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EARLY-CONFINEMENT STRATEGY TO TACKLING COVID-19 IN MOROCCO; A MATHEMATICAL MODELLING STUDY

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Abstract. Morocco is among the countries that started setting up confinement in the early stage of the COVID-19 spread. Comparing the number of cumulative cases in various countries, a partial lock-down has delayed the exponential outbreak of COVID-19 in Morocco. Using a compartmental model, we attempt to estimate the mean proportion of correctly confined sub-population in Morocco as well as its effect on the continuing spread of COVID-19. A fitting to Moroccan data is established. Furthermore, we have highlighted some COVID-19 epidemic scenarios that could have happened in Morocco after the deconfinement onset while considering a different combination of preventive measures.

Mathematics Subject Classification. 92-10.

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1. Introduction

Worldwide, at the time of writing, the COVID-19 pandemic has infected more than 582 million people and killed more than 6,41 million, and the spread reached all countries [33]. Health care departments worldwide are investing knowing more about COVID-19 and its transmission mode. In the absence of a vaccine or an effective treatment in the early stage of the COVID-19 pandemic, governments worldwide harried to make people aware of COVID-19 severity and educate them to consider all available protective measures in their life activities. Furthermore, they put detected cases and their known immediate network contacts in quarantine, hoping to inhibit the disease outbreak, but unsuccessfully. Being unable to control the disease spread, the authorities in many countries have rushed to survey quasi-total confinement of people to reduce the exposure to the virus and likely suppress the pandemic. [1, 18, 34].

Various attempts have been established to understand the sustainable spread of COVID-19 disease. In [18, 20, 34], the authors estimated some epidemiological key parameters such as per-capita per-day infection rate, mean incubation period, recovery rate and death rate related to China. The big COVID-19 challenge which confronts health care departments worldwide appears to be detecting or at least fairly estimating the number of total COVID-19 active cases. Indeed, infected individuals differ in the severity once in-host infection has begun to progress, also a small proportion among them who are supposed to be detected, and others might

Keywords. COVID-19, confinement, protective measures, compartmental models, basic reproduction number, fitting, backward bifurcation.

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be presymptomatic or almost asymptomatic to be away from screening, despite their significant contributions in spreading the disease [1, 34]. Besides, this presymptomatic infectious period allows hidden infectious individuals an invisible period of infectiousness, it has caused misguided indicators to understand the disease trend and the epidemic response to various intervention measures [6, 21].

Governments differ in the way they have surveyed the course of COVID-19 in their countries. In China, this epidemic has led to 82 thousand confirmed cases and more than 3000 deaths in May 2020. And thanks to the different strategy combinations that have been adopted starting with mask wear, keeping social distancing, reducing mixing in familial/public community, going to the total confinement of all citizens [1, 13, 27] with an intense testing panel, the government was able to control the COVID-19 spread within three months after reporting the first patient in Wuhan city on December 8, 2019 [35]. On the other hand, South Korea has followed a successful approach in curving the pandemic. It did not confine the population, instead, the government has adopted extreme social distancing measures, with the obligation of mask wear and an intense screening protocol of about 20,000 tests a day, accompanied by a complete tracing of the course and contacts of each positively tested person [18].

According to reported data on March 29, countries that have been harmfully affected by COVID-19, after China, are the USA, Spain, Italy, UK, France, Germany, Russia and Turkey [33]. In a similar tragedy as in Turkey, the Italian authorities did not take radical measures in the early COVID-19 invasion. Indeed, their ministry of health seems to be implementing a relaxing policy, which led to a significant increase in detected cases in a short period of time. Together with deaths, data showed that the situation was out of control in the early stage of the epidemic [7] before the serious announcement of the confinement.

Morocco has learned from the COVID-19 epidemic experienced in China, and from its exponential spread in Italy, and so has been among the countries such as Jordan and South Africa to adopt the confinement strategy in the early stage of the COVID-19 course. Comparing the number of cumulative cases in some countries [33], the lockdown intervention has delayed the COVID-19 outbreak in Morocco and provided some time for policymakers to reinforce hospital equipment, as well as the protective measures to confront and control the COVID-19 outbreak.

