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Analysis of the tradeoff between health and economic impacts of the Covid-19 epidemic

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2 ABSTRACT

3 Various measures have been taken in different countries to mitigate the Covid-19 epidemic.
4 But, throughout the world, many citizens don't understand well how these measures are taken
5 and even question the decisions taken by their government. Should the measures be more (or
6 less) restrictive? Are they taken for a too long (or too short) period of time? To provide some
7 quantitative elements of response to these questions, we consider the well-known SEIR model for
8 the Covid-19 epidemic propagation and propose a pragmatic model of the government decision-
9 making operation. Although simple and obviously improvable, the proposed model allows us
10 to study the tradeoff between health and economic aspects in a pragmatic and insightful way.
11 Assuming a given number of phases for the epidemic (namely, 4 in this paper) and a desired
12 tradeoff between health and economic aspects, it is then possible to determine the optimal
13 duration of each phase and the optimal severity level (i.e., the target transmission rate) for each
14 of them. The numerical analysis is performed for the case of France but the adopted approach
15 can be applied to any country. One of the takeaway messages of this analysis is that being
16 able to implement the optimal 4-phase epidemic management strategy in France would have
17 led to 1.05 million of infected people and a GDP loss of 231 billions € instead of 6.88 millions
18 of infected and a loss of 241 billions €. This indicates that, seen from the proposed model
19 perspective, the effectively implemented epidemic management strategy is good economically,
20 whereas substantial improvements might have been obtained in terms of health impact. Our
21 analysis indicates that the lockdown/severe phase should have been more severe but shorter,
22 and the adjustment phase occurred earlier. Due to the natural tendency of people to deviate from
23 the official rules, updating measures every month over the whole epidemic episode seems to be
24 more appropriate.

25 **Keywords:** Epidemic, Covid-19, SARS-CoV2, SEIR model, epidemic management strategy, behavior model

1 INTRODUCTION

26 One of the goals of this work is to provide a simple but exploitable model to measure the quality of the
27 epidemic management strategy implemented by a government to mitigate the health and macro-economic
28 impacts of the Covid-19 epidemic. The quality is measured in terms of the tradeoff between the total
29 number of infected people over a given period of time and the Gross Domestic Product (GDP) loss, under

30 a constraint of the total number of infected people requiring Intensive Care Units (ICU). To reach this
31 objective, we propose a behavioral model for governmental decision-making operations. Although we
32 assume a simple measure for the quality of the lockdown measures and a simple dynamical model (namely,
33 a classical susceptible-exposed-infected-removed (SEIR) model), the proposed approach is seen to be
34 sufficient to constitute a first step into capturing and quantifying the tradeoff under consideration. In
35 contrast with most studies conducted on the Covid-19 epidemic analysis where the primary goal is to refine
36 the SEIR model (see e.g., [1, 2, 3, 4, 5]) or employ the SEIR model by accounting for local variations
37 (by using a given SEIR model per geographical region - see e.g., [6]) or for the impact of class type (by
38 age, sex, risk level - see e.g., [7]) our approach is to use the standard SEIR model for an entire country
39 and choose a simple economic model to focus on the study of the tradeoff between health and economic
40 aspects.

41 Although there have been many several interesting studies on the economic impact of Covid-19 (see e.g.,
42 [8, 9, 10, 11, 12]), the pursued goal of these studies is not to model the behavior of the government. As a
43 consequence, the proposed tradeoff has not been analyzed, at least formally. In fact, the closest contribution
44 to this direction would be given by [13] where generic discrete-time epidemics over multiple regions
45 are considered, the particular 4-phase structure is not considered, the focus is not on Covid-19, and the
46 key aspect of the tradeoff analysis is neither developed nor analyzed. Additionally, the numerous studies
47 available on the problem of the transmission rate control generally concern the continuous-time control
48 approach. In this work, the focus is on a multiple phase approach (namely, 4 phases). In the literature
49 dedicated to epidemic control, one can for instance find that some recent studies on how the lockdown
50 strategies and quarantine can be planned in an optimal fashion [14, 15, 16, 17]. A common feature to all
51 these works on optimal control and lockdown planning is that the policies under consideration, vary over
52 time in a continuous manner, i.e., the lockdown policy is continuously evolving based on the infected
53 population or just on time. However, from the perspective of a government, implementing such policies is
54 not practical since daily changes of the epidemic control measures are difficult to be implemented and to
55 be followed by people.

56 Summarizing, compared to the existing literature on epidemics modelling and control of epidemics, the
57 main contribution of our work is fourfold:

- 58 • a model for capturing the tradeoff between health and economic aspect and therefore for the government
59 decision-making operation is proposed and studied;
- 60 • the focus is on multiple phase control policies and not on general continuous-time control policies (to
61 be precise, 4 phases are assumed, see Figure 1);
- 62 • the problem of finding the optimal features of the optimal epidemic management policy (i.e., the
63 target severity level for each phase and the switching time instants) is stated and solved exhaustively.
64 Additionally, to refine the analysis, we assume a simple model for the natural time drift in terms of
65 behavior of people;
- 66 • the numerical analysis of the tradeoff is dedicated to the Covid-19 epidemic and a case study for
67 France.

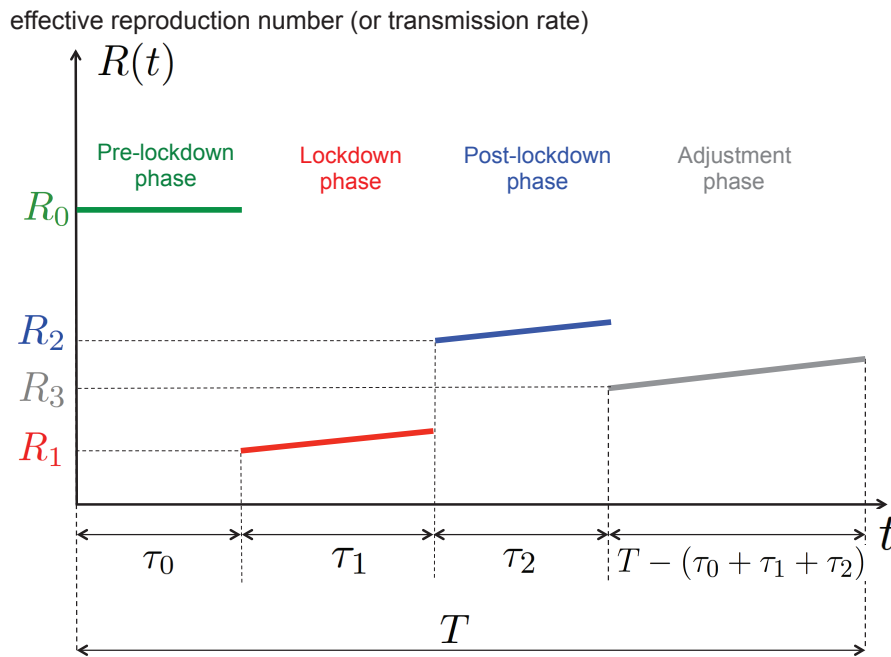


Figure 1. One of the goals of this work is to determine numerically, for a given tradeoff between health and economic costs, the best 4-phase epidemic management policy that is, the best values for $\tau_0, \tau_1, \tau_2, R_1, R_2, R_3$ (the epidemic time horizon T and the natural reproduction number R_0 being fixed).

