



Modelization of Covid-19 pandemic spreading: A machine learning forecasting with relaxation scenarios of countermeasures



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ABSTRACT

Background & objective: Mathematical modeling is the most scientific technique to understand the evolution of natural phenomena, including the spread of infectious diseases. Therefore, these modeling tools have been widely used in epidemiology for predicting risks and decision-making processes. The purpose of this paper is to provide an effective mathematical model for predicting the spread of Covid-19 pandemic.

Methods: Our mathematical model is performed according to a SIRD model for infectious diseases. Epidemiological data from four countries; Belgium, Morocco, Netherlands and Russia, are used to validate this model. Also, we have evaluated the efficiency of Morocco's Covid-19 countermeasures and simulated the different relaxation plans in order to predict the effects of relaxation countermeasures.

Results and conclusions: In this paper, we developed and validated a new way of data aggregation, modeling and interpretation to predict the spread of Covid-19, evaluate the efficiency of countermeasures and suggest potential scenarios. Our results will be used to keep the spread of Covid-19 under control in the world.

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Introduction

The Covid-19 pandemic is a novel infectious disease, 2019 Corona virus disease (Covid-19), caused by the Corona virus SARS-CoV-2, appeared on November 17th, 2019 in the city of Wuhan in central China, and since then the virus has spread throughout the world. The World Health Organization (WHO) first alerted China and its other member states of the danger of the virus before declaring it an international public health emergency on January 30th. On January 13, the first confirmed Covid-19 case was discovered outside mainland China. Later two cruise ships (the MS Westerdam and the Diamond Princess) were also infected. The total number of Covid-19 patients outside of China exceeded 1500 in mid-February. Since January 2020, the Chinese government had implemented cumbersome containment procedures, and has put several cities and whole region under lockdown, closing many public sites and deploying important sanitary means. On February 25th, the number of daily new Covid-19 cases reported outside China was higher than

the ones reported inside the country. On March 11th 2020, WHO switched its rhetoric and labeled the Covid-19 a pandemic, and then recommended implementing essential protective measures to prevent the saturation of intensive care services and strengthening preventive hygiene (elimination of physical contact, kisses and handshakes, end of gatherings and major events as well as unnecessary trips, promoting hand washing, enforcing quarantine, etc.). On April 5th 2020, more than 1 136 849 cumulative covid-19 cases have been confirmed worldwide, including nearly 62 879 deaths. In total, around 200 countries were affected by this global health crisis, with outbreaks of more than 20,000 confirmed cases in the following countries: United States, Spain, Italy, Germany, China, France, Iran, United Kingdom, Turkey, and Switzerland. In these countries, the death rate (number of deaths/number of confirmed cases) varies from 12.5% (United Kingdom) to 1.5% (Germany).

Several researches have been conducted to understand and modelize the spread of this virus. On the one hand, some researchers focused more on covid-19 symptoms through confirmed patients' case studies [1], developed new and rapid test to diagnose the virus [2] and looked for a new vaccine [3]. On the other hand, other researchers, were oriented towards understanding the spread model of this pandemic [4], using all available data, provided

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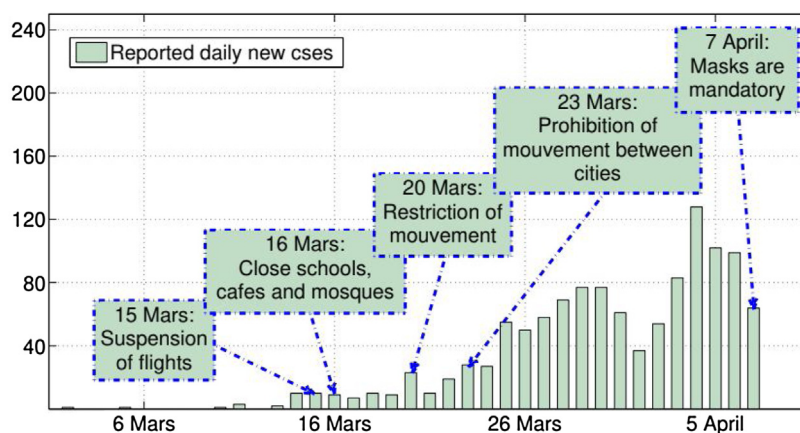


Fig. 1. Important Covid-19 control measures dates in Morocco.

by state health departments or WHO. However, the majority of these studies did not take into consideration social and cultural factors, others tried to emulate similar viruses to Covid-19 in terms of behavior, while the rest were interested in mathematical stochastic models in order to predict how the chain of transmission has changed over time, based on the data provided by China [5,6].

