences of various reopening scenarios on COVID-19 infections rates and available hospital resources in São Paulo - Brazil. We were able to use the Susceptible-Exposed-Infected-Recovered (SEIR) model to fit both accumulated death data and corrected accumulated cases data associated with COVID-19 for both Brazil and the state of São Paulo. In addition, we were able to simulate the consequences of reopening under different possible scenarios in Brazil, in special for the state of São Paulo. The model was able to provide a predicted scenario in which reopening could occur with minimal impact on human life considering people careful behavior in combination with continued social distancing measures.

Keywords: COVID-19; Brazil; São Paulo; SEIR model; pandemic; mathematical modelling; quarantine; reopening.
Introduction

In December 2019, a series of atypical pneumonia cases emerged in China caused by a new Coronavirus, officially called COVID-19 by the World Health Organization (WHO). As of April 25, 2020, 2,919,404 people have tested positive for COVID-19 and 203,164 deaths have been attributed to the virus worldwide, posing a great threat to public health. In Brazil, the first case was confirmed on February 26th and the number of positive cases rapidly increased to 59,196 and 4,045 deaths reported in all states of the federation as of April 25, 2020 (https://covid.saude.gov.br/). To prevent the spread of COVID-19, most countries have adopted social distancing policies and closed all non-essential businesses. However, this strategy has resulted in several economic repercussions. With increasing social pressure on politicians to reopen the economy, it is imperative we use high-fidelity mathematical modeling to predict consequences of various reopening scenarios on COVID-19 infections rates and available hospital resources.

Current research and prediction models, however, have focused on China, Europe, and the United States leaving many questions unanswered for several countries, including Brazil (1). For example, research has indicated the older adults (60+) are at the greatest risk of experiencing complications from COVID-19 (2). The death rate for older adults (60+) is 6.4% and increases up to 13.4% for more senior older adults (80+) whereas the death rate for young healthy adults is less than 1% (1). Given that Brazil has a large percentage of its population over the age of 60 years, especially in the urban areas of the South and Southeastern regions, the incidence of aggravated cases may be particularly high in comparison to countries with younger population demographics (3). It has also been debated whether environmental conditions (e.g., temperature, humidity) influence the behavior of the COVID-19 virus similar to the common cold and flu. Yet, the majority of the research investigating the virus has been conducted in environments different/opposite than that of
Brazil and other countries in the southern hemisphere (4,5). In addition, Brazil faces many economical and sociocultural challenges that may impact containment, mitigation, and suppression strategies differently than countries that are the current focus of most prediction models (3).

To fully understand the dynamic behavior of the virus on public health in a particular country, region, state, city, or organization it is important to consider factors such as testing rates and the availability of medical resources. Widespread testing is necessary to properly assess intervention strategies and allocate needed medical resources (6,7). However, laboratory testing to confirm exposure and/or diagnosis has been a major obstacle for the containment, mitigation, and suppression of COVID-19 worldwide. The actual number of people who have been infected with COVID-19 is unknown. What is known is the number of people who have lab-confirmed cases, which is dependent upon the number of people being tested and how the results are reported. Some countries are testing a higher percentage of the population (e.g., Iceland) and have more comprehensive reporting practices (e.g., Estonia) than others (8) (https://ourworldindata.org/covid-testing). In Brazil, the testing rates have been significantly lower (1375/million) than countries with higher per capita income such as the United Kingdom (7.886/million), United States (12.407/million), Germany (20.629/million) and France (7.103/million) (https://www.worldbank.org/) and has been limited to individuals with severe, life-threatening symptoms (https://covid.saude.gov.br/).

The availability of medical resources to treat people infected with COVID-19 can affect recovery and mortality rates associated with virus. More specifically, mortality rates may rise as hospitals become overwhelmed and have fewer resources. As such, the ability to accurately estimate the need for hospital beds and Intensive Care Units (ICU), for example, may be an important factor in combating COVID-19. For example, in a recent model forecasting the need for hospital beds based upon age and infection mortality rates (IFR), it
was assumed the 30% hospitalized cases would need to be placed in an ICU (50% of which were predicted not to survive) and with average hospital stays estimated at 16 days (9). In addition, research has indicated the availability of adequate medical assistance was highly correlated to the income status of countries (10). Unfortunately, in countries first impacted by the pandemic the demand for hospital beds and mechanical ventilators surpassed the local availability even in countries with high per capital income. In countries with a shortfall of health infrastructure and services, the COVID-19 pandemic may have even more dire consequences.

It is of utmost importance to determine not only the number of active cases, but also the number of hospital beds, ventilators and ICU’s that will be needed at a certain point in time to maximize the usage of public resources. According to the World Health Organization (WHO) gathering date which depict the true reality of the pandemic allows for more accurate modeling. In turn, higher fidelity mathematical models increase the reliability of predictions. These models may play an important role in helping governments and health providers prepare and combat the COVID-19 pandemic. For examples, prediction models may provide a framework for prototyping and studying possible intervention strategies and used as a guideline for when certain social distancing restrictions can be lifted (7).

The Susceptible-Exposed-Infected-Recovered (SEIR) model was a particularly useful and widely accepted mathematical model used in previous pandemics (i.e., Hubei, Wuhan and Beijing) (11). The purpose of the current analysis is to use the SEIR model to represent the behavior of COVID-19 and predict the outcome of the pandemic in São Paulo - Brazil. More specifically, the SEIR model will be used to predict the consequences of reopening under different possible scenarios in Brazil, especially for the state of São Paulo. Note, however, that this model can be applied to different countries, regions, states, cities, and/or organizations.
Methodology

The SUEIHCDR model

We present a generalized SEIR compartmental model using novel and recently suggested ideas and concepts (11) (https://apmonitor.com/do/index.php/Main/COVID-19Response; https://covid19-scenarios.org/about). The model was used to investigate the COVID-19 pandemic in Brazil and the state of São Paulo, the country epicenter (for the application of the model for different countries around the world please see (12). It is composed of eight compartments: Susceptible, Unsusceptible, Exposed, Infected, Hospitalized, Critical, Dead, and Recovered (SUEIHCDR, Figure 1).

The model assumes, at first that, the whole population is susceptible (Equation 1) to the disease. As time progresses, a susceptible person can either become exposed (Equation 5) to the virus or unsusceptible (Equation 2).

\[
\frac{dS(t)}{dt} = - \left( 1 - SD(t) \right) \frac{\beta S(t) I(t)}{N_{pop}} - \alpha(t)S(t) \tag{1}
\]

\[
\frac{dU(t)}{dt} = \alpha(t)S(t) \tag{2}
\]

where \( I(t) \) is the number of infectious people at time \( t \), \( N_{pop} \) is the population of the country, \( \beta \) is the infection rate, \( \alpha \) is a protection rate, and \( SD \) is a social distancing factor.

As in Peng et al. (2020) we introduced a protection rate \( \alpha \) factor to our susceptible equation (Equation 1). This protection rate was introduced to account for possible decreases in the number of susceptible people to the virus caused by factors other than social distancing, such as the usage of face masks, better hygiene, more effective contact tracing and possible vaccines and or drugs that may prevent infection. Different from the study of
Peng et al, (2020), however, we varied $\alpha$ across time (Equation 3). This time variation was introduced to reliably model people’s behavior, who are not commonly too concerned about the disease in the earlier stages of the epidemic, but as the number of infected and deaths increases, become more cautious about the virus.

\[
\begin{align*}
\alpha(t) &= \alpha_0 \frac{\log(t + 1)}{\log(t_{qo})}; \text{ until quarantine opening} \\
\alpha(t) &= \alpha_{qo}; \text{ after quarantine opening}
\end{align*}
\] (3)

where $\alpha_0$ is the reference value, that is the maximum value, $t_{qo}$ is the final time before quarantine opening, and $\alpha_{qo}$ is the new protection rate after the date that the quarantine is opened.