The first COVID-19 patient in Morocco was detected on March 2nd [24]. Two weeks later, on March 20, the Moroccan health department declared 74 cumulative cases [15]. By that time, the government had proceeded into international isolation, lock-down of schools, prohibition of people gatherings, closure of religious spaces and rural public souks, declaration of a state of a health emergency, restriction movement and announcement of quasi total confinement with few exceptions related to the population daily extreme needs. To succeed the confinement, authorities resorted to, assuming successfully, some preventive acts such as social distancing and regional separation, in order to avoid any disorder [26]. The government has continue educating individuals about COVID-19 and enhanced their awareness to fight against its transmissibility. On April 7, the authorities announced the obligation of mask wear in public areas [25], which took place one week later because of the masks' lack in markets. The following timeline summarizes all these interventions since the appearance of the first reported case in Morocco.

The aim of this study is to possibly inform on the possible scenarios that could have happened in the case of adopting a deconfinement on June 10, 2020 in Morocco using our model. The following paragraphs summarize the contribution of our work.

We have constructed a mathematical model for the COVID-19 spread in Morocco which incorporates the confinement onset and the obligation of masks wear. Firstly, we have showed that the confinement has decreased the basic reproduction number $\mathcal{R}_0$ to a lower value $\mathcal{R}_{0c} = (1-q)\mathcal{R}_0$ on the confinement official onset on March 20, where q is the proportion of correctly confined sub-population or simply the confinement efficiency ratio. On the other hand, the obligation of mask wear continues to reduce the basic reproduction number to $\mathcal{R}_{0cm} = (1-\epsilon)(1-q)\mathcal{R}_0$, where ϵ reflects the efficacy of mask wear.

Based on the model fitting to the reported data for Morocco between March 2, 2020 and December 31, 2020, we estimated that 66% of Moroccan individuals are correctly confined. Consequently, after the confinement onset, the basic reproduction number decreased from 4,24 to 1.41, unfortunately, still beyond 1 and the outbreak

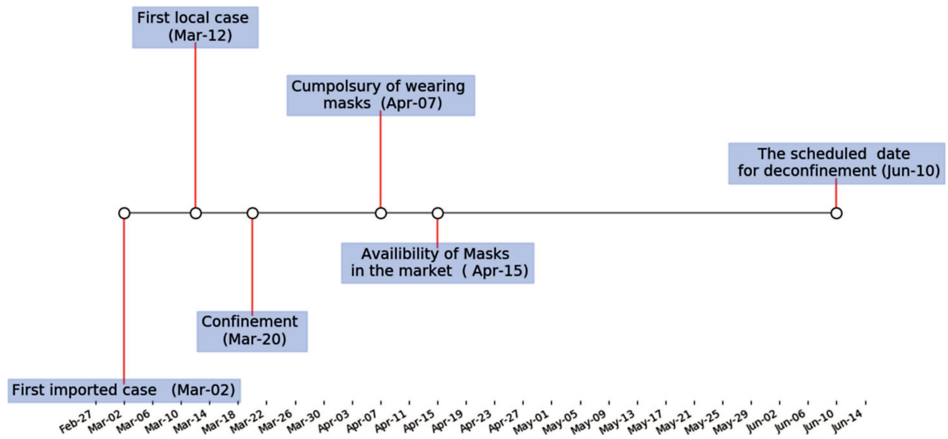


FIGURE 1. Timeline of different taken measures after the first imported and local confirmed case.

has carried on. Combining the confinement strategy together with mask wearing, with efficacy estimated at $\epsilon = 0.171$, the basic reproduction number has gone down but still greater than unity to take the value 1.17. Moreover, we obtained that the mean time between infection onset and detection is $\alpha^{-1} = 10$ days, and the transmission rate is $\beta = 0.605\,\text{day}^{-1}$.

