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► **To cite this version:**

Philippe Angot. EARLY ESTIMATIONS OF THE IMPACT OF GENERAL LOCKDOWN TO CONTROL THE COVID-19 EPIDEMIC IN FRANCE. 2020. <hal-02545893>

**HAL Id: hal-02545893**

**<https://hal.science/hal-02545893v1>**

Preprint submitted on 17 Apr 2020

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# EARLY ESTIMATIONS OF THE IMPACT OF GENERAL LOCKDOWN TO CONTROL THE COVID-19 EPIDEMIC IN FRANCE

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## Note#1

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17 April 2020

### Abstract

In this Note, I present an original dynamic model of progression of Covid-19 epidemic in France, the so-called *HOPE* model, which remains relatively simple. Our model follows at the best four reliable indicators: the number of patients in Hospitals and in Intensive Care Units (ICU's), the Outflux from Hospitals and the number of Deaths which are reported daily by the French Public Healthcare system. Then, we give results about the influence of the complete lockdown measures taken by the French government on March 17, 2020, initially for 15 days, then for 30 days and now until May 11, 2020 but perhaps further. We show the tremendous impact of the general lockdown on the infectious tsunami to avoid the huge natural disaster which should occur if it was not applied. Indeed, the number of deaths is found divided by the factor 120 by applying a complete lockdown of 60 days with an efficiency ratio evaluated to 75%. We discuss this impact with respect of the efficiency and/or the duration of the containment. In particular, we show that a small effort of +1% in the efficiency of the lockdown saves 600 human lives; reversely, a small relaxation of -1% in the lockdown respect costs 600 deaths more.

Next, we investigate the outbreak of an uncontrolled secondary wave of infection after the lockdown. Consequently, we show that the "stop and go" strategy is probably not a reasonable and sustainable scenario but rather a real crash test for the Healthcare system. Finally, we propose the suppression strategy called "successive damping cascade" after the general lockdown which allows the efficiency ratio to go progressively to zero within several less and less controlled secondary waves.

**Keywords** Covid-19 epidemic · Self or mandatory isolation · Quarantine · General lockdown · Transmission dynamics model · Generalized SEIR-ODE system · *HOPE* dynamic model · Epidemic mitigation · Epidemic suppression

## 1 Introduction

Two months ago, I did not know that I should have to learn basic features of infection diseases, coronavirus, SARS (Severe Acute Respiratory Syndrom), Covid-19 (or SARS-CoV-2) and epidemiology... However, we are all still waiting at this time for an efficient medical treatment to cure the very contagious and deadly Covid-19 infection or for a vaccine. Therefore, though being not an expert in epidemiology, I tried during these last months to answer many questions that I was wondering, both as a citizen and a researcher, about the drastic pandemic and fast progression of Covid-19, from China first, then in Europe, and now all over the world. Hence, I designed a deterministic transmission dynamics model, the so-called *HOPE*<sup>1</sup> model, which generalizes the standard SEIR (Susceptible - Exposed - Infective - Recovered)

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<sup>1</sup>*HOPE* acronym: project on Hospital Organization for People Exposed

compartmental model [1] to simulate the evolution of epidemic processes. Our model includes 11 classes of which the time evolution is based on the solution of a suitable nonlinear ODE (Ordinary Differential Equations) system. The present *HOPE* model tries to match both the important features of Covid-19 learned from the recent literature, e.g. [2, 3, 4, 5, 6, 7], and the current situation of the French Healthcare organization. Then, the main objective of the present study is to evaluate the impact of the complete lockdown, as made also in Wuhan and Hubei Province in China, Italy or Spain, over the spread and progression of epidemic. Indeed, the aim of the general containment is to limit the number of infectious contacts that each individual can have per day, *i.e.* the so-called reproduction number kept below 1. Hence, this should greatly mitigate the transmission dynamics of the infection to avoid the complete saturation of the Hospitals. Moreover, since half of the world is now in containment, it is crucial to evaluate the impact of lockdown and to design efficient strategies to avoid an uncontrolled secondary wave of infection. In this sense, this study should contribute to help the Public Healthcare system to make decision on their policy and more generally to give informations for all the people. We refer to [4, 8, 9, 10, 11] for other, more or less sophisticated models focusing on the spread of Covid-19 in France and the impact of non-pharmaceutical interventions. Some interesting data and results can be found from Chinese experience, e.g. [12, 13, 14].

## 2 Description of the *HOPE* transmission dynamics model

The French population size will be considered as a constant  $N = 67 \cdot 10^6$  during these short-term simulations since the natural births and deaths can be neglected. This population is also supposed to be homogeneous. Thus, we are not going to take account of the large disparities between the regional countries which would involve to develop a spatio-temporal model. Indeed, the reproduction number is surely smaller in a region having a low density of population than in a big city. However, the present model could be easily applied to another country or at the scale of any regional country or a town as soon as enough reliable data are available. Besides, the population is not structured to take account of age dependency, though the severity of Covid-19 infection is known to be stronger for senior people or having chronic diseases.

### 2.1 A multi-class model with four evolution branches

The *HOPE* transmission dynamics model follows the time evolution of the number of individuals in 11 classes corresponding to different phases of the infection, see Table 1. This generalizes the classical SEIR (Susceptible - Exposed - Infective - Recovered) compartmental model, see [1] and the references therein, based on the first SIR (Susceptible - Infective - Recovered) model described in the pioneering work [15]. The Susceptible class (S) gathers the naive population with regard to the disease (neither had it nor them immune) who can become infected and infective by Covid-19. Since this is a novel coronavirus, nobody has already acquired immunity and so, the number of (S) at the outbreak of infection is the size  $N$  of the entire population. The Exposed (E) individuals had at least an adequate contact with an infective person, *i.e.* a contact sufficient to become infected by Covid-19. They are in the incubation period, but after the latent time  $\tau_e$ , they already become infectious and contagious and enter the Infective class (I). The time  $\tau_e + \tau_i$  includes the incubation time and, after the onset of symptoms, the latency time of tracing to become a confirmed case. The Recovered (R) people have been cured and they are supposed to have acquired immunity at least for a few months<sup>2</sup>.

Next, the main feature of the present model is to consider four evolution branches as shown in Fig. 1. Indeed, it takes account of the Asymptomatic class (A) composed of people being infective but having no symptom at all. The Infective class (I) is also sub-divided into people having mild symptoms and going to the Quarantine class (Q) for a self isolation and cure at home, and patients having a severe form of infection which requires admittance in the Hospital class (H). Inside the Hospital (H), a fraction  $\mu$  (about one fifth) of patients, having a Severe Acute Respiratory Symptom (SARS), needs to enter the Ultimate care class (U), *i.e.* in the Intensive Care Unit (ICU). We also consider the Outflux class (O) of cured people leaving the Hospital (H) and the Deaths class (D) in Hospital only. The last branch simulates the exchange between the Susceptible class (S) and the Containment class (C),  $\tau_c$  being the duration of lockdown period,  $\omega$  the efficiency ratio and  $\lambda_0$  is the tuning factor to calibrate the quality of the lockdown.

Then, the incidence term in our model:  $\beta(I + A)/N$  can be interpreted as the average number of contacts with infectives per unit time of one susceptible. The coefficient  $\beta$  is the transmission rate that is the average number of adequate contacts (*i.e.* contacts sufficient for transmission) of a person per unit time. That would be probably better to consider an incidence differencing  $\beta$  according to Asymptomatics or Infectives as:  $(\beta_I I + \beta_A A)/N$  with  $\beta_A < \beta_I$ , but we have at this time no reliable data to estimate the coefficients  $\beta_I, \beta_A$ . Hence, we keep only a single coefficient  $\beta$  but with a fraction of Asymptomatic people not more than 20 – 30%.

