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Age-Structured Modeling of COVID-19 Epidemic in the USA, UAE and Algeria

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Abstract
As the COVID-19 is still spreading in more than 180 countries, according to WHO. There is a need to understand the dynamics of this infection and predict its the impact on the public health capacity. This work aims to forecast the progress of the disease in three countries from different continents: The United States of America, the United Arab Emirates and Algeria. The existing data shows that the fatality of the disease is high in elderly people and people with comorbidity. Therefore, we consider an age-structured model. Our model also takes into consider two main components of the COVID-19 (a) the number of Infected hospitalized people, therefore, we estimate the number of beds (acute and critical) needed (2) the possible infection of the healthcare personals (HCP). Hence, the model predict the peak time and the number of infectious cases at the peak before and after the implementation of non-pharmaceutical interventions (NPI), and we also compare this finding with case of full lockdown. Finally, we investigate the impact of the shortage of proper personal protective equipment (PPE) on the spread of the disease.

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1. Introduction

Since the first cases of COVID-19 in the city of Wuhan, China, the COVID-19 pandemic has affected the globe with more than 15 millions cases and over 600,000 deaths. The high transmission of the coronavirus among all age groups and the increasing fatalities among people with comorbidity have required governments to take different measures that have restricted human mobility and put many economies on hold.
Moreover, with the daily exponential increase of the number of cases, COVID-19 has overwhelmed the health care capacities of many countries [2]. As a result, there is a need to find the immediate solutions to the saturated capacity of hospitals by increasing the number of hospital acute and critical beds [3,4], as well as, providing the healthcare personnel (HCP) with enough and proper personal protective equipment (PPE) [5]. In fact, the HCP are vulnerable populations to the infection if there is not enough shortage of PPE, or if the PPE are not effectively used [6]. Recent report by the International Council of Nurses [7] has revealed that 90,000 HCP have been infected, and more than 260 nurses have died.

As the pandemic is still taking many lives everyday, it is very important to understand if the non-pharmaceutical interventions (NPI) [8] are effective in reducing the burden on the public health. Keep in mind that some countries choose to have drastic measures, other countries choose to not [9]. The decision of taking any measure to protect the population should take into consideration: (A) to protect the most vulnerable population, particularly the elderly population which has high mortality rate [10,11] (B) the capacity of the healthcare system [12] and the economical cost of such measures. In fact, American Hospital Association has estimated a total lost of $202.6 billion for America’s hospitals and health systems in four months [13].

Mathematical models are among highly used tools, by many governments, to help in decision making during this pandemic [20]. Many models were able to give different estimations of the end of the pandemic and the number of the people that could be infected in different countries [23,26–29]. However, there is a need for mathematical models that help to estimate the impact of the COVID-19 for the most vulnerable population: Elderly people. As this population is most likely to be hospitalized, due the current pandemic, such models should be able to estimate the hospital bed capacity needed to give the proper care to the COVID-19 patients in general and COVID-19 patients with comorbidities, which are mainly the elderly. As the majority of the countries, affected by the COVID-19, are implementing control measures to effectively contain the spread of this disease, it also important to evaluate, via mathematical models, the impact of such measure on the public health capacity. Finally, we need to get more insight of the effect the scarcity of the PPE on the dynamic of the spread of the disease.

For these purposes, we propose an age-structured model that investigates the projected number of infected cases, number of acute and critical hospital beds needed in three different countries USA, UAE, Algeria. To examine the impact of the NPI on each country, our estimations are made using the data before April 20th, 2020, and the second for data between April 21st and May 15th, 2020, where we will highlight the variations before April 20th, 2020, and the second for data between April 21st and May 15th, 2020, where we will highlight the variations between both scenarios.