2 METHODS

68 2.1 Epidemic model

69 To model the dynamics of the Covid-19 epidemic globally i.e., over an entire country, we assume
 70 a standard SEIR model. Let us respectively denote by $s, e, i,$ and r the fractions of the population:
 71 being susceptible to be infected by the SARS-Cov2 virus, having been exposed to it, being infected,
 72 and being removed (including recoveries and deceases). The epidemic is assumed to obey the following
 73 continuous-time dynamics:

$$\left\{ \begin{array}{l} \frac{ds}{dt}(t) = -\beta(t)i(t)s(t) \\ \frac{de}{dt}(t) = \beta(t)i(t)s(t) - \gamma e(t) \\ \frac{di}{dt}(t) = \gamma e(t) - \delta i(t) \\ \frac{dr}{dt}(t) = \delta i(t) \\ s(t) + e(t) + i(t) + r(t) = 1 \end{array} \right. \quad (1)$$

74 where:

- 75 • $\beta(t)$, $t \in \mathbb{R}$, represents the **time-varying** virus transmission rate;
- 76 • γ denotes the rate at which the exposed subject develops the disease (this includes people presenting
77 symptoms and asymptomatics). The period $\frac{1}{\gamma}$ is called the incubation period;
- 78 • δ denotes the removal rate and $\frac{1}{\delta}$ is called the average recovery period.

79 We assume that the the control action $u(t)$ taken by the decision-maker (the government or possibly a
80 more local decision-maker) has a **linear effect** on the transmission virus rate. Additionally, the effectiveness
81 of this action is assumed to undergo a non-controllable drift or attenuation effect due to the observed fact
82 that people tend to relax their effort over time [18][19], hence the presence of the attenuation factor $a(t)$
83 yields:

$$\beta(t) = R_0\delta - u(t)a(t) \quad (2)$$

84 where R_0 is the natural reproduction number (namely, without any control or population awareness),
85 $u(t) \in [0, U]$ is the control action or severity level of the lockdown measures. Note that U corresponds to
86 the most drastic or severe control action (in theory it could reach the value $R_0\delta$ and make the reproduction
87 number vanishing). In this work, $u(t)$ is a piecewise-constant function. For the numerical analysis, we will
88 assume $a(t)$ to be a linearly decreasing function of time (as detailed in the next section). Therefore, one
89 can define the time-varying effective reproduction number:

$$R(t) = \frac{\beta(t)}{\delta} = R_0 - \frac{u(t)a(t)}{\delta}. \quad (3)$$

90 As illustrated by Figure 1, we are solving an epidemic control problem in which determining the function
91 $u(t)$ or $R(t)$ amounts to jointly determining the switching instants τ_0, τ_1, τ_2 and the targeted reproduction
92 numbers R_1, R_2, R_3 ; T is a given period of time for the epidemic analysis. In particular, we will determine
93 the best duration of the lockdown phase τ_1 and the corresponding targeted reproduction number R_1 .
94 Figure 1 shows for instance that if the lockdown measures taken are such the reproduction number is R_1 at
95 the beginning of the lockdown phase, then, because of the drift induced by the typical human behavior, the
96 effective reproduction number increases over time.

97 2.2 Time drift or people behavior model

98 We propose here a model for the attenuation function $a(t)$, which quantifies the degree to which people
99 relax their effort to implement the government management measures. As the attenuation effect is negligible
100 when a new policy is released, we consider that $a(t) = 1$ when $t \in \{\tau_0, \tau_1, \tau_2\}$. The attenuation factor
101 is assumed to increase over time in each phase, and we assume the following piecewise linear behavior
102 between phases:

$$a(t) = \begin{cases} 1 & \text{for } t < \tau_0, \\ 1 - a_1(t - \tau_0) & \text{for } \tau_0 \leq t < \tau_1, \\ 1 - a_2(t - \tau_1) & \text{for } \tau_1 \leq t < \tau_2, \\ 1 - a_3(t - \tau_2) & \text{for } t \geq \tau_2. \end{cases} \quad (4)$$

103 where a_1 , a_2 , and a_3 respectively represent the attenuation coefficients during the lockdown phase, after
 104 the lockdown phase, and during the adjustment phase.

105 **2.3 Decision-maker behavior model**

106 The proposed model for the behavior of the decision-maker is based on the fact that it wants to obtain a
 107 given tradeoff between economic and health aspects. For the cost related to the economics loss, we assume
 108 the simplest reasonable model. That is, we assume that economic cost is quadratic in the control action. For
 109 the health cost, we assume that it is given by the number of infected people over the given period of time.
 110 Therefore, the proposed overall cost consists of a convex combination of these two costs. By minimizing
 111 the overall cost, one realizes the desired tradeoff between economic and health aspects. On top of this
 112 we impose the number of patients requiring intensive care to be under a given threshold N_{\max}^{ICU} . Thus, the
 113 corresponding minimization is performed under a constraint on the number of people infected at any time
 114 $t \in [0, T]: \sigma Ni(t) \leq N_{\max}^{\text{ICU}}$, N being the population size, N_{\max}^{ICU} the maximum number of ICU patients,
 115 and $0 \leq \sigma \leq 1$ is the percentage of infected people requiring intensive care. In France, official records
 116 state that the maximum cumulated number of ICU patients has reached 7 148 (on April 8, 2020) but the
 117 capacity over the whole territory has been evaluated to be greater than 15 000. By denoting $\alpha \in [0, 1]$ the
 118 weight assigned to the macroeconomic impact of the epidemic and $K_e > 0$, $K_h > 0$, $\mu > 0$ some constants
 119 (parameters) defined below, obtaining the desired tradeoff amounts to finding a solution of the following
 120 optimization problem (OP) while fixing α to a given value:

$$\begin{aligned} & \underset{u(t)}{\text{minimize}} \quad \left\{ \alpha K_e \left\{ \int_0^{\tau_0+\tau_1} u^2(t)dt + \frac{1}{\mu_1^2} \int_{\tau_0+\tau_1}^{\tau_0+\tau_1+\tau_2} u^2(t)dt + \frac{1}{\mu_2^2} \int_{\tau_0+\tau_1+\tau_2}^T u^2(t)dt \right\} \right. \\ & \quad \left. + (1 - \alpha) K_h [s(0) - s(T)] \right\} \tag{5} \\ & \text{subject to} \quad \forall t \in [0, T], \sigma Ni(t) \leq N_{\max}^{\text{ICU}} \\ & \quad \tau_1 \geq T_{\min} \\ & \quad \text{Equations (1) and (2)} \end{aligned}$$

121 where:

- 122 • $K_e > 0$ and $K_h > 0$ are constants that weight the economic and health cost functions (they also act as
 123 conversion factors allowing one to obtain appropriate units and orders of magnitude);
- 124 • τ_0 and τ_1 represent the lockdown starting time and duration, respectively. T_{\min} is the minimum
 125 lockdown duration to make the lockdown policies effective. The quantity τ_2 represents the duration of
 126 the post-lockdown phase;
- 127 • the parameters $\mu_1, \mu_2 \geq 1$ accounts for possible differences in terms of economic impact between the
 128 lockdown and post-lockdown phases;
- 129 • $s(0)$ and $s(T)$ are respectively the fractions of the population susceptible at the beginning and the end
 130 of the analysis.

