Mathematical Theory and Modeling
ISSN 2224-5804 (Paper) ISSN 2225-0522 (Online)
Vol.10, No.4, 2020

Modelling the Spread of COVID-19 with Impact of Awareness and Medical Assistance

Grace O. Agaba

Department of Mathematics/Computer Science, Benue State University, Makurdi, Nigeria
E-mail: omecheagaba@gmail.com

Abstract

Coronavirus disease 2019 originated from Wuhan, China and spread rapidly across the globe. The virus was first identified in Nigeria on 27th February, 2020 and announced by the Minister of Health on 28th February, 2020 through a press briefing. As at 4th May, 2020, the Nigeria Centre for Disease Control recorded a total of 2,802 confirmed cases of COVID-19 individuals with 93 fatalities. Available data from inception to 4th May, 2020 were extracted from Nigeria Centre for Disease Control (NCDC) situation reports and used to trace the epidemic curves of COVID-19 in Nigeria. Furthermore, the disease transmission rate and the basic reproduction number were estimated by using an SEIHR epidemic model with the influence of awareness and medical assistance through MATLAB application. The results of the numerical evaluation of the model indicated that awareness dissemination aid in reducing the spread of COVID-19 and medical assistance has significant impact. The disease transmission rate and the basic reproduction number were estimated as $\beta = 1.575$ and $R_0 = 1.904$ respectively. While the analysis predicted that the epidemic peak of COVID-19 in Nigeria will occur approximately 216 days from the inception of NCDC situation report. The overall outcome of the analysis advocates for more awareness campaign, accessible medical assistance and proper enforcement of adherence to strict measures for the control and possibly elimination of COVID-19.

Keywords: COVID-19, Nigeria, Model, Basic reproduction number, Epidemic peak

1. Introduction

The emergence of a new pneumonic plague has thrown the entire world into a state of uncertainty and fear of what the future holds. The disease which originated from animals to humans and thereafter transmitted from human-to-human has it source connected to the Huanan Seafood Wholesale Market in Wuhan, China (Arcede *et al*., 2020; Chen *et al*., 2020; Chen *et al*., 2020a; Lin *et al*., 2020; Traini *et al*., 2020). Coronavirus disease was first confirmed in December, 2019 in Wuhan, the capital city of Hubei Province of China and has spread rapidly within a short period from Wuhan to other Provinces of China and across the globe (Kuniya, 2020; Li *et al*., 2020; Meng and Jingtao, 2020; Rocklöv *et al*., 2020; Sahafizadeh and Sartoli, 2020; Tang *et al*., 2020; Tian *et al*., 2020; Wang *et al*., 2020; Zhang *et al*., 2020). The first public announcement was made on 12th December, 2019 in China by Wuhan Municipal Health Commission (WMHC) as a result of their initial cases. Consequently, the World Health Organization (WHO) named the coronavirus disease as 2019-nCoV on 10th January, 2020 (Chen *et al*., 2020a; Tang *et al*., 2020; Tian *et al*., 2020) and it was later renamed as COVID-19 on 11th February, 2020 (Choi and Moran, 2020; Kuniya, 2020; Tian, *et al*., 2020; Wang, *et al*., 2020). In addition, it was declared as pandemic by the WHO as a result of the rapid global spread of the infectious disease on 11th March, 2020 (Traini *et al*., 2020).

According to Arcede *et al*. (2020), Chen *et al*. (2020) and Tang *et al*. (2020), the pneumonic coronavirus belong to the coronaviridae family whose members include the known SARS (Severe Acute Respiratory Syndrome), MERS (Middle East Respiratory Syndrome), among other respiratory diseases and they have high record of human fatalities. Arcede *et al.* (2020) state that the number of human deaths recorded from COVID-19 infection is more than the total number of lives claimed by all its predecessors put together. Currently, there is no universal approved vaccine for the cure or treatment of COVID-19 patients (Arcede *et al*., 2020; Wang *et al*., 2020). Hence, most countries are employing the basic preventive measures recommended by WHO, such as awareness campaign for social distancing, washing of hands with soap under running water or the use of hand sanitizers, stay at home, quarantine and isolation, to control the spread of the disease.

COVID-19 is expected to peak within 14 days under the most restrictive measures while its incubation period is about 7 days (Tang *et al*., 2020). Consequently, exposed individuals are in most cases expected to be quarantine for 14 days. Rocklöv *et al.* (2020) advocated that early response against the spread of the coronavirus is a powerful force in curtaining the spread of the disease. They were of the opinion that if implemented many people would be protected from the virus infection and thereby escape the adverse effect of the disease. Similar advocacy was given by Tang *et al.* (2020) which thus necessitate social distancing and strict restriction in movement where possible, enforcing quarantine of suspected cases and the isolation of infected ones for medical assistance. Thus far in the absence of vaccine, these control measures were found to be effective against the rapid spread of COVID-19.

