REPORT #4: ESTIMATION OF MAXIMAL ICU BEDS DEMAND FOR COVID-19 OUTBREAK IN SOME CHILEAN REGIONS AND THE EFFECTS OF DIFFERENT MITIGATION STRATEGIES

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Abstract. In this document we estimate the maximal ICU (intensive care unit) beds capacity required by four Chilean regions (Arica, Ñuble, Araucanía, Magallanes) during the COVID-19 outbreak. For this purpose, we use the compartmental epidemiological model introduced in Report #2 [4] in order to simulate the effects of strategies presented in our previous Report #3 [5]: lockdown and the strategy consisting in contact tracing and isolation.

Contents

Disclaimer: This report has been written under the urgency due to the current COVID-19 outbreak situation in Chile. It aims to present some mathematical modeling tools and their corresponding predictions, helping to justify important decisions by policymakers. This material will surely improve during next weeks, with the addition of more data and corresponding scientific exchanges with colleagues. In this regard, some projections inferred by this report may contain inaccuracies related to the unknown scientific aspects of the newly born disease. Characterization of the containment and mitigation measures implemented in the regions, considered the available information until April 14, 2020. See all reports by our team at the webpage http://covid-19.cmm.uchile.cl/ or http://matematica.usm.cl/covid-19-en-chile/.

1. Introduction

As well as the evolution of the COVID-19 outbreak has been different in different countries, regions in Chile have shown heterogeneity in their processes or timeline, either in terms of the confirmation of the first cases, the growth of the number of cases, and also regarding the containment and mitigation measures that have been implemented.

In consideration to the greater number of cases (on average more than 50% during the period), Region Metropolitana has received the greatest attention. However, Ñuble, Araucanía and Magallanes have been reported as the regions with the highest cumulative incidence since the first MINSAL report on March 29 [8]. These three regions have remained in this situation to date, with rates per 100,000 population of 185.6, 115.1 and 70.2 for Magallanes, Ñuble and Araucanía respectively (see the epidemiological report at April 9 in [8]).

In fact, the most populated cities in these regions were declared lockdown during the last weeks: Chillán and Chillán Viejo in Ñuble (March 30), Temuco, Padre las Casas (March 28) and the urban part of Nueva Imperial (9 April) in Araucanía, and Punta Arenas in Magallanes (April 1).

Recently, Arica and Parinacota region have presented an important increase in the cumulative incidence per 100,000 population, from 2.4 in March 29 to 34.5 in April 9 [8]. To this date, all the confirmed cases in Arica and Parinacota region are reported as cases of the Arica city. General social distancing strategies, such as lockdown, have not been implemented in Arica.

In this context, the regional analysis becomes increasingly relevant. For this reason, this report is focused in the city of **Arica, and Ñuble, Araucanía and Magallanes regions** (see Figure 1).

2. Short description of the model

The disease spread within a particular city or region has been modeled using a deterministic compartmental model (see, for instance [2] and references therein). In our previous reports [6, 4, 5], our team has implemented this approach to the COVID-19 outbreak in

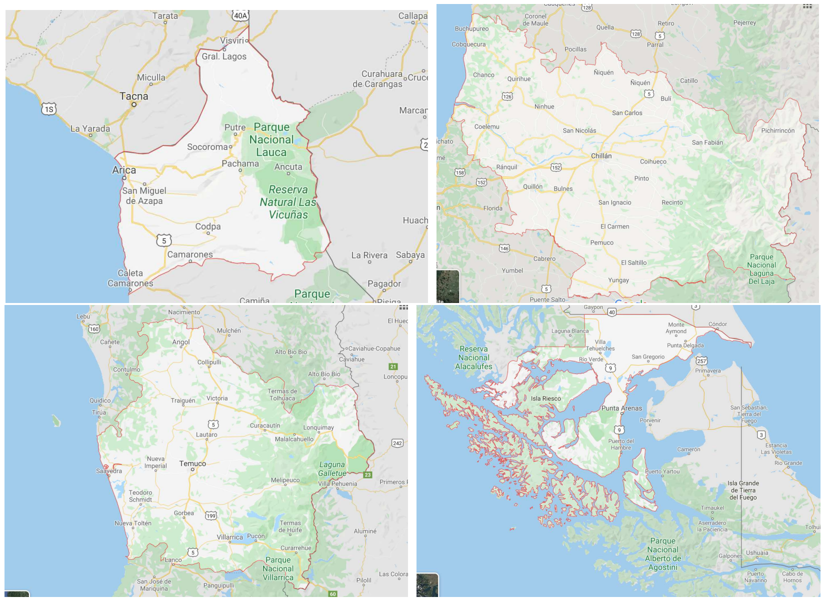

FIGURE 1. All the four regions (or districts) considered in this report: first panel up, Arica and Parinacota, second panel right: Ñuble; third panel left: Araucanía, and finally, Magallanes on the right.

Chile. The deterministic and compartmental approach that we develop here has some important advantages with respect to other approaches: among them, the most important are the simplicity and the rapidity to obtain results that can provide key insights and data for being used later in more complex models (e.g., stochastic, with interconnection between cities/districts, etc.).

The model proposed (see Appendix A for more details), previously introduced in [4], consists in a compartmental model, where the population is distributed into 8 groups corresponding to different stages of the disease:

- **Susceptible** (denoted by S): Persons not infected by the disease, but able to be infected by the virus.
- **Exposed** (denoted by E): Persons in the incubation period after being infected by the disease. In this stage, persons **do not have symptoms but they can infect other people** with a lower probability than people in the infectious compartments described below.
- **Mild infected or subclinical** (denoted by I^m): Persons infected that can infect other people. Persons in this stage are asymptomatic or present mild symptoms, **they are not detected and then not reported by authorities**. At the end of this stage, they pass directly to recovered state.
- **Infected** (denoted by I): Persons infected that can infect other people. Persons in this stage develop symptoms and **are detected and then reported by authorities**. People in this stage can recover or pass to some hospitalized state.

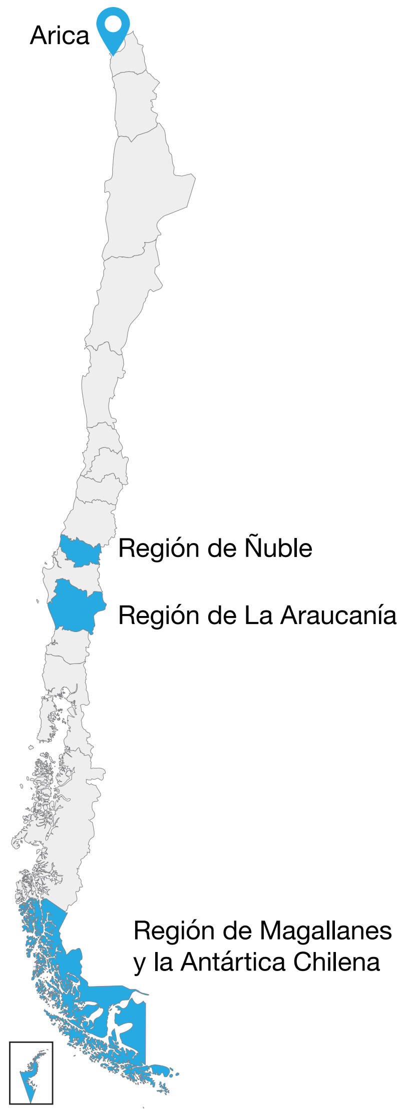

FIGURE 2. Location of the four studied places in the Chilean territory.

- **Recovered** (denoted by R): People that survive the disease, **is no longer infectious and have developed immunity to the disease**.
- **Hospitalized** (denoted by H): Persons hospitalized in basic facilities. People in this stage can infect other people. **After this stage, people recover or pass to use a ICU bed**.
- **Hospitalized in ICU beds** (denoted by H^c): People hospitalized in ICU beds. People in this stage can infect other people. After this stage, **people die or are hospitalized in basic facilities**.
- **Dead** (denoted by D): People who did not survive the disease.

The choice of the above stages and the transition between them (described below) are because our main purpose is to estimate the **maximal demand of ICU beds**. For this reason we are modeling that all people that need a ICU bed will pass by stage H^c without any constraint of availability.

3. Description of containment and mitigation strategies

The (indirect) control variables to be considered in our reports are the rate of contacts with infectious people. For a given time t (measured in days), we denote by $u_X(t)$ the rate of contact of susceptible people with a person in the stage $X \in \{E, I^m, I, H, H^c\}$ at time $t \geq t_0$ (t_0 the considered initial time).

The rates of contagious at time $t \geq t_0$ are given by

$$\beta_X(t) = p_X u_X(t) \qquad t \geq t_0,\ X \in \{E, I^m, I, H, H^c\}, \tag{1}$$

where p_X is the probability of a susceptible person (S) to be infected (i.e., to enter to the incubation stage E) after a contact with a person in the stage $X \in \{E, I^m, I, H, H^c\}$.

Additionally, for each control strategy $u_X(\cdot)$, with $X \in \{E, I^m, I, H, H^c\}$, we consider reference values (to be calibrated) $u_X^{\text{ref}} > 0$. If no mitigation strategy is applied in an interval of time $[t_1, t_2]$, one has

$$u_X(t) = u_X^{\text{ref}} \qquad \text{for all} \ \ t \in [t_1, t_2],\ X \in \{E, I^m, I, H, H^c\}. \tag{2}$$

Hence, mitigation strategies focused in reducing the contact rates satisfy $u_X(t) \in [0, u_X^{\text{ref}}]$ for all $t \geq t_0$, with $X \in \{E, I^m, I, H, H^c\}$. In this report we only consider strategies such that $u_X(t) = \alpha_X u_X^{\text{ref}}$, with $\alpha_X \in [0, 1]$. This value explains how the analyzed strategy impacts in the stage X.