We have, already, assessed how the authorities' interventions would affect the course of the COVID-19 outbreak. Despite the, seemingly, temporary control of the COVID-19 outbreak in Morocco, our model, and accordingly to data worldwide, has revealed that the lock-down solely is a short term strategy to gain some time to consider and prepare more preventive measures. To this end, we have predicted a COVID-19 outbreak in different situations after the eventual deconfinement onset on June 10 as announced by the government, to finally propose a progressive deconfinement accompanied by increasing some parameter values in order to avoid a second outbreak.

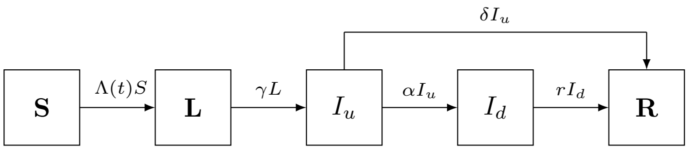
The remainder of this article is organized as follows. Section 2 is devoted to the mathematical modelling of the COVID-19 transmission in Morocco. Section 3 presents numerical simulations that allow us to reveal scientific discussions. Section 4 sheds more light on the effect of different preventive measures.

2. The mathematical model

Several previous research works are based on mathematical modeling of the COVID-19 epidemic [2, 3, 10, 23, 29, 31]. In [4], the authors give a model with diagnosed and undiagnosed individuals where both compartment of infected and recovered individuals are divided into the officially detected and undetected infected individuals. [2, 29, 31] propose models that take into account symptomatic and asymptomatic infectious compartments. Here the asymptomatic individual is supposed to be away from the official detection. The authors in [3, 9, 23] aim at studying the impact of lockdown on the dynamics of COVID-19 outbreak. [9] consider a three-dimensional mathematical model where the confined population is represented by a compartment Q. [3, 23] consider a time-dependent contact rate, to account for lockdown effect.

In comparison with the above-mentioned works, our mathematical model takes into account both, detected/undetected, symptomatic/ asymptomatic infected individuals, and also the confinement efficiency. We suppose that latent infected individuals are asymptomatic, and not yet infectious, and the infectious individuals may be symptomatic or asymptomatic so a part of them can be detected and isolated thanks to screening tests. For the confinement efficiency, our model considers the confinement in terms of a parameter q which represents the proportion of correctly confined individuals among the total population instead of considering a compartment for confined population.

The mathematical model in this study is made of 5 compartments, S is the number of susceptible individuals, L is the number of latent individuals and represent infected individuals not yet infectious. I_u representing the number of undetected infected individuals participating in the infection, while I_d representing the number of detected cases who do not participate in the infection thanks to their quarantine for hospitalization. The removed individuals from I_u and I_d are denoted R. The next diagram will describe the flow of individuals through the different compartments:



We then consider the following model:

$$\begin{cases} S' = -\Lambda(t) \\ L' = \Lambda(t) - \gamma L \\ I_u' = \gamma L - (\alpha + \delta) I_u \\ I_d' = \alpha I_u - r I_d \\ R' = r I_d + \delta I_u. \end{cases} \tag{1}$$

where γ^{-1} is the average time of latent non-infectious period, α is the screening rate and δ is the natural recovery rate of non detected infectious individuals. r is the recovery rate on detected cases see Table 1.

When you acquire the virus, it takes a few days of incubation to become infectious and more days before symptoms start to appear at an average of 5.2 days since infection [21]. Indeed, the virus spreads *via* infectious droplets and requires in-host a series of production stages (host cell infection, virus replication and viruses release) to reach a significant viral load responsible for the infectivity. To shed more light on the effect of the presymptomatic stage of infection we will consider a compartment of latent individuals L and another one for presymptomatic I_u and undetected infectious individuals in addition to the compartment of detected cases I_d.

On March 20, the Moroccan government stated a health emergency, by issuing an official document to limit mobility such as shopping, medication, treatment and categories of work. The aim was to prevent the spread of the disease. Before the confinement onset, individuals behaved in the way that expose them to infection with a contact rate c. While the per capita per day infection rate is $\beta = c\rho$, where ρ presents the probability of contamination through effective contact. Thus, we consider the following force of infection

$$\Lambda(t) = \beta I_u \frac{S}{N}, \text{ if } t \leq \text{ March 20} \tag{2}$$

where we counted only the proportion of contacts an infectious makes with susceptibles.