The first confirmed Covid-19 case in Netherlands first appeared on February 27th, 2020, in Tilburg city. The first Covid-19 death occurred on March 6th in Rotterdam. On March 16th, the Netherlands closed all its schools, daycare centers, bars, restaurants, sports clubs, and coffee shops. Also, Belgium was officially infected on February 4th, 2020. When a first case was confirmed; However schools were not closed until March 16th. On March 17th, Sophie Wilmès, the head of the Belgian government, announced a quarantine plan of the whole country.

Starting from March 9th, 2020 Morocco has implemented Covid-19 countermeasures. On March 16th, many public spaces were closed (Fig. 1); this decision has concerned cafes, restaurants, cinemas and theaters, party rooms, clubs, sports halls and game rooms. On March 20th, Morocco declared a state of health emergency and severely restricted the movement of the people, and has considered this action as the only inevitable way to keep the corona virus under control. Morocco made the use of a protective facemask mandatory starting from April 7th.

The first confirmed Covid-19 cases in Russia appeared on January 31st, 2020, after the arrival of two visitors from China. On February 2nd, roads and rail-way stations between Russia and China were officially closed. On March 30th, Russia closed all its borders except for goods, and enforced various Covid-19 countermeasures according to the medical severity of each region, thus closing restaurants and other non-essential businesses starting from March 28th. In Moscow, the mayor declared a lockdown on March 30th, 2020.

By studying the data delivered by the world countries, our mathematical model produces evidence that the spread the covid-19 is not random but follows a mathematical model [8]. There is no doubt that the selective tests save human lives and the available material resources, but the world is still far from the massive test campaigns declared by some countries. We should note that even without showing any symptoms, some infected people can still be asymptomatic carriers of COVID-19, thus Morocco, like the rest of the world, has no exact knowledge of the real number of Covid-19 infected people.

Our current understanding of COVID-19 virus incubation period is limited and different. On the one hand, authors in Ref. [9] expect that nearly every infected person who shows symptoms will be contagious in a period of 2–14 days; hence, COVID-19 virus should

be considered carried by anybody who has been in contact with a confirmed COVID-19 case or who has returned from a high-risk country for 14 days even if that person is asymptomatic [10,13]. On the other hand, other authors anticipate that the incubation period may be 19 days [12]. It's worth mentioning that 29.2% of admitted cases showed normal Computed Tomography (CT) scan and had no symptoms during hospitalization [14]. These cases were younger than the rest (median age: 14.0 years; $P = 0.012$).

A considerable amount of literature has been published on the spread Covid-19 prediction Models [15–17]. In this paper we have made three scientific contributions: (1) Covid-19 spread modeling and prediction, (2) evaluation of Covid-19 countermeasures efficiency, (3) proposition of countermeasures relaxation plans. The study aims to produce a mathematical model that produces predictions on the key data collected from Morocco and three more selected countries; Netherlands, Belgium and Russia. As these countries are at different stages of the pandemic, it is possible to imagine the evolution of the death rates. Although Morocco, unlike these countries, has adopted preventive measures at an early stage of the pandemic, it could still make good use of the efficient and effective countermeasures that Netherlands, Belgium and Russia have already taken.

Materials and methods

Model formulation

To modelize the progress of infectious diseases in a certain population, we can use consider SIRD model that places individuals into four different compartments relevant to the pandemic.

- Susceptible humans (S),
- Infected humans (I),
- Diagnosed humans (D),
- Recovered humans (hospitalization or even immunity by vaccination) (R). Individuals in the S compartment are vulnerable to catching the virus. Those already infected by the virus are called infected individuals. Diagnosed individuals are tested positive for Covid-19 virus, so they are in the D compartment and those who are immune by hospitalization or vaccination are in the R compartment. Fig. 2 describes the rate transmission of the virus within the model.