Furthermore, we also introduced a social distancing factor SD, which also varies with time (Equation 4). Social distancing was modeled as a logistic curve so that the model could account for the date ($t_{sd}$) when a possible quarantine measurement starts.

\[
\begin{align*}
SD(t) &= SD_0 \frac{1}{1 + e^{-(t - t_{sd})}}; \text{ until quarantine opening} \\
SD(t) &= SD_{qo}; \text{ after quarantine opening}
\end{align*}
\] (4)

where $SD_0$ is $SD$ reference value, that is the maximum value, and $t_{sd}$ is the time the $SD$ increases until reaching $SD_0$, before quarantine opening. After this date, the $SD$ value is equal to $SD_{qo}$.

Exposed people become infectious after an incubation time of $1/\gamma$ (Equation 5).

\[
\frac{dE(t)}{dt} = + \frac{(1 - SD(t))\beta S(t)I(t)}{N_{pop}} - \gamma E(t)
\] (5)

Infected people stay infected for a period of $1/\delta$ (Equation 6) days and can have three different outcomes. Considering $m$ as a specific parameter to account the fraction of infectious that are asymptomatic, it is possible to determine that a percentage of the infected ($l-m$) go hospitalized, another percentage of them ($l$) may die without hospitalization, and the rest of them ($m-l$) recover. $l$ was introduced as a function of time (Equation 7) so that the time
when hospital bed became unavailable could be modeled \((t_m)\), as well as the duration that hospital were full \((dur)\).

\[
\frac{dI(t)}{dt} = +\gamma E(t) - \delta I(t)
\]  
\[
l(t) = \begin{cases} 
  l_0 \frac{1}{1 + e^{-\tau_1 (t - t_1)}}, & t < 2t_1 + dur \\
  0.95 l_0 e^{(2t_1 + dur)}, & t \geq 2t_1 + dur 
\end{cases}
\]

where \(l_0\) is the inclination of the angular coefficient of the ramp up until reaching the maximum value reference value, \(t_1\) is the time when people started dying due the lack of available ICUs.

Hospitalized people (Equation 8) stay hospitalized for \(1/\zeta\) days and can either recover \((1-c)\) or become critical \((c - \text{specific parameter to account the fraction of hospitalized that becomes critical cases})\) needing to go an intensive care unit (ICU).

\[
\frac{dH(t)}{dt} = +(1 - m)\delta I(t) + (1 - f)\zeta C(t) - \zeta H(t)
\]

where \(\varepsilon\) is the inverse of the time people stay in the ICU.

A person stays on average \(1/\varepsilon\) in the ICU (Equation 9) and can either go back to the hospital \((1-f)\) or die \((f - \text{specific parameter to account the fraction of people in critical state that died})\).

\[
\frac{dC(t)}{dt} = +c\zeta H(t) - \varepsilon C(t)
\]

Therefore, recovered people (Equation 10) can either come straight from infection when the case is mild \((m-l)\) or from the hospital when the case is no critical \((1-c)\).

\[
\frac{dR(t)}{dt} = +(m - l)\delta I(t) + (1 - c)\zeta H(t)
\]

At last, death (Equation 11) arises either from lack of available treatment \((l)\), or from critical cases in the ICU \((f)\).
We used the fourth order Runge-Kutta numerical method to solve our system of ordinary differential equation in MATLAB (MathWorks Inc.R14a). To run our model to Brazil and the state of Sao Paulo, we used both coefficients estimated from outside sources (6) and coefficients found by optimization (15). First $l, r_l, t_l$, and $dur$ were set to zero. These coefficients were introduced in the model to so that the percentage of people that went from infectious to death without access to hospital care were considered. This is important for modelling the situation in countries such as Italy for example (13) (https://www.theguardian.com/world/2020/mar/09/italian-hospitals-short-beds-coronavirus-death-toll-jumps). We set it to zero in Brazil because the main purpose of the simulations is to estimate the number of hospital and ICU beds what will be needed considering the demand will be attended. Also, it is important to determine what scenarios could be contained in the number of beds we currently have available in the state and country. Data from the Brazilian national government indicates Brazil has 421,415 hospital beds and 30,941 ICU beds in the country (http://tabnet.datasus.gov.br/cgi/tabcgi.exe?cnes/cnv/leintbr.def). Additionally, data from the state government indicates São Paulo State has 90,603 hospital beds and 8,385 ICU beds in the State (http://tabnet.datasus.gov.br/cgi/tabcgi.exe?cnes/cnv/leintbr.def). Additionally, $t_{sd}$ was set considering the day the Governor of São Paulo officially declared they start reopening the state (14) (https://www.correiobrasiliense.com.br/app/noticia/brasil/2020/04/23/interna-brasil,847309/sao-paulo-tera-retomada-gradual-das-atividades-a-partir-de-11-de-maios.shtml). Finally, the last coefficient found by outside sources was $SD$. 

\[
\frac{dD(t)}{dt} = +l\delta I(t) + f\varepsilon\mathcal{C}(t)
\]
Determining Social Distancing

To determine the values for SD for Brazil and for the state of São Paulo we used two sources, the Google’s Community Mobility Reports (https://www.google.com/covid19/mobility/) and data obtained from the “Sistema de Monitoramento Inteligente (SIMI-SP)” (https://www.saopaulo.sp.gov.br/noticias-coronavirus/governo-de-sp-apresenta-sistema-de-monitoramento-inteligente-contra-coronavirus/).

São Paulo State SD value was obtained as the mean SD of the quarantine period of the data obtained by SIMI_SP (SD=54%).

In order to estimate SD for the country we used both São Paulo State SIMI_SP data and Google’s data for “residential percent change from baseline”. This variable estimates the percentual change in time of staying at home during the quarantine compared to before. Residential percent change from baseline for Brazil and for the state of São Paulo were low-pass filter filtered at 0.09 Hz (Butterworth 4th order). After filtering maximum values per day for Brazil and São Paulo were quantified. We found a linear regression fit of the values found this way for São Paulo and the data obtained for the state by SIMI_SP. The linear equation found was y=0.74884x+36.651. This equation was used to correct Google’s estimated SD value for Brazil (SD=53%).