The confinement has been imposed on the whole population. However, it might not have been totally effective. In fact, even though, some of the locked-down families keep interacting while trying to respect social distancing and working in distance, others have reached their daily needs, as usual, taking low protective measures. We assume here that an infectious individual may contact a susceptible, infectious, or exchange service with a confined person in distance. We suppose that the contact between infectious and confined is made on a distance basis such as, teaching, banking, consulting, shopping, and as a result the latter is not infected. Thus confined sub-population still serves and gets served without being infected. We assume that an infected individual is not considered as confined since correct confinement should have protected him/her. Under the confinement assumptions, the force of infection takes a new form in the period between the confinement onset and the date of availability of masks in the market:

$$\Lambda(t) = \beta I_u \frac{S - Q}{N} = \beta I_u \left(\frac{S}{N} - q \right) \text{ if } \text{ March 20} < t \leq \text{April 15.} \tag{3}$$

TABLE 1. Parameter definition.

Parameter	Description
β	Transmission rate
δ	Naturel removed rate (from undetected cases)
γ	Rate at which latent infected become detected infected(develop symptoms)
α	Detection rate
ε	Effectiveness of masks wear
r	Removed rate (recovery or death)
q	The confinement efficiency ratio

where Q is the number of individuals with correct confinement and q would be the confinement efficiency ratio.

In an effort to implement more ways of slowing the COVID-19 pandemic, the Moroccan government promulgated a law requiring citizens to wear masks in public areas. Actually, on the one hand, If the mask is worn by a susceptible individual, it offers efficacy against the acquisition of infection. On the other hand, if the wearer is already infected but unaware he/she is ill, the face-mask offers efficacy against their ability to transmit the infection to susceptible individuals [13]. Hence, when the masks became available in the market on April 15 (see Fig. 1), we assume that the force of infection would take the following new form

$$\Lambda(t) = (1-\epsilon)\beta I_u \left(\frac{S}{N} - q\right) \text{ if } t > \text{April 15}. \tag{4}$$

where ϵ represents the efficiency of using masks.

Table 1 summarizes all used parameters with definitions.

For the reproduction number corresponding to the COVID-19 outbreak, some works focus on the effective reproduction number R(t) and its calculation method [16, 22, 30], while others focus on the basic reproduction number $\mathcal{R}_0$ [2,9,29]. In our work, using concepts in [8] and techniques in [11], we calculate the basic reproduction number $\mathcal{R}_0$ which corresponds to the early stage of COVID-19 outbreak, and the effective reproduction number at the time of lockdown onset and the use of protective measures.

System (1) takes initial condition $(S_0, L_0, I_{u0}, I_{d0}, R_0) \in \mathbb{R}^5_+$. In the way as in [17], one can show that system (1) is well-posed and has a unique positive solution whenever the initial condition is positive.

The disease free-equilibrium at the beginning of the outbreak in Morocco is $x^* = (N, 0, 0, 0, 0)$ where $N = S+L+I_u+I_d+R$ is the number of the total population which is assumed to be constant. The only compartments that are infectious or that could be infectious after transitions are L and I_u. Therefore, by applying the approach in [11], the next generation matrix is given by FV^{-1} where:

$$F = \begin{pmatrix} 0 & \beta \\ 0 & 0 \end{pmatrix} \quad \text{and} \quad V = \begin{pmatrix} \gamma & 0 \\ -\gamma & (\alpha+\delta) \end{pmatrix}.$$

Hence, the basic reproduction number corresponding to the early stage of the COVID-19 outbreak in Morocco is $\mathcal{R}_0 = \rho(FV^{-1}) = \frac{\beta}{\alpha+\delta}$.