In this model, let $S(t)$, $I(t)$, $D(t)$, and $R(t)$ denote the number of individuals in the susceptible, infected, diagnosed and recovered compartments in respect to time (t) respectively. To describe the transmission diagram of Covid-19 disease in a certain population,

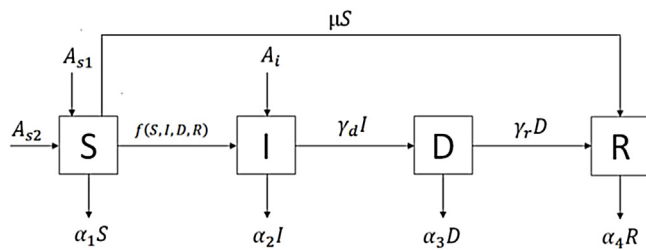


Fig. 2. Transmission diagram.

let's assume that the incidence $f(S, I, D, R)$ is defined by the number of new cases per time-unit, γ_r is the rate at which diagnosed individuals recover, γ_d is the rate at which the infected individuals are tested positive for covid-19 virus and $\alpha_1; \alpha_2; \alpha_3; \alpha_4$ denote the death rate. On the other hand, let A_{s1} and A_i be the traveling population rate of susceptible humans and infected humans respectively. The natural birth rate is denoted by A_{s2} . We assume that the vaccine is effective so that all vaccinated susceptible individuals become immune. Let μ represents the percentage of susceptible humans beings vaccinated. In addition, the incidence is described by the following equation:

$$f(S, I, D, R) = \beta C I \frac{S}{S + I + D + R} \quad (1)$$

where C is the number of contacts per time-unit and β is the probability of disease transmission per contact.

Taking all the above considerations into account we are led to the following dynamical system:

$$\begin{cases} S' = A_{s1} + A_{s2} - \mu S - f(S, I, D, R) - \alpha_1 S \\ I' = A_i + f(S, I, D, R) - (\alpha_2 + \gamma_d) I \\ D' = \gamma_d I - (\alpha_3 + \gamma_r) D \\ R' = \mu S + \gamma_r D - \alpha_4 R \end{cases} \quad (2)$$

Let's consider that countries did not suspend all flights right after finding the first diagnosed Covid-19 patient, yielding, $A_{s1} = 0$ and $A_{s2} = 0$. Note that this waiting time varies from a country to country (e.g., in Morocco this period is around one generation of infection).

Since we are interested in studying the dynamics of the number of individuals in (D) state compared to Covid-19, we will only consider the following states: Infected and Diagnosed patients. Furthermore, the precise value of β is still unknown, and it depends heavily on the intensity of control measures and its precise value is also difficult to estimate.

Fortunately, the incidence can be calculated from the daily new cases reported by the authorities, as will be discussed later in the next sub section. Furthermore, we denote

$$\sigma(t) = \beta C \frac{S}{S + I + D + R} - (\alpha_2 + \gamma_d) \quad (3)$$

And regard it as known as a function of time t . Thus the sub-system 2 becomes:

$$\begin{cases} I' = \sigma(t) I \\ D' = \gamma_d I - (\alpha_3 + \gamma_r) D \end{cases} \quad (4)$$

Since this paper focuses on the number of diagnosed patients over time, this problem can be reduced to the sub-model in Fig. 3 where there is no outcome from the diagnosed compartment, hence, the sub-system 4 becomes:

$$\begin{cases} I' = \sigma(t) I \\ D' = \gamma_d I \end{cases} \quad (5)$$

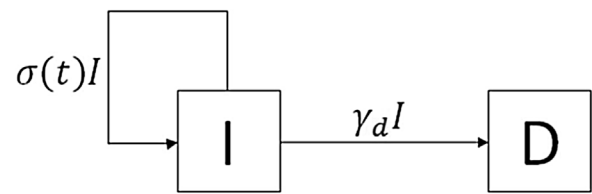
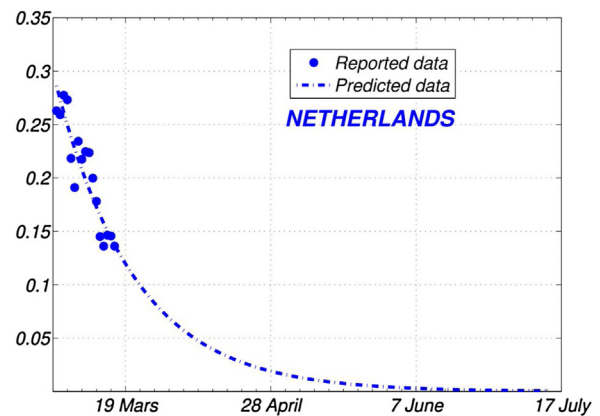


Fig. 3. Reduced transmission diagram.

