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A model of covid-19 transmission to understand the effectiveness of the containment measures: application to French data

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Abstract

The main objective of this paper is to answer the following question: are the containment measures imposed by the majority of world governments effective and sufficient to stop the epidemic of COVID-19? Thanks to a mathematical model that we have developed, we have been able to show that containment measures appear to have slowed the growth of the outbreak. Nevertheless these measures remain only effective as long as a very large fraction of the population remains confined. This means that if no further action is taken, a new wave of contamination larger than the former is expected very shortly after the end of containment date. The combined measures of the large scale test of detection of infected individuals and the social distancing were shown to be effective to overcome the outbreak. While taking separately the both latter measures is not sufficient to prevent a second wave.

Keywords: COVID-19; Basic reproduction ratio, containment measures, new wave
Mathematics Subject Classification (2000): 92D25; 37N25; 92D30.

1. Introduction

In December 2019, a disease that appeared in central China precisely in the city of Wuhan (Hubei Province) started to take its toll. On January 7, 2020, Chinese authorities admitted that the country was facing an epidemic caused by a new virus from the coronavirus family. First named "2019-nCoV", this virus will then be definitively named COVID-19 or SARS-COV-2 by the World Health Organization (WHO) [20]. COVID-19 disease has passed in a few weeks from a localized epidemic to a pandemic. This disease is now a public health emergency of international level and is currently affected more than 200 States with more than 250,000 deaths and nearly 3 millions people infected according to WHO. It is contagious with human-to-human

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transmission via respiratory droplets or by touching contaminated surfaces and then touching one's face. The most common symptoms are fever, cough, and difficulty breathing, but it can cause acute respiratory distress, which is often fatal.

The spread of the disease has enormous consequences for all sectors of society, endangering economics and finance of almost all countries in the world. In the current state of knowledge, there is no preventive vaccine, biomedical means of prevention or specific therapeutic means. International, national and local control strategies are essentially based on barrier measures, social distancing, wearing masks, confinement, screening and diagnosis according to various methods and symptomatic treatment. Today in different countries, research in all its dimensions has become an absolute priority. In particular any research which can help to understand, prevent and treat Covid 19 is encouraged at the highest political level of many countries. Following this urgency, models have already been proposed in order to study the dynamics and to control the pandemic [8, 13, 17, 14, 15, 16, 3]. But these models do not make explicitly the distinction between the confined individual, the quarantined individual and the isolated individual for the forecasting. In this paper, we propose a new model which could help to understand the effectiveness of the containment measures adopted across countries. The model will be used to predict different scenarios of the possible resurgences of the new waves of epidemic in France.

The paper is organized as follows. The next section presents the model. The basic reproduction ratio are established in Section 3. Section 4 is devoted to the formulation of the function which regulate the containment measures. In section 5, we identified the values of model parameters. The Section 6 presents the Simulation experiments for which five scenarios will be implemented: validation of model by comparison with the actual available data in France, testing the effectiveness of containment measures and Longer term forecasting of epidemic, study of the effectiveness of the large scale testing, study of social distancing measures and the combined study of the large scale testing and Social distancing measures. Concluding remarks will follow in Sections 7.

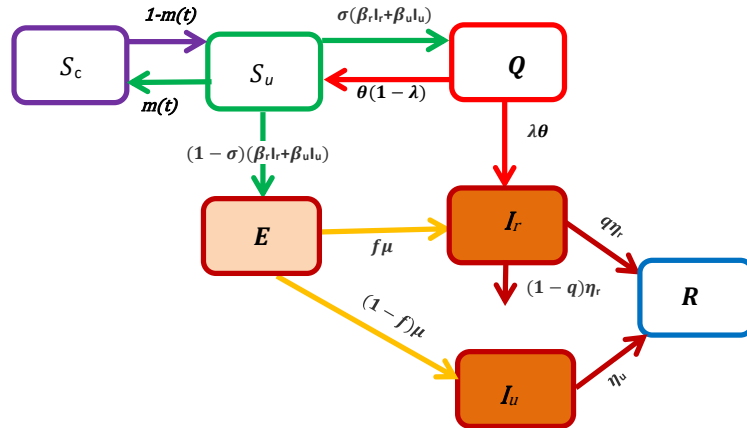


Figure 1: A schematic of the model for COVID-19 transmission. In this Figure, S_u represents the number of unconfined susceptible, S_c denotes the number of confined susceptible, I_r denotes the number of reported Infectious, I_u represents the number of unreported infectious or silent carriers, R denotes the number of recovered, Q denotes the number of quarantined. The arrow show the people moving between the compartments.

2. Model formulation

To model the COVID-19 transmission, we divide the human population into seven classes. Susceptible unconfined $S_u(t)$, susceptible confined $S_c(t)$, exposed $E(t)$, reported infectious $I_r(t)$, unreported infectious $I_u(t)$, quarantined $Q(t)$, recovered $R(t)$ at any time t , see in Figure 1.