Notice that, due to recommendations and most likely behavior, one should have

$$u_E^{\text{ref}} \approx u_{I^m}^{\text{ref}} > u_I^{\text{ref}} > u_H^{\text{ref}} \approx u_{H^c}^{\text{ref}} \approx 0, \tag{3}$$

because the contacts with people in incubation (E) or with mild symptoms (I^m) should be more frequent (because they do not know they are infected) than the contacts with infectious people with symptoms (I) or hospitalized (H or H^c), and we assume that people hospitalized are highly isolated. We summarize our assumptions on reference values u_X^{ref} here below:

Assumption 1. *We assume the following on parameters* u_X^{ref}*:* u_E^{ref}, $u_{I^m}^{\text{ref}}$, u_I^{ref}, u_H^{ref}, *and* $u_{H^c}^{\text{ref}}$*:*

(i) We assume that $u_H^{\text{ref}} = u_{H^c}^{\text{ref}} = 0$*, because we suppose that people hospitalized are highly isolated. For this reason,* u_H *and* u_{H^c} *are not longer considered as control variables. This approach is also used in* [13].

(ii) $u_E^{\text{ref}} = u_{I^m}^{\text{ref}}$*. This means that people in the incubation stage have the same rate of contact than as infected people with mild symptoms (and then, not detected).*

(iii) $\delta u_{I^m}^{\text{ref}} = u_I^{\text{ref}}$ *where* $\delta \in (0,1)$*. This represents that (symptomatic) infected people are more isolated than infected people with mild symptoms, unless an active search for subclinical cases would be implemented, strategy not considered in this report.*

We recall that the values u_X^{ref} are obtained after a calibration procedure (see Appendix B). However, thanks to Assumption 1, now we only need to determine u_E^{ref}.

Main objective of this report

The main objective of this document is to report, for different strategies represented by $u_E(\cdot)$, $u_{I^m}(\cdot)$, and $u_I(\cdot)$, the maximal ICU beds demand for different Chilean regions. The mitigation measures to be considered in this report are lockdown strategy and the strategy consisting in the contact tracing and isolation.

3.1. **Lockdown strategy.** The application of a lockdown strategy in an interval of time $[t_{\text{ref}}, t_{\text{ref}} + T_{\text{L}}]$ to a fraction $\eta \in (0,1]$ of the total population, is represented as a new control $u_X(t) = \alpha u_X^{\text{ref}}$ for all $t \in [t_{\text{ref}}, t_{\text{ref}} + T_{\text{L}}]$ where

$$\alpha = \eta\alpha_{\text{L}} + (1-\eta) < 1,$$

for some particular $\alpha_{\text{L}} \in (0,1)$ representing the adopted measure. This choice is standard in the literature [9]. That is, we model a reduction of the contact rate during an interval of time. Thus, the control path $u_X(\cdot)$ is a piecewise constant function. We assume that the factor α is the same for the three controls $u_E(\cdot)$, $u_{I^m}(\cdot)$ and $u_I(\cdot)$. This choice is supported by the fact that in average, population is equally affected by this restriction measure, in our model and in reality. Other interesting option could be to consider non constant reduction of contact rates in a given interval, as in [12], trying to represent the adaptation of the population to the lockdown measure. We plan to use of this kind of representation in future reports.

We are aware that to represent lockdown strategy through a constant reduction of (average) contact rates is a somehow crude simplification. Nevertheless, for policymakers, we think that this approach is more illustrative and flexible than the representation of mitigation measures through reductions of the basic reproductive number (as we did in Report #2), and also it is in line with recent literature and its recommendations [9, 10, 11, 12].

3.2. **Contact tracing and isolation strategy (cti for short).** This strategy consists of increasing efforts to locate contacts of detected cases (for example, family, work and social contacts) and, subsequently, isolate these people (monitored quarantine). Very probably these individuals are already infected but perhaps they are in the incubation stage (E) or they will present mild symptoms (I^m). Therefore, the objective is to reduce the rate of contacts for people in compartments E and I^m. Hence, we model this strategy by only reducing $u_E(t)$ and $u_{I^m}(t)$ during a long period of time. We think that this adequately represents the continued effort made in contact tracing and isolation, measure recommended by the Comité Asesor COVID-19 Chile, the advisor committee to the Chilean government, in one of their meeting [1], where they propose to define the *probable case* state, that is, the contacts of detected people.

Given a future date t_{ref} for starting the strategy, we represent the mitigation measure by $u_X(t) = \alpha_{\text{cti}} u_X^{\text{ref}}$ for $t \geq t_{\text{ref}}$, where $\alpha_{\text{cti}} \in [0, 1)$, for $X \in \{E, I^m\}$, that is, the reduction of contact rates for exposed and infected people with mild symptoms.

3.3. **Combination of strategies.** Finally, we consider a combination of lockdown and cti strategy. Given a future date t_{ref} for starting this strategy and a period of time T_{L} (for the lockdown), in the interval $[t_{\text{ref}}, t_{\text{ref}} + T_{\text{L}}]$ the strategy lockdown is applied combining with the cti strategy, that is, for all $t \in [t_{\text{ref}}, t_{\text{ref}} + T_{\text{L}}]$ one has

$$u_X(t) = \alpha_{\text{L}}\ \alpha_{\text{cti}} u_X^{\text{ref}} \quad \text{for} \quad X \in \{E, I^m\}; \ \text{and} \ \ u_I(t) = \alpha_{\text{L}} u_I^{\text{ref}}.$$

In addition, for all $t \geq t_{\text{ref}} + T_{\text{L}}$ one has

$$u_X(t) = \alpha_{\text{cti}} u_X^{\text{ref}} \quad \text{for} \quad X \in \{E, I^m\},$$

eventually changing the intensity of the cti strategy after the lockdown.

For the sake of simplicity, and also motivated by recent literature (e.g., [9, 10, 11]), we consider the values indicated in Table 1 for the parameters introduced in previous sections.

Notation	**Value(s)**	**Meaning**
δ	0.2	an symptomatic has δ times the contact rate of an infected with mild symptoms
α_{L}	0.25	reduction of contacts during lockdown
α_{cti}	0.75, 0.5	reduction of contacts during focalized quarantines (after tracing contacts)

TABLE 1. Values used for the simulations of introduced strategies.

The values of t_{ref} (date where new measures start) and T_{L} (period of lockdown) will depend of each case study (see Section 4).

3.4. **Current strategies in chosen Chilean regions.** As of April 14, 2020, in the four populations where we are focused in this report (Arica, Ñuble, Araucanía, Magallanes) we observe that there are containment and/or mitigation measures that are currently being implemented. We represent this situation by

$$u_X(t) = \hat{\alpha}_X u_X^{\text{ref}} \qquad X \in \{E, I^m, I\},$$

where $\hat{\alpha}_X \in (0, 1)$ depends of the measure currently adopted in each region or city.

We describe now the current strategies in each population and how we represent that.

- **Arica:** In this city the lockdown has not been implemented. We will assume that the current strategy is cti with *moderate intensity* ($\alpha_{\text{cti}} = 0.75$). That is

$$\text{(current situation in Arica)} \qquad u_X(t) = \alpha_{\text{cti}} u_X^{\text{ref}} \qquad X \in \{E, I^m\} \ \text{ and } \ u_I(t) = u_I^{\text{ref}}.$$

- **Ñuble, Araucanía, Magallanes:** In these regions a lockdown in the main cities has been implemented. In addition, we assume that a cti strategy with *moderate intensity* ($\alpha_{\text{cti}} = 0.75$) has been implemented. Therefore, the current situation is represented by

$$u_X(t) = \alpha_R \alpha_{\text{cti}} u_X^{\text{ref}} \qquad X \in \{E, I^m\} \text{ and } u_I(t) = \alpha_R u_I^{\text{ref}},$$

for $R \in \{\text{Ñuble, Araucanía, Magallanes}\}$, where

$$\alpha_R = \eta_R \alpha_{\text{L}} + (1 - \eta_R) < 1,$$

with

$$\eta_R = \frac{\text{(population of cities with lockdown)}}{\text{(Total population of the region)}} \qquad R \in \{\text{Ñuble, Araucanía, Magallanes}\}.$$

The values η_R and α_R used for each region where a lockdown regime is in place, are indicated in Table 2.

Region	η_R	α_R	**Cities with lockdown**
Ñuble	0.396	0.703	Chillán and Chillán Viejo
Araucanía	0.293	0.780	Temuco, Padre las Casas and urban part of Nueva Imperial
Magallanes	0.746	0.441	Punta Arenas

Table 2. Values used for simulating current lockdown regimes in Ñuble, Araucanía and Magallanes.

The strategies considered for Arica city and for Ñuble, Araucanía and Magallanes regions will be a combination of strategies as described in Section 3.3. Starting from the current strategies applied to each population, in a future date t_{ref} we simulate an additional measure: (i) Additional measure for Arica: a total lockdown of the city, eventually increasing the intensity of cti; (ii) Additional measure for Ñuble, Araucanía, and Magallanes: extending the lockdown, eventually increasing the intensity of cti. The strategy in time for each population is depicted in Figure 3.