In this section, we present the mathematical model for predicting the pandemic of COVID-19. The model is an age-structured model [16–18,25,31] that takes into consideration the age as a factor of the progress and severity of this disease. The corresponding model is given by the following structure:

\[
\begin{align*}
\frac{dS(t,a)}{dt} &= -\beta S(t,a) \int_0^\infty I(t,\theta)d\theta - \alpha C(t)S(t,a), \\
\frac{dI(t,a)}{dt} &= \beta S(t,a) \int_0^\infty I(t,\theta)d\theta + \alpha C(t)S(t,a) - (\gamma + \delta(a))I(t,a), \\
S(t,0) &= 0, \\
I(t,0) &= 0, \\
S(0,a) &= S_0(a) \in L^1(0,\infty), \\
I(0,a) &= I_0(a) \in L^1(0,\infty), \\
C(0) &= C_0 \in \mathbb{R}^+, 
\end{align*}
\]

(2.1)

where \(S(t,a), I(t,a)\) are, respectively, the fraction of the susceptible and infected individuals at time \(t\) and age \(a\). \(C(t)\) represents the fraction of hospitalized individuals at time \(t\). The hospitalized individuals mean those who are infected and in a need for acute or critical beds. This fraction of the population might infect their soundings including the HCP. This situation can happen when the right PPE is not available or is not efficient to protect from the COVID-19 infection. In our model, we consider the parameter \(x\) that measures the degree of protection of the HCP. Meaning, when \(x = 0\) there is full protection, for \(x = 1\) there is no protection. This rate changes from one country to another depending on how much of the medical protection standards are followed and the supply of PPE is available. In the context of our study, it is natural to assume that the standard of the protection of the HCP against COVID-19 is higher in the UAE and USA than in Algeria.

The parameter \(1/\mu\) represents the average time spent by an infected person in the hospital care before either she/he dies or recovers. In general, this value is between 10 and 20 days [14,15]. In our context, we suppose that \(\bar{\mu} = 15\). This parameter can be written as \(\mu = \mu_1 + \mu_2\), with \(\mu_1\) is the mortality rate and \(\mu_2\) is the recovery rate as a result of a successful medical intervention. The parameter \(\bar{\mu} = 10\) is the average of the infection period [32,22]. \(\beta\) is the transmission rate. The integral \(\int_0^\infty I(t,a)da\) represents the total fraction of the infectious individuals at time \(t\). We also make the assumption that the infectiousness of the COVID-19 depending on the age of the patient, we consider the following function.
\[ \delta(a) = \begin{cases} \delta^* & \text{if } a \geq \tau, \\ 0 & \text{if } a < \tau, \end{cases} \quad (2.2) \]

where \( \tau = 60 \). It is very important to mention that the initial conditions will be considered depending on the country considered as it is presented in following Table 2.

For the well-posedness of the systems, we define the following space

\[ \mathbb{H} = L^1(0, +\infty) \times L^1(0, +\infty) \times \mathbb{R}^*, \]

with \( L^1(0, +\infty) \) is the space of functions that are positive and Lebesgue integrable, which is equipped with the norm

\[ \| (\phi, \psi, \chi) \|_{\mathbb{H}} = \int_0^{+\infty} |\phi(\theta)|d\theta + \int_0^{+\infty} |\psi(\theta)|d\theta + |\chi|. \]

We suppose that the initial conditions \((S_0, I_0, C_0) \in \mathbb{H}\). Using a similar approach as in [21,16], we can deduce that (2.1) has a unique positive solution for initial conditions that belongs to the space \( \mathbb{H} \).

We define the basic reproduction number \( \mathcal{R}_0 \), which represents the number of the new infectious cases by one infected individual in the infection period during a given time of spread of the COVID-19 [19,33].

\[ \mathcal{R}_0 = \beta S_0 \int_0^{+\infty} e^{-\omega t} \int_0^{+\infty} \delta(a)da \left( 1 + \frac{\delta(a)}{\mu} \right) da. \]