<sup>2</sup>At this time, this property is only an assumption for Covid-19 and this should be confirmed or not in the near future.

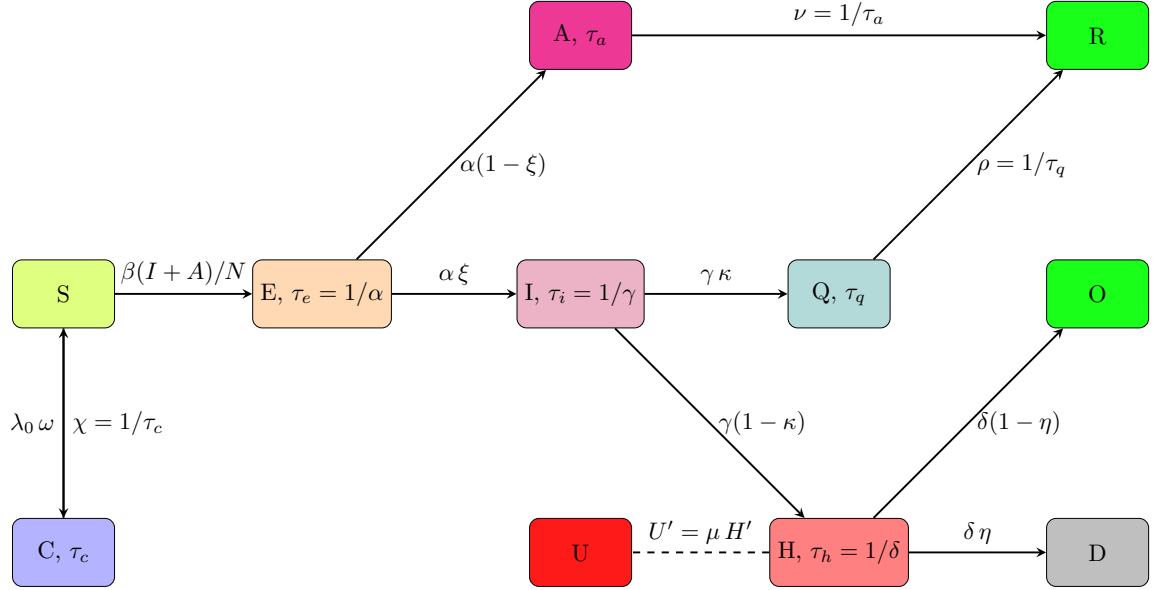


Figure 1: Flow diagram of the HOPE model showing the four main branches: the Asymptomatic people (A), the infective people having only mild symptoms and going to self isolation in Quarantine at home (Q), and the patients having a severe infection requiring admittance in a Hospital (H). The mean duration  $\tau$  spent in a class gives the corresponding mean outflux rate per time unit:  $1/\tau$ . The coefficient  $\beta$  is the transmission rate. The fraction of infected (and infectious) individuals who are symptomatic is  $\xi$ ; the fraction of infective people who have mild symptoms is  $\kappa$ ; the ratio of patients in Hospital who pass away is  $\eta$ . The proportion of patients in Hospital requiring Ultimate care (U) in Intensive Care Units (ICU's) is  $\mu$ . The coefficient  $\lambda_0$  is the tuning factor to calibrate the quality of the containment (C).

Fianlly, the ODE system of the HOPE model corresponding to the flow diagram in Fig. 1 reads as a nonlinear Cauchy problem on the time interval  $(0, T)$ :

$$\begin{cases} S'(t) = -\beta(I + A)S/N - \lambda_0\omega S + \chi C \\ C'(t) = \lambda_0\omega S - \chi C \\ E'(t) = \beta(I + A)S/N - \alpha E \\ I'(t) = \alpha\xi E - \gamma I \\ A'(t) = \alpha(1 - \xi)E - \nu A \\ Q'(t) = \gamma\kappa I - \rho Q \\ H'(t) = \gamma(1 - \kappa)I - \delta H \\ D'(t) = \delta\eta H \\ O'(t) = \delta(1 - \eta)H \\ R'(t) = \nu A + \rho Q \end{cases} \quad \text{for all } t \in (0, T), \quad (1)$$

and

$$U'(t) = \mu H'(t), \quad \text{for all } t \in (0, T), \quad (2)$$

Notation	Description (Number in each class)
S	Susceptible individuals likely to become infective
E	Exposed people in the latent period
A	Asymptomatic infectious individuals
I	Symptomatic Infective individuals (with mild or severe infection)
Q	Infected people with mild symptoms isolated in Quarantine
H	Infected people with severe symptoms cured in Hospital
U	People with SARS needing Ultimate care in ICU of Hospital
D	Deaths (caused by Covid-19) in Hospital
O	Cured people Outflux from Hospital
R	Recovered people with at least temporary immunity for several months
C	Susceptible people in the Containment class
s, e, a, i, etc...	Fractions of the population in the classes above, e.g. $s := S/N$

Table 1: Summary of variables of the HOPE model

where the parameters  $\alpha, \beta, \gamma, \delta, \eta, \kappa, \mu, \nu, \omega, \rho, \xi, \chi$  and  $\lambda_0$  are non-negative coefficients. It is clear that the sum of all derivatives in (1) equals 0 and the sum of all class quantities equals the constant population size  $N$ . Thus, the last differential equation in (1) can be possibly omitted and the class  $R$  is then calculated by:

$$R(t) = N - S(t) - C(t) - E(t) - I(t) - A(t) - Q(t) - H(t) - D(t) - O(t), \quad \text{for all } t \in (0, T). \quad (3)$$

The ODE system is supplemented by the initial conditions at time  $t = 0$ :

$$\begin{aligned} I(0) = I_0 > 0, \quad A(0) = A_0 = (1 - \xi) I_0 / \xi, \quad C(0) = E(0) = Q(0) = R(0) = 0, \\ H(0) = H_0, \quad U(0) = U_0, \quad D(0) = D_0, \quad O(0) = O_0 \\ S(0) = N - I_0 - A_0 - H_0 - D_0 - O_0. \end{aligned} \quad (4)$$

where  $\xi$  is the fraction of symptomatic individuals among all the infectives. The initial value problem (1,2,4) is well-posed on the time interval  $(0, T)$  by the Cauchy-Lipschitz theorem, e.g. [16], since the right-hand sides are smooth functions.

The basic reproduction number  $\mathcal{R}_0$  is defined at the outbreak of epidemic (ideally with no control measures) as the average number of secondary infections that occur when one infective is introduced into a completely susceptible host population during the whole infectious period of this infective. That means a non zero initial value  $I_0 > 0$ . Then it appears by a global stability analysis, e.g. for the SIR model [1], the fundamental criterion between two stable equilibria:

If  $\mathcal{R}_0 > 1$ , then the epidemic can start and spread. If  $\mathcal{R}_0 \leq 1$ , then the epidemic declines until extinction.