An individual moves to the susceptible unconfined class, S_u , either from the confined class at a rate $1 - m(t)$ or from the quarantined class at a constant rate $\theta(1 - \lambda)$. The fundamental parameter that we have introduced in our model to study the containment measures is the parameter $m(t)$, it can be interpreted as the fraction of confined susceptible individuals at any time t . When the susceptible individuals are exposed to the virus, then the exposition provides either the reported class, I_r or the unreported class, I_u that are asymptomatic carriers. Without making any distinction about the origin of the infection, we assume that a fraction σ of Susceptible unconfined individuals which has been in contact with an infectious individual is quarantined with contact tracing while the other fraction $(1 - \sigma)$ who is missed from the contact tracing move to the exposed class E once effectively infected or stay in compartment S_u otherwise. Then, the quantities $(1 - \sigma)(\beta_r I_r + \beta_u I_u)S$ and $\sigma(\beta_r I_r + \beta_u I_u)S$ represent the inflow of new individuals into the exposed class E and quarantined class Q respectively. The parameters β_r and β_u are the transmission rate of reported and unreported cases respectively. We assume that reported individuals will participate into the infections with a lower rate than those unreported because they are generally isolated at the hospital or at home. However, they can transmit the infection to caregivers or their entourage. Moreover, they may have first been asymptomatic carriers contributing to the transmission of the virus. To simplify the notation, we set $\beta_u = \beta$ and $\beta_r = \varrho\beta_u = \varrho\beta$ where $\varrho \in [0, 1]$. The parameter ϱ represents the infectivity of the reported cases and for $\varrho = 1$, the reported and unreported have the same level of infectivity. Among the quarantined individuals, a fraction λ of individuals are effectively infected and moves in the reported infectious class, I_r , after an average duration of isolation, $1/\theta$, and a fraction $1 - \lambda$ returns to the susceptible class without being reported infectious. We assume that only a fraction f of the individuals of exposed class becomes reported infectious and enters to the class I_r at a rate μ where $1/\mu$ represents the average length of the exposed period while the other fraction $(1 - f)$ moves to the infectious unreported infectious class I_u at a rate μ .

With the above considerations, the model describing the spread of COVID-19 takes the form:

$$\left\{ \begin{array}{l} \frac{dS_c}{dt} = m(t)S_u - (1 - m(t))S_c \\ \frac{dS_u}{dt} = (1 - m(t))S_c - m(t)S_u - \beta(\varrho I_r + I_u)S_u + \theta(1 - \lambda)Q \\ \frac{dE}{dt} = (1 - \sigma)\beta(\varrho I_r + I_u)S_u - \mu E \\ \frac{dI_r}{dt} = \mu f E + \theta\lambda Q - \eta_r I_r \\ \frac{dI_u}{dt} = \mu(1 - f)E - \eta_u I_u \\ \frac{dR}{dt} = \eta_r I_r + \eta_u I_u \\ \frac{dQ}{dt} = \sigma\beta(\varrho I_r + I_u)S_u - \theta Q. \end{array} \right. \quad (2.1)$$

This model (2.1) is supplemented together with initial data $S_c(\tau_0), S_u(\tau_0), E(\tau_0), I_r(\tau_0), I_u(\tau_0), R(\tau_0)$

and $Q(\tau_0)$.

Let $DI_r(t)$, $DI_u(t)$, $CI_r(t)$ and $CI_u(t)$ denotes the daily number of reported cases, unreported one, the cumulative number of reported cases and unreported cases respectively at any time t . These quantities are obtained by solving the following equations

$$\begin{cases} \frac{dDI_r(t)}{dt} = \mu f E(t) + \theta \lambda Q(t) - DI_r(t) \\ \frac{dDI_u(t)}{dt} = \mu(1-f)E(t) - DI_u(t) \\ \frac{dCI_r(t)}{dt} = \mu f E(t) + \lambda \theta Q(t) \\ \frac{dCI_u(t)}{dt} = \mu(1-f)E(t). \end{cases} \quad (2.2)$$

with initial conditions $DI_r(\tau_0)$, $DI_u(\tau_0)$, $CI_r(\tau_0)$ and $CI_u(\tau_0)$

3. Basic reproduction number

The fundamental key concept in epidemiology is the basic reproduction number. Commonly denoted by \mathcal{R}_0 , it is the expected number of secondary cases produced by a typical infective individual introduced into a completely susceptible population, in the absence of any control measure [6, 19]. Mathematically, \mathcal{R}_0 is the spectral radius of the next generation matrix. If we denotes K the next generation matrix, it can be obtained by construction (cf. for instance [1, 7, 10]). Using this method, we obtain the following formula for K :

$$K = S_u(\tau_0) \begin{bmatrix} (1-\sigma)f\frac{\beta_r}{\eta_r} + (1-\sigma)(1-f)\frac{\beta_u}{\eta_u} & (1-\sigma)\lambda\frac{\beta_r}{\eta_r} \\ \sigma f\frac{\beta_r}{\eta_r} + \sigma(1-f)\frac{\beta_u}{\eta_u} & \sigma\lambda\frac{\beta_r}{\eta_r} \end{bmatrix}.$$

where each element of K has a concept of \mathcal{R}_0 and $S_u(\tau_0)$ is the number of susceptible at the disease free equilibrium. By computing the spectral Radius of K , we obtain the formula of \mathcal{R}_0 as follows :

$$\mathcal{R}_0 = [(1-\sigma)f + \sigma\lambda]\frac{\varrho\beta S_u(\tau_0)}{\eta_r} + (1-\sigma)(1-f)\frac{\beta S_u(\tau_0)}{\eta_u} \quad (3.3)$$

where $\beta_u = \beta$ and $\beta_r = \varrho\beta$. We can prove that, when $\mathcal{R}_0 < 1$ then the disease free equilibrium is locally asymptotically stable, while it is unstable when $\mathcal{R}_0 > 1$.

The quantity $\mathcal{R}_r := [(1-\sigma)f + \sigma\lambda]\varrho\beta S_u(\tau_0)/\eta_r$ represents the average number of secondary infections produced by one reported infective individual during its infectious period, $1/\eta_r$; $\mathcal{R}_u := (1-\sigma)(1-f)\beta S_u(\tau_0)/\eta_u$ represents the average number of secondary infections produced by one unreported infective individual during its infectious period, $1/\eta_u$;

4. Construction of the containment rate

To analyze the effectiveness of containment measures, we assume that a fraction $m(t)$ of susceptible individuals in the population is confined at any time t . Furthermore, we introduce a parameter p which indicates the maximum percentage of the population that the government

confines. This fraction should be greater than the quantity $1 - 1/\mathcal{R}_0$ to be sure of its effectiveness [22, 7]. This parameter varies from country to country and can be set in advance for a given country. Let τ_0 denotes the starting date of epidemic, τ_1 represents the date at which a government decides to apply the containment measures, τ_2 denotes the date at which a fraction p of the population is confined, τ_3 Stands for the date at which the government decides to exit progressively the containment measures because either the restrictions take effect or there are budget or social limitations and τ_f denotes the date for the end of the containment measures. Now, we divide the containment rate $m(t)$ into four phases:

Phase 0: Period without containment measures (from date τ_0 to τ_1), then $m(t) = 0$.