At the moment of the confinement onset, a fraction of the population is not in contact with infectious individuals. Then, the force of infection takes the form (3) and the matrix F becomes:

$$F = \begin{pmatrix} 0 & (1-q)\times\beta \\ 0 & 0 \end{pmatrix}.$$

The effective reproduction at this time is $\mathcal{R}_{0c} = (1-q)\times\mathcal{R}_0$. After the use of masks, another fraction ϵ of the susceptible population is protected. Hence, the force of the infection takes the form (4) and the matrix F becomes:

TABLE 2. Initial conditions.

Parameter	S_0	L_0	I_{u0}	I_{d0}	R_0
Value	35 887 422	6	2	1	0

TABLE 3. Parameter estimates.

Parameter	Value range	Source	Parameter	Value range	Source
β	$0.605\,\text{day}^{-1}$	Fitted	ϵ	0.171	Fitted
α	$0.101\,\text{day}^{-1}$	Fitted	γ	$0.333\,\text{day}^{-1}$	Estimated from [32]
δ	$0.041\,\text{day}^{-1}$	Fitted	r	$0.085\,\text{day}^{-1}$	Fitted
q	0.667	Fitted			

$$F = \begin{pmatrix} 0 & (1-q)\times(1-\epsilon)\beta \\ 0 & 0 \end{pmatrix}.$$

The effective reproduction number at this time is given by $\mathcal{R}_{0cm} = (1-q)\times(1-\epsilon)\times\mathcal{R}_0$.

3. Numerical results

We choose the initial time to be March 2nd, the day when the first infected case was detected $I_{d0} = 1$, and there were no removed individuals $R_{u0} = R_0 = 0$. The initially undetected cases spend 11 days as a conservative period for developing symptoms and then being detected [5]. Thus initially, $I_{u0} + L_0 = 8$ which is the number of reported cases between March 2 and March 13. Similarly, since the transmission begins at most 3 days before symptom onset [32], we take $L_0 = 6$ the number of reported cases between March 5 and March 13. Table 2 summarizes the initial condition of system (1).

The value of γ is estimated from [32] to be 0.33 and the other parameters are calibrated by fitting our model to public data for Morocco in [15,33] from March 2 to December 31 using "*Optimize Module*" on Python.

To accurately estimate the parameters β, q and ϵ appearing in the force of infection, we follow the chronology of the various adopted measures presented in Figure 1. We first provide an estimation of the transmission rate β using the first period before the confinement onset when ϵ and q have no effect yet. Secondly, we use the period from March 2 to April 15 when the use of masks has no effect to estimate the confinement efficiency ratio q. Finally, we use all reported data up to 31 December to estimate ϵ and the other parameters α and δ. Note that to calibrate $\beta, \alpha, q, \epsilon$ and δ we fit the cumulative cases which means "$\alpha \times I_u$" to public data published in [15,33].

To obtain the removal rate r, we can use two methods that give approximatively the same results. In the first method, we use all the above-fixed parameters and fit our model to the public data of reported active cases between March 2 and December 31. While in the second method, we consider the discrete demographical model (5), presented here under, where the removal rate r is the only unknown parameter:

$$G_0 = N_0 \quad \text{and} \quad G_{i+1} = N_{i+1} + (1-r)G_i,\ i = 0, 1, ..T-1 \tag{5}$$

where T is the number of days in the period from March 2 to December 31, N_i and G_i are respectively the number of daily reported cases and the number of active cases in the ith day with $i \in \{1, .., T\}$. Hence, by fitting the above discrete model to public data using least-square optimization algorithm on Python we obtain the mean value of the removal rate to be $r = 0.085$. Table 3 presents the parameter values found by that process.