In our case, the basic reproduction number  $\mathcal{R}_0$  of the HOPE model should be determined rigorously by a global stability analysis, e.g. [16, 17], of the ODE system (1). We can also deduce  $\mathcal{R}_0$  from previous studies having some analogies with our model, e.g. [18, 19]. Then,  $\mathcal{R}_0$  appears as the sum of two terms corresponding to the two infective branches in Fig. 1:

$$\mathcal{R}_0 = \xi \frac{\beta s_0}{\gamma} + (1 - \xi) \frac{\beta s_0}{\nu} = \beta s_0 \left( \frac{\xi}{\gamma} + \frac{1 - \xi}{\nu} \right), \quad \text{with } s_0 = S_0/N \approx 1. \quad (5)$$

This equation will allow us to determine the transmission rate  $\beta$  for a given  $\mathcal{R}_0$ .

Since we are facing a novel coronavirus, the host population has not yet any infection-acquired immunity. Thus, in the absence of control measures at the outbreak of the epidemic, the initial fraction of susceptibles verifies  $s_0 \approx 1$ . Then, let us recall the proportion  $p^*$  of total population having already been infected that is required to prevent us from a new stage of epidemic spread, *i.e.* to reach the herd immunity threshold. From the above stability criterion, we have now:

$$\mathcal{R}_0 (1 - p) \leq 1, \quad \text{i.e. } p \geq p^* := 1 - 1/\mathcal{R}_0. \quad (6)$$

In conclusion, the main originality of the present model compared to other known models of Covid-19 spread in France [4, 8, 9, 10, 11], is that the HOPE model follows daily four crucial and reliable indicators  $H, U, O, D$  which are

Notation	Description	Default	Range / source
$\mathcal{R}_0$	basic reproduction number	5	(2.5 – 5) [11, 20]
$\beta$	effective transmission rate per time unit (day)	0.833	from Eq. (5)
$\tau_e = 1/\alpha$	mean duration of latent infectious period	5 days	(3 – 5) [3, 5]
$\tau_i = 1/\gamma$	delay from infectious to confirmation	4 days	(2 – 6) [3, 5]
$\tau_a = 1/\nu$	mean period for Asymptomatic people to become non infectious	14 days	
$\xi$	proportion of Symptomatics among all infectives	0.80	
$\kappa$	proportion of mild infections among symptomatic people	0.80	from [21]
$\tau_q = 1/\rho$	mean duration of self isolation in Quarantine	14 days	
$\tau_h = 1/\delta$	mean cure period in Hospital or before Death	15 days	
$\eta$	probability of Death from Covid-19 in Hospital	0.25	fitted
$\mu$	fraction of patients in Hospital requiring Ultimate care in ICU	0.21	fitted
$\tau_c = 1/\chi$	duration of complete lockdown	60 days	(30 – 75)
$\omega$	efficiency ratio of complete lockdown	0.75	(0 – 0.95)
$\lambda_0$	tuning factor to calibrate the quality of lockdown per time unit	1/5.85	fitted

Table 2: Summary of parameters of the HOPE model

reported each evening by the French Public Healthcare system (Santé Publique France SPF<sup>3</sup>) since the beginning of the lockdown. Indeed, the tuning factor  $\lambda_0$  will be adjusted so that the model results fit at the best these data.

## 2.2 Estimating the parameters and calibration of the model

The baseline assumption for our reference simulations is that the basic reproduction number of Covid-19 epidemic equals  $\mathcal{R}_0 = 5.0$ , although simulations are also made with  $\mathcal{R}_0$  within the range (2.5 – 5). Indeed, many Chinese works show estimates of  $\mathcal{R}_0$  within the range (2.2 – 3.5), see [12, 13, 14] and the references therein. Besides, it is estimated  $\mathcal{R}_0 = 2.48$  in [8], whereas it is estimated  $\mathcal{R}_0 = 4.8$  in [11] taking into account a long viral shedding period of 20 days. The last result is in close agreement with the work [20] which finds  $\mathcal{R}_0 = 4.7$  and 6.3. Given the  $\mathcal{R}_0$  value, then the transmission rate  $\beta$  is calculated from Eq. (5) using the estimated values of the other parameters in Table 2.

The crucial unknowns for the modelling are the real number of both symptomatic and asymptomatic infectives. It is well-known that the number of confirmed Covid-19 cases by PCR test and reported by Santé Publique France (SPF) is largely under-estimated since the rate of tracing in France was till now very weak. Indeed at the end of March 2020, it is estimated in [4] that the percentage of total population infected in France is 3% [1.1% – 7.4%], that is about 2 millions persons, whereas it is reported by SPF only 52, 128 confirmed cases on March 31, 2020. That is the reason why the HOPE model does not especially follow this indicator which is not reliable for the calibration. However, we also need for our modelling the proportion  $(1 - \xi)$  of Asymptomatic people that is not known precisely. It is often reported that there is 50% or more Asymptomatic people but it was also estimated a proportion of 20% asymptomatic patients, *i.e.*  $\xi = 0.80$ , on the Diamond Princess cruise ship that was quarantined in Japan. Thus, we shall keep  $\xi = 0.80$  as the default value but this should be confirmed.

The starting date  $t = 0$  for all the simulations is March 17, 2020 which corresponds to the beginning of the general lockdown in France. The initial conditions are summarized in Table 3. The unknown value  $I_0$  is chosen within the low range of (30, 000 – 90, 000) reported by SPF on March 21, 2020 to be the most probable number of infected persons in France. Then, the evolutions of the different classes are calculated over the duration of the containment period, either  $\tau_c = 60$  or  $\tau_c = 75$  days, and later after the lockdown. Recall that the lockdown duration in Wuhan was 76 days.

Therefore, we first define the reference simulation as the case with the complete lockdown applied since March 17, 2020 for a duration of 60 days or possibly 75 days. Clearly, the lockdown in France is less strict and complete than in China. Contagions can still occur inside the contained households, in the open shops and supermarkets, in the hospitals or at work (for any activity impossible by telework) and in the public transports, even if then are largely restricted. Indeed, while the incubation period is reported within the range (5 – 7) days, the Hospitals and ICU's have still many entrances for Covid-19 infection after one month lockdown. Moreover, it is supposed that there exists a non negligible proportion of asymptomatic infective people. For all these reasons, we assume that after a few days of transient regime from the beginning of lockdown, we have reached a permanent containment regime with an average efficiency ratio equal to  $\omega = 75\%$ , chosen arbitrarily. This reference case allows us to fit the initial condition  $I_0$  in Table 3 and the

<sup>3</sup>Santé Publique France (SPF): url=<https://www.santepubliquefrance.fr>

Notation	Description	Default	Range / source
$N$	total population size	$67 \cdot 10^6$	
$I_0$	number of confirmed and reported Covid-19 cases	7,730	SPF
$H_0$	number of patients in Hospital	2579	SPF
$U_0$	number of patients in Ultimate care ICU	699	SPF
$O_0$	number of patients in Outflux going out Hospital	602	SPF
$D_0$	number of Deaths in Hospital	175	SPF
$I_0$	number of symptomatic infectives taken into account	35,000	fitted

Table 3: Summary of initial conditions at the beginning of lockdown on March 17, 2020

tuning factor  $\lambda_0$  in Table 2. Indeed, the model is calibrated by adjusting the factor  $\lambda_0$  in such a way that the numerical results of the main indicators:  $H$ ,  $U$ ,  $O$  and  $D$ , fit at the best the corresponding data reported daily by SPF. Then, the comparisons between the reference case and other cases investigating variations of the lockdown efficiency ratio  $\omega$ , including the case of no containment with  $\omega = 0$ , can be considered as relevant.