Optimization

Fifteen of our model coefficients were found by optimization. We gathered accumulated cases, recovered cases, accumulated deaths, and tests per million people data from trust sources (https://www.worldometers.info/coronavirus/; https://ccs2.ufpel.edu.br/wp/2020/04/15/ufpel-apresenta-primeiros-resultados-do-estudo-sobre-covid-19-no-rs ) for the first 20 countries in number of total cases and Iceland , on April 25, 2020, and from the state of São Paulo official website
Furthermore, we gathered the percentage of people over 65 years of age for each country (www.indexmundi.com). We assume that the number of deaths is more reliable to measure of the epidemic since sub-testing has been largely reported for the covid-19 and in most places only cases that demand medical attention are being tested (8) (https://ourworldindata.org/covid-testing; https://ccs2.ufpel.edu.br/wp/2020/04/15/ufpel-apresenta-primeros-resultados-do-estudo-sobre-covid-19-no-rs ). As such we multiplied the number of cases in Brazil by a correction factor. To determine this factor, we took two information into consideration the death rate in Iceland, the country with the greatest percentage of test per habitant in the time of this analyses (15) (https://www.worldometers.info/coronavirus/) and each countries percentage of people over 65% years considering the increase in death rate with age (1). First, we found a linear regression fit of the death rate and the percentage of people in each country over 65 years of age for the 21 countries from which data was gathered. The linear equation found was y=0.004x+0.01. Using this equation, we corrected Brazil’s death rate and determined the correction factor by diving Brazil’s corrected death rate by Iceland’s corrected death rate. Factor found for Brazil was 17.7 and we used the same factor for the state of Sao Paulo (epicenter of the epidemic in Brazil).

Furthermore, we used a custom build MATLAB global optimization algorithm using Monte Carlo iterations and multiple local minima searches to find 15 different inputs to the
model. The algorithm was tested for the best solution considering all inputs varying within ranges obtained from the WHO and several publications (16–18) (Table 1), by minimizing a goal function \((J)\) as a combination of Active Cases and Death time series (Equation 12).

\[
\begin{align*}
J &= (1 - p) \times RMSE(Active\ Cases) + p \times RMSE(Deaths) \\
p &= \frac{\text{mean(Active Cases)/mean(Death)}}{\text{mean(Active Cases) + 1}}
\end{align*}
\]

Data under 50 active cases were discarded. Initial values for each compartmental parameter had ranges proportional to the following initial values (Table 1): infected initial values \((I_0)\) were determined as the corrected actives cases first value greater than 50; exposed initial values \((E_0)\), hospitalized initial values \((H_0)\), and critical cases initial values \((C_0)\), had initial values proportional to \(I_0\) considering model parameters \((m, c, f)\); deaths initial values \((D_0)\) were obtained from the accumulated deaths real data; similarly, recovered initial values \((R_0)\) were obtained from the recovered real data. Results are presented as mean (standard deviation). The model results presented are based on an average of 1250 runs.

After the fitting, the parameters were used to predict the numbers of Infected, Recovered, Deaths, Hospital and ICU beds per day varying the SD value and the protection rate \((\alpha)\) value to account for different possible scenarios after the quarantine opening. To better illustrate the effects of changes in \(\alpha\), instead of presenting the value of the coefficient itself in the tables and figures, we exhibited the effect of \(\alpha\) in the susceptible people (Equation 1). Thus, in results section we used protection \((\%)\) as the percentage of people that have become unsusceptible (Equation 2) by the end of the epidemic in relation to the population of Brazil or the state of São Paulo. We ran hundreds of different scenarios for both Brazil and São Paulo. We simulated the reopening on May 11\(^{th}\); the day the State governor decreed the state will start re-opening (14).
At last, a Confidence Interval of 95% estimated using Monte Carlo for a 2% error was used in order to show the range of the results.

Results

Our model was able to accurately fit the data for both the country of Brazil and the state of São Paulo (Figure 2). Current protection percentage is approximately 65% for Sao Paulo and 75% for Brazil.

Tables 2 present the optimized model inputs for April 25, 2020. For Brazil, we have: protective rate ($\alpha$) was 0.023; mean infectious rate ($\beta$) was 0.67; mean fraction of infectious that are asymptomatic or mild ($m$) was 0.95; the fraction of severe cases that turn critical ($c$) was 0.33; the mean fraction of critical cases that are fatal ($f$) was 0.52. For São Paulo, we have: protective rate ($\alpha$) was 0.018; mean infectious rate ($\beta$) was 0.57; mean fraction of infectious that are asymptomatic or mild ($m$) was 0.92; the fraction of severe cases that turn critical ($c$) was 0.29; the mean fraction of critical cases that are fatal ($f$) was 0.51. Table 2 also shows the inverse values of $\gamma$, $\delta$, $\zeta$, $\epsilon$: the latent period was 0.3 day for Brazil and 0.5 day for São Paulo; the infectious period was 7.9 days for both Brazil and São Paulo; the hospitalized period was 4.4 days for both Brazil and São Paulo; and the ICU period was 13.4 days for Brazil and 12.9 day for São Paulo. The reproductive number ($R_0$) estimated from the model is also presented in Table 2, $R_0$ found was 3.88 for Brazil and 3.53 for São Paulo State.

Results for 50 different scenarios considering Brazil’s data on April 25, reopening on May 11th, and SD ranging from 0 to 0.53 (current estimate for Brazil during quarantine) protection rate ranging from 31-99% are displayed in Table 3. The results indicate that changes to either SD or protection rate can cause quite different outcomes. Considering a
protection rate of approximately 75% the current optimized value found for the country, varying SD from 13 to 40% cause a drop in model results of 18,754,357 to 3,412,191 in total infections, 184,781 to 34,000 in deaths, 1,905,610 to 199,940 in total hospitalizations, 39,291 to 10,566 in peak hospitalization in one day, 353,659 to 65,072 total ICU beds used, 37,023 to 9,086 peak ICU beds used in one day and 18,569,577 to 3,378,191 in recovered people.

From the data in table 3 a magnitude of comparisons and projections can be made, for instance if we find the mean values across high protection percentages (80-99%) and compare them across different social distance percentages (Table 4), we can see that adopting an approximate 20% over a 40% SD strategy after coming back from quarantine can result in an approximate double of the number of deaths (approximate form 28 thousand to 57 thousand).

Figure 3 illustrates the accumulated cases (a), total recuperated cases (b), accumulate deaths (c) and percentage of Unsusceptible or Protected people (d) in Brazil considering data on April 25 and reopening on May 11th, with SD of 13% and protection of 76%, with a 95% confidence interval on a 2% error variation of every input parameter to the model. To complement, Figure 4 illustrates active cases (a), hospital beds per day usage (b), ICU beds per day usage (c) and accumulated deaths (d) in in Brazil considering Brazil’s data on April 25 and reopening on May 11th, with SD of 13% and protection of 76%, also with a 95% confidence interval on a 2% error variation of every input parameter to the model.

Table 5 shows the results for Brazil filtered to illustrate only simulated scenarios of changes in SD and protection with reopening starting May 11th, 2020 that didn’t cause the peak in the number of ICUs beds to be greater than the number in the country (30,941 beds). From the table we can conclude that the minimum protection is 64% when associated to a 40% SD, and the minimum possible SD is 13%, when associated to an 81% protection. Furthermore, by adopting a more realistic protection percentage by using as the current one
displayed in the state of Sao Paulo (65%) as a mirror to the country, we find the minimum SD to be 40%. At this scenario, the projected peak in ICU day usage would be about 9 thousand.

Results for 50 different scenarios considering the state of São Paulo data on April 25 reopening on May 11th with SD ranging from 0 to 0.54 (current estimate for São Paulo during quarantine) protection rate ranging from 12-99% are displayed in Table 6. Again, results indicate that changes to either SD or protection rate can cause quite different outcomes. Considering a protection rate of approximately 67% the current optimized value found for the country, dropping SD from 40% to 13% cause an increase in model results from 996,657 to 7,600,658 in total infections, 12,881 to 98,225 in deaths, 88,895 to 678,032 in total hospitalizations, 3,153 to 31,292 in peak hospitalization in one day, 25,346 to 193,283 total ICU beds used, 2,350 to 24,441 peak ICU beds used in one day and 983,777 to 7,502,433 in recovered people.