4. Results

We have simulated the model described in Report #2 (see [4] or Appendix A), under regimes described in previous sections, for the Arica city and Ñuble, Araucanía and Magallanes regions.

Our starting point has been the calibration of the data to match the observation of detected cases in mentioned populations [8] and the current *effective reproductive number* $\mathcal{R}$ estimated for each population by Mauricio Canals et al. in [3] and reported in Table 3.

Table 3 above shows a high effective reproductive number for Arica city and Magallanes region. On the other hand, Ñuble and Araucanía regions exhibit effective reproductive numbers below one, which indicates that the COVID-19 outbreak will eventually die out if the current mitigation strategies are maintained in these two regions. However, both regions still present a high cumulative incidence and both also have a relatively low availability of

Rate of contact during time in regions

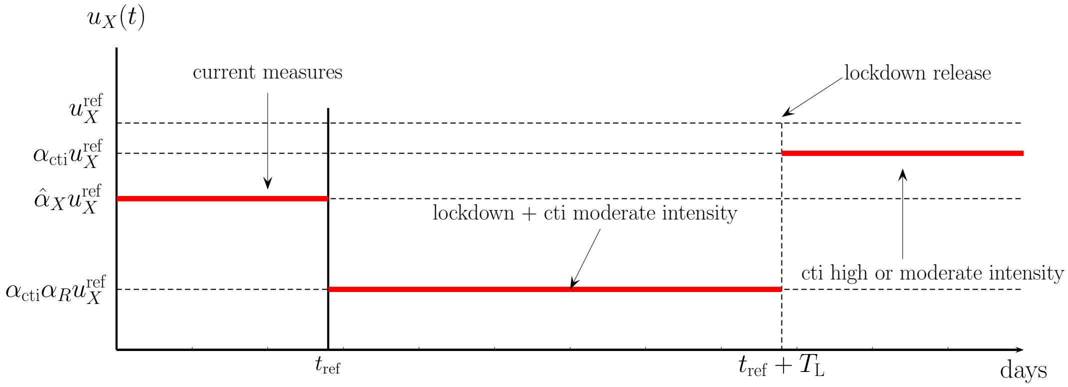

FIGURE 3. Rates of contacts $u_X(t)$ during time for the strategies (lockdown + cti) to be simulated. In Arica $\hat{\alpha}_X = \alpha_{\text{cti}}$ (moderate) and in Ñuble, Araucanía and Magallanes $\hat{\alpha}_X = \alpha_R \alpha_{\text{cti}}$ (moderate) (see values of α_R in Table 2).

Effective reproductive numbers by region

City/Region	$\mathcal{R}$
Arica	2.10
Ñuble	0.90
Araucanía	0.86
Magallanes	1.43

TABLE 3. Effective reproductive numbers in Arica city and Ñuble, Araucanía and Magallanes regions, reported in [3].

ICU beds in these moments (approximately 25 ICU beds each according to Canals et al. [3]). This justifies the detailed analysis regarding the maximal ICU beds capacity presented in this section.

Once the calibration is made (see the procedure description in Appendix B), in a second step we performed several computational processes aiming to describe the behavior of the outbreak in each population under the strategy described in Section 3.3 and depicted in Figure 3.

4.1. **Arica city.** The strategies simulated for Arica city are:

- **Arica Baseline**: The current situation that we assume is cti with moderate intensity ($\alpha_{\text{cti}} = 0.75$).

- **Strategy Arica 1**: Two weeks of lockdown for all the city starting at $t_{\text{ref}} =$ Thursday April 16, continuing with cti strategy in moderate intensity ($\alpha_{\text{cti}} = 0.75$).

- **Strategy Arica 2**: Two weeks of lockdown for all the city starting at $t_{\text{ref}} =$ Thursday April 16, and with cti strategy in high intensity ($\alpha_{\text{cti}} = 0.5$) after the lockdown.

In Table 4 we report, associated to each strategy, the following indicators: the case fatality ratio (% of death over all infected detected cases), the maximal demand of hospitalized in non complex services ($H_{\max}$), the maximal demand of ICU beds ($H^c_{\max}$) and the dates when these two demands are reached (denoted by $t_{\max}$ and $t^c_{\max}$, respectively).

Results for Arica city

Strategy	Case fatality ratio	$H_{\max}$	$t_{\max}$ (date)	$H^c_{\max}$	$t^c_{\max}$ (date)
Arica Baseline	0.51%	2172	August 22, 2020	338	September 5, 2020
Arica 1	0.51 %	2161	September 12, 2020	336	September 26, 2020
Arica 2	0.51 %	1357	October 27, 2020	217	November 10, 2020

Table 4. Results obtained for different strategies applied to Arica city.

The evolution in time of hospitalized and the occupancy of UCI beds are depicted in Figures 4 and 5. In these figures, the strategies are compared with the baseline scenario (current situation: without lockdown).

Strategy Arica 1: Lockdown (2 weeks) from April 16 + cti moderate intensity

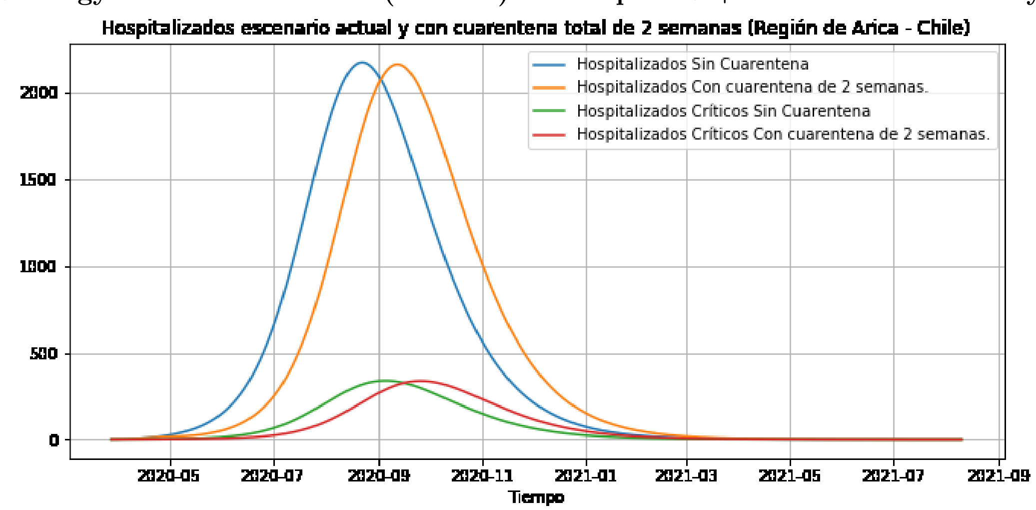

Figure 4. Lockdown strategy applied during 2 weeks since Thursday April 16 and cti with moderate intensity as the current situation.

Our results describe **only a shift effect in the peak of maximal demand for hospital resources** when lockdown strategy is implemented without additional measures (Figure 4) and a **flatten effect** of these curves when cti strategy with high intensity is applied (Figure 5).

Strategy Arica 2: Lockdown (2 weeks) from April 16 + cti high intensity

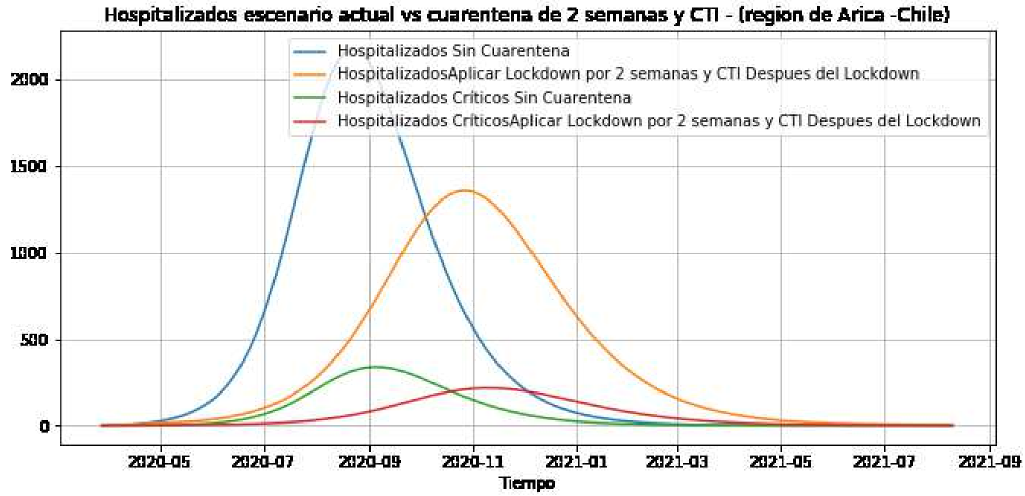

FIGURE 5. Lockdown strategy applied during 2 weeks since Thursday April 16 and cti with high intensity after the lockdown.

4.2. **Ñuble region.** The strategies simulated for Ñuble region are:

- **Ñuble Baseline**: The current situation, that is, lockdown for Chillán and Chillán Viejo cities. We consider in this scenario that the lockdown will be released on Thursday April 23. In addition, we assume the current situation consists also in the application of cti strategy with moderated intensity, which is maintained after the lockdown is released.