### 3 Results and discussion

We present hereafter the results obtained by numerical simulation using Scilab<sup>4</sup> ode package, including Runge-Kutta methods, to solve the ODE system (1,2,4) of the HOPE model. All the simulations are made with the time step  $\delta t = 1/3$  (8 hours) or  $\delta t = 1/6$  to verify that the mesh convergence is reached.

#### 3.1 The dangerous strategy "do nothing" leading to a natural disaster

Let us first consider the scenario "do nothing" that does not apply any general containment, *i.e.* with  $\omega = 0$ , apart from reported confirmed patients who are isolated in quarantine for mild infections or admitted in Hospital for severe infections, as described by the HOPE model. The result for the reference case with  $\mathcal{R}_0 = 5$  and a proportion of 20% of asymptomatic infectives, *i.e.*  $\xi = 0.80$ , is shown in Fig. 2. The corresponding number of deaths after 180 days, indicated in the caption, is 2.77 millions. In these results, the number of patients in Hospital or Ultimate ICU's are not significant since they are overwhelmed by the tsunami wave of the infection. Other cases with 50% of asymptomatic infectives or with  $\mathcal{R}_0 = 3$  are shown in 3. As expected, the resulting number of deaths is far more sensitive to the fraction of asymptomatic people than to the value of  $\mathcal{R}_0$ . Indeed, the asymptomatic people have a very weak form of infection and thus the probability to die with Covid-19 is nearly 0.

To validate our simulation code of the model, it is interesting to compute the fraction  $p_\infty$  of the total population who have been finally infected at the end of the epidemic and to compare it with the theoretical result. Indeed, it is stated early in [15] and also in [1] on the basis of the SIR model that  $p_\infty$  is the solution of the following equation:

$$p_\infty \mathcal{R}_0 + \ln(1 - p_\infty) = 0. \quad (7)$$

This result should also hold for a more complex model whatever the number of branches if we take care to count the cumulative number of all the individuals who have been finally in contact with the infection. Hence for our model, we must have  $p_\infty$  equal to the sum below taken after a sufficiently long time  $t_\infty$  of simulation:

$$p_\infty = R(t_\infty) + O(t_\infty) + D(t_\infty). \quad (8)$$

The Table 4 shows an excellent agreement for this verification.

We conclude that the strategy "do nothing" is very dangerous to apply since it requires that the Public Healthcare system must be able to trace, isolate and care all the infective people and their contact cases. Considering that the Covid-19 infection provides many asymptomatic people, this seems absolutely impossible.

<sup>4</sup>Scilab: [url=https://www.scilab.org](https://www.scilab.org)

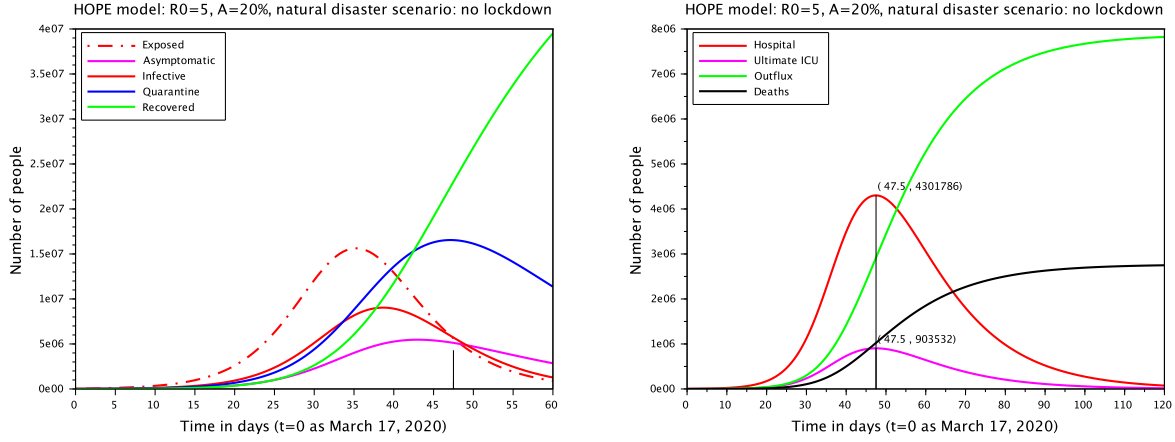


Figure 2: Evolution of number of people in all the classes except Susceptible: catastrophic scenario with no containment –  $\mathcal{R}_0 = 5$ ,  $\xi = 0.80$ :  $D(180 d) = 2.77 \cdot 10^6$  deaths.

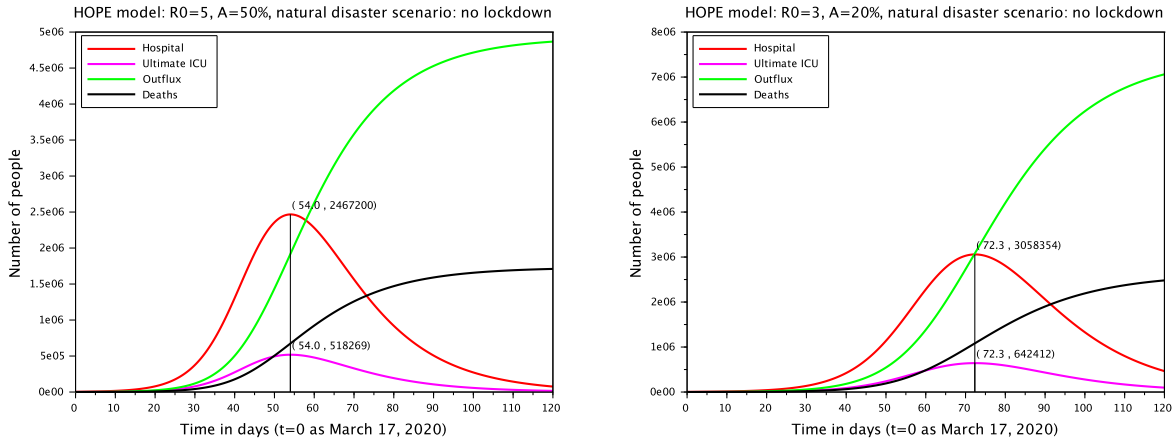


Figure 3: Evolution of number of people in the classes of the main indicators: catastrophic scenario with no containment – Left:  $\mathcal{R}_0 = 5$ ,  $\xi = 0.50$ :  $D(180 d) = 1.73 \cdot 10^6$  deaths – Right:  $\mathcal{R}_0 = 3$ ,  $\xi = 0.80$ :  $D(180 d) = 2.62 \cdot 10^6$  deaths

$p_\infty$	$\mathcal{R}_0 = 2.5$	$\mathcal{R}_0 = 3$	$\mathcal{R}_0 = 5$
Theoretical	0.8926	0.9405	0.9930
Present	0.8925	0.9405	0.9930

Table 4: Comparison of  $p_\infty$  versus  $\mathcal{R}_0 = 2.5$

### 3.2 The mitigation strategy by complete lockdown

Due to the urgency of the situation in the Public Healthcare system, it was decided to apply a complete lockdown with household containment starting on 17 March 2020 in addition to personal protection measures and social distancing. Let us evaluate the impact of the general lockdown starting with the simulation of the reference case:  $\mathcal{R}_0 = 5$ ,  $\xi = 0.80$  and  $\tau_c = 60$  days of containment with an average efficiency ratio of  $\omega = 0.75$ . The result of the latter scenario is shown in Fig. 4. As indicated in particular in the caption, the number of patients in hospitals and ICU's should be  $H = 16,516$  and  $U = 3,626$ , respectively and the number of deaths should reach  $D = 23,240$  after 60 days of

containment. Compared to the case with no lockdown in Fig. 2, this shows the tremendous impact of the lockdown in terms of saving human lives. Indeed, the number of deaths is divided by the factor 120.