Fig. 4. The net basic adequate contact rate 5×104 .

Model analysis

In this section we will engage in a discussion in order to validate the proposed model. It's clear that In order to compute the net basic adequate rate $\sigma(t)$, it is necessary to calculate the number of infected patients (I) for each day. Since only data of newly diagnosed Covid-19 patients are available, we need to estimate I based on it. Let $\sigma^*(t)$ denotes the estimated value of $\sigma(t)$ which is defined by the following equation:

$$\sigma^*(t) = \frac{I^*(t)}{I^*(t)} \quad (6)$$

where $I^*(t)$ denotes the estimated value of $I(t)$.

Let's assume that the time between two generations of infection is j_0 days. That is to say, we can roughly assume that a patient exposed at day t will be treated at day $t + j_0$. Thus, it can be estimated that the number of patients admitted during $t' \approx t + j_0$ is equal to the number of exposed individuals on day t . We can then estimate (I) of each day by assuming that the average number of days from exposure to the Covid-19 virus to the definite diagnosis is equal to j_0 . Moreover, this period may vary from one country to another due to several conditions and parameters related to each country, such as the incubation period for COVID-19, the number of tests performed per day, the climate, the average age of infected persons, other medical history of infected persons and so on.

Let's now show the net basic adequate rate identification obtained from the linear regression of $\sigma^*(t)$. Fig. 4 gives the above $\sigma^*(t)$ related to Netherlands from 29 February, 2020 to April 3th, 2020, the continuous curve is the net basic adequate rate $\sigma(t)$ of Netherlands according to Eq. [6], the horizontal axis is the time starting from 29 February, 2020. With the above prediction, we can now carry out some numerical simulations to validate our model by choosing four countries, each one is in a specific phase of the spread of the virus, thereafter, we can discuss the effectiveness of control measures adopted in Morocco including the timing as well. This may be useful to see whether or not these control measures could be relaxed and lifted earlier.

Figs. 5–8 depict the total COVID-19 patients' number (reported by Ref. [11]) and the results simulated by our model. The simulated

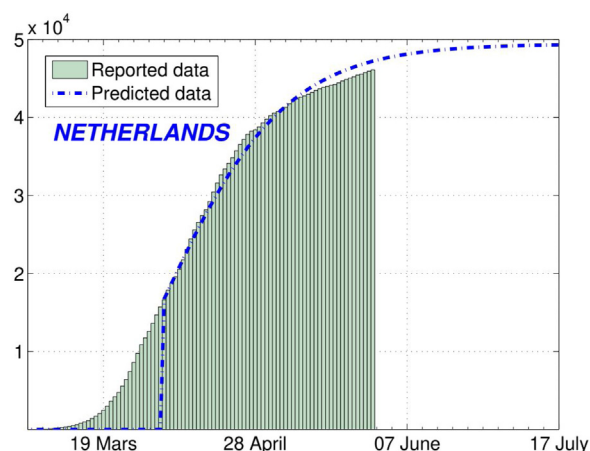


Fig. 5. The predicted curve and the reported [11] of the total number of the COVID-19 patients in Netherlands (the dates of reported data used as an input for prediction are: 29 Feb–3 April, 2020).