- **Strategy Ñuble 1**: To continue with the lockdown for Chillán and Chillán Viejo cities until Thursday April 30. Then, after April 30 only a cti strategy with moderated intensity is applied.

- **Strategy Ñuble 2**: To continue with the lockdown for Chillán and Chillán Viejo cities until Thursday April 23. Then, after April 23 a cti strategy with high intensity is applied.

In Table 5 we report, associated with each strategy, the following indicators: the case fatality ratio (% of death over all infected detected cases), the maximal demand of hospitalized in non complex services ($H_{\max}$), the maximal demand of ICU beds ($H^c_{\max}$) and the dates when these two demands are reached (denoted by $t_{\max}$ and $t^c_{\max}$, respectively).

Results for Ñuble region

Strategy	**Case fatality ratio**	$H_{\max}$	$t_{\max}$ (date)	$H^c_{\max}$	$t^c_{\max}$ (date)
Ñuble Baseline	0.51 %	678	October 28, 2020	155	November 8, 2020
Ñuble 1	0.51 %	672	November 8, 2020	153	November 19, 2020
Ñuble 2	0.5 %	42	November 22, 2020	9	December 3, 2020

TABLE 5. Results obtained for different strategies applied to Ñuble region.

The evolution in time of hospitalized and the occupancy of UCI beds are depicted in Figures 6 and 7. In these figures, the strategies are compared with the baseline scenario (current situation) consisting in the lockdown for Chillán and Chillán Viejo cities until April 23.

Strategy Ñuble 1: Lockdown until April 30 + cti moderate intensity

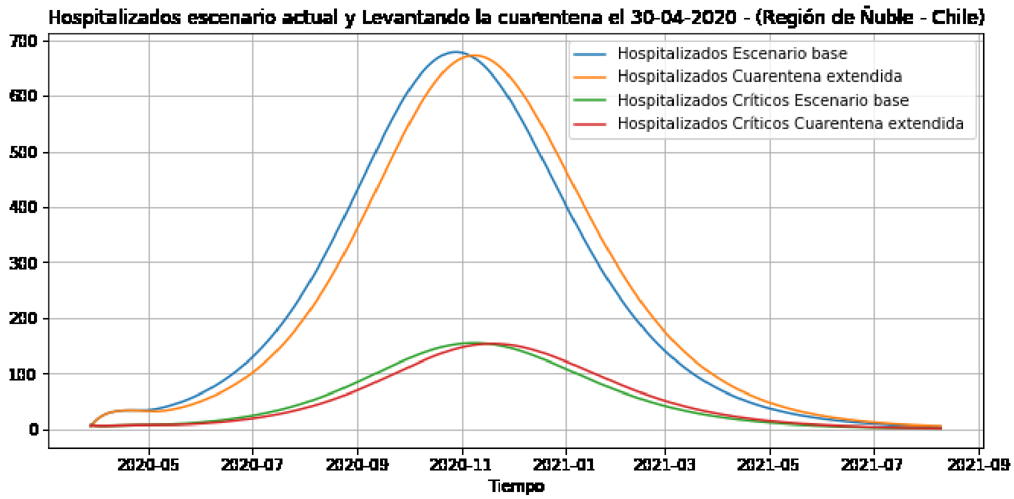

FIGURE 6. Lockdown strategy applied until Thursday April 30 and cti with moderate intensity.

Strategy Ñuble 2: Lockdown until April 23 + cti high intensity

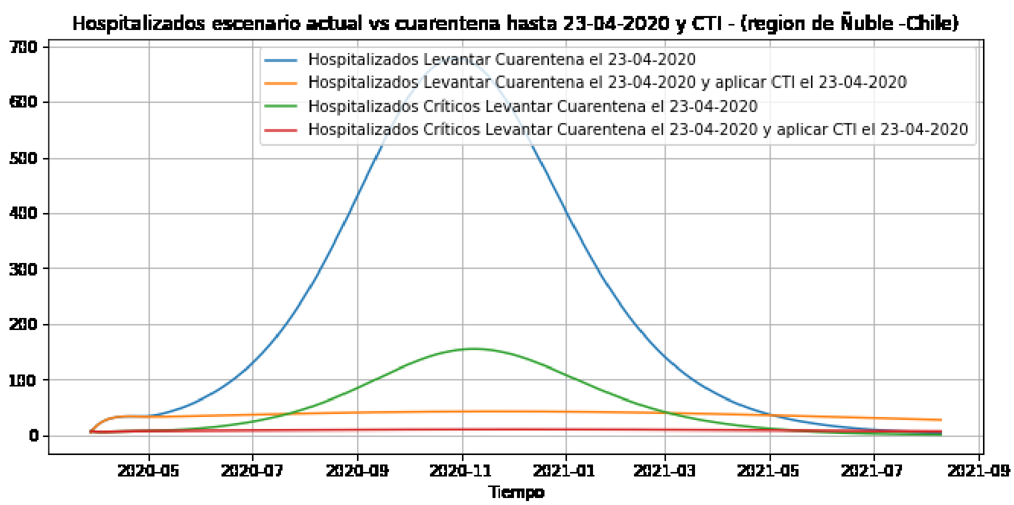

FIGURE 7. Lockdown strategy applied until Monday April 23 and cti with high intensity after the lockdown is realeased.

As we expected, our results describe **a shift in the peak with a small reduction in the amplitud in the demand for hospital resources** when lockdown strategy is implemented and a **flatten effect** of these curves when cti strategy with high intensity is applied. Moreover, our simulations confirm that Strategy 2, which combines lockdown with a high intensity cti strategy, is extremely effective in reducing the peaks of beds demand.

They become at most inexistent. This is due to the fact that its effective reproductive number ($\mathcal{R} = 0.9$) is lower than one in these moments.

4.3. **Araucanía region.** The strategies simulated for Araucanía region are:

- **Araucanía Baseline**: The current situation, that is, lockdown for Temuco, Padre las Casas and the urban part of Nueva Imperial. We consider in this scenario that the lockdown will be released on Thursday April 23. In addition, we assume a cti strategy with moderated intensity is being applied.

- **Strategy Araucanía 1**: To continue with the lockdown for Temuco, Padre las Casas and the urban part of Nueva Imperial until Thursday April 30. Then, after this date, the lockdown is released and only a cti strategy with moderated intensity is applied.

- **Strategy Araucanía 2**: To continue with the lockdown for Temuco, Padre las Casas and the urban part of Nueva Imperial until Thursday April 23. Then, after this date, the lockdown is released and only a cti strategy with high intensity is applied.

In Table 6 we report, associated with each strategy, the following indicators: the case fatality ratio (% of death over all infected detected cases), the maximal demand of hospitalized in non complex services ($H_{\max}$), the maximal demand of ICU beds ($H^c_{\max}$) and the dates when these two demands are reached (denoted by $t_{\max}$ and $t^c_{\max}$, respectively).

Results for Araucanía region

Strategy	**Case fatality ratio**	$H_{\max}$	$t_{\max}$ (date)	$H^c_{\max}$	$t^c_{\max}$ (date)
Araucanía Baseline	0.5%	552	January 31, 2021	125	February 11, 2021
Araucanía 1	0.49 %	546	February 13, 2021	124	February 24, 2021
Araucanía 2	0.58 %	44	April 16, 2020	9	April 29, 2020

Table 6. Results obtained for different strategies applied to Araucanía region.

The evolution in time of hospitalized and the occupancy of UCI beds are depicted in Figures 8 and 9. In these figures, the strategies are compared with the baseline scenario (current situation) consisting in the lockdown for Temuco, Padre las Casas and the urban part of Nueva Imperial until April 23.

Strategy Araucanía 1: Lockdown until April 30 + cti moderate intensity

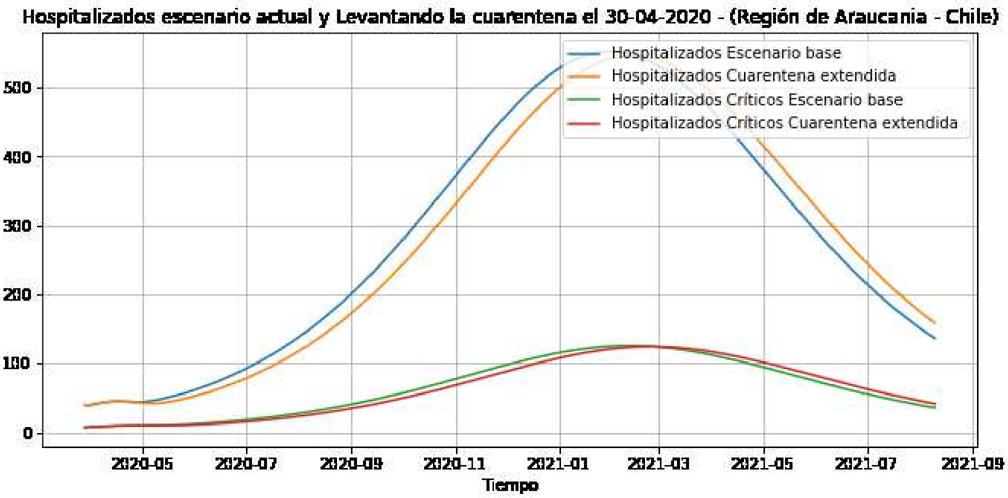

FIGURE 8. Lockdown strategy applied until Thursday April 30 and cti with moderate intensity.