131 We would like to make additional comments concerning the parameter μ_1, μ_2 . The motivation for introduc-
 132 ing μ_1, μ_2 is twofold. First, after lockdown, people are more aware and act more responsibly than before
 133 lockdown. This means that automatic and costless population distancing typically occurs [8, 20, 21]. Taking
 134 $\mu_1, \mu_2 \geq 1$ precisely amounts to having a smaller reproduction number without any cost for the government.
 135 Additionally, as people typically tend to relax their effort to implement the epidemic management measures

136 as time passes, it makes sense to assume that $\mu_1 \geq \mu_2$ in our model. It also allows one to account for the
 137 fact that, after lockdown, the economic activity grows after the lockdown and the effects of the pandemic
 138 starts vanishing. This means that, in some sense we ignore memory effects due to lockdown measures.
 139 Further refinements of the proposed model might be considered to account for the lockdown memory
 140 effects. This is out of the scope of the present paper but we believe that, this would correspond to assuming
 141 $\mu_i < 1$.

142 2.4 4-Phase optimal control with piecewise constant control actions

143 Solving analytically the optimization problem given by (5) is not trivial. However, since we restrict our
 144 attention to a certain class of control policies, the problem turns out to be solvable through exhaustive
 145 search. Assuming the attenuation factor $a(\tau_0) = a(\tau_1) = a(\tau_2) = 1$ (no attenuation at the beginning of
 146 each phase) and a constant control action in each phase, by using the relation $u(t) = \delta[R_0 - R(t)]$, the OP
 147 (5) can be rewritten under a more convenient form for numerical purposes:

$$\text{minimize}_{(\tau_0, \tau_1, \tau_2, R_1, R_2, R_3)} \left\{ \begin{array}{l} \alpha K_e \delta^2 (R_0 - R_1)^2 \tau_1 + \frac{\alpha K_e \delta^2 (R_0 - R_2)^2 \tau_2}{\mu_1^2} + \\ \frac{\alpha K_e \delta^2 (R_0 - R_3)^2 [T - (\tau_0 + \tau_1 + \tau_2)]}{\mu_2^2} + (1 - \alpha) K_h [s(0) - s(T)] \end{array} \right\} \quad (6)$$

subject to $\forall t \in [0, T], \sigma Ni(t) \leq N_{\max}^{\text{ICU}}$
 $\tau_1 \geq T_{\min}$
 $R_2 > R_1 + 0.2$
 Equations (1) and (2).

148 where R_i represents the desired or target reproduction number over Phase $i \in \{1, 2, 3\}$ without considering
 149 the attenuation factor (also, it is the reproduction number at the start of i -th phase). The second constraint is
 150 introduced here as there is a gap between lockdown reproduction number and after lockdown reproduction
 151 number. Finally, the conversion factors K_e and K_h are chosen as follows. The rationale behind the choice
 152 of K_e is that when choosing $\alpha = 1$ the GDP loss should correspond to the best estimations made by
 153 economists. The GDP loss over the lockdown period for a given country is denoted by ΔGDP , the
 154 conversion factor K_e is chosen as follows:

$$K_e \delta^2 (R_0 - R_1)^2 \tau_1 = \Delta\text{GDP}. \quad (7)$$

155 For France for example, the GDP loss during the lockdown has been evaluated (on April 20) to be around
 156 120 billions € according to the OFCE [22]. At last, the constant K_h is merely chosen as $K_h = N$, that is,
 157 when $\alpha = 0$ the cost function corresponds to the number of people infected over the considered period of
 158 time.

3 RESULTS

159 3.1 General simulation setup

160 To perform exhaustive search over the sextuple of variables $(\tau_0, \tau_1, \tau_2, R_1, R_2, R_3)$, time and amplitudes
 161 are quantized; we thus use hat notations to indicate corresponding values are quantized. Time is discretized
 162 with a step of 24 hours (that is, one sample for each day) and a time horizon of $\hat{T} = 300$ days (which

163 approximately corresponds to 10 months that is the interval [March 1st, December 31th], for the tradeoff
 164 figure presented in Sec 3.4, for computational convenience, we take $\hat{T} = 210$ days corresponding to 7
 165 months from March 1st to September 30th) is assumed. The sets for the possible lockdown starting days,
 166 the lockdown duration (in days), post-lockdown phase duration, and the reproduction numbers are as
 167 follows: $\hat{\tau}_0 \in \{1, 2, \dots, 30\}$, $\hat{\tau}_1 \in \{T_{\min}, T_{\min} + 1, \dots, 90\}$, $\hat{\tau}_2 \in \{1, 2, \dots, 120\}$, $\hat{R}_1 \in \{0.4, 0.2, \dots, 1.5\}$,
 168 $\hat{R}_2 \in \{0.4, 0.2, \dots, 1.5\}$, $\hat{R}_3 \in \{0.4, 0.2, \dots, 1.5\}$. Excluding Figure 5, due to the physical characteristics of
 169 the epidemics in France, we set $T_{\min} = 30$ because the lockdown duration is at least 4 weeks or 1 month
 170 to make the lockdown effective in real systems [24][25][26]. The SEIR model parameters are as follows:
 171 $\frac{1}{\delta} = \frac{1}{0.1857} = 5.4$ days, $\frac{1}{\gamma} = \frac{1}{0.16} = 6.25$ days; these choices are consistent with many works and in
 172 particular the studies performed for France [23] and Italy [16]. The population size is set to $N = 66.10^6$, the
 173 maximum number of patients requiring intensive care is set to $N_{\max}^{\text{ICU}} = 15.10^3$, and $\sigma = 1.5\%$ [24][25][26].
 174 Notice that this number is only reached for very small values of α (for which the total number of people
 175 infected over the analysis duration would be around 9 millions). The exposed population on March 1 2020
 176 is initialized to $Ne(0) = 1.33.10^5$. This number is obtained from analyzing the data provided in [24]. We
 177 consider the number of reported deaths at a given time to be a more reliable way of tracking the evolution
 178 of the pandemic rather than the reported number of infected people. Indeed, as soon as one examines
 179 absolute values, they typically become irrelevant. For example, during lockdown, because of the lack of
 180 tests and measurements, the real number of infected people was much higher than the official number. Now,
 181 even when tests were performed intensively, because of false positives, the absolute number of infected
 182 were again completely unreliable. For a prevalence of 1/1000 and a test reliability of 5% of false positives
 183 we see that the number of infected for 1000 people is declared to be about 50 whereas the actual number of
 184 infected is only 1. Motivated by these critical issues, we have considered figures which are much more
 185 reliable such as the number of deceases due to Covid-19 in France [23][24]. From the number of deaths and
 186 the global average rate (worldwide) of the mortality rate (in the range 0.3% – 0.5% when averaged over
 187 classes of ages and countries), the reconstructed number of infected people turns out to be more accurate.
 188 Therefore, by fixing the mortality rate to a given value (in [23] for instance, the mortality rate averaged
 189 over all the classes of infected people is evaluated to be around 0.53% for France), one can estimate the
 190 exposed and infected population size 3 to 4 weeks before the measured number of deaths due to Covid-19.
 191 For our computation, the initial conditions of the ordinary differential equations (ODE) equations are
 192 chosen as $s(0) = 1 - e(0)$, $i(0) = r(0) = 0$, and the ODE is solved by using the Matlab `ode45` solver.
 193 Concerning the economic cost for France related to Covid-19, the GDP loss over the lockdown period
 194 is estimated by the OFCE [22] to be 120 billions € and we have, as reliable figures, that $\tau_1^{\text{France}} = 55$
 195 days with $R_0^{\text{France}} = 3.5$ and $R_1^{\text{France}} = 0.6$. We therefore take $K_e = 7.379.10^9$ €/day. Values of the
 196 reproduction number for the first two phases come from past and quite accurate evaluations (see e.g., [25]).
 197 The value $R_2^{\text{France}} = 0.9$ is less accurate and corresponds to the assumption that the government has been
 198 aiming at giving as much as freedom to the population while avoiding a second wave. Based on available
 199 statistics on Covid-19 in France [26], the attenuation coefficients of the drift model have been chosen as
 200 follows: $a_1 = 0.1\%$, $a_2 = 0.2\%$, $a_3 = 0.2\%$. Unless stated otherwise, the economic impact parameters are
 201 chosen as $\mu_1 = 1.41$ (i.e., $\mu_1^2 \sim 2$) and $\mu_2 = 1.3$. Also, when α is assumed to be fixed, it is set to 10^{-4} .