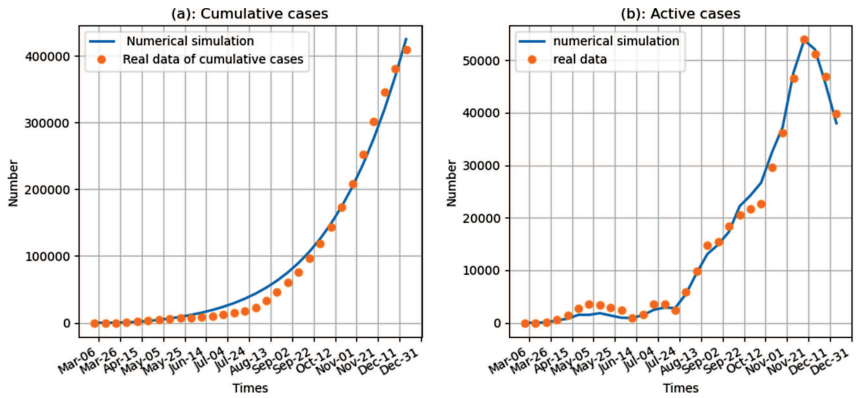


FIGURE 2. Fitting graphs to real data from March 2 to December 31. (a) presents cumulative cases and (b) presents active cases.

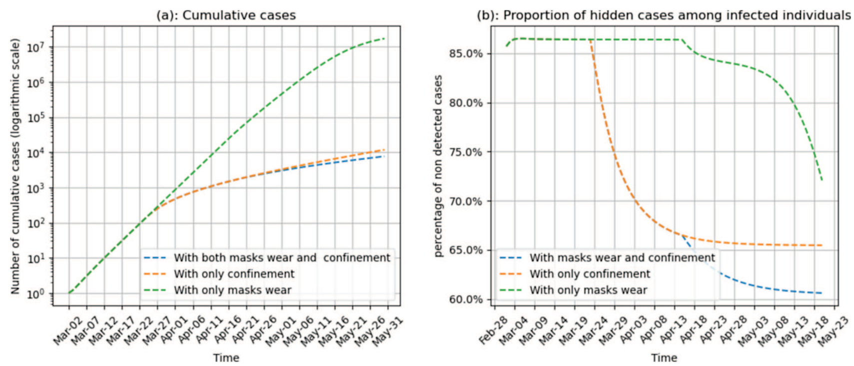


FIGURE 3. Evolution of the number of cumulative cases (a) and the percentage of undetected cases (b) from March 2nd to May 29 with confinement and/or wearing mask.

Figure 2 shows the evolution of the number of cumulative and active cases from March 2 up to December 31, 2020 obtained by our numerical simulation (represented by lines) and the real data to which our model is fitted (represented by dots). The simulation result shows that our model fits well with the real data of both cumulative and active cases.

Figure 3 investigates the impact of the protective measures on the intensity of the COVID-19 outbreak. It shows that adopting both mask wear and confinement in Moroccan strategy reduces significantly the proportion of hidden cases "I_u" (see Fig. 3b), and consequently the outbreak of the disease by reducing the growth rate of the number of cumulative cases (see Fig. 3a). On the other hand, adopting mask wear only or confinement only reduces the proportion of hidden cases, but until may, their rate stays over 65%. Whereas adopting confinement only was able to improve the curve of cumulative cases to be less than 10^4 during May, which was not possible in the case of wearing masks only, where the number of cumulative cases exceeds one million at the end of April.

The Figure 4 shows how the situation could be in Morocco by proposing a deconfinement on June 10, 2020 with different proportions q. We can see that in the event of complete deconfinement or with a small proportion of q the epidemic has been renewed. However, by adopting a partial deconfinement with values greater than $q = 0.67$ the epidemic curves have levelled off.

Figure 5 investigates a progressive deconfinement implemented in two stages. In the first stage, between June 10 and August 10 2020, we choose some values of q around 0.7 with which the curve plateaus and we

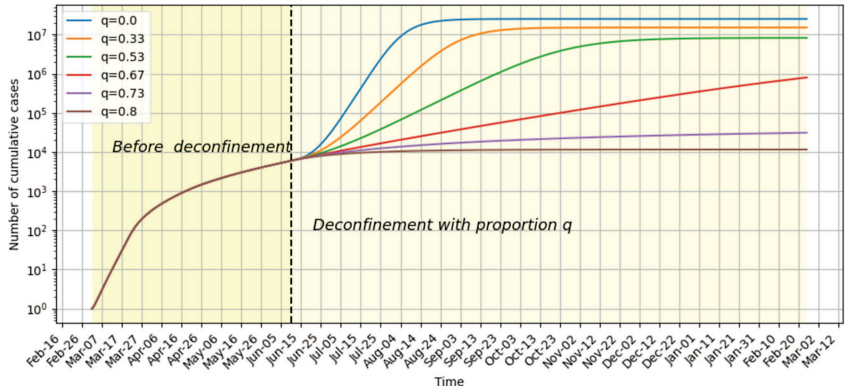


FIGURE 4. Partial deconfinement with different proportion q on June 10, 2020.