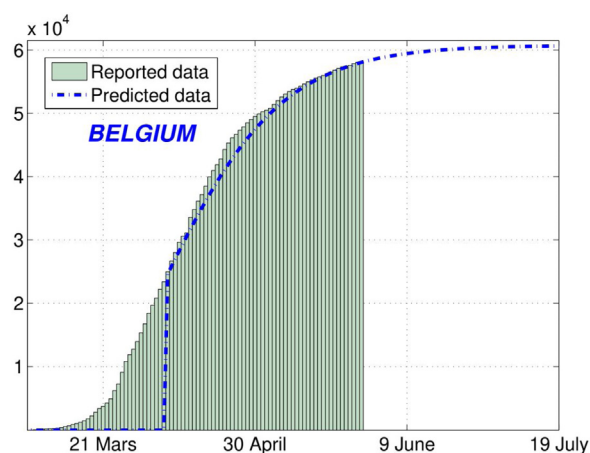


Fig. 6. The predicted curve and the reported [11] of the total number of the COVID-19 patients in Belgium (the dates of reported data used as an input for prediction are: 2 Mars–6 April, 2020).

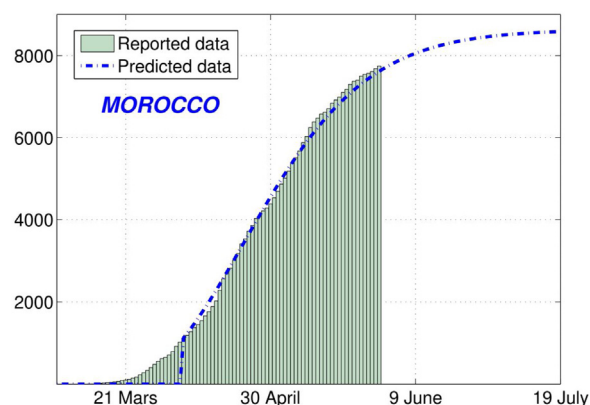


Fig. 7. The predicted curve and the reported [11] of the total number of the COVID-19 patients in Morocco (the dates of reported data used as an input for prediction are: 2 Mars–5 April, 2020).

result shows that the reported data is very close to the predicted data for the four chosen countries. This simulation matches with real data, serving as a validation of the model. Furthermore, we can see from these figures that the total number of the COVID-19 patients will not stop increasing before 17 July and 2 August in

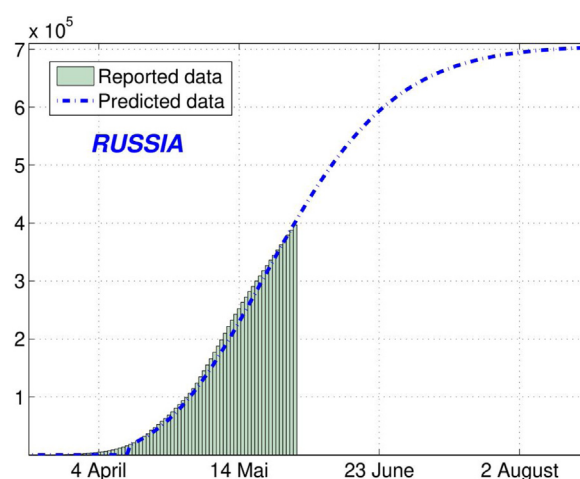


Fig. 8. The predicted curve and the reported [11] of the total number of the COVID-19 patients in Russia (the dates of reported data used as an input for prediction are: 16 Mars–14 April, 2020).

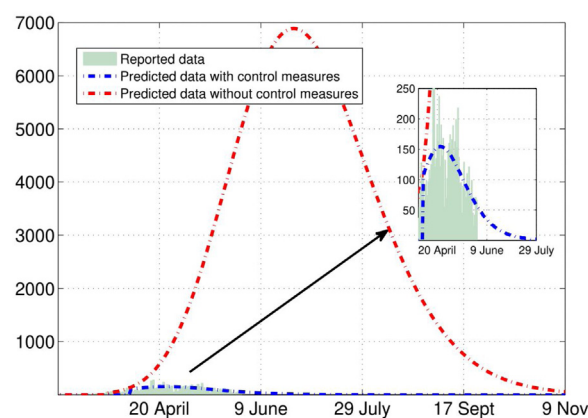


Fig. 9. A comparison between the predictions of the daily new diagnosed persons in Morocco with and without control measures.

Netherlands and Russia respectively, while in Morocco and Belgium before 19 July. That means that the virus infects individuals in a period of at least 4 months from the date of detection of the first infected person.