Strategy Araucanía 2: Lockdown until April 23 + cti high intensity

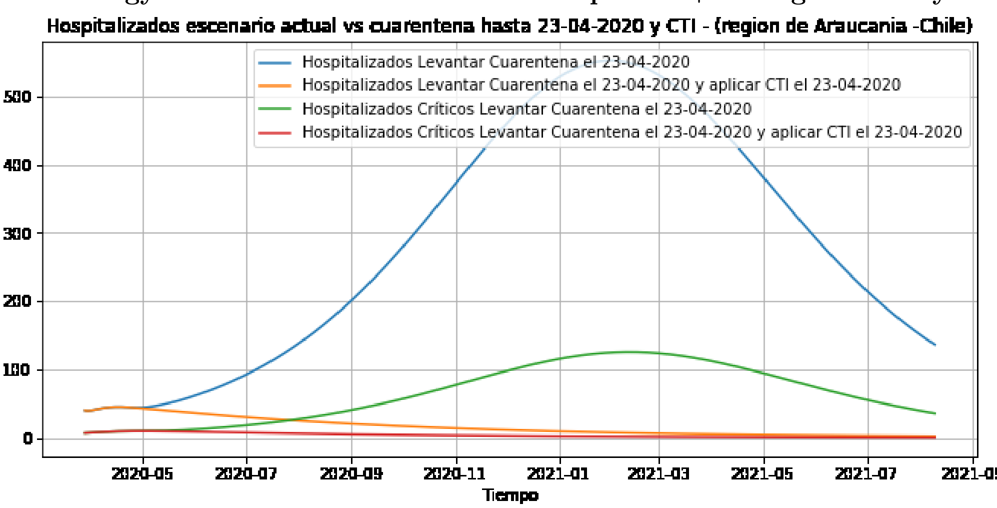

FIGURE 9. Lockdown strategy applied until Thursday April 23 and cti with high intensity after the lockdown is realeased.

As we expected, our results describe **a shift in the peak with a small reduction in the amplitud in the demand for hospital resources** when lockdown strategy is implemented and a **flatten effect** of these curves when cti strategy with high intensity is applied. Moreover, our simulations confirm that Strategy 2, which combines lockdown with a high intensity cti strategy, is extremely effective in reducing the peaks of beds demand. They become at most inexistent. This is due to the fact that its effective reproductive number ($\mathcal{R} = 0.86$) is lower than one in these moments.

4.4. **Magallanes region.** The strategies simulated for Magallanes region are:

- **Magallanes Baseline**: The current situation, that is, lockdown for Punta Arenas city. We consider in this scenario that the lockdown will be released on Thursday April 23. In addition, we assume a cti strategy with moderated intensity is being applied.

- **Strategy Magallanes 1**: To continue with the lockdown for Punta Arenas city until Thursday April 30. Then, after this date, the lockdown is released and only a cti strategy with moderate intensity is applied.

- **Strategy Magallanes 2**: To continue with the lockdown for Punta Arenas city until Thursday April 23. Then, after this date, the lockdown is released and only a cti strategy with high intensity is applied.

In Table 7 we report, associated with each strategy, the following indicators: the case fatality ratio (% of death over all infected detected cases), the maximal demand of hospitalized in non complex services ($H_{\max}$), the maximal demand of ICU beds ($H^c_{\max}$) and the dates when these two demands are reached (denoted by $t_{\max}$ and $t^c_{\max}$, respectively).

Results for Magallanes region

Strategy	**Case fatality ratio**	$H_{\max}$	$t_{\max}$ (date)	$H^c_{\max}$	$t^c_{\max}$ (date)
Magallanes Baseline	0.51 %	2625	June 20, 2020	426	July 1, 2020
Magallanes 1	0.51 %	2612	June 25, 2020	425	July 7, 2020
Magallanes 2	0.51%	2139	July 2, 2020	360	July 14, 2020

Table 7. Results obtained for different strategies applied to Magallanes region.

The evolution in time of hospitalized and the occupancy of UCI beds are depicted in Figures 10 and 11. In these figures, the strategies are compared with the baseline scenario (current situation) consisting in the lockdown for Punta Arenas city until April 23.

Strategy Magallanes 1: Lockdown until April 30 + cti moderate intensity

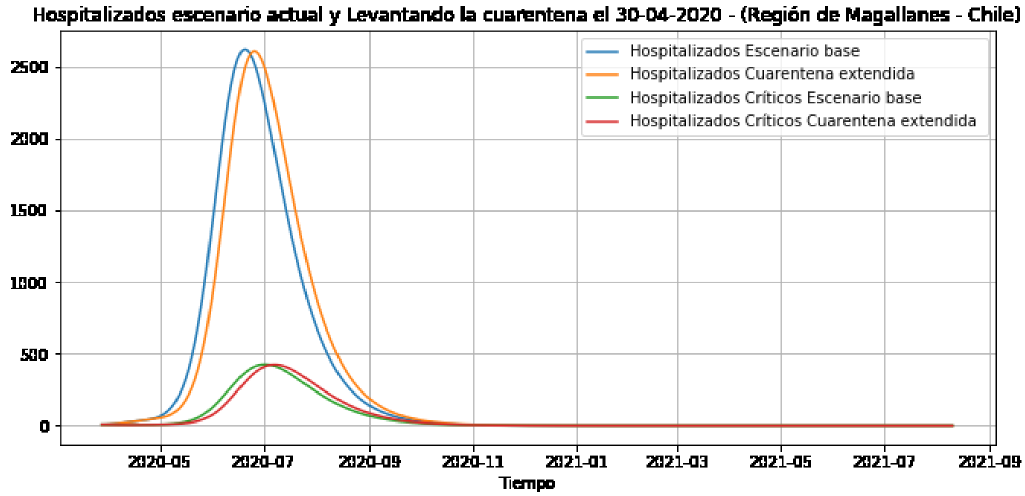

FIGURE 10. Lockdown strategy applied until Thursday April 30 and cti with moderate intensity.

Strategy Magallanes 2: Lockdown until April 23 + cti high intensity

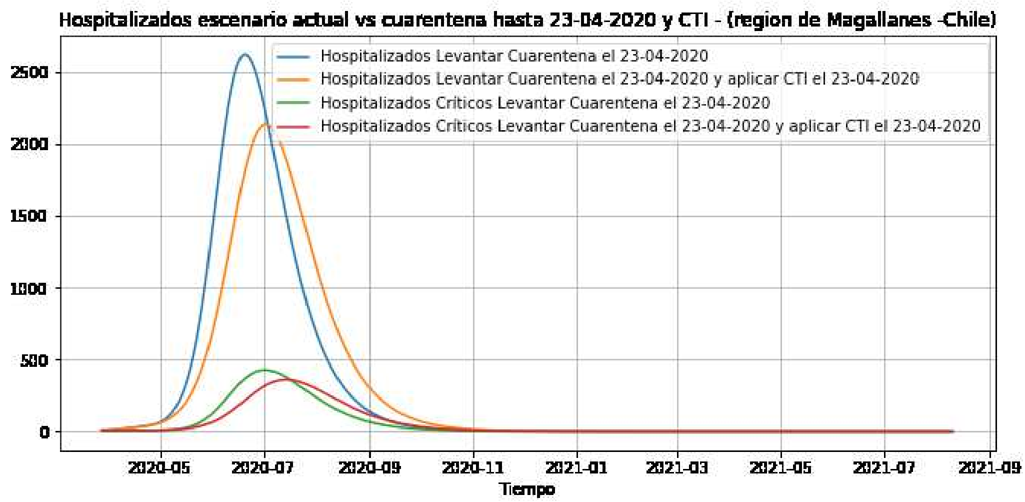

FIGURE 11. Lockdown strategy applied until Thursday April 23 and cti with high intensity after the lockdown is released.

As we expected, our results describe **a shift in the peak with a small reduction in the amplitud in the demand for hospital resources** when lockdown strategy is implemented and a **flatten effect** of these curves when cti strategy is applied. However, the effect of Strategy 2, which combines lockdown with a high intensity cti strategy, is not as effective as it is for Ñuble and Araucanía regions. The reason behind this seems to be its high effective reproductive number ($\mathcal{R} = 1.43$) and its high number of infectious.

5. Recommendations and final remarks

- We think the current development of the model might be useful to observe the direction of changes associated with different strategies. In this sense and in the light of results obtained in Section 4, **we can develop some recommendations**:
  - **Arica city:** Today authorities have announced the lockdown for Arica city since April 16 (our baseline strategy in Section 4.1). We observe that this mitigation strategy only postpone the peak of maximal demands for hospital resources (Figure 4). In order to flatten the curve, additional efforts of contact tracing and focalized (surveilled) quarantines need to be implemented (Figure 5). We recommend to use the lockdown period in order to implement an intensive program in this direction.
  - **Ñuble region:** This region has an effective reproductive number ($\mathcal{R} = 0.86$) lower than one. This means that the COVID-19 outbreak will die out if the current partial lockdown is maintained for a long time. However, since this strategy seems impossible in practice, we have simulated more realistic alternatives. We thus observe that a one-week lockdown preceded by important efforts of contact tracing and focalized (surveilled) quarantines has a major impact in the reduction of peak of maximal demands for hospital resources (Figure 7). Longer lockdowns only postpone these peaks, which could be recommendable if more time to implement contact tracing and focalized (surveilled) quarantines is needed. We thus recommend to use the lockdown period in order to implement an intensive program in this direction.
  - **Araucanía region:** The analysis here is similar to Ñuble region. We also recommend to use the lockdown period in order to implement an intensive program of contact tracing.
  - **Magallanes region:** The current situation in this region is extremely worrying. Besides its high number of incidence, the availability of ICU beds is depleted according to recent reports (cf. Canals et al. [3]). On the other hand, Strategy 2, which combines lockdown with a high intensity cti strategy, is not as effective as it is for Ñuble and Araucanía regions. We thus recommend to adopt measures that reduce its effective reproductive number, for instance, longer and more strict lockdowns, and closely monitoring the evolution of the outbreak in this region.