Phase 1: Period when containment is taking place until the government reaches its maximum containment effort (from date τ_1 to τ_2). In this phase we assume that the function m increases exponentially and reach the value p at date τ_2 . It follows that m takes the form $m(t) = 1 - \exp(-a(t - \tau_1))$ where $a = -\ln(1 - p)/(\tau_2 - \tau_1)$.

Phase 2: Period where the maximum effort is maintained (from date τ_3 à τ_4) and $m(t) = p$.

Phase 3 Period at which the government decides to relax the containment measures (from date τ_3 to τ_f). This drop is linearly depending on the time so that the value of m at date τ_f equals to 0. Then m is described as follows $m(t) = p + b(t - \tau_3)$, where $b = -p/(\tau_f - \tau_3)$.

5. Model parameters

5.1. Chosen Values: $CI_r(\tau_0), S_u(\tau_0), f, \mu, \theta, \tau_0$ and τ_3

Initial conditions: We started the simulations at the moment where in France, the cumulative number of reported cases were identified with 12 individuals, ie precisely on the date $\tau_0 = 25$ February. Then $CI_{r0} = 12$. The population of France is around 66 999 000 inhabitants [4], thus, we set $S_c(\tau_0) = 66 999 000$. At that date, there were no confined individuals, thus $S_c(\tau_0) = 0$.

Value of parameter f : Approximately 80% of infected people are asymptomatic [20]. Then, only 20% of infectious individuals is reported, thus $f = 0.2$.

Value of parameter τ_1 : The starting date of the containment was fixed on March 17, then $\tau_1 = 17$ March.

Value of parameter τ_3 : According to the announcement of French government of April 13, a gradual containment will start on May 11. So for model validation, we fixed $\tau_3 = 11$ May.

Value of parameter τ_f : We fixed the end date of containment measures on September 1.

Value of parameter μ : The mean incubation period $1/\mu$ was fixed to 5 days see [20, 12, 2].

Value of parameter θ : We considered 14 days to isolate the quarantined individuals, therefore, $1/\theta = 14$ days.

5.2. Estimated values: $\tau_2, \lambda, \varrho, p, \beta, \sigma, q, E(\tau_0)$ and $Q(\tau_0)$

By calibrating the model with the data corresponding to the cumulated reported cases for France, we identified some values of model parameters giving a good fit of the observed data obtained in [5]. The parameter values and initial conditions estimated are listed in Table 1.

Value of parameters τ_2 and p : we estimate that the government has successfully confined 93% of the population on the date April 12, thus, $\tau_2 = 12$ April and and $p = 0.93$. This value means that 93% of the population was confined on date τ_2 equals to April 12th, thus $S_c(\tau_2) = 62$

300 700. In this case, we get 7% of the population that remains active and we set $S_u(\tau_2) = 4\ 689\ 300$. Note that this number corresponds approximately to 15.78% of active population in France which was 29 700 000 according to INSEE in 2017 [18].

Value of parameter σ : The value of parameter σ was calibrated to 0.4. This value means that among individuals who have been in contact with infectious people (reported case or not), only 40% are quarantined and 60% could be infectious or remain susceptible without getting sick. *Value of parameters η_r and η_u :* we found that the mean duration of infectious period for unreported individuals, $1/\eta_u = 4$ days and for reported ones, $1/\eta_r = 10$ days. These values are in the range of values with those observed in the literature, see for instance in [21] where the authors show that the individuals with severe COVID-19 tend to have a long infectious period (virus-shedding period).

Value of parameters β_r , β_u and ϱ : We estimated that the infectivity of reported cases ϱ is equals to 0.40 compared to infectivity of unreported which is 1.

The transmission rate $\beta_u = \beta$ of unreported individuals is estimated to $2.115 \times 10^{-8} \text{ day}^{-1}$, then the transmission rate of reported individuals equals to $\beta_r = \beta\varrho = 0.846 \times 10^{-8} \text{ day}^{-1}$. *Value of parameter q :* We estimated that the disease-induced death rate $(1-q)\eta_r$ to 0.0220 day^{-1} . Thus, the fraction of reported individuals that becomes recovered equals to $q = 0.78$ and the fraction of reported individuals that dies equals to $1 - q = 22\%$.

Value of parameters $E(\tau_0)$, $Q(\tau_0)$ and $I_r(\tau_0)$: we estimate that at date τ_0 , we have $Q(\tau_0) = 33$, $I_u(\tau_0) = 46$ and $E(\tau_0) = 103$.

6. Simulation experiments: application to French data

6.1. Scenario 1: validation of model with French data

We selected for model validation, the data obtained for daily reported (DRI_r) and cumulative reported (CRI_r) cases for France see [5]. Some constants and parameters involved in the model were listed in Table 1. Some model parameters were estimated by minimizing the χ^2 test statistic as an error function

$$\chi^2 = \frac{\sum_{l=1}^n (obs(t_l) - sim(t_l))^2}{obs(t_l)^2} \quad (6.4)$$

where n is the number of observed data and $obs(t_l)$ and $sim(t_l)$ are the observed and calculated data at time t_l respectively. The estimated parameters and the constants are listed in Section 5.

The results of this scenario are illustrated on the figures 3.