Result

We conducted a comparative simulation to evaluate the effectiveness of the drastic control measures taken by the Moroccan government. To do so we will compare the evolution of the contagion with and without countermeasures (Fig. 9). Note that after the first period (15 days from the first diagnosed case), the Moroccan government has decided to shut down schools cafes and mosques, one day after suspending international flights, we consider this period to represent the spread of the virus with no countermeasures, and we will predict including only the corresponding reported data the evolution of the virus during the next months. Fig. 10 shows that the number of diagnosed cases would have reached the peak in about 116 days (15 June) instead of 53 (23 April) and with a number of positive cases approaching 600 K.

The simulation proves that the control measures helped contain the pandemic, thus flattening the curve and reducing the virus's spread speed. Note that other studies have shown that shifting the quarantine 2 days after the reference date had notable effect on the pandemic evolution as to double the number of cases [7]. Note that the full control measures include: imposing full quarantine except

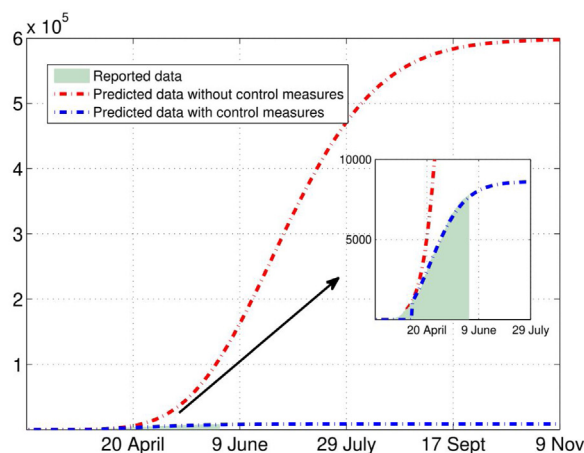


Fig. 10. A comparison between the predictions of the total number of diagnosed persons in Morocco with and without control measures.

for necessary businesses with social distancing on March 20th, followed by the prohibition of movement between cities which made containing and dismantling small contagion areas and preventing mass spread, the third measures consisted in making the use of facemasks mandatory which reduced the probability of contagion.

Discussion

To understand and modelize the spread of this virus, several researches have been conducted through analyzing symptoms of patient's case studies [18], designing new and rapid tests to detect the virus [2] and looking for a new vaccine [3]. Using all available data, provided by countries or WHO, other studies were oriented towards understanding the spread model of the virus [4]. Note that the majority of these studies did not take into consideration the social and cultural factors, others tried to copy similar virus behavior to Covid-19, while other researches were interested in mathematical stochastic models in order to estimate how transmission had varied over time based on the data provided by China [5,6].

However, due to the poor available information about the simulation of relaxation plans of Covid-19 countermeasures, this section describes the effectiveness of the Morocco's countermeasures as well as the right times for their gradual relaxation. In Ref. [1] authors presented the effectiveness of countermeasures in Morocco and predicted that the cumulative percent of infected cases will keep increasing until achieving a constant value on 15 May. This, however, was not the case since the authors did not take into consideration the impact of the incubation period where infected persons are not yet diagnosed and may transmit the virus.

The outbreak control

Let's now discuss whether or not these control measures could have been relaxed and lifted earlier. Note that the SARS virus naturally declines at the rate of 0.01 per time unit [18]. However, this paper considers the reported data of Morocco from 2-March to 24-March as a progressive relaxation phase, where not all control measures are adopted, which will serve to identify the progressive relaxation parameters of the model in Morocco. By using these data, we can deduce that the corresponding decline is equal to $1 - 0.9872$ with an initial value of 0.2251 yielding $\bar{\sigma}(t) = 0.2918(0.9872)^t - 0.0667$. We take $\sigma(t)$ equal to $\sigma^*(t)$ for $t \leq t_0$ and $\bar{\sigma}(t)$ for $t > t_0$. To find the optimum date to start lifting lockdown, we conducted a simulation, where we predict the evolution of the spread if relaxation is performed 16, 30 or 44 days from the peak, the simulation, taking