Now, we are interested in approximating the transmission rate \( \beta \). Obviously, this rate changes from one country to another as each country has a different level of intervention such as lockdown, social distancing, and curfew. Calculating the total fraction of the infected individuals and the susceptible ones by integrating the first and the second equation of the model (2.1), we obtain

\[ \frac{di(t)}{dt} = -\beta s(t) (i(t) + z C(t)), \]
\[ \frac{dC(t)}{dt} = (\beta s(t) - \gamma) i(t) + z \beta s(t) C(t) - \int_t^{+\infty} \delta(a) I(t, a) da, \]
\[ \frac{dI(t)}{dt} = \int_t^{+\infty} \delta(a) I(t, a) - \mu C(t), \]

where

\[ i(t) = \int_0^{+\infty} I(t, a) da \text{ and } s(t) = \int_0^{+\infty} s(t, a) da. \]

We also have

\[ 0 \leq \int_t^{+\infty} \delta(a) I(t, a) da \leq \delta^* i(t). \quad (2.4) \]

By replacing the inequality (2.4) into the third equation of the system (2.3), we get the following inequality:

\[ 0 < C(t) < C(0) e^{-\mu t} + \delta^* \exp^{-\mu t} \int_0^{+\infty} i(s) ds. \quad (2.5) \]

As any pandemic, there is an exponential growth in the beginning of the time series of number of cases. Therefore, we assume that the total fraction of the infected individuals \( i(t) \) has the following special form:

\[ i(t) = x_1 \exp^{\gamma t}, \quad (2.6) \]

where \( x_1 \) represents the proportion of the declared infection cases by the World Health Organization [34] on the first of April, 2020. To obtaining the best value of \( x_2 \) at which is an approximation to the declared infection cases, we use the method of least squares method for approximation the real data by an exponential functional. The obtained results are highlighted in Table 3. From the second equation of (2.3) we get

\[ \beta = \frac{\beta (t) + \int_t^{+\infty} \delta(a) I(t, a) da}{(s(t) - \gamma) i(t) + z \beta s(t) C(t)}. \quad (2.7) \]

Using Eqs. (2.4), (2.5) and (2.6), then (2.7) verifies the following inequality:

\[ \tilde{\beta} \leq \beta \leq \bar{\beta}, \]

with

\[ \tilde{\beta} = \frac{(x_2 + \gamma) x_1}{x(0) x_1 + z x(0) C(0)} \] and \( \bar{\beta} = \frac{x_2 + \gamma + \delta^*}{x(0)} \).

By a variation of the value of \( \beta \) in the interval \([\tilde{\beta}, \bar{\beta}]\), we retrieve the maximum of the real data, and we obtain the values of \( \beta \) for each country as it is highlighted in Table 3.

### 3. Simulation of COVID-19 peak using data before 20/04/2020

Based on these approximations, we give the following prediction on the COVID-19 epidemic in the USA, the UAE, and Algeria.

In the case of the USA, from Fig. 2, we expect the peak to be reached at \( t = 45 \) (which means May 05th) with a proportion of 0.007786 of the total population to be infected, that is, 2,555,365 infection cases. Currently, the number of active cases is around 1,364,000, which is 1 M more than our estimation. In fact, our finding reflects the possible number of cases in the USA if no containment measures were taken. The infection will end after three months it starting which means by the end of June. At \( t = 58 \), our simulation shows that the number of hospital beds needed will reach 833960. Moreover, Fig. 2 shows that infection will appear mostly in the aged individuals.

In the case of the UAE and based on the parameters values in Table 3, Fig. 3 represents the number of the infection cases, as well as the prediction the time pandemic peak outbreak. Based on our simulation, the number of infected cases would reach its highest at \( t = 56 \) starting from the first of April 2020, meaning on May 26th, with the proportion 1.67% of the total of population to be infected, which is equivalent to 165360 infection cases. Next, it will decrease brutally and the infection will disappear 100 days starting from the first of April.
2020, which means around July 9th. On the other hand, the maximum number of beds needed will 63138 on June 6th, 2020.