An example of a scenario that provided an enabling environment for human-to-human transmission of COVID-19 is the cruise ship Diamond Princess. The coronavirus disease was first identified on the ship on 3rd February, 2020 with 10 initial cases having contact history with the index case that was on board between 21st and 25th January, 2020. As at 20th February, 2020 about 17% of 3,700 people on board were tested positive to COVID-19 (Rocklöv *et al.*, 2020). The high transmission rate of the virus could be accrued to the fact that the people were in a confined space with relative homogeneous mixing which is a characteristic of a cruise ship. Aside the cruise ship, most of the imported cases were by air travellers hence spreading the virus internationally through commercial air travel (Chen *et al*., 2020a).

In Nigeria, the first case of COVID-19 was confirmed on 27th February, 2020 and announced by the Minister of Health at a press briefing on 28th February, 2020. The index case is an Italian worker of a company in Nigeria. He came into Lagos State through the Turkish airline from Milan, Italy on 24th February, 2020 and tested positive to the virus. More cases were recorded afterwards as a result of more people entering the country from overseas (NCDC, 2020). As at 25th March, 2020, confirmed cases of COVID-19 in Nigeria were all imported cases. According to WHO situation report – 66, the local transmission of the disease in Nigeria began on 26th March, 2020 (WHO, 2020). Hence supplementing the reason why an early lockdown of all international and local borders would have curtailed the spread of the virus.

The rapid rate at which the coronavirus disease is spreading and the high fatality rate recorded across the globe have sprung many researches in search for answers. Mathematically, most of these scholars predicted the early transmission rate, the epidemic peak, determine the basic reproduction number from available data of COVID-19 cases within a defined period, among other measures of evaluating the disease control, in different countries such as China (Kucharski *et al*., 2020; Lin *et al*., 2020; Meng and Jingtao, 2020; Tang *et al*., 2020; Tian *et al*., 2020, Zhang, *et al*., 2020), Italy (Traini *et al*., 2020), Korea (Choi and Moran, 2020), Iran (Sahafizadeh and Sartoli, 2020), Japan (Kuniya, 2020), among others. These were done using the basic epidemic models, Susceptible-Infected-Removed (SIR) or/and the Susceptible-Exposed-Infective-Removed (SEIR) to generate in some cases an extension such as SEIAR, SEIHR, SEAIHR, SEIRD, SEDQIR, and other related mathematical models respectively.

This paper studies the spread of COVID-19 in Nigeria by extending the SEIR epidemic model to an SEIHR model with consideration for the symptomatic and asymptomatic infective individuals and also the impact of awareness in reducing susceptibility and the administration of medical assistance in aiding recovery. This was done by fitting the epidemic curves with the extracted real data of the confirmed, discharged (recovered) and death cases of COVID-19 from the NCDC situation reports s/n: 001 to 66, that is, from the first situation report of 29th February, 2020 to 4th May, 2020 (NCDC, 2020).

2. Methods

2.1 Model derivation

This study derived an SEIHR (Susceptible-Exposed-Infective-Hospitalized-Recovered) compartmental model described by the diagram in Figure 1.

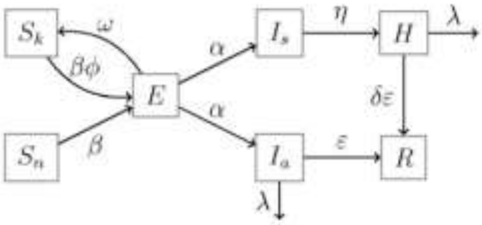

Figure 1: Model diagram: dynamics of transition associated with the various population groups.

Similar to Agaba *et al.* (2017), the model accounted for the proportion p of the susceptible individuals aware of the spread of the disease and are adhering to some control measures thereby reducing their susceptibility by the factor $0 < \emptyset < 1$. Hence, $S = S_k + S_n = pS + (1-p)S$ with S_k denoting the aware susceptible and S_n representing the unaware susceptible individuals respectively within a total population, N. Likewise, the infective individuals were also considered in terms of the symptomatic infective, I_s and the asymptomatic infective, I_a population. By taking q to denote the proportion of the I_s population it implies that $I = I_s + I_a = qI + (1-q)I$. The symptomatic infective is considered to represent individuals who developed symptoms of COVID-19 and were clinically confirmed positive to the virus.

The parameter β represents the transmission rate of the coronavirus disease from the infective to the susceptible, α is the rate at which the exposed become infective during the incubation period of the virus and ε is the recovery rate. Hence, $1/\alpha$ is the incubation period of COVID-19. The recovery rate of the symptomatic infective is considered to be enhanced by the factor δ as a result of the medical assistance received which facilitated their recovery process. The parameter λ is the disease-related death rate while η is the rate at which the symptomatic infective were hospitalized or isolated and ω denotes the rate at which the suspected cases among the exposed individuals were confirmed negative and reintegrated with their families.