6.2. Scenario 2: effectiveness of containment measures

The objective of this scenario is to analysis if the outbreak might die for different values of the date at which the containment measures are relaxed, namely τ_3 . Then, the value of the latter is assumed varying from May 11, June 01 and 30. The end date of containment measures τ_f , is fixed to September 1. The values of the parameters used are listed in tables 1 excepted the containment function m that varies (see Figure 2(b)).

The results of this scenario are illustrated on the figures 4.

Table 1: List of parameters meanings and the parameter ranges for which the model was solved

Name	Meaning	Value
p	Maximum fraction of the susceptible that a government can confine	0.93
f	Fraction of Exposed that becomes reported infectious	0.2
ϱ	Infectivity of reported individuals	0.4
λ	Fraction of quarantined individuals that becomes infectious	0.3
q	Fraction of reported individuals that becomes recovered	0.78
σ	Fraction of individuals which is quarantined with contact tracing	0.2
$\beta_r = \varrho\beta$	Transmission rate of reported individuals	0.846×10^{-8}
$\beta_u = \beta$	Transmission rate of unreported individuals	2.115×10^{-8}
$(1 - q)\eta_r$	Disease-induced death rate	0.0220
$1/\mu$	Average length of the exposed period	5
$1/\eta_r$	Average length of infectious period of reported individuals	10
$1/\eta_u$	Average length of infectious period of unreported individuals	4
$1/\theta$	Average length of the quarantine period	14
$m(t)$	The fraction of confined susceptible at any time t	$[0 - p]$, see Fig. 2
τ_0	Starting date of the epidemic	February 25
τ_1	Starting date of the containment	March 17
τ_2	Date at which a fraction p of the population is confined	April 12
τ_3	Decision date of relaxation of the containment measures	May 11-June 28
τ_f	End date of containment measures	Sep. 01
Initial values	Meaning	Value
$S_c(\tau_0)$	Initial confined susceptible population	0
$S_u(\tau_0)$	Initial unconfined susceptible population	66990000
$E(\tau_0)$	Initial exposed population	103
$I_r(\tau_0)$	Initial reported population	12
$I_u(\tau_0)$	Initial reported population	46
$R(\tau_0)$	Initial recovered population	0
$Q(\tau_0)$	Initial quarantined population	33

6.3. Scenario 3: effectiveness of the large scale testing

To investigate the effectiveness of the large scale test of detection of infected individuals, the date at which the containment measures are relaxed, τ_3 , is fixed to May 11; the end date of containment measures, τ_f , is fixed to September 01. We assume that between the dates τ_3 , and τ_f , the fraction of reported cases f increases linearly and reach 200% of its initial value and the fraction of susceptible individuals which is quarantined σ is also increased linearly to reach 200% of its initial value (see Figure 2(c)), the initial values is estimated in scenario 1. The values of the other parameters is listed in tables 1 excepted the containment function m that varies (see Figure 2(b)).

The results of this scenario are illustrated on the figures 5.

6.4. Scenario 4: Social distancing measures

To study the social distancing measures, the date at which the containment measures are relaxed, τ_3 , was fixed to May 11; the end date of containment measures, τ_f , is fixed to September 01. We assume that between the dates τ_3 , and τ_f , the transmission rate β decreases linearly to reach 75% of its initial value (see Figure 2(d)). The values of the other parameters is listed in tables 1 excepted the containment function m that varies (see Figure 2(b)).

The results of this scenario are illustrated on the figures 6.

6.5. Scenario 5: Combined effects of large scale testing and Social distancing measures

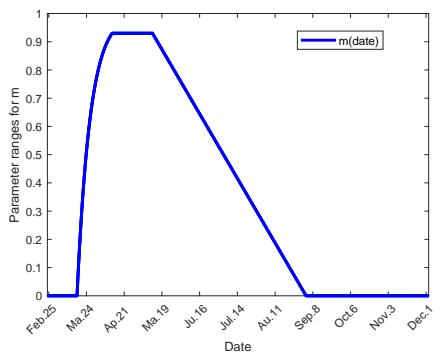
To test the combined effects of large scale testing and Social distancing measures, we combine the conditions of scenario 1 and 2. The date at which the containment measures are relaxed, τ_3 , is fixed to May 11; the end date of containment measures, τ_f , is fixed to September 01. Between the dates τ_3 and τ_f , we assume that f increases linearly to reach 200% of its initial value, σ increases linearly to reach 200% of its initial value and β decreases of 75% of its initial value see Figure 2(d) for these different variations of parameter values.

The results of this scenario are illustrated on the figures 7.

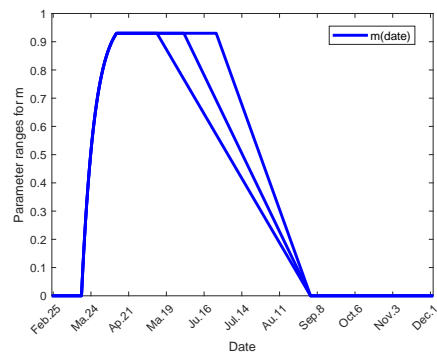
7. Discussion and conclusion

This model takes into account the measures of confinement, distinguishing between confined individuals, quarantined individuals and isolated individual. Many values were estimated to fit the beginning of expansion of disease in France, other were inferred from expert opinions see Section 5.