202 To justify the choice of the attenuation parameters, that is, $a_1 = 0.1\%$, $a_2 = 0.2\%$, $a_3 = 0.2\%$, we apply
 203 the French policy into our model. By comparing the active cases obtained from our model and the statistics,
 204 it can be illustrated in Fig. 2 that our model matches well with the statistics, especially in the second-half of
 205 the plot, where the number of tests conducted are sufficiently large. This validate the choice of our model
 206 and parameters. The mismatch on March and April are mainly due to the lacking number of tests that were
 207 taken during the early outbreak of the pandemic, leading to a much lower reported number of active cases.

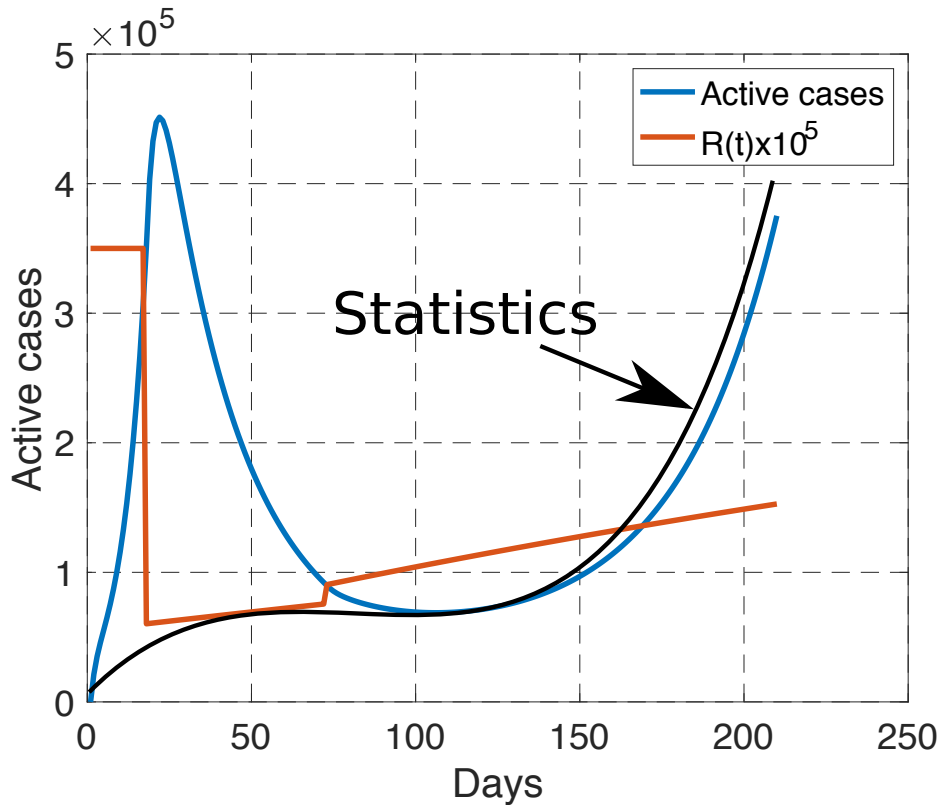


Figure 2. Comparison between our model (blue curve) and the reported statistics (black curve) from March 1st to September 30th. When the number of tests are sufficiently large, our model matches well with the reported statistics. The reproduction number is linearly increasing during each phase, and is discontinuous during the transition between phases.

208 3.2 Optimal tradeoff between economic and health impacts

209 With the proposed government decision-making model, implementing a desired tradeoff between the
 210 health cost and economic cost merely amounts to choosing a given value for the parameter α . Figure 3
 211 depicts for various values of α in the interval $[10^{-7}, 10^{-4}]$ the total GDP loss and number of infected
 212 people that is obtained after choosing the (quantized version of the) sextuple $(\tau_0, \tau_1, \tau_2, R_1, R_2, R_3)$ that
 213 minimizes the combined cost given by Equation (6). At one extreme, when α is relatively large ($\alpha = 10^{-4}$)
 214 (that is, when the government aims at minimizing the economic cost in the first place - always under the
 215 ICU capacity constraint) we see that the best epidemic management strategy leads to a GDP loss over the
 216 entire study period [March 1, September 30] is about 206 billions € with 7.16 millions infected, and 15 000
 217 patients requiring intensive care. At the other extreme, when α is relatively small ($\alpha = 10^{-7}$), the GDP
 218 loss reaches values as high as 295 billion € with a total number of newly infected people over the period
 219 [March 1, September 30] as low as 23 162. To evaluate the efficiency of the epidemic management strategy
 220 of the French government policy, we have represented the point corresponding to the estimated number
 221 of infected people and GDP loss by September 30; with our model, the GDP loss over the period of time
 222 of interest is 241 billion € and the total number of infected people is about 6.88 million. What the best
 223 tradeoff curve indicates is that there were management policies that would allow the French government to
 224 have a better "performance" both in terms of GDP loss and the number of infected people. For instance, we
 225 indicate a point for which it would have been possible to have about 1.05 million people infected (that is,
 226 about 6 times less than what is estimated with the current policy) while ensuring a total GDP loss of 231