In the case of Algeria, Fig. 4 shows the prediction of the peak number at $\frac{t}{2} = 51$, which is on May 21st, with the proportion 0.0005579 of the total of population which is equivalent to 23,052 of the population been infected. We also predict the end of the pandemic to be at end of June and beginning of July. In terms of the number of hospital beds needed, we estimated the peak of the number of hospital beds to be, 8545 beds, on May 31st; by the end of June all beds related to epidemic will be released.

4. The influence of the measures taken after 21/04/2020 on the spread of COVID-19

As the prediction of the previous section were based on the data from the beginning of April until April 20th. In this section, we are interested in analyzing the impact of the NPI, taken by different governments after April 20th, on reducing the burden of the disease on the health care capacity. For this purpose, we use the data of number of infections in the three countries, reported by WHO [34], between April 21st and May 15th.

By using the same method as the previous section, we obtain the values of $x_1$ and $x_2$ on the following figure (see Fig. 5).

Which leads us to the new estimation of parameters in the following table (see Table 4).

Next, we use these estimations to investigate the peak of the epidemic. Similar to the approach of the previous section, we get the results of Fig. 6.

Consequently, we observe a clear reduction of the number of the infected people at the peak of the pandemic in the three countries (As shown in Table 5). Moreover, with the NPI, the peak day of each country will be delayed compared to the previous estimation. For the USA, the peak is on $t = 53$ (May 13th), for UAE $t = 63$ (June 2nd) and for Algeria $t = 61$ (May 31st).

5. The impact of the full lockdown on the spread of COVID-19

Since not all the countries were able to stop the community transmission of the COVID-19 by the NPI, we would like to know how a full lockdown, if it was applied, would have affected the progress of the COVID-19. The full lockdown means to completely restrict all social movements. For this purpose, we choose the transmission rate as a constant before applying the lockdown and it exponentially decreases after applying the lockdown [24]. By using this assumption and based on the results obtained in the previous section, we can see that the transmission rate becomes smaller (see Tables 3 and 5). Therefore, we consider the transmission rate as a decreasing function of time. More precisely, we suggest the following form of $\beta(t)$

\[
\beta(t) = \beta_0 e^{-\lambda t}
\]

Table 3  Estimation of $x_1, x_2$, the transmission rate and the basic reproduction number.

| Country | $x_1$     | $x_2$ | $\beta_0$ | $\beta(t)$ | $R_0$ |
|---------|-----------|-------|-----------|------------|-------|
| USA     | 4.9725 x 10^{-4} | 0.091 | 0.1966    | 0.2364     | 2.526 |
| UAE     | 6.7139 x 10^{-3} | 0.15  | 0.2528    | 0.2679     | 2.640 |
| Algeria | 1.44 x 10^{-4}  | 0.09  | 0.1920    | 0.2172     | 2.149 |

Fig. 1  The approximation $x_1$ and $x_2$ using the data [34] where the values used in Table 3 are used for each sample and $t = 0$ represents the date 01/04/2020.
Fig. 2  Numerical simulation of the spread of COVID-19 epidemic in USA with data fitting, where the red color curve is the declared infection cases by WHO [34] and the blue curves is the approximations offered by the model.

Fig. 3  Predicting the spread of COVID-19 epidemic in UAE, where the red color curve is the declared infection cases by WHO [34] and the blue curves is the approximations offered by the model.
Indeed, we consider that $b_0$ takes the values highlighted in Table 3, $l = 0.16$ (see [24]) and $T$ represents the time of applying the lockdown where it is supposed to be applied at $T = 30$. In Fig. 7, we investigated the influence of this restriction on the peak of the epidemic and the date of the end of the infection.

\[
\beta(t) = \begin{cases} 
  b_0 & \text{if } t < T \\
  b_0 \exp^{-\mu(t-T)} & \text{if } t > T.
\end{cases} \quad (5.1)
\]

The Fig. 7 shows the simulation of the number of infected people and number of the beds needed in the case of the full lockdown. The blue curves represent the obtained results in Figs. 2–4, i.e. without lockdown, which is summarized in the Table 6. The green curves represent the time series of the epidemic in each country in the case of the lockdown. The findings of this case is presented in the Table 7.