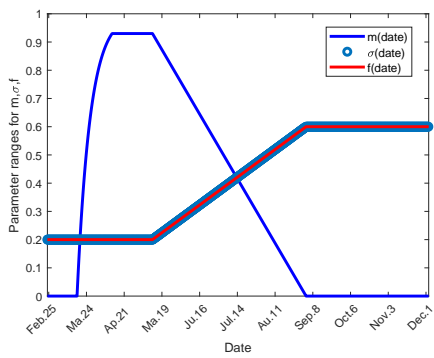
Figure 3 shows the adequacy of the model for predicting the evolution of number of cases in the beginning of the crisis until mid April 21. It also shows that as soon as confinement is reduced or stopped, the daily reproduction number \mathcal{R}_0 value increases again and a new wave of epidemics is to be expected as soon as its value is higher than 1. This is observed on Figures 4 (for longer term forecasting), such waves begin to appear very shortly after reduction of confinement, once the incubation period is spent. These values will allow predicting the effectiveness of the containment measures as well as the intensity of possible resurgences of the new waves of epidemic in France. Indeed, the measures of confinement have a strong impact on the value of the daily reproduction number \mathcal{R}_0 . Figures 4 shows that, while it was equal to nearly 5 in the beginning of the disease, before confinement, it decreased to about 0.5 as long as confinement of most people takes place and increased to a lower value, between 2 and 2.5, that is about half its former value. But even if its value is reduced, it remains higher. It is also to note that, unexpectedly, its value



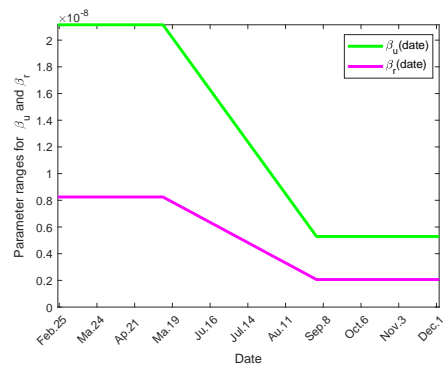
(a)



(b)



(c)



(d)

Figure 2: Parameter ranges (a) For scenario 1, (b) for scenario 2, (c) for scenario 3 (d) for scenario 4, (c) and (d) for scenario 5

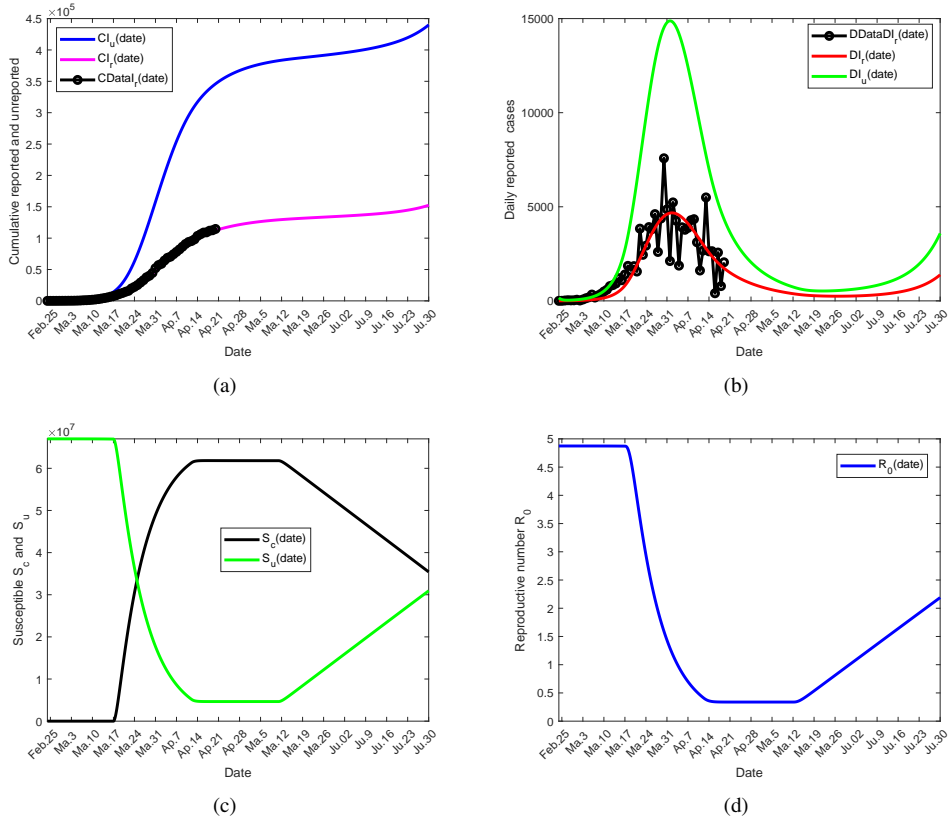


Figure 3: Scenario 1: forecasting of epidemic spreading using the model simulation and comparison with the currently available data. The date at which the containment measures are relaxed, τ_3 , was fixed to May 11; the end date of containment measures, τ_f , was fixed to September 01. (a) The cumulative number of reported $CI_r(date)$ cases simulated, and observed data $CI_rData(date)$. (b) The daily number of reported $DI_r(date)$ and unreported $DI_u(date)$ cases from the model and observed data $DDataI_r(date)$. (c) The confined and unconfined susceptible S_c and S_u . (d) The daily reproductive number $R_0(date)$. In this scenario, the values of the parameters were estimated and listed in tables 1 excepted for the fraction of reported cases, $f = 0.2$, the fraction of susceptible individuals which are quarantined, $\sigma = 0.2$ and the containment function m which varies between 0 and 1 (see Figure 2(a))