Figure 5 illustrates the accumulated cases (a), total recuperated cases (b), accumulate deaths (c) and percentage of Unsusceptible or Protected people (d) in São Paulo considering data on April 25 and reopening on May 11th, with SD of 13% and protection of 67%, with a 95% confidence interval on a 2% error variation of every input parameter to the model. To complement, Figure 6 illustrates active cases (a), hospital beds per day usage (b), ICU beds per day usage (c) and accumulated deaths (d) in in Brazil considering Brazil’s data on April 25 and reopening on May 11th, with SD of 13% and protection of 67%, also with a 95% confidence interval on a 2% error variation of every input parameter to the model.

Table 7 show the results for São Paulo filtered to illustrate only simulated scenarios of changes in SD and protection with reopening starting May 11th, 2020 that didn’t cause the peak in the number of ICUs beds to be greater than the number in the state (8,385 beds). From the table we can conclude that the minimum protection is 53% when associated to a 40% SD, and the minimum possible SD is 13%, when associated to a 97% protection.
Furthermore, as it happened for the analyses of the country, by adopting a more realistic protection percentage as the current one displayed in the state of São Paulo (65%) we find the minimum SD would be 40%. This scenario would roughly represent the peak in a day usage of 2,500 ICU. Additionally, at a protection rate of 67% and SD of 26% the peak in ICU bed virtually matches the number of beds in the state (Figure 7c).

Finally, Figure 7 illustrates the accumulated cases active cases (a), hospital beds per day usage (b), ICU beds per day usage (c) and accumulated deaths (d) in São Paulo considering data on April 25 and reopening on May 11th, with SD of 13% and 26% and protection of 62% and 67%, with a 95% confidence interval on a 2% error variation of every input parameter to the model.

Discussion

As many country, states, cities, and organizations struggle with the decisions to lift social distancing measures put in place to limit the spread of COVID-19 and reopen economies, it is important to understand the associated risks and plan for appropriate public health measures. We present a novel generalized SEIR compartmental model to predict death rates and the number of hospital and ICU beds as social distancing measures are lifted. The model was used to predict the consequences of reopening under different possible scenarios in Brazil, in special for the state of São Paulo.

SEIR compartmental model

We developed a SEIR compartmental model to predict mortality rates and the need for public health resources due to COVID-19. While countries throughout the world have reported vastly different mortality rates (https://www.worldometers.info/coronavirus/) our model assumed that the mortality rate was constant for all countries, considering only differences in age across the populations. Several factors may account for differences in
mortality rates between countries including testing, demographics, and available medical resources. The lack of widespread testing and comprehensive epidemiological investigations have been major issues for many countries, including Brazil. When testing is limited to those with severe, life-threatening symptoms, mortality rates are likely inflated. With more testing people with mild symptoms are identified, resulting in lower mortality rates. Countries with higher testing rates most likely provide a more accurate representation. Iceland, recognized as testing a larger percentage of the population (10%) than any other country, has a reported mortality rate at approximates 0.6% (15). Thus, in our model, we used data from Iceland to correct the number of total cases of Brazil and São Paulo and account for a lack of testing.

The demographics of the population may account for differences in mortality rates between countries. Symptoms of COVID-19 tend to be more severe in older adults resulting in higher mortality rates (13.4% for people over 80 years) than young adults (less than 1%) (1). For countries with older population demographics, mortality rates may be particularly high. As such, we applied a correction in the confirmed cases to our model, correcting by the age of the population. The underlying bias of our assumption that the mortality rate is constant for all countries when corrected by population age, is that there are no differences among mortality rates for countries concerning factors such as genetic influence, comorbidities prevalence (e.g., diabetes, obesity, high blood pressure), or virus mutations. However, recent research has indicated such factors can affect mortality rates associated with COVID-19 (e.g., (5,19). It may be necessarily to account for such factors as more data becomes available.

Finally, it was crucial to our model to use coefficients that were known from outside sources, so that future scenarios can be monitored by the government specially considering social distancing measures. To do so, for São Paulo we used data obtained from cell-phone companies; and for the country, we used both the cell-phone data for São Paulo and Google
estimates of number of people following social distancing recommendations and staying at home. Consequently, our model assumes that cell-phone data is an accurate measure of social distancing; and, for Brazil, that differences in google and cell-phone estimates from the state of São Paulo can be reflected across the country.

**Model Application**

We used the SEIR compartment model to investigate the COVID-19 pandemic in Brazil and in the state of São Paulo. The results indicated that the model accurately fit both accumulated death data and corrected accumulated case data for both Brazil and São Paulo (Figure 2). Our model predicted a basic reproduction number \( R_0 \) for Brazil of 3.82 and Sao Paulo 3.52. The basic reproduction number represents the average number of secondary cases that result from the introduction of a single infectious case in a susceptible population (20). Considering the importance of such parameter, several investigations have used various methods to estimate this parameter for COVID-19 and our values fall within the range of values reported so far. In their review, Liu et al. (2020) reported two studies using stochastic methods that estimated \( R_0 \) ranging from 2.2 to 2.68, six studies using mathematical computation methods with results ranging of 1.5 to 6.49, and three studies using statistical methods such as exponential growth with estimations ranging from 2.2 to 3.58.

Additionally, we found latent periods of 0.3 and 0.5 days and infectious period of approximately 8 days for Brazil and São Paulo, respectively. The mean estimated latent period found here is smaller than some previously reported, such as in PENG et al (2020) and GUAN et al (2020) (21) who estimates the latent median times around 2-3 days. Nevertheless, our results corroborate with the idea that COVID-19 transmission may occur in the pre-symptomatic phase and that COVID-19 patients may have an inconsiderable latent
non-infectious period. The mean infectious period of 8 days is within expected range estimated by recent publications (4,22). We found hospitalization periods of 4.4 days and ICU period of 13.4 days for both Brazil and São Paulo. The estimation for ICU time is similar to (23) (https://www.pnas.org/content/suppl/2020/04/03/2004064117.DCSupplemental), which estimates 13.5 days, and mean total hospital time, including ICU time, is in accordance with (9), which estimates around 16 days. Similar or even the same coefficients were expected for both places, since São Paulo is the epicenter of the pandemic in Brazil containing 22% of all active cases of the country.