- It is important to mention that there is among the scientific community great discrepancies on the exact percentage of asymptomatic/symptomatic persons present in this outbreak. Some international reports place the range between 20% and 50%. In previous report #2 [4], we informed three different scenarios, including few (20%), half (50%) and large (75%) amount of undetected contagious people considering as case study the city of Santiago. Here, in this report we inform our results with a 50% of ratio asymptomatic/symptomatic.

- Our model does not consider a learning effect of the population due to the application of lockdowns after lifting. Indeed, epidemiologists have pointed out to us that previous pandemics in Chile have strongly changed the behavior of the entire population for at least a long time. This idea will be explored in future reports.

- Our model does not consider important consequences in the dynamics and health population due to the related economic crisis triggered by the COVID-19 outbreak. This phenomenon is of independent interest, and may be considered in forthcoming reports.

- In our next report, we expect to describe the effect of lockdown feedback strategies, that is, lockdowns activated when an indicator overshoot a given threshold.

- The parameters identification described in Appendix B is a poor and ill-conditioned method. We are working on improving that. It is known (see [12]) that the parameter identification of an outbreak model before the peak can produce large errors in the outputs. For this reason, the approach introduced in this reports only allows estimating the magnitude order of maximal demands, but it is not appropriate for deducing an accurate estimation of daily cases.

- Monitoring and analyzing each region as a specific case would provide rich information in order to design and implement measures tailored to each specific context. Certainly, more disaggregated data would allow analysis of smaller geographic areas, with their particularities, providing more detailed information for the application of specific measures. Unfortunately, information at the municipality or district level is not delivered on a daily basis, and information at a more disaggregated level is not reported.

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Appendix A. Description of the model dynamics

In this Section we present additional information on the model that we consider in our simulations. For more details, the reader can consult our Report #2 [4].

Recall the state variables $\mathbf{x} = (S, E, I^m, I, R, H, H^c, D)$ introduced in Section 2. In our model, the evolution of state variables is described by the following system of ordinary differential equations:

$$(4)\quad \begin{cases} \dot{S} &= \mu_b N - S\overbrace{\left(\frac{\beta_E E + \beta_{I^m} I^m + \beta_I I + \beta_H H + \beta_{H^c} H^c}{N}\right)}^{\Lambda(\mathbf{x},u):\ \text{rate of contagious}} - \mu_d S \\ \dot{E} &= S\left(\frac{\beta_E E + \beta_{I^m} I^m + \beta_I I + \beta_H H + \beta_{H^c} H^c}{N}\right) - (\gamma_E + \mu_d) E \\ \dot{I^m} &= (1-\phi_{EI})\gamma_E E - (\gamma_{I^m} + \mu_d) I^m \\ \dot{I} &= \phi_{EI}\gamma_E E - (\gamma_I + \mu_d) I \\ \dot{R} &= \gamma_{I^m} I^m + \phi_{IR}\gamma_I I + \phi_{HR}\gamma_H H - \mu_d R \\ \dot{H} &= (1-\phi_{IR})\gamma_I I + (1-\phi_D)\gamma_{H^c} H^c - (\gamma_H + \mu_d) H \\ \dot{H^c} &= (1-\phi_{HR})\gamma_H H - (\gamma_{H^c} + \mu_d) H^c \\ \dot{D} &= \phi_D \gamma_{H^c} H^c. \end{cases}$$

This model represents an extension of a SEIRHD model which aims to better describe an outbreak where part of the population has been infected by a virus, but an important part presents no or just mild symptoms. It turns out that this is the particular case of the virus SARS-CoV-2, as it is presented in several international reports [9, 12]. Schematically speaking, the structure of the model with the transitions between different stages is presented in Figure 12.

Appendix B. Parameters and calibration

The parameters to be identified (literature and/or calibration) are

$$(5)\qquad P = (p, \mu_b, \mu_d, \gamma, \phi, u^{\text{ref}}) \in [0,1]^5 \times \mathbb{R}_+ \times \mathbb{R}_+ \times [0,1]^5 \times [0,1]^3 \times \mathbb{R}_+^5 \subset \mathbb{R}^{20}.$$

The descriptions of these parameters are the following:

- $p = (p_E, p_{I^m}, p_I, p_H, p_{H^c})$ are the probabilities of contagious (see (1)) when a susceptible person is in contact with a person in stages E, I^m, I, H, and H^c.
- μ_b is the natality rate in the city and μ_d is the mortality rate, both measured in $[\text{day}]^{-1}$;[1]
- Parameters γ_X measured in $[\text{day}]^{-1}$ are the rate of transition from a disease stage $X \in \{E, I^m, I, H, H^c\}$ to the following stage, where γ_X^{-1} represents the mean duration of stage X;
- ϕ_{EI} is the fraction of exposed people who become infected (with symptoms);
- ϕ_{IR} is the fraction of infected people that recover;
- ϕ_{HR} is the fraction of hospitalized (in normal services) people that recover;

[1] Note that our simulations are for a particualr period of time (less than one year), in which case these rates do not impose important changes to the population size.

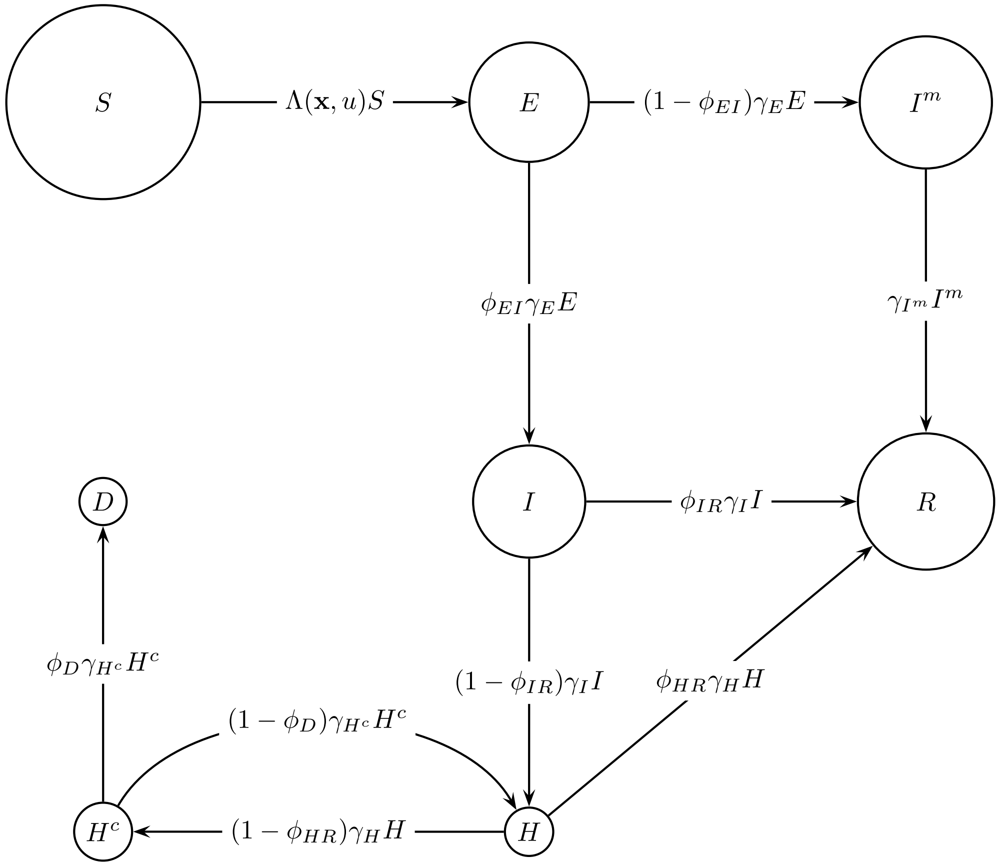

FIGURE 12. **Structure of the mathematical model for the dynamics of COVID-19 in an isolated city.** Each circle represents a compartment. Susceptible individuals (S), and different disease states: exposed (E), mild infected (I^m), infected (I), recovered (R), hospitalized (H), hospitalized in ICU beds (H^c), and dead (D). Natural natality and mortality flows are not represented.

- ϕ_D is the fraction of hospitalized people in ICU beds that die;
- The vector $u^{\text{ref}} = (u_E^{\text{ref}}, u_{I^m}^{\text{ref}}, u_I^{\text{ref}}, u_H^{\text{ref}}, u_{H^c}^{\text{ref}})$ contains references values of rates of contact.

Unfortunately, we have not found yet literature about the probabilities of contagious p_X. The most used modeling approach in the recent literature related to COVID-19 is to estimate the rates of contagious β_X (see (1)). We have preferred to separate the probability of contagious p_X and the contact rates u_X because these quantities are comparable between different stages of the disease while the contagious rates are not. In Assumption 1 we take as hypothesis some relations between contact rates. In the next assumption we proceed similarly with the probabilities of contagious, based in discussions with epidemiologists.