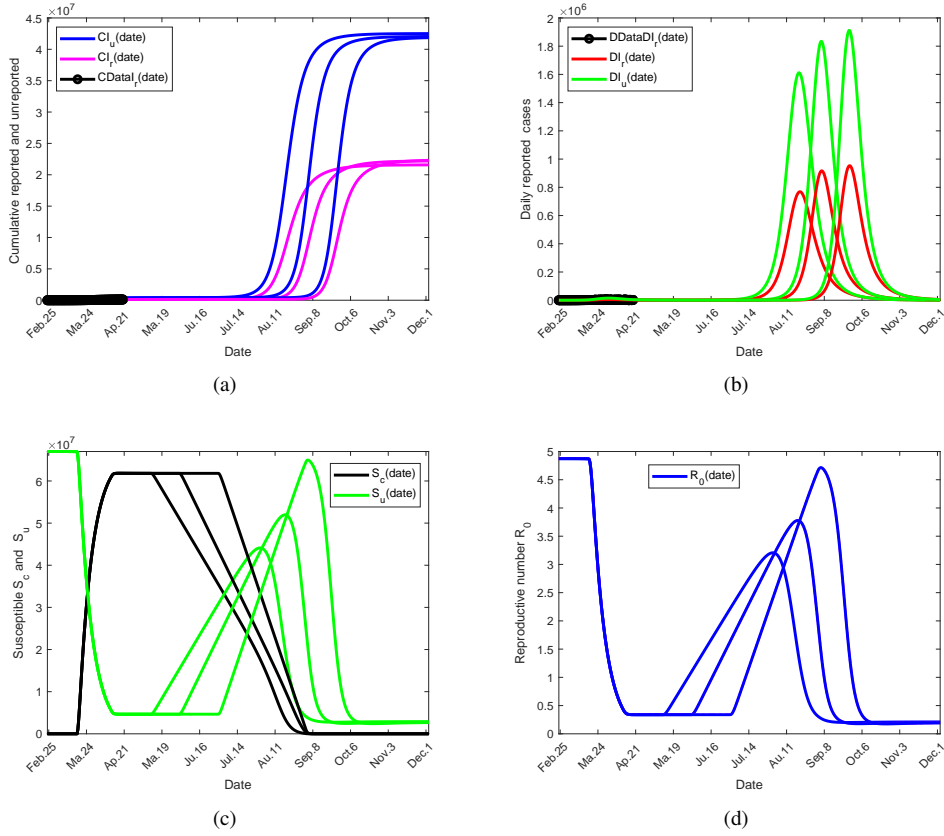


Figure 4: Scenario 2: longer term forecasting of epidemic spreading according to different values of the date at which the containment measures are relaxed, τ_3 that varies between May 11, June 01 and 30. The end date of containment measures τ_f , was fixed to September 1. (a) The cumulative number of reported $CI_r(date)$ and unreported $CI_u(date)$ cases simulated, and observed data $CDatI_r(date)$. (b) The daily number of reported $DI_r(date)$ and unreported $DI_u(date)$ cases from the model and observed data $DDatDI_r(date)$. (c) The confined and unconfined susceptible S_c and S_u . (d) The daily reproductive number $R_0(date)$. In this scenario, the values of the parameters were estimated and listed in tables 1 excepted the fraction of reported cases, $f = 0.2$, the fraction of susceptible individuals which are quarantined, $\sigma = 0.2$ and the containment function m varies between 0 and 1 (see Figure 2(b))

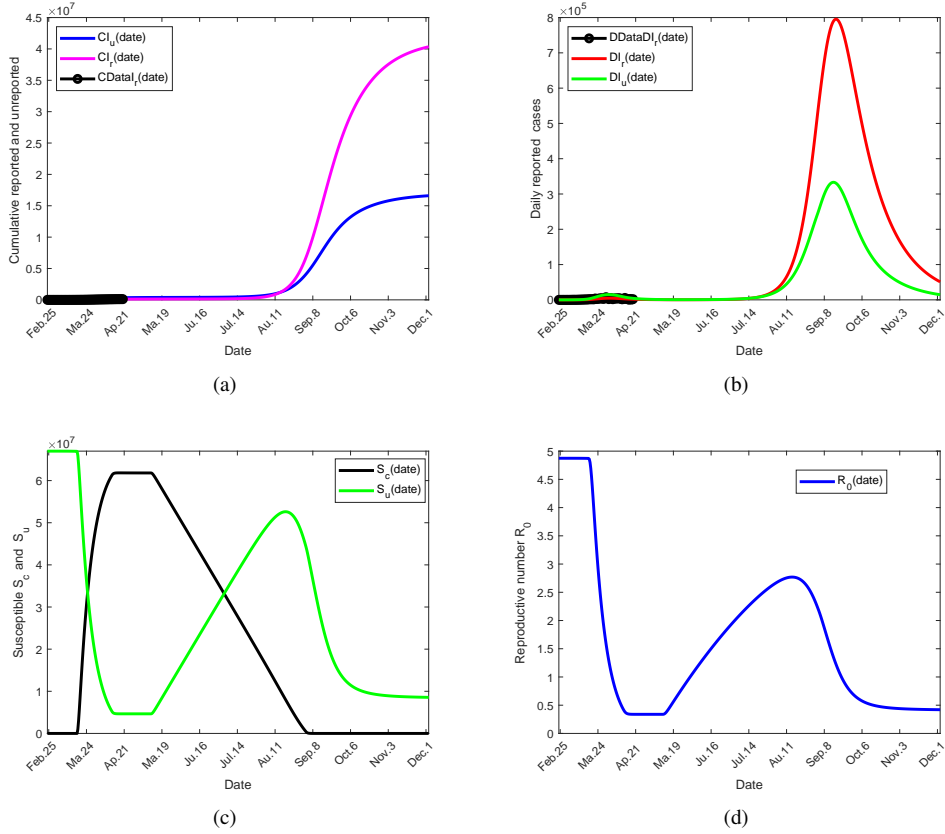


Figure 5: Scenario 3: Longer term forecasting of epidemic spreading in case of large scale tests of detection on infected individuals. τ_3 , was fixed to May 11; τ_f , was fixed to September 01. Between the dates τ_3 and τ_f , the parameter f was assumed increase linearly to reach 200% of its initial value, σ increased linearly to reach 200% of its initial value (see Figure 2(c)). The values of the other parameters were listed in tables 1 excepted m that varies (see Figure 2(b)). (a) The cumulative number of reported $CI_r(\text{date})$ and unreported $CI_u(\text{date})$ cases simulated, and observed data $CDataI_r(\text{date})$. (b) The daily number of reported $DI_r(\text{date})$ and unreported $DI_u(\text{date})$ cases from the model and observed data $DDataI_r(\text{date})$. (c) The confined and unconfined susceptible S_c and S_u . (d) The daily reproductive number $R_0(\text{date})$.