Reopening

COVID-19 has not only resulted in a public health crisis resulting in millions of infections and thousands of deaths worldwide, it has also caused great economic suffering due to social distancing measures and large-scale closures of schools, businesses, and government services put in place to slow the spread of the virus and minimize the loss of human life. As such, when to reopen economies has become a hotly debated issue worldwide. Opening the economy too soon may result in greater cost to human life while continued closure may result in economic crisis (24). Therefore, knowing when and how to reopen economies is of utmost important. Since we already have a scheduled date for the process of re-opening in the state of São Paulo, and possibly the rest of the country as well, we used this date in our simulation. Simulations produced by our model, indicated the capacity of public health care resources (ICU beds) in Brazil was not great enough to sustain the projected infection rates if social distancing measures were lifted too soon. However, projections also indicated values for social distancing and protection that can help yield a safe return post quarantine.
We found that considering the current protection percentage displayed in the state of São Paulo (65%) the minimum social distance that should be adopted by both the country of Brazil and the state of São Paulo would be 40%; the current values for the country and State now during quarantine are 53 and 54%. At this scenario, the projected peak in ICU day usage would roughly represent the peak in a day usage of 9,000 for the country and 2,500 ICU for the state (Table 7). In more practical terms, an protection percentage of 65% consists of having 65% of the people during the pandemic period so aware and cautious, that by using masks (25,26) and having high standard of hygiene and social behavior (https://behavioralscientist.org/handwashing-can-stop-a-virus-so-why-dont-we-do-it-coronavirus-covid-19/; https://theconversation.com/coronavirus-how-behaviour-can-help-control-the-spread-of-covid-19-132247), the probability of these people to be infected is assumed to be zero (27). Our results indicate that 65% is the current percentage found in São Paulo today. It is imperative that governments and media keep on educating people so that this number does not drop. For instance, if during post-quarantine period, we keep of a 40% social distance percentage, but the percentage of cautious protected people drops to 35%, the projected need of ICU beds in the highest day of the pandemic only in the state of São Paulo goes up to 50 thousand. In other words, considering the total number of ICU available in the state (8,385 beds) and in the country (30,941 beds), the results would be disastrous. Figure 7 illustrates that São Paulo by adopting a 27% social distance, which means 50% of the current state social distance during quarantine, and a protection percentage of 67% could have the peak ICU beds during the pandemic matching the state total capacity. Although this could be used to argue for adopting such social distancing strategy, it is imperative to note that ICU beds are not only used for COVID-19 related urgencies; thus, projected number should be well under the margin used here. At last, our model was able to provide specific guidelines considering the
current official timeframe in which reopening could occur with minimal impact on human life if done carefully and in combination with continued social distancing measures.

**Conclusion**

To prevent the spread of COVID-19 most countries have adopted social distancing policies and closed all non-essential businesses. Such measures have caused great economic suffering with government leaders under increasing pressure to reopen economies despite the continued threat of COVID-19 on public health. We used SEIR compartment model to predict the consequences of reopening under different possible scenarios in Brazil, especially for the state of São Paulo. Our model was able to provide a predicted scenario in which reopening could occur with minimal impact on human life considering people careful behavior in combination with continued social distancing measures.

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**Conflict of interest statement**

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Table Legends:

Table 1: Input coefficients to the model and respective ranges.

Table 2: Optimized inputs for Brazil and São Paulo State, for April 25, 2020.

Table 3: Results for Brazil simulating different scenarios of changes in social distancing (SD) and percentage of protected people (Prot) with reopening starting May 11th, 2020. Values considering keeping the current social distance SD=0.53 are also displayed for comparison purposes.

Table 4: Mean of high protection percentages (80-99%) simulated results for Brazil across different social distance percentages (SD) with reopening starting May 11th, 2020. Values considering keeping the current social distance SD=0.53 are also displayed for comparison purposes.

Table 5: Results for Brazil filtered to show simulated scenarios of changes in Social Distancing (SD) and percentage of protected people (Prot) with reopening starting May 11th, 2020 that didn’t cause the peak in the number of ICUs beds to saturate the number of beds in the country.

Table 6: Results for São Paulo simulating different scenarios of changes in Social Distancing (SD) and percentage of protected people (Prot) with reopening starting May 11th, 2020. Values considering keeping the current social distance SD=0.53 are also displayed for comparison purposes.

Table 7: Results for São Paulo filtered to show simulated scenarios of changes in Social Distancing (SD) and percentage of protected people (Prot) with reopening starting May 11th, 2020 that didn’t cause the peak in the number of ICUs beds to saturate the number in the state.
Figure Legends

Figure 1: SUEIHCDR model info graphic description; it is composed of eight compartments Susceptible, Unsusceptible, Exposed, Infected, Hospitalized, Critical, Dead, and Recovered. \( \beta \) is the infection rate, \( SD \) is a social distancing factor, \( \alpha \) is a protection rate, \( m \) is the fraction of infectious that are asymptomatic, \( I-m \) is the percentage of the infected go hospitalized, \( I \) is the percentage of infected people that may die without hospitalization, \( I-c \) is the percentage of hospitalized people that recovers, \( c \) is the fraction of hospitalized that becomes critical cases needing to go an intensive care unit (ICU) and \( f \) is the fraction of people in critical state that dies.

Figure 2: Fitted model results for accumulated cases and deaths for Brazil (a and c – left) and Sao Paulo state (b and d - right), considering the data from February 02 until April 25 and using a 95% confidence interval.

Figure 3: Model results for accumulated cases (a), total recuperated cases (b), accumulate deaths (c) and percentage of Unsusceptible or Protected people (d) in Brazil, with SD of 13% and protection rate of 76%, using a 95% confidence interval. Quarantine opening occurs in May 11.

Figure 4: Model results for active cases (a), hospital beds per day (b), ICU beds per day (c) and accumulated deaths (d) in Brazil, with SD of 13% and protection rate of 76%, using a 95% confidence interval. Quarantine opening occurs in May 11.

Figure 5 Model results for accumulated cases (a), total recuperated cases (b), accumulate deaths (c) and percentage of Unsusceptible or Protected people (d) in São Paulo, with SD of 13% and protection rate of 67%, using a 95% confidence interval. Quarantine opening occurs in May 11.

Figure 6: Model results for active cases (a), hospital beds per day (b), ICU beds per day (c) and accumulated deaths (d) in Brazil, with SD of 13% and protection rate of 67%, using a 95% confidence interval. Quarantine opening occurs in May 11.
Figure 7: Model results for active cases (a), hospital beds per day (b), ICU beds per day (c) and accumulated deaths (d) in São Paulo state, for different scenarios of SD and Protection rate. Quarantine opening occurs in May 11.
Table 1: Input coefficients to the model and respective ranges.

| Coeff. | Lower bound | Higher bound |
|--------|-------------|-------------|
| $\alpha$ | 0.01 | 0.12 |
| $\beta$ | 0.5 | 1.2 |
| $\gamma$ | 0.5 | 5.00 |
| $\delta$ | 0.07 | 0.50 |
| $\zeta$ | 0.20 | 0.33 |
| $\epsilon$ | 0.05 | 0.14 |
| $m$ | 0.65 | 0.99 |
| $c$ | 0.10 | 0.50 |
| $f$ | 0.35 | 0.55 |
| $E_0$ | $E_0/2$ | $2E_0$ |
| $I_0$ | $I_0/2$ | $2I_0$ |
| $H_0$ | $H_0/2$ | $2H_0$ |
| $C_0$ | $C_0/2$ | $2C_0$ |
| $Re_0$ | $Re_0/2$ | $2Re_0$ |
| $D_0$ | $D_0/2$ | $2D_0$ |
Table 2: Optimized inputs for Brazil and São Paulo State, for April 25, 2020.