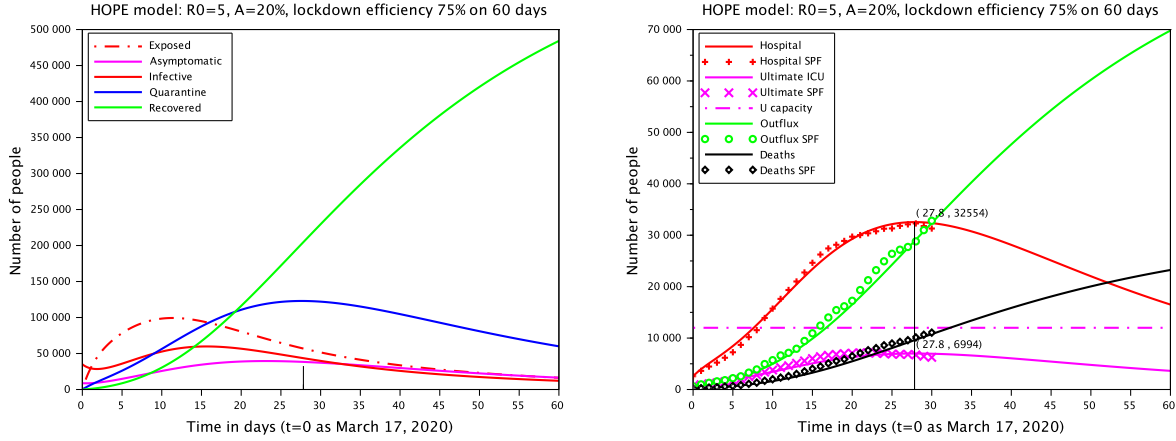


Figure 4: Evolution of number of people in the classes except Susceptible and Contained with complete lockdown:  $\tau_c = 60$  days, efficiency ratio  $\omega = 0.75$  – At 60 days:  $H = 16,516$ ,  $U = 3,626$ ,  $D = 23,240$  deaths,  $(I + A) = 28,522$ ,  $S/N = 0.114$ ,  $C/N = 0.876$ ,  $(R + O + D)/N = 0.862\%$ . Ultimate capacity is taken as 12,000 beds in ICU’s

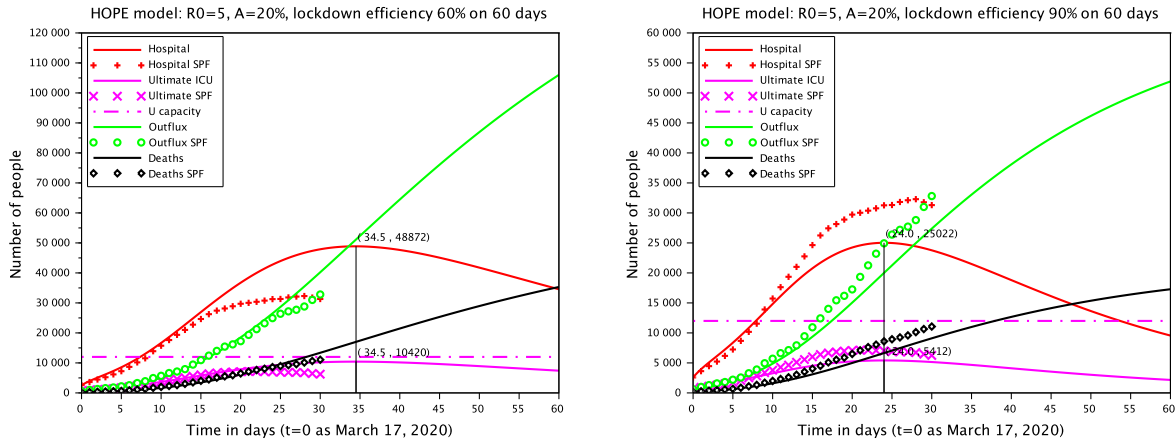


Figure 5: Evolution of number of people in the classes of indicators with complete lockdown of  $\tau_c = 60$  days. Left: efficiency ratio  $\omega = 0.60$  – At 60 days:  $H = 34,544$ ,  $U = 7,412$ ,  $D = 35,315$  deaths,  $(I + A) = 68,203$ ,  $S/N = 13.7\%$ ,  $C/N = 0.846$ ,  $(R + O + D)/N = 1.33\%$  – Right: efficiency ratio  $\omega = 0.90$  – At 60 days:  $H = 9,558$ ,  $U = 2,165$ ,  $D = 17,280$  deaths,  $(I + A) = 14,830$ ,  $S/N = 9.69\%$ ,  $C/N = 0.896$ ,  $(R + O + D)/N = 0.632\%$

It is clear that the absolute value of  $\omega = 75\%$  for the efficiency has only a subjective meaning on the quality of the lockdown since it was chosen in arbitrary way. However, the comparisons with other scenarii varying around the reference case are surely relevant. Hence, it is interesting to evaluate variations of the efficiency ratio on the main indicators:  $H$ ,  $U$ ,  $O$ ,  $D$ , chosen in this study. This is in fact all the more interesting than it is the first time in the History that many populations are effectively contained all over the world. The comparison in Fig. 5 show the cases with  $\omega = 60\%$  and  $\omega = 90\%$ , respectively. Next, small variations of  $\pm 5\%$  in the efficiency ratio around the reference case with  $\omega = 75\%$  and  $\tau_c = 60$  days are summarized in Table 5 showing a variation of  $\pm 3,000$  deaths after 60 days of lockdown. Therefore, the conclusion that we may have in mind is that a small effort of  $+1\%$  in the efficiency of the lockdown saves 600 human lives; reversely, a small relaxation of  $-1\%$  in the lockdown respect costs 600 deaths more.

Efficiency	$\omega = 70\%$	$\omega = 75\%$	$\omega = 80\%$
Hospital maximum	36,500 +12.1%	32,554	29,479 -9.50%
Ultimate maximum	7,822 +11.8%	6,994	6,348 -9.24%
Deaths at 60 days	26,280 +13.1%	23,240	20,831 -10.4%

Table 5: Influence of small variations  $\pm 5\%$  of efficiency on the reference case of lockdown:  $\omega = 75\%$ ,  $\tau_c = 60$  days

The scenario with a longer lockdown  $\tau_c = 75$  days is also calculated and represented in Fig. 6. In that case, the number of patients in hospitals and ICU's should be reduced to  $H = 7,910$  and  $U = 1,819$ , respectively and the number of deaths should reach  $D = 24,932$  after 75 days of containment.