Assumption 2. *We assume the following on parameters p_X: p_E, p_{I^m}, p_I:*

(i) $p_E = 0.5p_{I^m}$*, because in part of the exposed stage (first 2-3 days) people are not contagious;*

(ii) $p_{I^m} = 0.15 p_I$, *because people infected without or with mild symptoms are considerable less contagious than infected people with symptoms, for instance, they do not cough.*

Thanks to Assumption 2, in order to determine the probabilities of contagious, we only need to determine or fix the value p_I. In this report we use the value $p_I = 0.75$.

Based in the daily reports given in [8] we take the following values of ratios ϕ_{EI}, ϕ_{IR}, ϕ_{HR}, and ϕ_D.

Notation	Value	Meaning
ϕ_{ER}	0.85	fraction of infected people (with symptoms and detected) that recover
ϕ_{HR}	0.85	fraction of hospitalized people that recover
ϕ_D	0.2	fraction of hospitalized people in UCI bed that die

Table 8. Values of parameters ϕ_{EI}, ϕ_{IR}, ϕ_{HR} deduced from [8].

Recall that $\phi_{EI} \in [0,1]$ is the fraction of exposed people that will present symptoms. These persons are identified and being passed to the infected compartment (I), and not to (I^m) (see system (4) or Figure 12). This fraction is a parameter but in this report we fix the value $\phi_{EI} = 0.5$ (see Report #2 [4] for scenarios associated to this parameter).

For the natality and mortality rates we take the values estimated from CENSO 2017 Chile, that is $\mu_b = 3.57 \cdot 10^{-5}$ and $\mu_d = 1.57 \cdot 10^{-5}$ both measured in $[\text{day}]^{-1}$.

For the rest of parameters, we consider a range of values taken from literature and the consideration of the authors of this report.

Notation	Unit	Range of values	References
γ_E	$[\text{day}]^{-1}$	$[1/6, 1/4]$	[7, 12, 16]
γ_{I^m}	$[\text{day}]^{-1}$	$[1/14, 1/7]$	[7, 12]
γ_I	$[\text{day}]^{-1}$	$[1/14, 1/7]$	[12, 15]
γ_H	$[\text{day}]^{-1}$	$[1/10, 1/2]$	[9, 13, 14]
γ_{H^c}	$[\text{day}]^{-1}$	$[1/15, 1/10]$	[7, 9]
u_E^{ref}	$[\text{day}]^{-1}$	$[0, 3]$	modeling team

Table 9. Range of values for parameters used in model (4).

For a vector of parameters P in the ranges given in Table 9, we compute the detected cases at day $d \in \{03/03, \ldots, \text{today}\}$ given by model (4), that is

$$C(d, P) = \int_{t_0}^{d} \phi_{EI} \gamma_E E(t) dt.$$

This allows selecting the unfixed parameters in P to fit the above quantity to daily reports until today and also the current effective reproductive number $\mathcal{R}$ for each city/region to be simulated, estimated in [3] and reported in Table 3.

In figures 13, 14, 15, and 16 we show the curves obtained by the above procedure in comparison with daily number of detected cases reported by authorities, for Arica city and Ñuble, Araucanía and Magallanes regions.

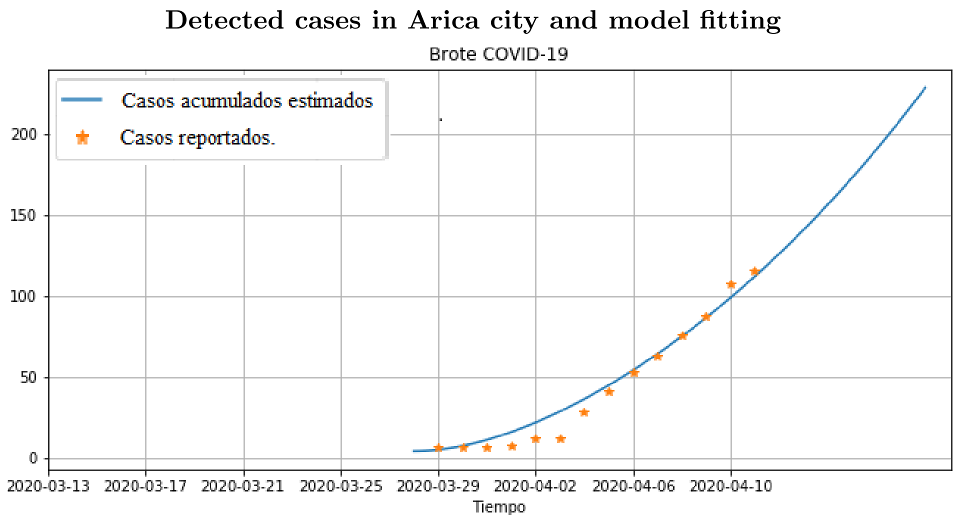

FIGURE 13. Detected infected cases in Arica city: daily reports and model output for an effective reproductive number $\mathcal{R} = 2.10$.

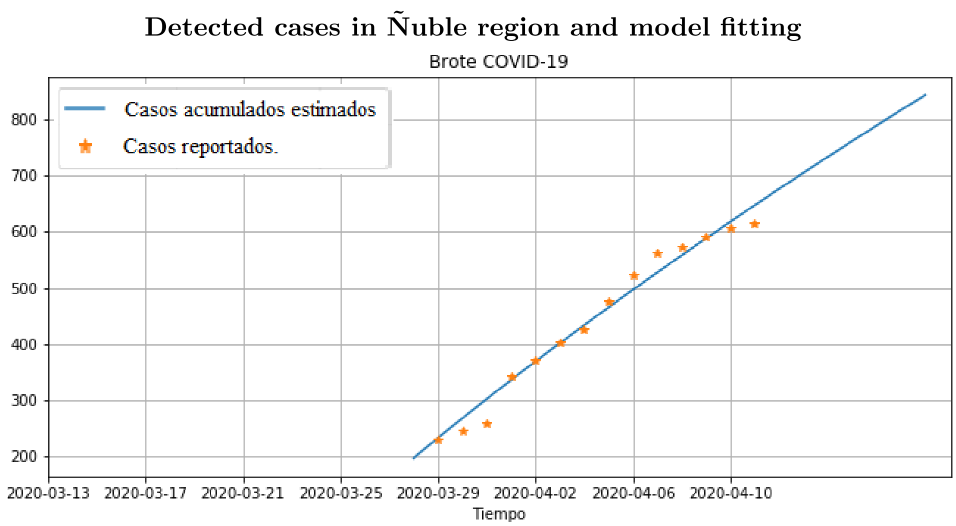

FIGURE 14. Detected infected cases in Ñuble region: daily reports and model output for an effective reproductive number $\mathcal{R} = 0.90$.

Detected cases in Araucanía region and model fitting

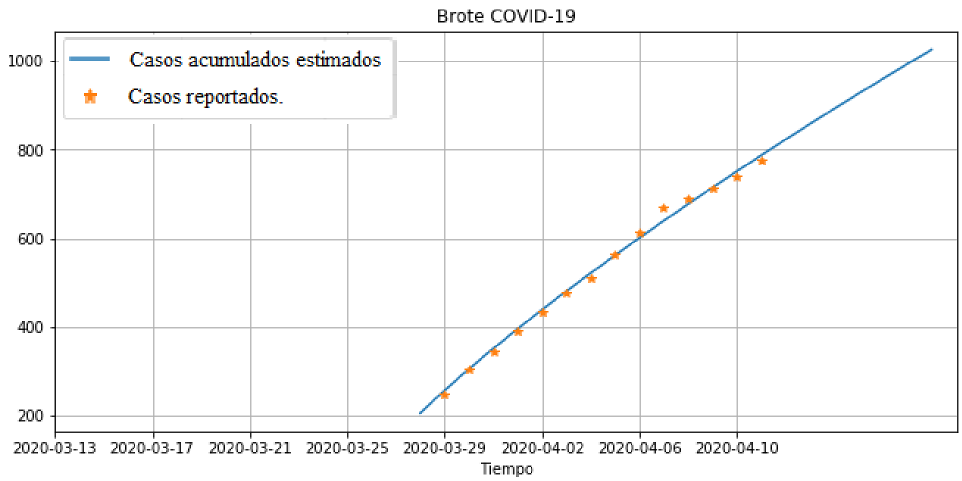

FIGURE 15. Detected infected cases in Araucanía region: daily reports and model output for an effective reproductive number $\mathcal{R} = 0.86$.

Detected cases in Magallanes region and model fitting

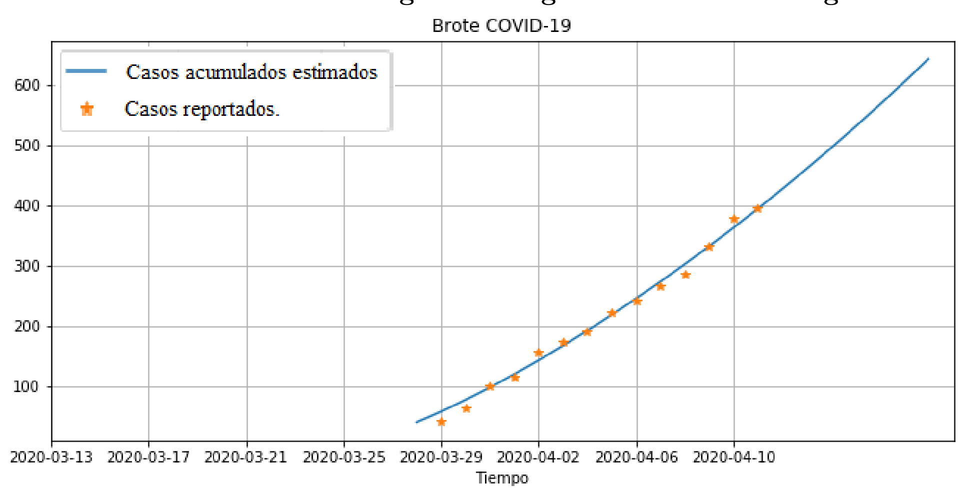

FIGURE 16. Detected infected cases in Magallanes region: daily reports and model output for an effective reproductive number $\mathcal{R} = 1.43$.