| Coeffs | Brazil | São Paulo State |
|--------|--------|-----------------|
| $\alpha$ | 0.023 | 0.018 |
| $\beta$ | 0.67 | 0.57 |
| $\gamma$ | 3.29 | 1.86 |
| $\delta$ | 0.13 | 0.13 |
| $\zeta$ | 0.23 | 0.22 |
| $m$ | 0.95 | 0.92 |
| $c$ | 0.33 | 0.29 |
| $fa$ | 0.52 | 0.51 |
| $E_0$ | 19.00 | 20.00 |
| $I_0$ | 39.00 | 36.00 |
| $I_0^H$ | 7.00 | 32.00 |
| $C_0$ | 27.00 | 27.00 |
| $R_0$ | 0.00 | 0.00 |
| $D_0$ | 0.00 | 0.00 |
| $SD$ | 0.53 | 0.54 |
| $m_{sd}$ | 89.00 | 89.00 |
| $R_0^F$ | 3.88 | 3.53 |
| $Latent$ | 17.70 | 17.70 |
| $Infectious$ | 0.3 | 0.5 |
| $Hospitalized$ | 7.9 | 7.9 |
| $Critical$ | 4.4 | 4.4 |
| $R_0^I$ | 13.4 | 12.9 |
Table 3: Results for Brazil simulating different scenarios of changes in Social Distancing (SD) and percentage of protected people (Prot) with reopening starting April 25, 2020. Values considering keeping the current social distance $SD=0.53$ are also displayed for comparison purposes.

| SD (%) | Prot (%) | DR (%) | Infect | Deaths | Hosp peak_Hos | ICU peak_ICU | Recov |
|--------|----------|--------|--------|--------|--------------|--------------|-------|
| 53     | 99       | 0.010  | 226740 | 22628  | 132912       | 10566        | 43306 |
| 53     | 96       | 0.010  | 2347725| 23428  | 137620       | 10566        | 44839 |
| 53     | 89       | 0.010  | 2418946| 24139  | 141794       | 10566        | 46198 |
| 53     | 82       | 0.010  | 2474809| 24695  | 145067       | 10566        | 47264 |
| 53     | 77       | 0.010  | 2513639| 25082  | 147342       | 10566        | 48003 |
| 53     | 71       | 0.010  | 2567150| 25611  | 150472       | 10566        | 49017 |
| 53     | 64       | 0.010  | 2637308| 26289  | 154544       | 10566        | 50315 |
| 53     | 55       | 0.010  | 2788560| 27605  | 162995       | 10566        | 52833 |
| 53     | 44       | 0.009  | 3503005| 32124  | 198488       | 10566        | 61493 |
| 53     | 31       | 0.006  | 11626037|    66271 | 548786       | 95587        | 127027  |
| 40     | 98       | 0.010  | 2471742| 24665  | 144888       | 10566        | 47206 |
| 40     | 95       | 0.010  | 2676086| 26703  | 156864       | 10566        | 51105 |
| 40     | 89       | 0.010  | 2913615| 29070  | 170784       | 10566        | 55637 |
| 40     | 82       | 0.010  | 3167859| 31598  | 185676       | 10566        | 60475 |
| 40     | 77       | 0.010  | 3412191| 34000  | 199940       | 10566        | 65072 |
| 40     | 71       | 0.010  | 3948375| 39014  | 230738       | 10566        | 74669 |
| 40     | 64       | 0.009  | 5491736| 51387  | 314708       | 10566        | 98364 |
| 40     | 56       | 0.008  | 13757587|   104459  | 731142       | 50206        | 37999  |
| 40     | 47       | 0.007  | 43229033| 304508  | 2264721      | 2325954      | 1271267 |
| 27     | 98       | 0.010  | 2796176| 27900  | 163903       | 10566        | 53397 |
| 27     | 95       | 0.010  | 3317005| 33093  | 194247       | 10566        | 63336 |
| 27     | 89       | 0.010  | 4161802| 41508  | 243929       | 10566        | 79442 |
| 27     | 82       | 0.010  | 5508374| 54798  | 322643       | 10566        | 104878 |
| 27     | 77       | 0.010  | 7392227| 72746  | 431589       | 11168        | 139232 |
| 27     | 71       | 0.009  | 12833567| 104459  | 731142       | 50206        | 37999  |
| 27     | 65       | 0.009  | 24175845| 217904  | 1371966      | 16598        | 231407 |
| 27     | 59       | 0.009  | 40212583| 366099  | 2292574      | 80107        | 75988  |
| 27     | 53       | 0.009  | 54954193| 516600  | 3166366      | 131764       | 988665 |
| 27     | 47       | 0.007  | 67131737| 645893  | 3895277      | 188704       | 1236277 |
| 18     | 98       | 0.010  | 3119276| 31122  | 182839       | 10566        | 59563 |
| 18     | 95       | 0.010  | 4089754| 40797  | 239716       | 10566        | 78081 |
| 18     | 88       | 0.010  | 6045478| 60266  | 354298       | 13348        | 115342 |
| 18     | 81       | 0.010  | 9691921| 96131  | 567253       | 18742        | 183985 |
| 18     | 76       | 0.010  | 14445426| 141717  | 842748       | 23630        | 271240 |
| 18     | 71       | 0.010  | 23392175| 226272  | 1358853      | 43908        | 433092 |
| 18     | 66       | 0.010  | 33656446| 324973  | 1954195      | 70536        | 622011 |
| 18     | 60       | 0.010  | 44376109| 431173  | 2581662      | 107075       | 825267 |
| 18     | 55       | 0.010  | 54376593| 532156  | 3170193      | 150509       | 1018531 |
| 18     | 50       | 0.010  | 63470909| 624507  | 3706054      | 198568       | 1195271 |
| 13     | 98       | 0.010  | 3326195| 33185  | 194966       | 10566        | 63512 |

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|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 13 | 95 | 0.010 | 4645403 | 46337 | 272281 | 12273 | 88684 | 11399 | 4599066 |     |     |     |     |     |     |
| 13 | 88 | 0.010 | 7539823 | 75143 | 441849 | 17446 | 143816 | 16297 | 7464680 |     |     |     |     |     |     |
| 13 | 81 | 0.010 | 12845700 | 127402 | 751842 | 272282 | 243835 | 25630 | 12718298 |     |     |     |     |     |     |
| 13 | 76 | 0.010 | 18754357 | 184781 | 1095610 | 39291 | 353659 | 37023 | 18569577 |     |     |     |     |     |     |
| 13 | 71 | 0.010 | 27729860 | 271815 | 1617491 | 61394 | 520244 | 57565 | 27458045 |     |     |     |     |     |     |
| 13 | 66 | 0.010 | 36677604 | 359651 | 2139624 | 89200 | 688359 | 82849 | 36317953 |     |     |     |     |     |     |
| 13 | 61 | 0.010 | 45750453 | 449929 | 2671119 | 124371 | 861139 | 114025 | 45300524 |     |     |     |     |     |     |
| 13 | 57 | 0.010 | 54374203 | 536426 | 3177397 | 165067 | 1026682 | 149103 | 53837777 |     |     |     |     |     |     |
| 13 | 52 | 0.010 | 62418068 | 617313 | 3649895 | 209770 | 1181485 | 186546 | 61800755 |     |     |     |     |     |     |
Table 4: Mean of high protection percentages (80-99%) simulated results for Brazil across different social distance percentages (SD) with reopening starting May 11th, 2020. Values considering keeping the current social distance SD=0.53 are also displayed for comparison purposes.

| Prot (%) | SD (%) | Infect | Deaths | Hosp | peak_Hos | ICU | peak_ICU | Recov |
|----------|--------|--------|--------|------|----------|-----|----------|-------|
| 80-99%   | 13     | 7089280| 70517  | 415235 | 16878 | 134961 | 15698 | 7018764 |
| 80-99%   | 18     | 5736607| 57079  | 336026 | 13306 | 109243 | 12344 | 5679528 |
| 80-99%   | 27     | 3945839| 39325  | 231226 | 10566 | 75263  | 9195  | 3906514 |
| 80-99%   | 40     | 2807325| 28009  | 164553 | 10566 | 53606  | 9086  | 2779316 |
| 80-99%   | 53     | 2377223| 23722  | 139348 | 10566 | 45402  | 9086  | 2353500 |
Table 5: Results for Brazil filtered to show simulated scenarios of changes in Social Distancing (SD) and percentage of protected people (Prot) with reopening starting May 11th, 2020 that didn't cause the peak in the number of ICUs beds to saturate the number of beds in the country.