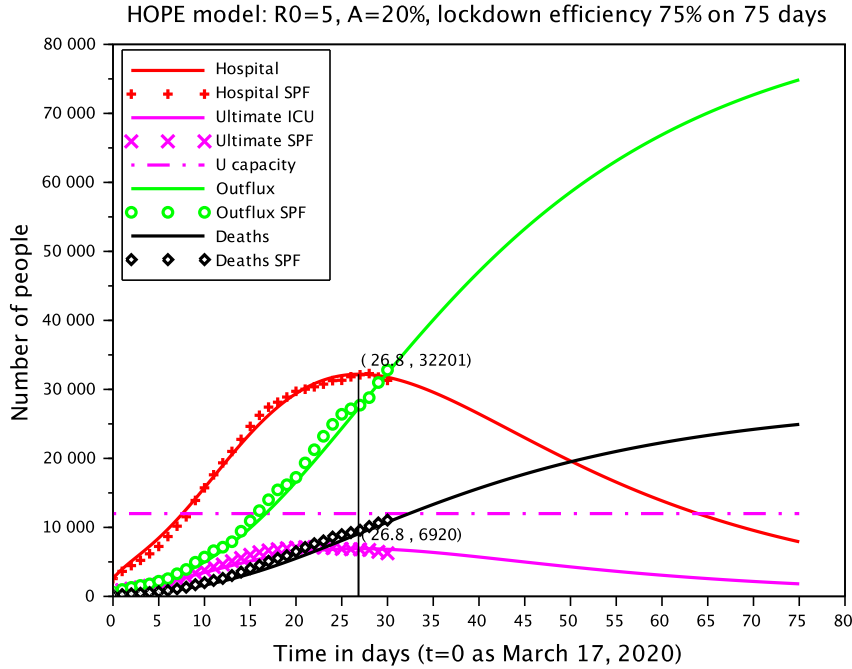


Figure 6: Evolution of number of people in the classes of indicators with complete lockdown:  $\tau_c = 75$  days, efficiency ratio  $\omega = 0.75$  – At 75 days:  $H = 7,910$ ,  $U = 1,819$ ,  $D = 24,932$  deaths,  $(I + A) = 11,883$ ,  $S/N = 0.0953$ ,  $C/N = 0.895$ ,  $(R + O + D)/N = 0.916\%$ . Ultimate capacity is taken as 12,000 beds in ICU's.

### 3.3 Secondary wave and strategy "stop and go" after the lockdown

At the end of the lockdown period, it is important to notice that the proportion of the total population who has been already infected by Covid-19, and thus having acquired immunity is expected to be very small. Indeed, the objective of the containment is exactly to prevent the large majority of population from meeting the infection. This is confirmed with what we have calculated: after 60 or 75 days lockdown, we get  $(R + O + D)/N = 0.862\%$  and  $(R + O + D)/N = 0.916\%$ , respectively; see Fig. 4 and Fig. 6. By taking account of the additional value of this proportion before our simulations, that means that 1 or 2% of the total population only has met the Covid-19 infection. This is thus very far from the theoretical fraction  $p^* = 1 - 1/\mathcal{R}_0$  in Eq. (6) to reach the herd immunity preventing us from a new wave of epidemic. Indeed, we have  $p^* = 60\%$ ,  $66\%$  and  $80\%$  for  $\mathcal{R}_0 = 2.5$ , 3 or 5. Therefore, whatever the duration and efficiency of the lockdown, the outbreak of a secondary wave of infection is expected a few days

after the end of lockdown. This is confirmed by the simulation results given in Fig. 7 for a 60 days lockdown. At this time  $t = \tau_c$ , the ratio  $\omega$  takes the value 0 and all the people in the Containment (C) are suddenly released inside the Susceptible (S) population, as shown in Fig. 7-Left. The outbreak of a secondary wave of infection also occurs after 75 days lockdown as well, as shown in Fig. 8.

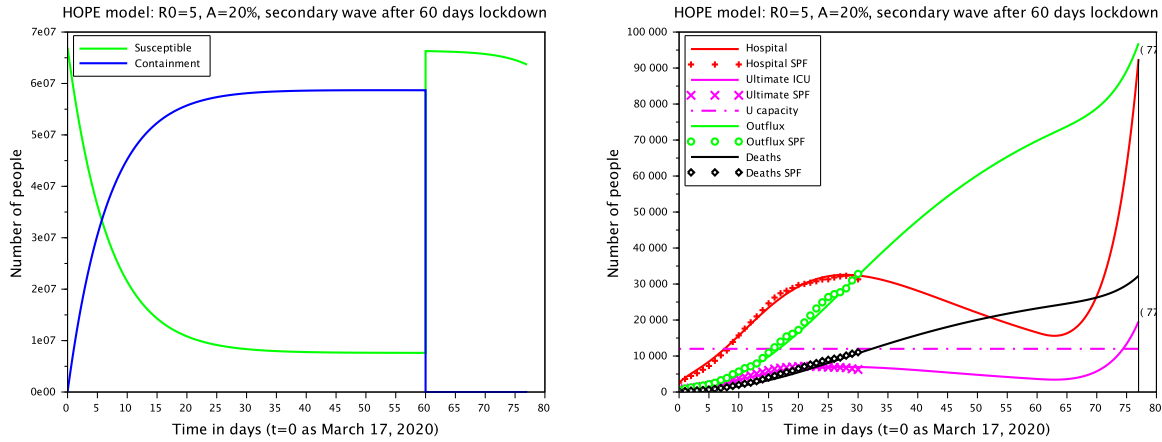


Figure 7: *Outbreak of a secondary wave after a complete lockdown of  $\tau_c = 60$  days and efficiency ratio  $\omega = 0.75$ .*

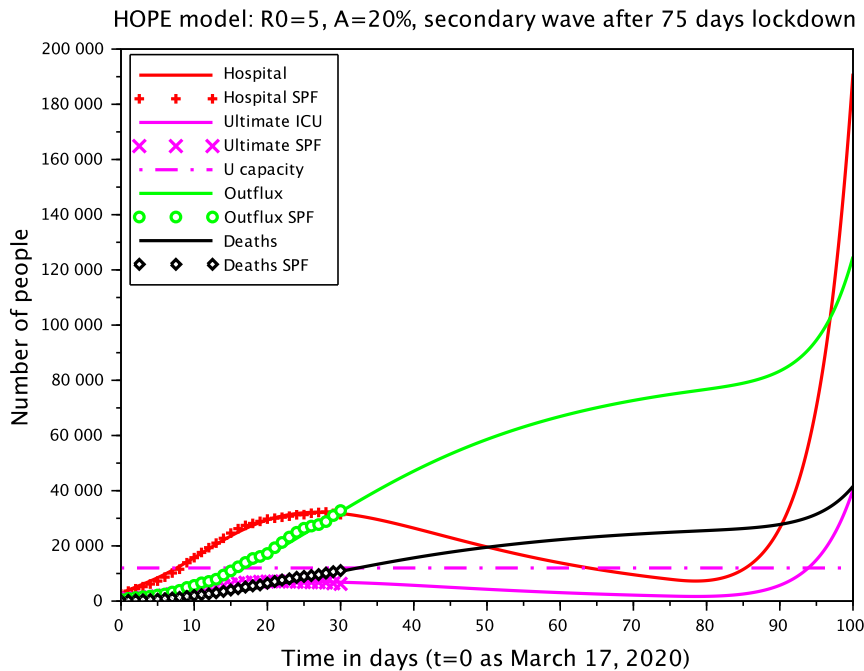


Figure 8: *Outbreak of a secondary wave after a complete lockdown of  $\tau_c = 75$  days and efficiency ratio  $\omega = 0.75$ .*

It is important to notice that the secondary wave goes fast and strong only after 5 or 10 days after the end of lockdown. Then, the hospitals and ICU's are thus saturated very fast which prevent us from applying the strategy "stop and go" reported by some media. Therefore, the stop-and-go cyclic strategy to reach the herd immunity stage after stage does not seem a reasonable and sustainable solution. Indeed, this should involve to alternate several lockdown periods of 1 or 2 months with release periods of 5 or 10 days only, to avoid the complete saturation of hospitals.