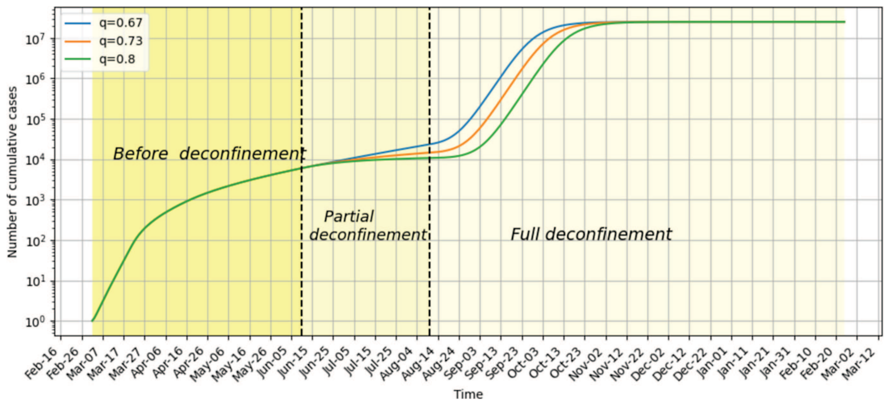


FIGURE 5. Progressive deconfinement with values around $q = 0.7$ on June 10 followed by total deconfinement ($q = 0$) on August 10, 2020.

assume that only a proportion q of the population keeps confined. In the second stage, from August 10, we assume that all the population became deconfined. The epidemic curves in this figure illustrate that in all cases, even with a large proportion of q on June 10, the disease has been renewed on August 10.

A progressive deconfinement by increasing the detection rate α or the effectiveness of protective measures ϵ could be a choice to gradually revive the economy and avoid a second wave of propagation. In Figures 6 and 7 we investigate such progressive deconfinement. We first, increase α or ϵ on June 10 and suppose that only 34% of the population has been kept confined. Then, on 10 August, we suppose that all the population has been deconfined. It appears that in the case of an increase in α on June 10 the number of reported cases increases immediately for one day allowing to isolate more infected cases, then the curve plateaus rapidly later (for $\alpha \geq 0.3$). Conversely, in the case of keeping the old value of detection rate $\alpha = 0.101$ after June 10, the number of reported cases keeps growing.

On the other side, a significant increase in the parameter ϵ also could make it possible to switch to progressive deconfinement and avoid further propagation. For example, exceeding the threshold $\epsilon = 0.7$ allows a continuous decrease in the number of cases even after a total deconfinement on August 10 Figure 7. However, for values around 0.54, the curve of the cumulative cases plateaus during the first stage of deconfinement but increases later on.

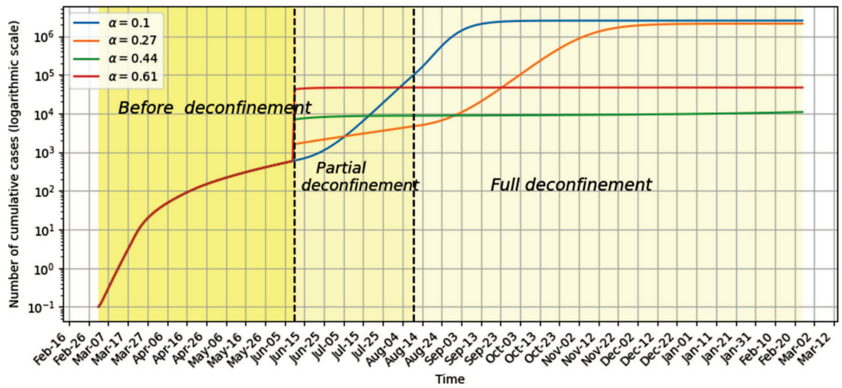


FIGURE 6. Progressive deconfinement showing evolution in number of cumulative cases with different values of α on June 10: firstly, 34% of the population still confined between June 10 and August 10 and secondly deconfining the full population on August 10, 2020.