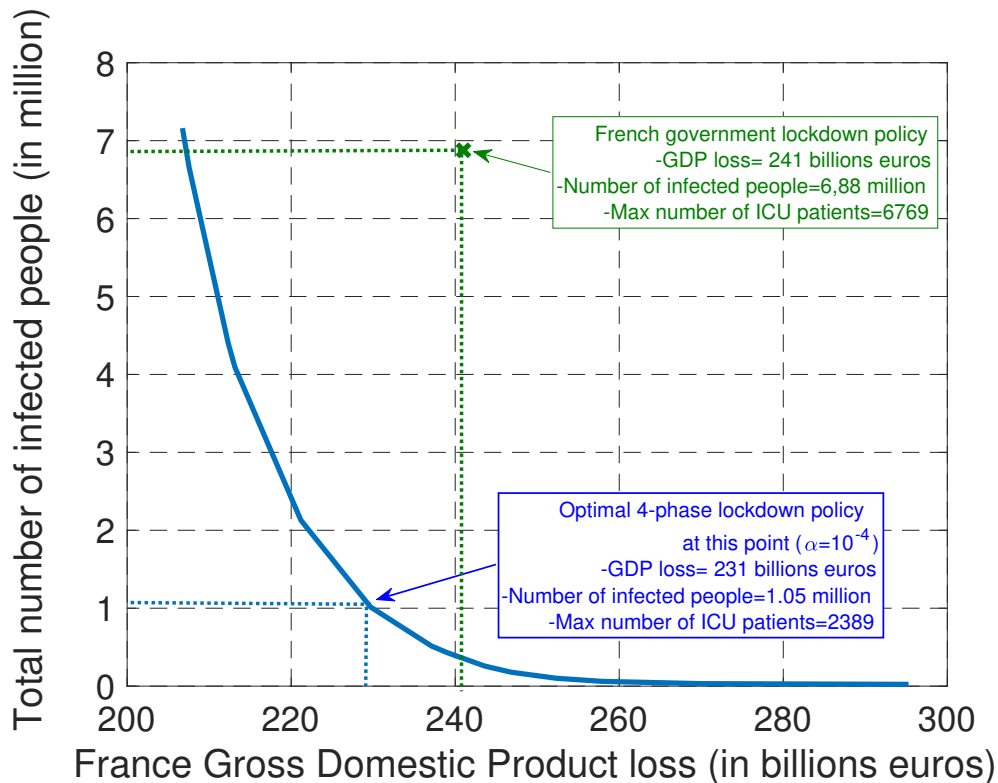


Figure 3. The plots represent the possible tradeoffs between health cost (measured in terms of the total number of infected people) and economic cost (measured in terms of GDP loss) that can be obtained (by choosing the best epidemic management policy). In particular, with the assumed model, it is seen, in retrospect, that it would have been possible to divide the number of infected people by about 6 while saving about 10 billions € in terms of GDP with the optimal 4-phase strategy.

227 billions €. Which type of epidemic management strategy should be used to have such an outcome? The
 228 next sections provide a detailed analysis of the features of the optimal strategy.

229 3.3 Optimal features of the optimal epidemic management strategy

230 One of the important features for controlling the Covid-19 epidemic which has been well commented in
 231 newspapers in various countries is the lockdown starting time. To minimize the health cost, the answer
 232 is ready: the lockdown phase should always start as soon as possible. But when one wants to realize a
 233 tradeoff between health and economic costs, the answer is less immediate. For different values for μ_1 and
 234 μ_2 , Figure 4 provides the best day to start locking down the population, for one hundred values of α ranging
 235 from 10^{-4} to 10^{-6} . The main message of this figure is that, even for (relatively) large values for α (that is,
 236 when the economic cost dominates the health cost), the optimal lockdown starting day should be before
 237 March 4th (i.e., $\tau_0 \leq 4$). This clearly shows that, once an epidemic has been declared, invoking economic
 238 damages to delay the lockdown phase is not acceptable. Note that this conclusion holds when economic
 239 losses are assumed to be uniform over time ($\mu_1 = \mu_2 = 1$). When the economic cost associated with a
 240 given intensity or severity level is lower after lockdown than during it (here $\mu_1 = 1.41$ and $\mu_2 = 1.3$), it is
 241 always optimal to start locking down as soon as possible. Note that our model does not capture the possible
 242 fact that population needs to be psychologically prepared to follow the lockdown measures. In France,
 243 by March 17, there were official figures about the epidemic which were sufficiently critical to make the

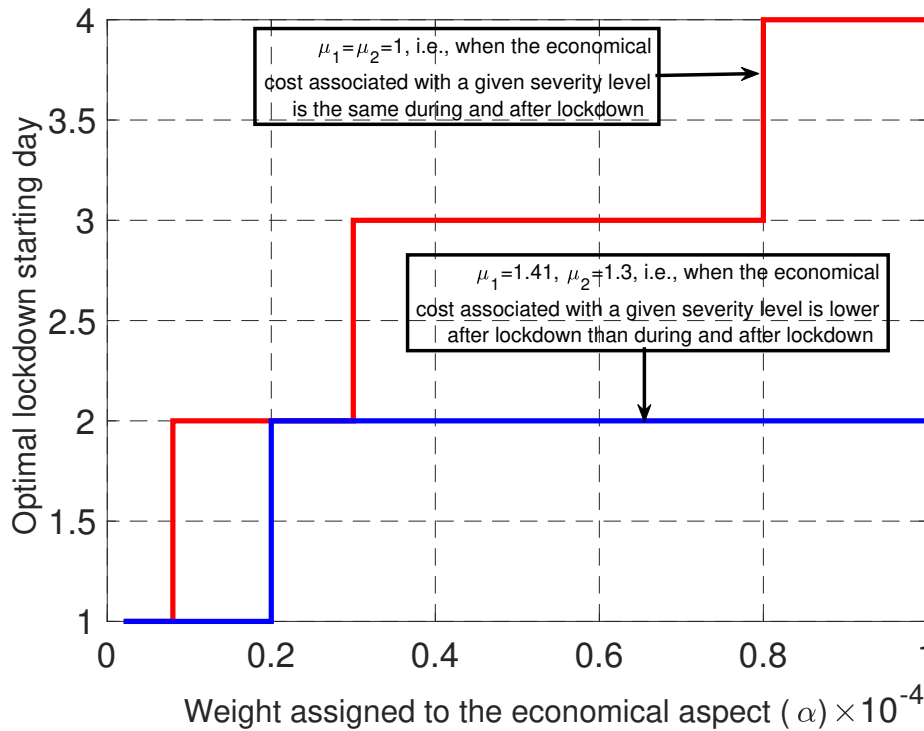


Figure 4. When economic losses are assumed to be uniform over time ($\mu = 1$), there is some economic incentive to delay the lockdown, but this delay is seen to be at maximum 4 days. When economic losses are lower after lockdown than during it, it is beneficial to start the lockdown faster, up to 3 days delay.

244 population accept the measures whereas, starting on March 4 (the optimal starting date for $\mu_1 = \mu_2 = 1$)
 245 the situation might have not been critical enough to create full adhesion to government measures.