### 3.4 The suppression strategy of "successive damping cascade" after lockdown

The outbreak of a secondary wave after the general lockdown studied in the previous Section 3.3 shows that the further waves after lockdown cannot remain free of control as long as the herd immunity is not reached. This explains why managing the after-lockdown is a very touchy operation. Hereafter, we propose a strategy called "successive damping cascade" to suppress the epidemic within several damped waves after the lockdown until an efficient vaccine deployment. Hence, this operation should be sufficiently slow to gradually release the contained people into the Susceptible population.

Let us first investigate the case of a single secondary wave after the one controlled by the lockdown. At the time  $t = \tau_c$ , the efficiency ratio  $\omega$  of the containment is switched from its nominal value 0.75 to a value  $\omega_{min}$ , with  $0 < \omega_{min} < 0.75$ , and then the proportion  $\omega_{min} C$  of contained people is kept into (C) whereas the remaining part  $(1 - \omega_{min}) C$  is released into the Susceptible population (S). The objective will be to keep for example the variable  $U$  below the threshold value  $U_c := 5000$  (normal number of beds in ICU's) while minimizing the number of deaths. Here, we shall roughly estimate  $\omega_{min}$  semi-empirically using the numerical simulations although this surely could be carried out using the mathematical control theory that deserves a further specific work. Two examples are given in Fig. 9 with  $\omega_{min} = 0.525$  or  $\omega_{min} = 0.638$  which results in far less deaths after the complete lockdown of 60 days and efficiency ratio of 75%. These results are far better after a longer lockdown of 75 days as shown in Fig. 10.

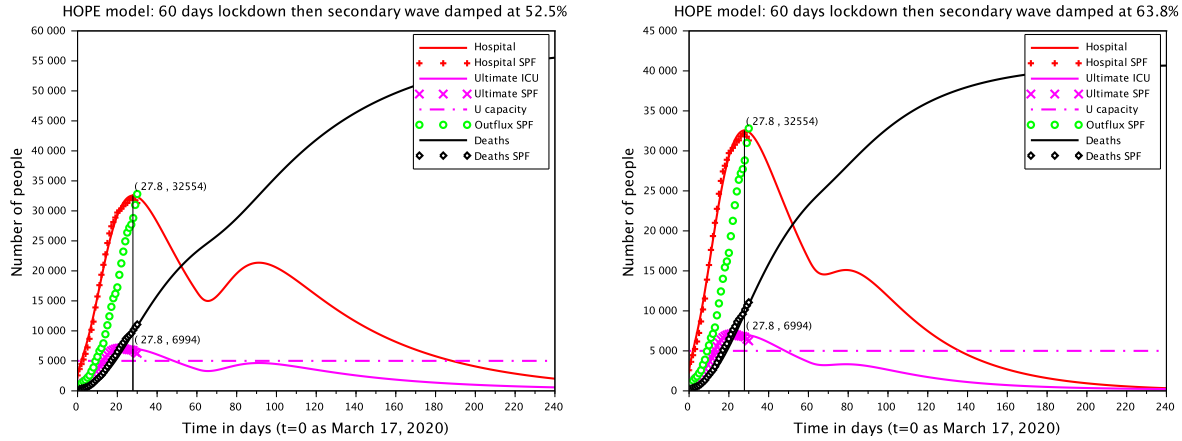


Figure 9: *Outbreak of a secondary wave damped at the ratio  $\omega_{min}$  after a complete lockdown of  $\tau_c = 60$  days and efficiency ratio  $\omega = 0.75$  – Left:  $\omega_{min} = 0.525$  – Right:  $\omega_{min} = 0.638$ .*

Now we can investigate the outbreak of another damped tertiary wave by using the same principle and thus reproducing the operation described above after the secondary wave at time  $t = \tau_c + \tau_r$ , where the release time  $\tau_r$  is also optimized. An example is shown in Fig. 11 after 75 days lockdown that yields a final efficiency ratio of the containment equal to 42% within 240 days. Then the same procedure can be iterated to get a final ratio going to zero. This strategy can be improved a lot by taking into account the capacity of the Public Healthcare system to practice an efficient policy of massive and fine screening and then of isolating all the confirmed cases and their contact cases and possibly an important fraction of the asymptomatic infective people.

Finally, it is important to point out that such scenarii after the lockdown represent only states of unstable local equilibrium in the country considered as a closed system. That means that a small perturbation, like new enhancement of untraced infectives coming from inside or outside, can produce an uncontrolled tsunami wave of infection as long as the herd immunity is not reached. Nevertheless, this strategy of "successive damping cascade" is a suitable temporary solution waiting for an efficient medical treatment of Covid-19, preventive or not, until the deployment of a vaccine.

## 4 Conclusion and perspectives

These first results must be considered as early estimations in France due to some uncertainties which can be minimized further when the infection will be far better screened by the Public Healthcare system throughout a large majority of the population. However in the absence of a vaccine, it is clear that the strategy "do nothing" with no containment at all and letting the nature play with the herd immunity is very dangerous and resulting in a real disaster. We have also pointed

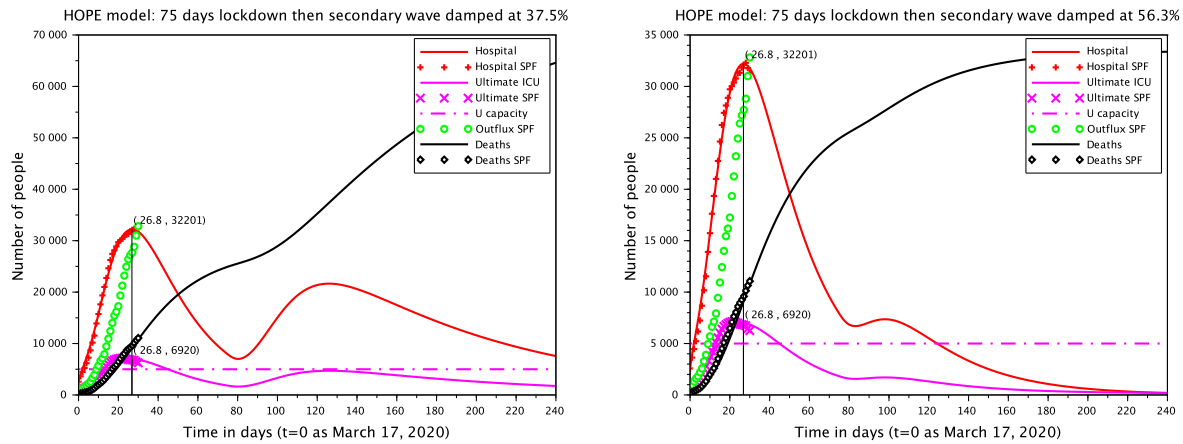


Figure 10: *Outbreak of a secondary wave damped at the ratio  $\omega_{min}$  after a complete lockdown of  $\tau_c = 75$  days and efficiency ratio  $\omega = 0.75$  – Left:  $\omega_{min} = 0.375$  – Right:  $\omega_{min} = 0.563$ .*