From these two tables, we find that the UAE would benefit the most from a 30-day full lockdown as the number of...
**Table 4** Estimation of $x_1, x_2$, the transmission rate and the basic reproduction number on the period between April 21st to May 15th, 2020.

| Country | $x_1$   | $x_2$   | $\bar{\beta}$ | $\tilde{\beta}$ | $\bar{\tilde{\beta}}$ | $R_0$  |
|---------|---------|---------|----------------|------------------|------------------------|--------|
| USA     | 0.0023  | 0.0260  | 0.1368         | 0.2074           | 0.2155                 | 2.0822 |
| UAE     | $7.3458 \times 10^{-4}$ | 0.045  | 0.1466         | 0.1769           | 0.1972                 | 1.7768 |
| Algeria | $6.5779 \times 10^{-5}$ | 0.038  | 0.1433         | 0.1571           | 0.19                   | 1.5777 |

**Fig. 6** The influence of the measures taken after 21/04/2020 on the value of the pandemic peak of COVID-19.
infected people will drop to 24% from the original estimation and then Algeria with 43.3%. However, the USA will benefit less from this measure with a drop to only 72.2%. Similarly in the case of hospital beds needed, with a full lockdown, the UAE needs will drop to 13.1% from the original estimation. In the case of Algeria, the number of hospital beds needed will drop to 23.8%, and for the USA it will drop by more than half, to 44.7%. By applying such strict measures, our simulations show that the epidemic would finish after 63 day, which means by June 2nd, 2020.

6. The effect of the PPE on the spread of COVID-19

In this section, we are interested in analyzing the efficacy of the availability of the PPE on the spread of the COVID-19 among the HCP. In our model (2.1), the parameter that represents this efficacy is \( \alpha \). In reality, as the number of the infected cases increases the HCP are obligated to increase their work load, which makes them more susceptible to infection, particularly if there is a shortage or an improper use of the PPE. Therefore, we consider that \( \alpha \) is an increasing functional in \( i(t) \). and we choose the following special form:

\[ \alpha(i(t)) = 1 - \exp^{-\rho N \int_0^t \frac{1}{i(t)} \, dt}. \]

\( N \) is the total size of the population and \( \rho \) is the percentage of individuals that uses the PPE.

In fact, \( \alpha(0) = 0 \) (there is no infection) then \( \alpha = 0 \), which means the PPE is available, and there is no chance for an HCP to be infected during their contact with an infected person at the hospital. On the other hand, for \( \alpha(1) = 1 \), which means that all the population is infected, \( \alpha \) approaches 1, i.e. the PPE is scarce or unable to protect the HCP.

### Table 5

| Country | USA | UAE | Algeria |
|---------|-----|-----|---------|
| The number of infected at the peak without NPI | 2 555 | 165 | 23 052 |
| The number of infected at the peak with NPI | 1 968 | 45 | 12 355 |

Fig. 7 The effect of the full lockdown on the spread of COVID-19 in the USA ((A) and (B)), the UAE ((C) and (D)) and Algeria ((E) and (F)). The blue figures represent the case of the absence of restriction and the green curves represent the case of the full lockdown.
By replacing $z$ with $z(t)$ in the system (2.1), we obtain the simulations of the Fig. 8. In these plots, we can see that the availability of the PPE affects the peak of the epidemic, where the peak becomes higher, the green curve represents the dependence on the availability of the PPE to the infected case $a_i(t)$, where the blue curve shows the times series of the disease in Figs. 2–4. In these simulations, we calculated the number of nurses and doctors of each country and estimated the $q = 0.715\%$ for the USA, $q = 0.117\%$ for the UAE and $q = 0.16\%$ for Algeria.

From these simulations, it is clear that the shortage of the PPE could cause doubling of the number of infected cases as well as the number of hospital beds needed. However, it does not affect the time of the peak nor the end of the epidemic. Which conclude the importance of the availability PPE is lowering the number of the transmission the healthcare facility, long term care and among the general public.