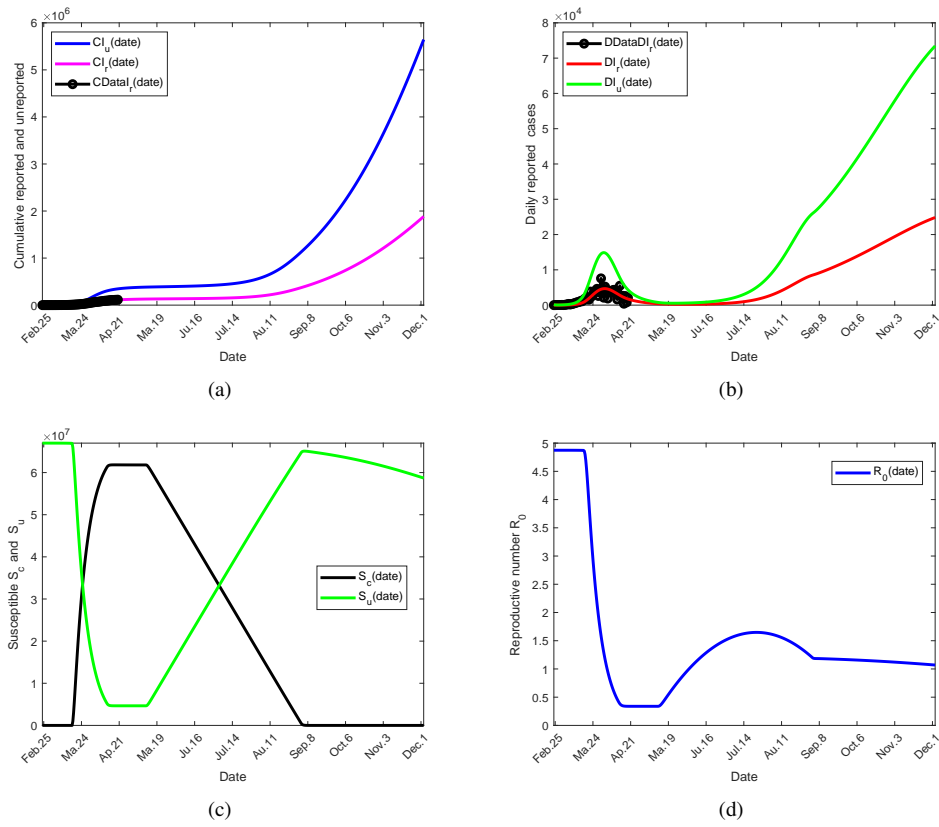


Figure 6: scenario 4: Longer term forecasting of epidemic spreading in case of social distancing. τ_3 , was fixed to May 11; τ_f , was fixed to September 01. Between the dates τ_3 and τ_f , the parameter β decreases of 75% of its initial value see Figure 2(d). The values of the other parameters are listed in tables 1 excepted m that varies (see Figure 2(b)). (a) The cumulative number of reported $CI_r(date)$ and unreported $CI_u(date)$ cases simulated, and observed data $CData_r(date)$. (b) The daily number of reported $DI_r(date)$ and unreported $DI_u(date)$ cases from the model and observed data $DDataDI_r(date)$. (c) The confined and unconfined susceptible S_c and S_u . (d) The daily reproductive number $R_0(date)$.