246 A second key feature of the Covid-19 epidemic control strategy was the lockdown phase duration
 247 namely, the value of τ_1 . To better explore the relationship between τ_1 and α (the tradeoff), we relax the
 248 lockdown duration constraint here and set $T_{\min} = 1$. For $(\mu_1, \mu_2) = (1, 1)$ and $(\mu_1, \mu_2) = (1.41, 1.3)$,
 249 Figure 5 provides the optimal lockdown duration (in days) for values of α ranging from 10^{-4} to 10^{-6} . For
 250 $(\mu_1, \mu_2) = (1, 1)$ (i.e., when economic losses are uniform over time), the optimal duration ranges from 53
 251 days to 83 days for a large fraction of the considered interval for α . Interestingly, we see that these values
 252 are relatively close to the lockdown duration effectively imposed in France namely 55 days. For larger
 253 values of μ_1 and μ_2 , the optimal lockdown duration is seen to be much smaller. Therefore, if economic
 254 losses are uniform over time, the French government policy seems to be very coherent. On the other hand,
 255 if the economic impact is smaller after lockdown, our study suggests shorter lockdown durations. In fact,
 256 our results show the existence of a critical value for the tradeoff parameter α above which the second phase
 257 of the management of the epidemic should not be present. This means that the optimal control consists of
 258 three phases instead of four.

259 To conclude this section, let us consider Figure 6. For the by default scenario studied in this paper
 260 ($(\mu_1, \mu_2) = (1.41, 1.3)$, $\alpha = 10^{-4}$), the figure represents the evolution of number of infected people,
 261 that is, $N_i(t)$, and the transmission rate when the optimal policy is adopted. First, it is seen that for the
 262 health-economic tradeoff corresponding to $\alpha = 10^{-4}$, there is no interest in delaying the lockdown phase.

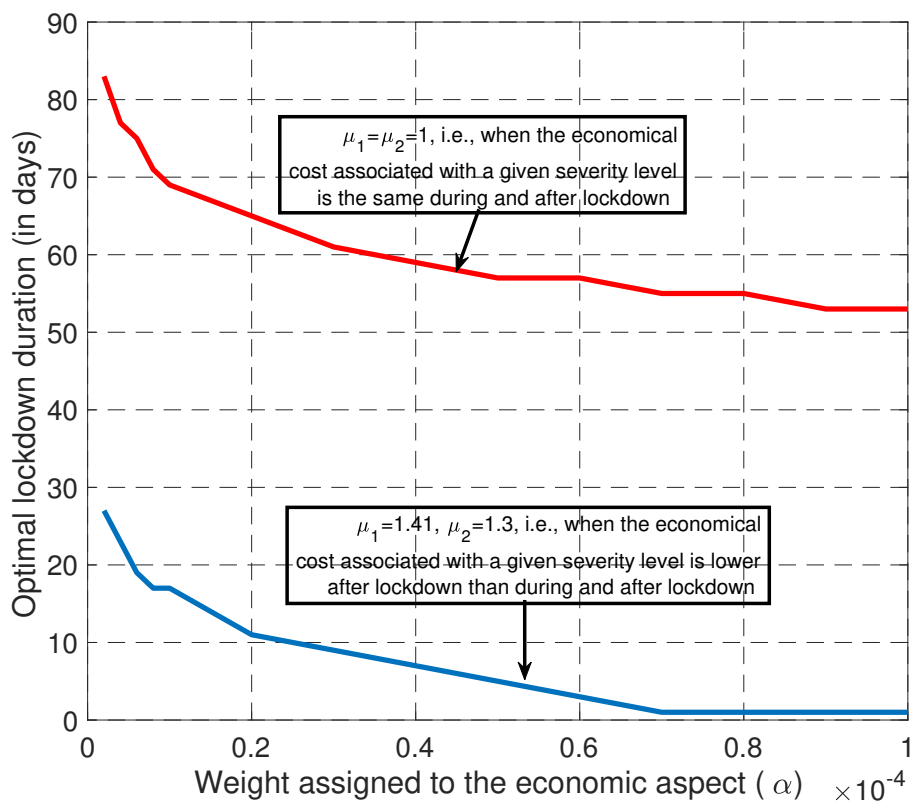


Figure 5. When economic losses are assumed to be uniform over time ($\mu = 1$), it is optimal to have a long lockdown (typically between 60 – 80 days) whatever the tradeoff desired. But, if the economic losses of the third phase are less than during lockdown, the lockdown phase should be shorter.

263 By "lockdown" phase, the authors mean that it might be any type of phase for which the reproduction
 264 number is as low as 0.4 (versus the estimated 0.6 in France); very efficient digital tracing and intensive use
 265 of face masks is also an option which has been successfully adopted in countries such as South Korea (see
 266 e.g., [27]). The optimal lockdown phase duration is seen to be about 1 month (instead of 2 for France). We
 267 see that the existence of an adjustment phase is part of the optimal policy. For this point, we see that the
 268 adjustment phase should have occurred much before in France (end of June versus end of September). The
 269 next section is precisely dedicated to the impact of the adjustment phase.

270

271 3.4 Lockdown policies with different R_0

272 Since the natural reproduction number R_0 depends on temperatures, population density, may vary over
 273 time due to mutation effects, and in any case is not known perfectly, it is of interest to study the impact
 274 of R_0 on the obtained characteristics for the optimal epidemic management policy. This is what Fig. 7
 275 represents. It is seen that large variations on R_0 do not involve large variations on the starting day. For
 276 instance, moving from $R_0 = 2$ to $R_0 = 3.5$ only changes the optimal date by one day (Day 2 instead of
 277 Day 3), which confirms the need to act fastly even when the transmission is more limited (e.g., thanks
 278 to higher temperatures or lower population density). Note that this holds even if the economic impact
 279 is accounted for. It is also good for economical aspects to react fastly to an epidemics. For the optimal