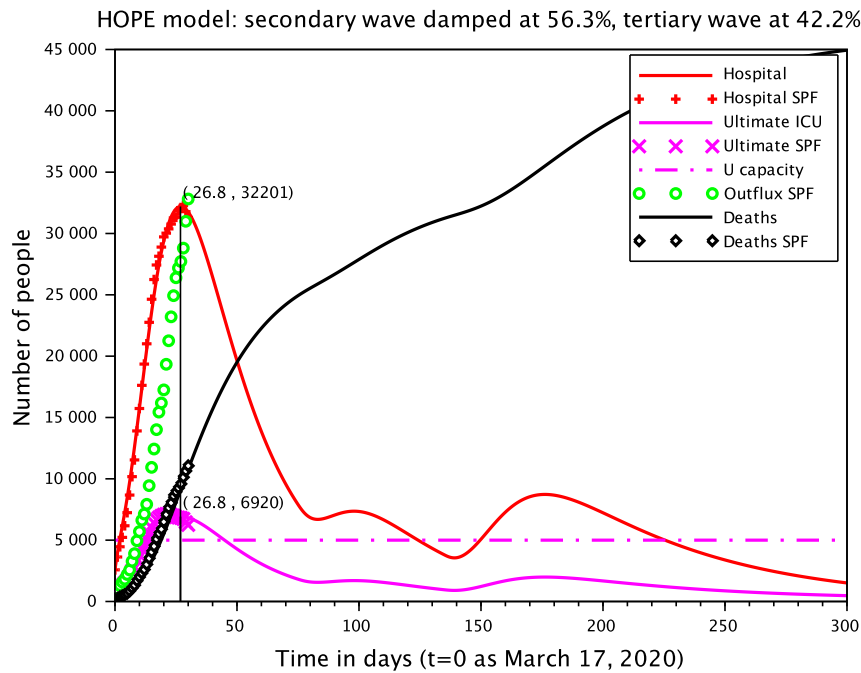


Figure 11: *Outbreak of a secondary wave damped at the ratio 56.3%, then a tertiary wave damped at 42.2% with the release time  $\tau_r = 60$  days after a complete lockdown of  $\tau_c = 75$  days and efficiency ratio  $\omega = 0.75$ .*

out the importance of finding a clever strategy to gradually suppress the general lockdown and proposed the suitable suppression strategy of "successive damping cascade".

In the future weeks, we are going to improve the model, to get rid of some limitations and to finer calibrate the parameters with newly available and reliable data. This will allow us to capture more precisely different scenarii on how to suppress the containment gradually in order to avoid a possible uncontrolled wave of epidemic. Indeed, we have shown that the mitigation by general lockdown does produce, as expected, far less recovered people than necessary to reach the herd immunity.

**Conflicts of interest and Sponsoring.**

The *HOPE* project is a personal research program of the author to contribute to Covid-19 Epidemic challenge which, up to now, has received no public or private grant from any institution or company. So, the author receives no specific funding for this project and declares no competing financial or personal interests.

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**Recall.**

**University, as School or Hospital, are not companies; Health, Education, Knowledge and Research are not goods. If I give you my pen, then it is yours and no more mine for sure. But, if I give you one idea, then can you tell me to whom it belongs to from now ?**

**References**

- [1] H. W. Hethcote. The Mathematics of Infection Diseases. *SIAM Rev.*, 42(4):599–653, 2000.
- [2] R. M. Anderson, H. Heesterbeek, D. Klinkenberg, and T. D. Hollingsworth. How will country-based mitigation measures influence the course of the COVID-19 epidemic ? *The Lancet*, 395(10228):931–934, 2020.
- [3] N. M. Ferguson *et al.* Impact of non-pharmaceutical interventions (NPIs) to reduce COVID-19 mortality and healthcare demand. *Imperial College COVID-19 Response Team*, (16 March):1–20, 2020.
- [4] S. Flaxman, S. Mishra, and A. Gandy *et al.* Estimating the number of infections and the impact of non-pharmaceutical interventions on COVID-19 in 11 european countries. *Imperial College COVID-19 Response Team*, (30 March):1–35, 2020.
- [5] A. J. Kucharski, T. W. Russell, C. Diamond, Y. Liu, J. Edmunds, S. Funk, and R. M. Eggo. Early dynamics of transmission and control of COVID-19: a mathematical modelling study. *The Lancet Infectious Diseases*, pages 1–7, 2020.
- [6] C. Fraser, S. Riley, R. M. Anderson, and N. M. Ferguson. Factors that make an infectious disease outbreak controllable. *Proc. Nat. Acad. Sci. USA*, 101(16):6146–6151, 2004.
- [7] M. Lipsitch, T. Cohen, and B. Cooper *et al.* Transmission dynamics and control of severe acute respiratory syndrome. *Science*, 300(5627):1966–1970, 2003.
- [8] R. Djidjou-Demasse, Y. Michalakis, M. Choisy, M. T. Sofonea, and S. Alizon. Optimal COVID-19 epidemic control until vaccine deployment. *medRxiv*, pages 1–20, 2020.
- [9] L. Di Domenico, G. Pullano, P. Coletti, N. Hens, and V. Colizza. Report#8: Expected impact of school closure and telework to mitigate COVID-19 epidemic in france. Technical report, March 2020.
- [10] P. Magal and G. Webb. Predicting the number of reported and unreported cases for the COVID-19 epidemic in south korea, italy, france and germany. *SSRN*, 2020.
- [11] L. Roques, E. K. Klein, J. Papaix, and S. Soubeyrand. Mechanistic-statistical sir modelling for early estimation of the actual number of cases and mortality rate from COVID-19. *medRxiv*, pages 1–9, 2020.
- [12] X. Liu, G. Hewings, S. Wang, M. Qin, X. Xiang, S. Zheng, and X. Li. Modelling the situation of COVID-19 and effects of different containment strategies in china with dynamic differential equations and parameters estimation. *medRxiv*, 2020.
- [13] L. Peng, W. Yang, D. Zhang, C. Zhuge, and L. Hong. Epidemic analysis of COVID-19 in china by dynamical modeling. *medRxiv*, pages 1–18, 2020.
- [14] Y. Zhang, C. You, and Z. Cai *et al.* Prediction of the COVID-19 outbreak based on a realistic stochastic model. *medRxiv*, (10 March 2020):1–38, 2020.
- [15] W. O. Kermack and A. G. McKendrick. A contribution to the mathematical theory of epidemics. *Proc. Royal Soc. London A*, 115(772):700–721, 1927.
- [16] S. Benzoni-Gavage. *Calcul différentiel et équations différentielles*. Mathématiques appliquées pour le Master (SMAI). Dunod (Paris), 2ème éd., 2014.

- [17] L. Perko. *Differential Equations and Dynamical Systems*, volume 7 of *Texts in Applied Mathematics*. Springer-Verlag (New York), 2nd ed., 1993.
- [18] H. W. Hethcote, M. Zhién, and L. Shengbing. Effects of quarantine in six endemic models for infection diseases. *Math. Biosciences*, 180:141–160, 2002.
- [19] M. Y. Li, H. L. Smith, and L. Wang. Global dynamics of an seir epidemic model with vertical transmission. *SIAM J. Appl. Math.*, 62(1):58–69, 2001.
- [20] S. Sanche, Y. Ting Lin, and C. Xu *et al.* The novel coronavirus 2019-nCoV is highly contagious and more infectious than initially estimated. *arXiv*, (2002.03268):1–11, 2020.
- [21] J.-F. Delfraissy. Avis du conseil scientifique Covid-19. Technical Report 12 mars, Palais de l’Elysée, 2020.