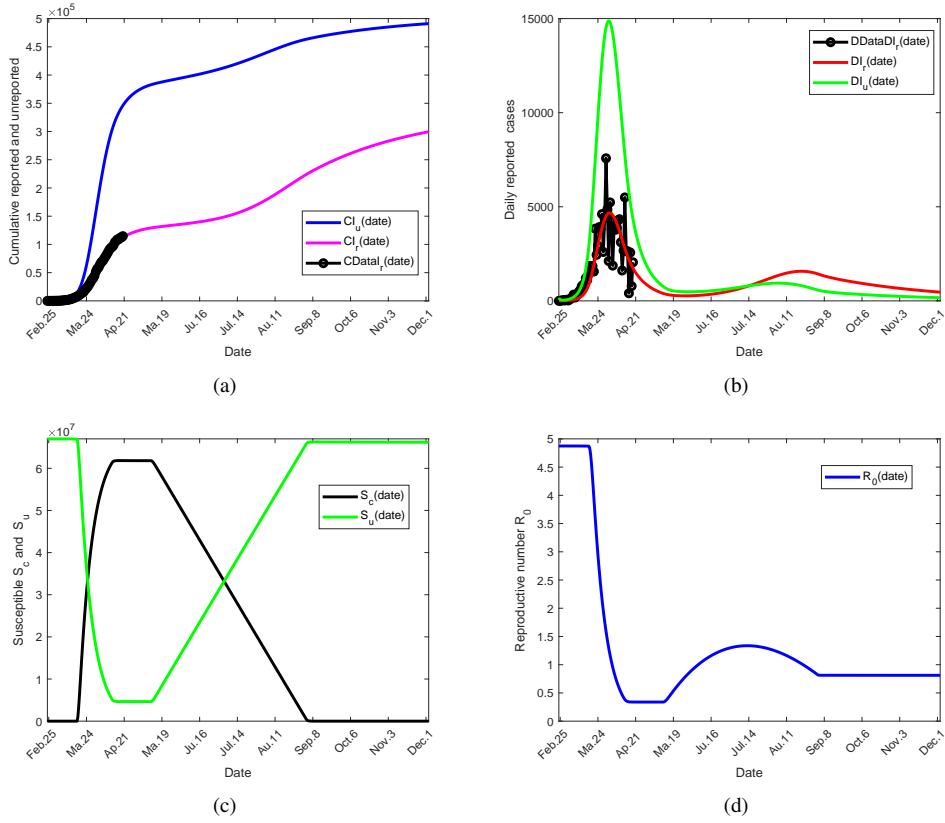


Figure 7: Scenario 5: Longer term forecasting of epidemic spreading in case of both social distancing and large scale tests. τ_3 , was fixed to May 11; τ_f , was fixed to September 01. Between the dates τ_3 and τ_f , the parameter f increases linearly to reach 200% of its initial value, σ increases linearly to reach 200% of its initial value (see Figure 2(c)). β decreases to 75% of its initial value see Figure 2(d). The values of the other parameters are listed in tables 1 excepted m that varies (see Figure 2(b)). (a) The cumulative number of reported $CI_r(date)$ and unreported $CI_u(date)$ cases simulated, and observed data $CData_r(date)$. (b) The daily number of reported $DI_r(date)$ and unreported $DI_u(date)$ cases from the model and observed data $DData_r(date)$. (c) The confined and unconfined susceptible S_c and S_u . (d) The daily reproductive number $\mathcal{R}_0(date)$.

was lower when end of confinement was earlier. As soon as the \mathcal{R}_0 value is higher than 1, a new wave of epidemics is expected. Figure 3-4 show that they will be observed at the end of summer if containment is relaxed from Mid-May to September. Delaying the very end of confinement to mid December results in a later and higher wave but not as late as could be expected from the delay in the end of confinement. At the end of 2020, all French people are expected to be either reported or unreported infected individuals. This wave is earlier as expected development of vaccines, i.e. it will not be possible to avoid it unless other methods of prophylaxis or treatment are developed. However, some of those values may change with evolution of measures of prevention such as social distancing, large scale testing, treatment of the disease.

Social distancing directly influences the transmission rate which is expected to dramatically decrease with the increasing tendency to wear masks. Its effect was investigated in scenario 3 where the transmission rate was assumed decrease linearly to reach the value 75 % of its initial one as shown on Figure 2(d). The results of this scenario are shown on Figures 5. To decrease the transmission rate, we suspect that the use of masks and systematic hand washing could be considered. The results show that this measure without further action is insufficient to eliminate the disease.

The effectiveness of the *large scale test of detection* of infected individuals was analysed and shown on Figures 6. The fraction of reported cases, from date τ_3 to date τ_f , the fraction of reported cases f was assumed increase linearly to reach the value 200% of its initial one and the fraction of susceptible individuals which is quarantined σ was also increased linearly to reach the value 200% of its initial one (see Figure 2(c)). The date at which the containment measures are relaxed, τ_3 , was fixed to May 11; the end date of containment measures, τ_f , was fixed to September 01. The containment function m (see Figure 2(b)). This measures are possible by increasing by tracking all former contacts of any newly reported case, and systematic tests, the fraction of individuals which are quarantined with contact tracing. Results show that this measure without further action is also insufficient to control the outbreak.

The *combined measures* of large scale testing and Social distancing measures was studied in scenario 5. The transmission rates (reported and unreported individuals) were assumed decrease from 75% to the date τ_2 to the date τ_f (see Figure 2(d)). The date at which the containment measures are relaxed, τ_3 , was fixed to May 11; the end date of containment measures, τ_f , was fixed to September 01. The containment function m (see Figure 2(b)). The Figures 7, show the effectiveness of these combined measures and the potential of such a strategy.

In the absence of any control measure, the basic reproduction number \mathcal{R}_0 is equal to 4.8739. Most of this value is due to the weight of transmission by unreported individuals ($\mathcal{R}_u = 3.9671$) and the weight of transmission by reported cases accounts for much less ($\mathcal{R}_r = 0.9068$). These values show that the major number of secondary infections is produced by the unreported individuals. With increasing use of appropriate tests, reported individuals will be more precisely diagnosed, thus the fraction of reported cases f will increase and thus the importance of \mathcal{R}_r in the total value of \mathcal{R}_0 will increase. Since the infectivity of reported individuals was estimated at 0.4 compared to infectivity of unreported which is 1, the increase in \mathcal{R}_r will be very small. Therefore, the reported individuals will have a lower propensity to transmit the virus. Through strong measures of prevention, the probability of contaminating other people will be lower.

With the confinement measures, the minimal percentage (critical fraction) of susceptible individuals that should be protected to eliminate the COVID-19 equals to $1 - 1/\mathcal{R}_0$ (see for instance [7, 22]). By confining any fraction of susceptible greater than the minimal fraction, we increase the kinetics of elimination of the disease. By fitting the model with the French data, we estimated that this fraction of susceptible individuals which is maintained confined was equals to $p = 93\%$.

This value belongs to the critical interval, namely $[1 - 1/\mathcal{R}_0, 1] \simeq]0.8, 1]$.

By analyzing the results of simulations, we can conclude that the containment measures appear to have slowed the growth of the COVID-19 outbreak. Our model predicts that a second big wave of the epidemic is inevitable if the French government begins to relax containment measures of May 11 (see Figure 3 and Figure 4). The Figures show that the containment measures adopted in France are effective when a fraction $p = 93\%$ of susceptible individuals are maintained confined, but once this fraction begins to lower, a new wave of contamination starts. This means that if no further action is taken, even if there is only one infected individual in the population, a new wave of contamination similar to the former might occur after the end of confinement date.

In this article, we formulated a new model to describe the spread of COVID-19 to understand the effectiveness of the containment and quarantine measures. It is able to reproduce observed data from other countries.

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