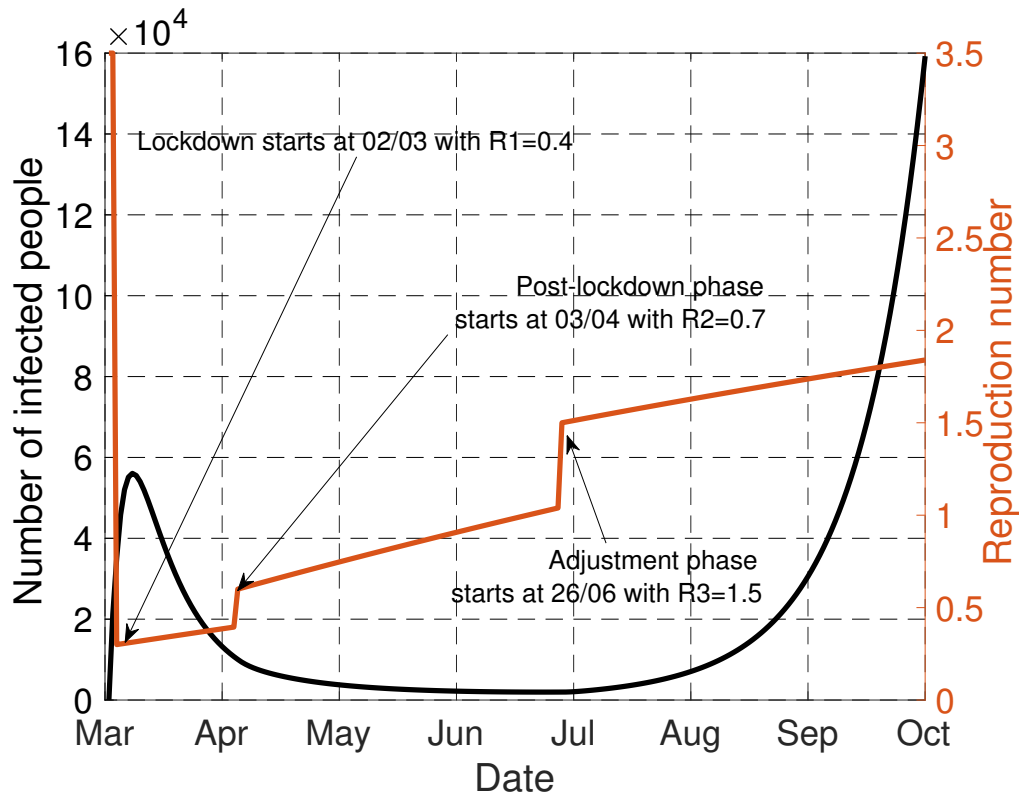


Figure 6. This figure represents the evolution of number of infected people ($N_i(t)$) and the transmission rate when the optimal policy is adopted.

280 reproduction number during lockdown (namely, R_1) it is also seen that moving a scenario in which $R_0 = 2$
 281 to $R_0 = 3.5$ does not change very significantly the results: the target severity (or freedom) level would
 282 correspond to $R_1 = 0.4$ instead $R_1 = 0.6$, which shows that the severity should be high during lockdown
 283 even in countries or regions where transmission is more limited.

284 Alternatively, the impact of R_0 uncertainty can be evaluated by adding a perturbation on R_0 . It is assumed
 285 that what is known to determine the optimal parameters is $\hat{R}_0 = R_0 + \Delta$, Δ being a Gaussian noise
 286 $\Delta \sim \mathcal{N}(0, \sigma^2)$. The reproduction number have to stay in a given interval of physical relevance of the
 287 form $[R_{\min}, R_{\max}]$. Thus the noise is imposed to stay in the interval $[-R_0 + R_{\min}, -R_0 + R_{\max}]$. With
 288 $R_0 = 3.5$, $R_{\min} = 1$ and $R_{\max} = 4$, Fig. 8 depicts the average bias for τ_0 and R_1 induced by uncertainty
 289 on R_0 . The average biases for τ_0 and R_1 are defined by $\mathbb{E}_\Delta[|\hat{R}_1 - R_1|]$ and $\mathbb{E}_\Delta[|\hat{\tau}_0 - \tau_0|]$, where \hat{R}_1 and $\hat{\tau}_0$
 290 are obtained with the noisy reproduction number \hat{R}_0 . Remarkably, the impact of the corresponding noise on
 291 the results is seen to be very reasonable and does not affect the main conclusions drawn in the first version
 292 of the paper. This indicates that the conducted analysis is robust against some forms of uncertainties. But
 293 of course, as mentioned previously, a deeper analysis would be required to state more general conclusions.

294 3.5 Impact of the adjustment phase

295 Always for the typical scenario presented in the general setting part, Figure 9 depicts the evolution of
 296 the number of infected people (in France) for the policy effectively implemented over the period [March
 297 1, September 30]. Here, only the adjustment phase is assumed to be optimizable. The figure allows one
 298 to quantify the impact of the severity level of the adjustment phase. Without the adjustment phase, the

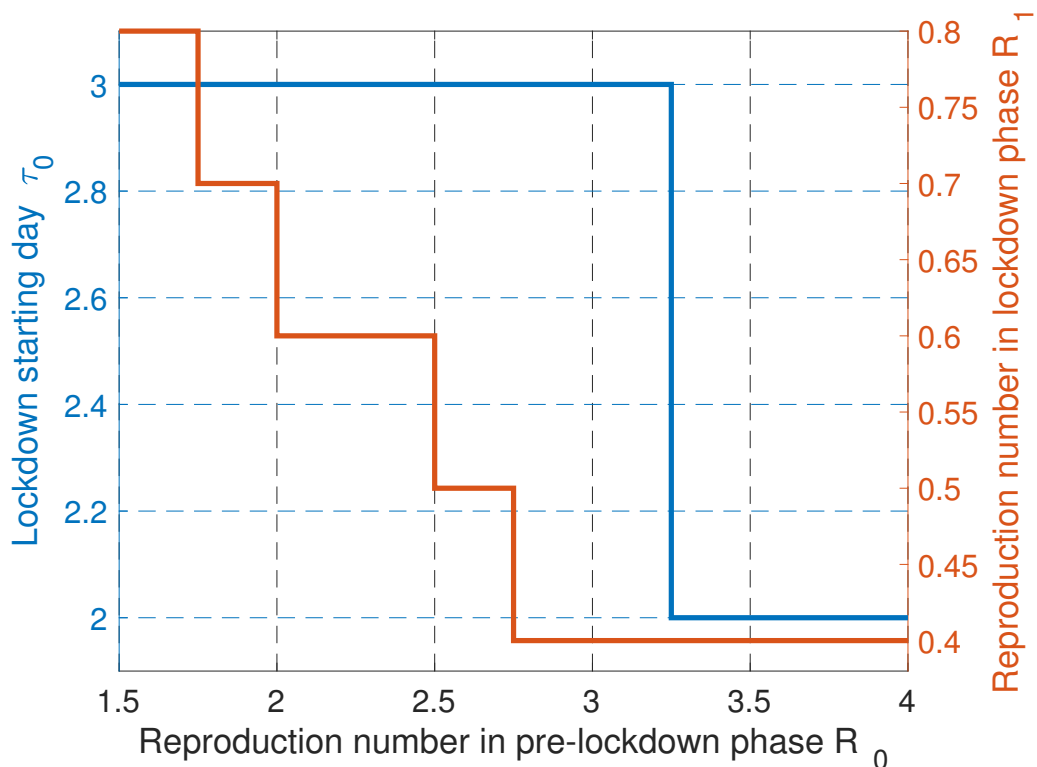


Figure 7. Comparison of lockdown policies with different R_0 . When the situation is worse, a sooner and more strict lockdown strategy should be applied.

299 fraction of infected people is such that the number of people requiring intensive care exceeds the double of
 300 the maximum ICU capacity of France. However, by implementing measures such that $R(t) < 1.2$ over
 301 the adjustment phase, the constraint on the ICU capacity is not violated by the end of 2020. Furthermore,
 302 to avoid the overwhelming health service for a longer time, it is better to implement measures such that
 303 $R(t) < 1$ over the adjustment phase since the fraction of infected people will be non-increasing with
 304 $R(t) < 1$.