### 7. Conclusion

In this paper, we presented an age-structured model to predict the size of epidemic in three different countries: the USA, the UAE and Algeria. This model takes in consideration the number of hospital beds needed for the COVID-19 patients that need either acute or critical care.

#### Table 6

The main characteristic of the pandemic in the absence of the restriction of human movement strategy. The time $t = 0$ refers to the date 01/04/2020.

| No restriction | End of pandemic | Time of the peak of the number of IC | Number of IC at this peak | Time of the peak of the number of HBN | Peak of the number of HBN |
|----------------|-----------------|-------------------------------------|---------------------------|----------------------------------------|--------------------------|
| USA            | $t = 90$        | $t = 45$                            | 2 555 400                 | $t = 58$                               | 833 690                  |
| UAE            | $t = 100$       | $t = 56$                            | 165 360                   | $t = 65$                               | 63 138                   |
| Algeria        | $t = 94$        | $t = 51$                            | 23 052                    | $t = 63$                               | 8 545                    |

#### Table 7

The main characteristic of the pandemic in the case of full lockdown. The time $t = 0$ refers to the date 01/04/2020.

| No restriction | End of pandemic | Time of the peak of the number of IC | Number of IC at this peak | Time of the peak of the number of HBN | Peak of the number of HBN |
|----------------|-----------------|-------------------------------------|---------------------------|----------------------------------------|--------------------------|
| USA            | $t = 63$        | $t = 30$                            | 1 846 800                 | $t = 40$                               | 372 840                  |
| UAE            | $t = 63$        | $t = 35$                            | 39 829                    | $t = 42$                               | 8 275                    |
| Algeria        | $t = 63$        | $t = 30$                            | 9 995                     | $t = 42$                               | 2 039                    |

Fig. 8  The effect the PPE on the spread of COVID-19 in USA (A and B), UAE (C and D) and Algeria (E and F), where the blue figures represent the case where $z$ is constant and the green curves represent the case where the PPE depends on the number of infected.
We first consider the number of infected cases from the beginning of the epidemic until April 20th, 2020. We calculated the basic reproduction number $R_0$ for each country data set. We also estimated the time peak of each country and the number of the cases and hospital beds needed. By looking at the current data of each country, we had overestimated the number of cases at the peak as well as the time of the peak. Naturally, the number of beds needed was also overestimated. In fact, these estimations did not take in consideration the efforts that each country made, after April 20th, 2020, to contain the pandemic, and it shows the possible impact of the COVID-19 if the governments did not take the right measures to protect the public health.

By assuming that all these countries started the NPI measures after April 20th, we fitted our model to the data between April 21st and May 14th, 2020 to re-estimate the main parameters of our model. The prediction of the characteristic of the pandemic is highlighted in Table 5. Compared to the previous scenario, the main conclusions are: (a) the three countries made substantial efforts to reduce the spread of COVID-19 disease, which shows clearly the reduction of the basic reproduction number, (b) the NPI measures were able to reduced the size of the pandemic and delayed its peak.

Next, we investigated the question of the possible impact of a full lockdown, if applied, on the population to contain the spread of the disease. We assumed that each country applied the full lockdown starting from April 20th. With this scenario, in 30 days the virus would vanish from the three countries and community infection would disappear. Although such measure will have economical effects on each country and psychological effects on the population, it will help to reduce the burden on the healthcare capacity as shown in the Tables 6 and 7.

In the last part of the paper, we studied the effect of the unavailability or improper use of the PPE on the COVID-19 among the HCP. By assuming that the infection could be transmitted to the HCP, via the patients in acute and critical conditions, our simulation showed that such scenario would double the number of the infected people and numbers of hospital beds needed at the peak of the pandemic. Which is a clear indication of the importance of providing enough stocks of PPE to HCP as well as for the care givers in long-term care facility.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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