This calibration process leads to the selection of the parameters of model (4) for our different cases study, reported in Table 10.

Finally, as part of the calibration process, we also fit initial values for exposed and mild infected persons (E_0 and I_0^m, respectively), at initial time t_0 = March 28, 2020. In the estimation of initial conditions we consider the total population in each city/region (CENSO 2017) and an estimation of cases in t_0. All these values are summarized below in Table 11.

Notation	Unit	Arica	Ñuble	Magallanes	Araucanía	References
p_E	none	0.0563	0.0563	0.0563	0.0563	Assumption 2
p_{I^m}	none	0.1125	0.1125	0.1125	0.1125	Assumption 2
p_I	none	0.75	0.75	0.75	0.75	Assumption 2
μ_b	$[\text{day}]^{-1}$	$3.57 \cdot 10^{-5}$	$3.57 \cdot 10^{-5}$	$3.57 \cdot 10^{-5}$	$3.57 \cdot 10^{-5}$	INE-Chile (2017)
μ_d	$[\text{day}]^{-1}$	$1.57 \cdot 10^{-5}$	$1.57 \cdot 10^{-5}$	$1.57 \cdot 10^{-5}$	$1.57 \cdot 10^{-5}$	INE-Chile (2017)
γ_E	$[\text{day}]^{-1}$	0.148	0.221	0.170	0.216	[7, 12, 16], fitted
γ_{I^m}	$[\text{day}]^{-1}$	0.0762	0.141	0.095	0.136	[7, 12], fitted
γ_I	$[\text{day}]^{-1}$	0.0762	0.141	0.095	0.136	[12, 15], fitted
γ_H	$[\text{day}]^{-1}$	0.0762	0.141	0.095	0.136	[9, 13, 14], fitted
γ_{H^c}	$[\text{day}]^{-1}$	0.06833	0.091	0.075	0.0893	[7, 9], fitted
ϕ_{EI}	none	0.5	0.5	0.5	0.5	[8], modeling team
ϕ_{IR}	none	0.85	0.85	0.85	0.85	[8], modeling team
ϕ_{HR}	none	0.85	0.85	0.85	0.85	[9, 13, 8], modeling team
ϕ_D	none	0.2	0.2	0.2	0.2	[9, 12, 8], modeling team
u_E^{ref}	$[\text{day}]^{-1}$	1.32	1.423	2.540	1.277	Fitted
$u_{I^m}^{\text{ref}}$	$[\text{day}]^{-1}$	1.32	1.423	2.540	1.277	Assumption 1
u_I^{ref}	$[\text{day}]^{-1}$	0.198	0.285	0.508	0.255	Assumption 1
u_H^{ref}	$[\text{day}]^{-1}$	0	0	0	0	Assumption 1
$u_{H^c}^{\text{ref}}$	$[\text{day}]^{-1}$	0	0	0	0	Assumption 1

TABLE 10. Values for parameters used in model (4).

State	Arica	Ñuble	Araucanía	Magallanes	Source
S_0	229.473	479.759	956.176	165.855	Censo 2017
E_0	0	329	468	198	Fitted
I_0^m	212	324	375	441	Fitted
I_0	4	197	205	39	[8]
H_0	1	5	40	3	modeling team
H_0^c	0	7	7	8	modeling team
R_0	0	0	2	0	modeling team
D_0	0	0	0	0	[8]

TABLE 11. Initial conditions for (4), considering the total population of Arica city and Ñuble, Araucanía and Magallanes regions, for initial time t_0 = March 28, 2020.

REFERENCES

[1] X. Aguilera, C. Araos, R. Ferreccio, F. Otaiza, G. Valdivia, M. T. Valenzuela, P. Vial, and M. O'Ryan. Consejo Asesor COVID-19 Chile (30 marzo 2020), 03 2020. URL: https://ciperchile.cl/wp-content/uploads/Minuta-Consejo-asesor-COVID-30-marzo.docx.pdf.pdf.

[2] F. Brauer and C. Castillo-Chávez. *Mathematical models in population biology and epidemiology*, volume 40 of *Texts in Applied Mathematics*. Springer-Verlag, New York, 2001. URL: https://doi-org.usm.idm.oclc.org/10.1007/978-1-4757-3516-1, doi:10.1007/978-1-4757-3516-1.

[3] M. Canals, A. Canals, and H. Ramírez et al. Informe COVID-19 Chile al 11/4/2020. Technical report, Escuela de Salud Pública, Universidad de Chile, 04 2020. URL: https://www.dropbox.com/s/04ym0rr63z0ma57/canals_et_al_20200411.pdf?dl=0.

[4] A. Cancino, C. Castillo, P. Gajardo, R. Lecaros, C. Muñoz, C. Naranjo, J. Ortega, and H. Ramírez. Report #2: Estimation of maximal ICU beds demand for COVID-19 outbreak in Santiago, Chile. Technical report, CMM-AM2V-CEPS, 03 2020. URL: http://covid-19.cmm.uchile.cl/.

[5] A. Cancino, C. Castillo, P. Gajardo, R. Lecaros, C. Muñoz, J. Ortega, and H. Ramírez. Report #3: Estimation of maximal ICU beds demand for COVID-19 outbreak in Santiago (Chile) and

the effects of different mitigation strategies. Technical report, CMM-AM2V-CEPS, 03 2020. URL: http://covid-19.cmm.uchile.cl/.

[6] A. Cancino, P. Gajardo, R. Lecaros, C. Muñoz, J. Ortega, and H. Ramírez. Report #1: Estimation of maximal ICU beds demand for COVID-19 outbreak in Santiago, Chile. Technical report, CMM-AM2V, 03 2020. URL: http://covid-19.cmm.uchile.cl/.

[7] S. Cauchemez and C. Tran Kiem. Personal communication: Model description for the coronavirus disease 2019 (COVID- 19) considering age classes. Technical report, Mathematical Modelling Of Infectious Diseases, Institut Pasteur, 03 2020.

[8] Ministerio de Salud Chile. Cifras Oficiales COVID-19 Chile, 04 2020. URL: https://www.gob.cl/coronavirus/cifrasoficiales/.

[9] N. Ferguson, D. Laydon, G. Nedjati-Gilani, N. Imai, K. Ainslie, M. Baguelin, S. Bhatia, Z. Boonyasiri, A.and Cucunubá, G. Cuomo-Dannenburg, et al. Impact of non-pharmaceutical interventions (npis) to reduce covid-19 mortality and healthcare demand. Technical report, Imperial College COVID-19 Response Team, 03 2020.

[10] The Organisation for Economic Co-operation and Development. Flattening the covid-19 peak:containment and mitigation policies. Technical report, 03 2020. URL: https://read.oecd-ilibrary.org/view/?ref=124_124999-yt5ggxirhc&Title=Flattening.

[11] G. Giordano, F. Blanchini, R. Bruno, P. Colaneri, A. Di Filippo, A. Di Matteo, M. Colaneri, et al. A SIDARTHE Model of COVID-19 Epidemic in Italy. *arXiv preprint arXiv:2003.09861*, 2020.

[12] B. Ivorra, M.R. Ferrández, M. Vela-Pérez, and A.M. Ramos. Mathematical modeling of the spread of the coronavirus disease 2019 (COVID- 19) considering its particular characteristics. The case of China. Technical report, MOMAT, 03 2020. URL: https://doi-org.usm.idm.oclc.org/10.1007/s11538-015-0100-x.

[13] J. R. Koo, A. R. Cook, M. Park, Y. Sun, H. Sun, J. T. Lim, C. Tam, and B. L. Dickens. Interventions to mitigate early spread of sars-cov-2 in singapore: a modelling study. *The Lancet Infectious Diseases*, 2020/03/25 2020. URL: https://doi.org/10.1016/S1473-3099(20)30162-6, `doi:10.1016/S1473-3099(20)30162-6`.

[14] Q. Li, X. Guan, P. Wu, X. Wang, L. Zhou, Y. Tong, R. Ren, K. Leung, E. Lau, J. Y Wong, et al. Early transmission dynamics in wuhan, china, of novel coronavirus–infected pneumonia. *New England Journal of Medicine*, 2020.

[15] T. Liu, J. Hu, M. Kang, L. Lin, H. Zhong, J. Xiao, G. He, T. Song, Q. Huang, Z. Rong, et al. Transmission dynamics of 2019 novel coronavirus (2019-ncov). *bioRxiv*, 2020.

[16] World Health Organization. Report of the who-china joint mission on coronavirus disease 2019, 03 2020. URL: https://www.who.int/docs/default-source/coronaviruse/who-china-joint-mission-on-covid-19-final-report.