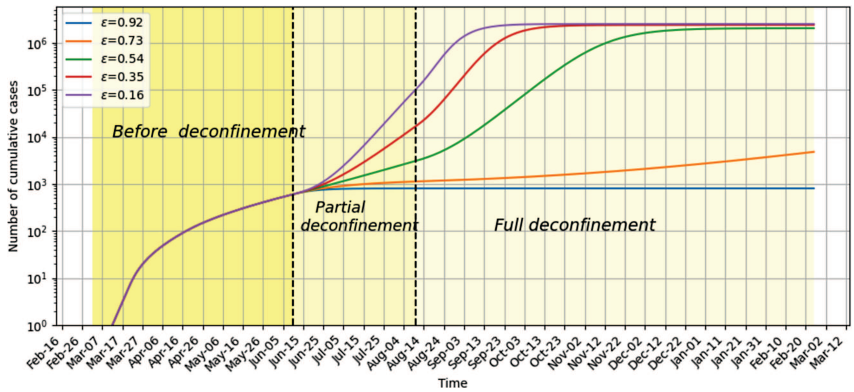


FIGURE 7. Progressive deconfinement showing evolution in number of cumulative cases with different values of ϵ on June 10: firstly, 34% of the population still confined between June 10 and August 10 and secondly deconfining the full population on August 10.

4. DISCUSSION

In the present study, our model has been applied for predicting how could be the course of the COVID-19 epidemic in Morocco, taking into account the confinement impact. The model shows in Figure 2 a good fit to reported cumulative cases. According to the numerical simulations, on average, 66% of the Moroccan population has respected and followed the confinement rules, which is coherent with the reported facts published in [14].

Actually, the confinement was applied in order to reduce the contacts among individuals [28], thus suppressed the value of the basic reproduction number $\mathcal{R}_0$ from 4.24 to 1.41. Later on, imposing masks wear, has minimized the probability of infection which further reduced the reproduction number to 1.17.

Clearly, maintaining total confinement in the long-term is a source of major social and economic costs [12, 19]. Therefore, our model can be used to inform on possible scenarios that could have happened in the case of adopting a deconfinement on June 10 2020 in Morocco in the absence of a vaccine. For the first scenario, we considered a full deconfinement (Fig. 4 the curve for $q = 0$), which has lead to a second wave of the epidemic, it is the worst scenario to face. And then we considered other scenarios with partial deconfinement, by varying the values of the proportion of confined individuals q, we have examined the effects of these changes, where halting the spread requires a light deconfinement with q close to 0.66 corresponding to the proportion of correctly confined individuals.

From all of these scenarios in our studies, it appears that acting on a few parameters allows a successful deconfinement strategy. We, therefore, studied the modification of two parameters: the detection rate α, and the effectiveness of the protective measures ϵ. The first parameter was considered in Figure 6, one can clearly notice the impact of increasing α, on the suppression of the disease, especially for $\alpha \geq 0.44$. The second was considered in Figure 7, one can see that the more effective the protective measures, the more we can make the virus disappear.

Based on the results in Figure 7, it could have been possible to eradicate the disease, in the absence of a vaccine, beginning by adopting a partial deconfinement where 34% of the population stays confined after June 10, while the authorities continue on sensitizing people on how to break down the transmission chain and highly invest to make available all protective measures especially the most efficient, to finally deconfine the entire population on August 10.

And as an added value of this study, we hope these findings will prompt the authorities adopting such strategies to prevent the aggravation of the situation when natural disasters or sever pandemics similar to COVID-19 occur.

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