| SD (%) | Prot (%) | DR (%) | Infect | Deaths | Hosp | peak_Hos | ICU | peak_ICU | Recov |
|--------|----------|--------|--------|--------|------|----------|-----|----------|-------|
| 40     | 98       | 0.010  | 247174 | 24665  | 14488 | 10566    | 47206| 9086     | 2447077|
| 40     | 95       | 0.010  | 267608 | 26703  | 15686 | 10566    | 51105| 9086     | 2649383|
| 40     | 89       | 0.010  | 291361 | 29070  | 17078 | 10566    | 55637| 9086     | 2884545|
| 40     | 82       | 0.010  | 316785 | 31598  | 18567 | 10566    | 60475| 9086     | 3136261|
| 40     | 77       | 0.010  | 341219 | 34000  | 19994 | 10566    | 65072| 9086     | 3378191|
| 40     | 71       | 0.010  | 394837 | 39014  | 23073 | 10566    | 74669| 9086     | 3909361|
| 40     | 64       | 0.009  | 549173 | 51387  | 31470 | 10566    | 98364| 9086     | 5440349|
| 27     | 98       | 0.010  | 279617 | 27900  | 16390 | 10566    | 53397| 9086     | 2768276|
| 27     | 95       | 0.010  | 331700 | 33093  | 19442 | 10566    | 63336| 9086     | 3283912|
| 27     | 89       | 0.010  | 416180 | 41508  | 24392 | 10566    | 79442| 9086     | 4120294|
| 18     | 98       | 0.010  | 311927 | 31122  | 18283 | 10566    | 59563| 9086     | 3088154|
| 13     | 95       | 0.010  | 332619 | 33185  | 19496 | 10566    | 63512| 9463     | 3293010|
| 27     | 82       | 0.010  | 550837 | 54798  | 32264 | 10566    | 104878| 9523     | 5453575|
| 18     | 95       | 0.010  | 408975 | 40797  | 23971 | 10566    | 78081| 9964     | 4048957|
| 27     | 77       | 0.010  | 739222 | 72746  | 43158 | 11168    | 13923 | 10773    | 7319481|
| 13     | 95       | 0.010  | 464540 | 46337  | 27228 | 12273    | 88684 | 11399    | 4599066|
| 18     | 88       | 0.010  | 604547 | 60266  | 35429 | 13348    | 11534 | 12561    | 5985211|
| 27     | 71       | 0.009  | 128335 | 120893 | 73863 | 16598    | 23140 | 16088    | 12712674|
| 13     | 88       | 0.010  | 753982 | 75143  | 44184 | 17446    | 14381 | 16297    | 7464680|
| 18     | 81       | 0.010  | 969192 | 96131  | 56725 | 18742    | 18398 | 17765    | 9595791|
| 18     | 76       | 0.010  | 144454 | 141717 | 84275 | 26360    | 27124 | 25080    | 14303709|
| 13     | 81       | 0.010  | 128457 | 127402 | 75184 | 27228    | 24385 | 25630    | 12718298|
Table 6: Results for São Paulo simulating different scenarios of changes in Social Distancing (SD) and percentage of protected people (Prot) with reopening starting May 11th, 2020. Values considering keeping the current social distance SD=0.53 are also displayed for comparison purposes.

| SD (%) | Prot (%) | DR (%) | Infect | Deaths | Hosp | peak_Hos | ICU | peak_ICU | Recov |
|--------|----------|--------|--------|--------|------|----------|-----|----------|-------|
|       |          |        | DR (%) | Infect | Deaths | Hosp | peak_Hos | ICU | peak_ICU | Recov |
| 53     | 98       | 0.013  | 483646 | 6307   | 43251 | 3153     | 12410 | 2350     | 477339 |
| 53     | 92       | 0.013  | 506951 | 6610   | 45333 | 3153     | 13006 | 2350     | 500341 |
| 53     | 83       | 0.013  | 528559 | 6891   | 47263 | 3153     | 13559 | 2350     | 521669 |
| 53     | 75       | 0.013  | 546363 | 7122   | 48853 | 3153     | 14014 | 2350     | 539242 |
| 53     | 69       | 0.013  | 559334 | 7289   | 50010 | 3153     | 14344 | 2350     | 552044 |
| 53     | 62       | 0.013  | 578231 | 7531   | 51690 | 3153     | 14819 | 2350     | 570701 |
| 53     | 53       | 0.013  | 615355 | 7981   | 54933 | 3153     | 15704 | 2350     | 607374 |
| 53     | 42       | 0.012  | 735744 | 9194   | 64788 | 3153     | 18093 | 2350     | 726550 |
| 53     | 28       | 0.010  | 1627379| 15546  | 129413| 12122    | 30616 | 4650     | 1611833|
| 40     | 98       | 0.013  | 554316 | 7225   | 49564 | 3153     | 14218 | 2350     | 547090 |
| 40     | 92       | 0.013  | 628344 | 8187   | 56176 | 3153     | 16111 | 2350     | 620156 |
| 40     | 83       | 0.013  | 727415 | 9474   | 65024 | 3153     | 18642 | 2350     | 717941 |
| 40     | 75       | 0.013  | 853425 | 11095  | 76252 | 3153     | 21832 | 2350     | 842330 |
| 40     | 69       | 0.013  | 996657 | 12881  | 88895 | 3153     | 25346 | 2350     | 983777 |
| 40     | 62       | 0.013  | 1357710| 17034  | 119938| 3153     | 33522 | 2350     | 1340676|
| 40     | 53       | 0.011  | 2818135| 31494  | 239294| 8776     | 61997 | 6541     | 2786641|
| 40     | 44       | 0.010  | 7989781| 80848  | 659022| 38072    | 159202| 7908932  |
| 27     | 97       | 0.013  | 684352 | 8916   | 61179 | 3153     | 17543 | 2424     | 913371 |
| 27     | 91       | 0.013  | 925419 | 12048  | 82712 | 3153     | 23707 | 2749     | 15137059|
| 27     | 82       | 0.013  | 1420834| 18464  | 126932| 3153     | 3550  | 3550     | 1402369 |
| 27     | 74       | 0.013  | 2358540| 30338  | 210119| 3153     | 5136  | 5136     | 2328202 |
| 27     | 68       | 0.013  | 3563757| 45075  | 315912| 9138     | 88701 | 7397     | 3516863 |
| 27     | 62       | 0.013  | 5788199| 71868  | 510267| 3153     | 12575 | 5716332  |
| 27     | 55       | 0.012  | 9092017| 112783 | 801530| 32837   | 221954| 22708    | 8979234 |
| 27     | 48       | 0.013  | 12523450|318084 | 1108391|46331   |309629 |36493     |12366112 |
| 27     | 42       | 0.013  | 15622540|220211 |1637447|67490   |390909 |52235     |15423892 |
| 27     | 35       | 0.011  | 18375689|308145 |1387447|67490   |390909 |52235     |15423892 |
| 18     | 97       | 0.013  | 831617 | 10830  | 74334 | 3766    | 21310 | 2929     | 8140193 |
| 18     | 91       | 0.013  | 1354359| 17621  | 121026| 3592    | 34674 | 4215     | 1336737 |
| 18     | 81       | 0.013  | 2622001| 34025  | 234152| 9300    | 66952 | 7364     | 2587976 |
| 18     | 73       | 0.013  | 4657009| 60054  | 415206| 16057   | 118173| 12751    | 4596955 |
| 18     | 68       | 0.013  | 6388698| 82111  | 569076| 22737   | 161577| 18004    | 6306587 |
| 18     | 62       | 0.013  | 8514079| 109335 | 758208| 32491   | 215149| 25551    | 8404744 |
| 18     | 56       | 0.013  | 10930334|140584 |973782 |46057   |276640 |35822     |10789750 |
| 18     | 51       | 0.013  | 13312089|171622 |1186695|62360   |337711 |47852     |13140468 |
| 18     | 45       | 0.013  | 15570930|201156 |1388779|80730   |395825 |61041     |15369774 |
| 18     | 39       | 0.013  | 17692576|228909 |1578598|100645  |450436 |74953     |17463667 |
| 13     | 97       | 0.013  | 933421 | 12153  | 83428 | 4364    | 23913 | 3351     | 921268  |
|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 13 | 90 | 0.013 | 1687947 | 21956 | 150823 | 7061 | 43203 | 5489 | 1665991 |
| 13 | 80 | 0.013 | 3502444 | 45450 | 312775 | 13564 | 89433 | 10663 | 3456994 |
| 13 | 72 | 0.013 | 5897289 | 76286 | 526220 | 23222 | 150112 | 18228 | 5821003 |
| 13 | 67 | 0.013 | 7600658 | 98225 | 678032 | 31292 | 193283 | 24441 | 7502433 |
| 13 | 62 | 0.013 | 9511162 | 122916 | 848449 | 41829 | 241869 | 32411 | 9388246 |
| 13 | 57 | 0.013 | 11603702 | 150067 | 1035287 | 55428 | 295295 | 42478 | 11453635 |
| 13 | 51 | 0.013 | 13665134 | 176892 | 1219475 | 71131 | 348078 | 53821 | 13488242 |
| 13 | 46 | 0.013 | 15646474 | 202707 | 1396559 | 88499 | 398875 | 66054 | 15443767 |
| 13 | 41 | 0.013 | 17535106 | 227321 | 1565361 | 107173 | 447308 | 78877 | 17307785 |
Table 7: Results for São Paulo filtered to show simulated scenarios of changes in Social Distancing (SD) and percentage of protected people (Prot) with reopening starting May 11th, 2020 that didn’t cause the peak in the number of ICUs beds to saturate the number in the state.