4 DISCUSSION

305 In this work, we propose to model the behavior of a government as far as the epidemic control is concerned.
 306 The proposed model, despite its simplicity, has the merit of being able to capture the fundamental tradeoff
 307 between economic and health aspects. Obviously, to capture other effects such as the psychological effects
 308 of measures on people, a more general model should be considered. The proposed model allows one to
 309 provide quantitative answers to issues which have been well commented in the media. For example, even
 310 when a government chooses to assign a high value to the economic aspect, it is seen that the best strategy is
 311 almost always to implement a severe phase as soon as possible. This severe phase involves locking the
 312 population down, as most countries did, or to make intensive use of digital tracing and face masks as South
 313 Korea did. In the latter case, a loss in terms of privacy is the price to be paid for having more freedom.
 314 When inspecting the obtained numerical results performed for France, it is seen that the optimal features
 315 for the lockdown/severe phase require targeting a **reproduction number smaller** than the one achieved in
 316 France (0.4 vs 0.6), while having a **shorter duration for the severe phase** (1 month instead of 2). Note

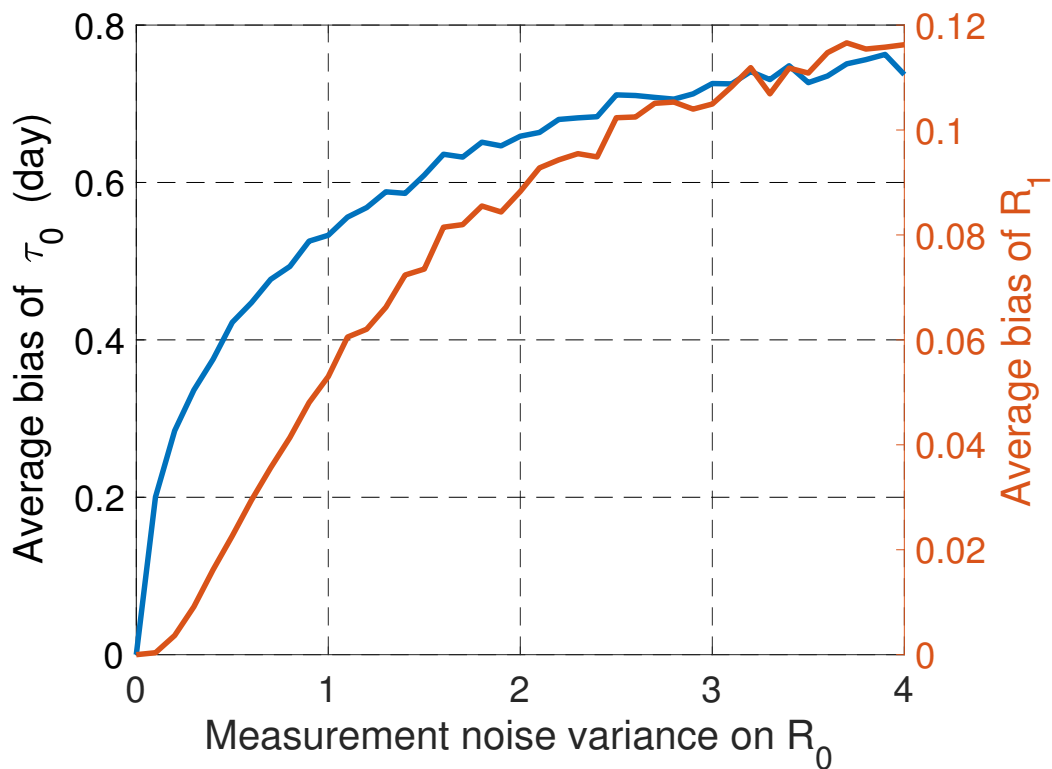


Figure 8. Influence of uncertainties on R_0 on the optimal values for τ_0 and R_1 .

317 that some countries adopted measures which were more severe than France. For instance, China has been
 318 imposing the use of a given food supply system which was very efficient in terms of epidemic mitigation
 319 [28, 29, 30]. Then, by planning an adjustment phase at the right time, we have seen that as a final result,
 320 the number of infected people can be reduced by a factor of 6 when compared to the current French policy
 321 (1.05 million of infected instead of 6.88 millions for the current policy) while having similar GDP losses
 322 (231 billions € instead of 241 billions €). We have seen that by considering a simple model as we have
 323 studied, the need for an adjustment phase could have been anticipated. Such a phase is necessary to avoid
 324 the number of patients under intensive care exceeding the capacity of the ICUs. Also, because of the natural
 325 tendency of humans to deviate from rules over time, it appears that measures should be **updated about**
 326 **every month** and not less frequently.

AUTHOR CONTRIBUTIONS

327 SL, CZ, VV, and CM designed the proposed model. SL and CZ conducted the review of the related
 328 literature. SL collected the data to calibrate the assumed model. CZ and SL performed the simulations. All
 329 authors contributed to the writing of the manuscript.

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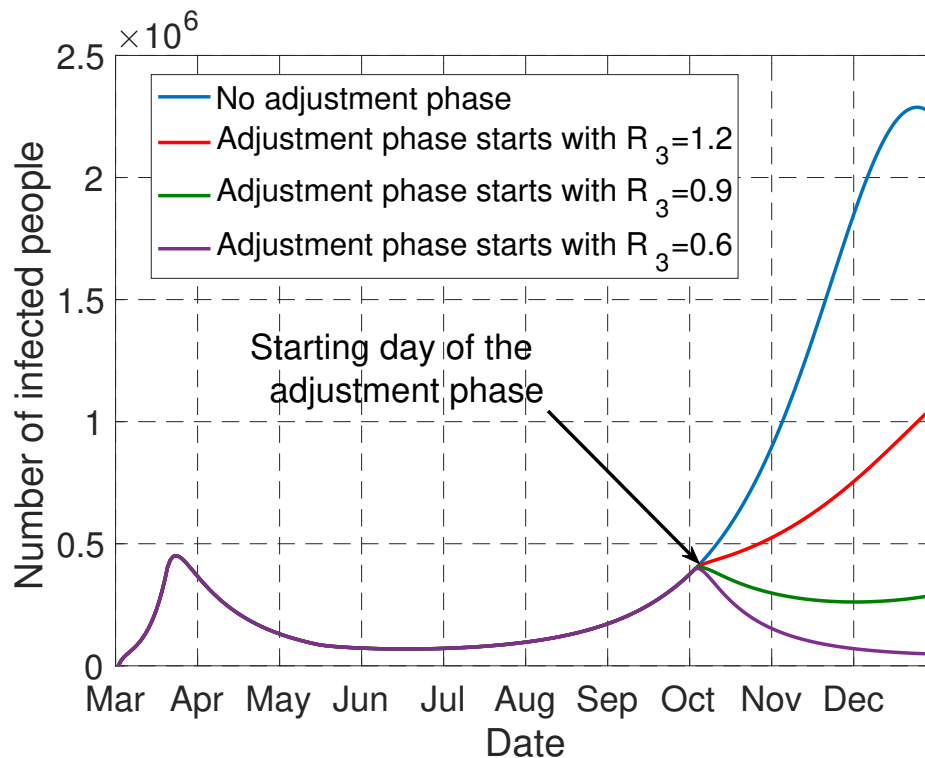


Figure 9. The figure shows the impact of the adjustment phase. Only by imposing $R(t) < 1.2$ over this phase, the number of people admitted in ICU does not exceed the capacity of France by the end of 2020.

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 332 National Research Center CNRS. Part of this manuscript has been released as a pre-print at medRxiv [31].

DATA AVAILABILITY STATEMENT

333 Publicly available datasets were analyzed in this study. This data can be found in the following website:
 334 www.santepubliquefrance.fr.

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