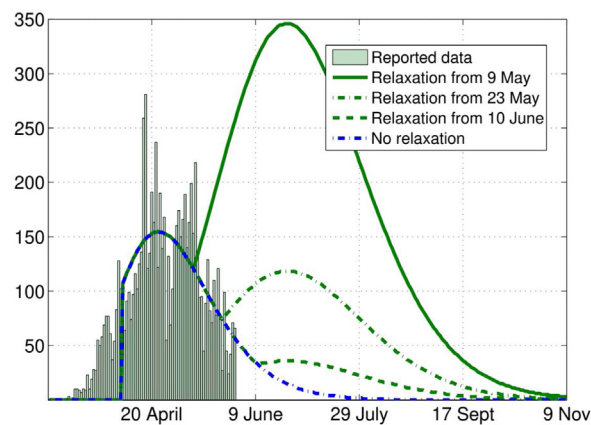


Fig. 11. Impact of control measures relaxation scenarios on the daily new confirmed patients: the case of Morocco.

into consideration the above natural decline rate of the Covid-19 virus, showed with certainty that the number of cases will rise again, but the main goal is to maintain the number of cases under control (can be handled by the health care infrastructure). Fig. 11 shows that the relaxation date has a huge impact on the second wave of contagion, and that premature relaxation could have a devastating impact as to annihilate all the previous efforts. That's why we recommend starting lifting the lockdown gradually at least two contagion periods from the peak of the contagion. In the following section we will expose our vision to how the relaxation should be performed.

Relaxation measures

In this section we will expose a cautious roadmap to lift the lockdown in Morocco based on our prediction model, and WHO's recommendations, taking into consideration the availability of four key elements: First the ability of the health infrastructure to provide necessary care for new cases. Second the availability of facemasks. Third the testing and contact-tracing mechanisms capacity, in addition to the readiness and pro-activity of the health care system and its capacity to dismantle clusters of cases if needed. Before revealing our vision it is fundamental to establish an inventory of activities sorted out by two keys (importance and contagion risk). The authorities should also be confident that easing control measures will not risk a second peak of infections due to high-risk activities, but since even the most complex prediction models cannot predict with certainty the impact of lifting restrictions, we recommend to err on the side of caution and lift control measures in three steps distanced by at least one incubation period. In the first step we recommend, according to our predictions in Figs. 11 and 12, reopening low-risk activities, while maintaining social distancing and travel restrictions between regions, this step should be applied from 10 June based on the prediction in Fig. 12, as for the essential but high-risk activities, some restrictions should be applied to ensure social distancing with close monitoring. In this step workers continue to work from home, and avoid public transportations wherever possible, while maintaining the most vulnerable citizens shielded. The second step, after a full assessment justified by the validity of the four key elements, will include inter-regional travel, as more activities will reopen and some sport and social events respecting social distancing criteria will be allowed, but this step should be carried out with rigorous monitoring standards that should allow imposing some restrictions if needed. In the last step, according to the evolution of the previous, places of worship, leisure facilities and remaining businesses, except those that are crowded by design and where maintaining social distancing is impossible.

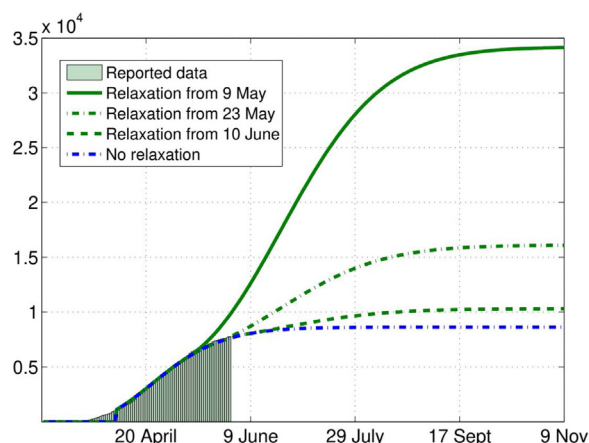


Fig. 12. Impact of control measures relaxation plans on the total number of confirmed patients: the case of Morocco.

Conclusion

The present study has gone some way towards enhancing our understanding of Covid-19 spreading. Our model shows great results and the predictions meet the official update data, countermeasures efficiency evaluation is also presented, and the proposition of relaxation plans are important to keep the Covid 19 virus spread under control. Further works are needed to fully understand the implication of other indicators like weather. Other machine learning algorithms can be used in order to modelize multi parameters vector data.

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Competing interests

None declared.

Ethical approval

Not required.

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