| SD (%) | Prot (%) | DR (%) | Infect | Deaths | Hosp | peak_Hos | ICU | peak_ICU | Recov |
|--------|----------|--------|--------|--------|------|----------|-----|----------|-------|
| 40     | 98       | 0      | 554316 | 7225   | 49564| 3153     | 14218| 2350     | 547090|
| 40     | 92       | 0      | 628344 | 8187   | 56176| 3153     | 16111| 2350     | 620156|
| 40     | 83       | 0      | 727415 | 9474   | 65024| 3153     | 18642| 2350     | 717941|
| 40     | 75       | 0      | 853425 | 11095  | 76252| 3153     | 21832| 2350     | 842330|
| 40     | 69       | 0      | 996657 | 12881  | 88895| 3153     | 25346| 2350     | 983777|
| 40     | 62       | 0      | 1357710| 17034  | 119938| 3153     | 33522| 2350     | 1340676|
| 27     | 97       | 0      | 684352 | 8916   | 61179| 3153     | 17543| 2424     | 675436|
| 27     | 91       | 0      | 925419 | 12048  | 82712| 3450     | 23707| 2749     | 913371|
| 18     | 97       | 0      | 831617 | 10830  | 74334| 3766     | 21310| 2929     | 820788|
| 13     | 97       | 0      | 933421 | 12153  | 83428| 4364     | 23913| 3351     | 921268|
| 27     | 82       | 0      | 1420834| 18464  | 126932| 4435    | 36332| 3550     | 1402369|
| 18     | 91       | 0      | 1354359| 17621  | 121026| 5392    | 34674| 4215     | 1336737|
| 27     | 74       | 0      | 2358540| 30338  | 210119| 6365    | 59698| 5136     | 2328202|
| 13     | 90       | 0      | 1687947| 21956  | 150823| 7061    | 43203| 5489     | 1665991|
| 40     | 53       | 0      | 2818135| 31494  | 239294| 8776    | 61997| 6541     | 2786641|
Figure 1
Figure 2

Covid-19 Model Fitting Results Brazil 04-25-2020

Accumulated Cases

Date

02/29 03/10 03/20 03/30 04/09 04/19 04/29 05/09

Accumulated Deaths

Date

02/29 03/10 03/20 03/30 04/09 04/19 04/29 05/09

Covid-19 Model Fitting Results for São Paulo 04-25-2020

Accumulated Cases

Date

02/29 03/10 03/20 03/30 04/09 04/19 04/29 05/09

Accumulated Deaths

Date

02/29 03/10 03/20 03/30 04/09 04/19 04/29 05/09
Figure 3

COVID-19 Model Results for Brazil 04-25-2020

Accumulated Cases

Date

02/29 04/09 05/19 06/28 08/07 09/16 10/26 12/05

0 5,000,000 10,000,000 15,000,000 20,000,000 25,000,000

Recuperated Cases

Date

02/29 04/09 05/19 06/28 08/07 09/16 10/26 12/05

0 50,000 100,000 150,000 200,000 250,000

Accumulated Deaths

Date

02/29 04/09 05/19 06/28 08/07 09/16 10/26 12/05

0 20 40 60

Unsusceptible

Date

02/29 04/09 05/19 06/28 08/07 09/16 10/26 12/05

95% CI 2% Error Data
Figure 4

Covid-19 Model Results for Brazil 04-25-2020

Active Cases

Hospital Beds per day

ICU Beds per day

Accumulated Deaths

ICU threshold

SD=13% / Protection=76%

95% CI / 2% Error
Figure 5

Covid-19 Model Results for São Paulo 04-25-2020

Accumulated Cases

Recuperated Cases

Accumulated Deaths

Unsusceptible

SD=13% / Protection=67%
95% CI / 2% Error
Data
Figure 6

Covid-19 Model Results for São Paulo 04-22-2020

- **Active Cases**
  - x-axis: Date from 02/29 to 12/05
  - y-axis: Number of active cases, ranging from 0 to 1,000,000

- **Hospital Beds per day**
  - x-axis: Date from 02/29 to 12/05
  - y-axis: Number of hospital beds, ranging from 0 to 20,000

- **ICU Beds per day**
  - x-axis: Date from 02/29 to 12/05
  - y-axis: Number of ICU beds, ranging from 0 to 120,000

- **Accumulated Deaths**
  - x-axis: Date from 02/29 to 12/05
  - y-axis: Number of accumulated deaths, ranging from 0 to 120,000

The ICU threshold is marked with a dotted line, and the SD=13% and 95% CI are shown with different line styles.
Figure 7

Covid-19 Model Results for São Paulo 04-22-2020

- Active Cases
- Hospital Beds per day
- ICU Beds per day
- Accumulated Deaths