Consequently, the following model equation is obtained for evaluating the spread of COVID-19.

$$\begin{aligned}
\frac{dS}{dt} &= -\frac{\beta\phi pSI}{N} - \frac{\beta(1-p)SI}{N} + \omega E,\\
\frac{dE}{dt} &= \frac{\beta\phi pSI}{N} + \frac{\beta(1-p)SI}{N} - (\alpha+\omega)E,\\
\frac{dI}{dt} &= \alpha E - [\eta q + (\varepsilon+\lambda)(1-q)]I,\\
\frac{dH}{dt} &= \eta qI - (\delta\varepsilon+\lambda)H,\\
\frac{dR}{dt} &= \varepsilon(1-q)I + \delta\varepsilon H,
\end{aligned} \tag{1}$$

while the total death recorded as a result of the disease infection is computed using $\dot{D} = \lambda(1-q)I + \lambda H$. The initial conditions are $S(0) > 0$, $E(0) \geq 0$, $I(0) \geq 0$, $H(0) \geq 0$, $R(0) \geq 0$, $D(0) \geq 0$.

2.2 Basic reproduction number

Based on NCDC situation report s/n:1 (NCDC, 2020), the initial confirmed case is one. Hence,

$$I_s(0) = qI(0) = 1 \quad \Rightarrow \quad I(0) = 1/q.$$

Furthermore, $E(0) = H(0) = R(0) = D(0) = 0$ which gives

$$S(0) = N - I(0) = N - 1/q.$$

Analysing the model at its steady state gave the basic reproduction number as

$$R_0 = \frac{\alpha\beta(\phi p + 1 - p)S_0}{(\alpha+\omega)[\eta q + (\varepsilon+\lambda)(1-q)]N}, \quad S_0 = S(0)$$

$$\Rightarrow \quad R_0 = \frac{\alpha\beta(\phi p+1-p)}{(\alpha+\omega)[\eta q+(\varepsilon+\lambda)(1-q)]}\left[1-\frac{1}{q\times 1.959\times 10^8}\right] \tag{2}$$

and with $R_0 < 1$ the model equation has a stable disease-free state. At which point the endemic state is not feasible, indicating that COVID-19 will gradually die out from the population. But with $R_0 > 1$, the disease-free state is unstable whereas at this point the endemic steady state exists and is stable. Hence, COVID-19 will continue to spread within the population until it reaches its peak.

3. Results

The mathematical model was studied numerically via the application of MATLAB to determine the dynamics of the model and also the effect of varying some parameter values on the model dynamics. Figures 2 to 4 explain the results for the stability regions of the model indicating the disease-free and endemic steady states respectively as regards the variation of certain parameters. The results indicate that the portion above the lines represent the regions for the stable endemic steady state with $R_0 > 1$. While with $R_0 < 1$, the portion below the lines indicate that the endemic steady state is not feasibly within these regions whereas the disease-free steady state exists and is stable.

Furthermore, the model was used to fit the curves for the data extracted from NCDC situation reports for the cumulative number of confirmed, discharged (recovered) and death cases of COVID-19 in Nigeria. The data took effect from the inception of NCDC situation reports to the 66th day, 4th May, 2020 (Figure 5). The outcome estimated the value for the disease transmission rate as $\beta = 1.575$. Table 1 gives the summary of parameter values used.

Table 1: Definition of Parameter values.

Description	Parameter	Value
Disease transmission rate	β	1.575
Factor for reduced susceptibility	ϕ	0.14
Proportion of the aware susceptible	p	0.45
Transition rate of the exposed to the infected	α	0.14
Reintegrated rate of the exposed to the susceptible	ω	0.382
Proportion of the symptomatic infective	q	0.9
Recovery or discharged rate	ε	0.07
Factor that amplifies recovery rate	δ	2
Isolation rate	η	0.14
Disease-related death rate	λ	0.03
Total population of Nigeria	N	1.959×10^8

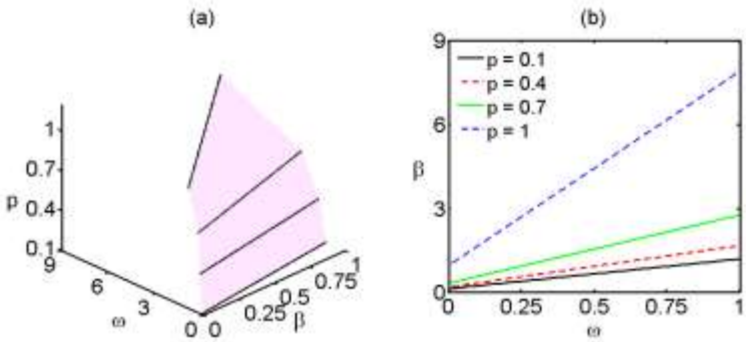

Figure 2: Stability region of the model for varied values of β, ω and p shown in (a) three dimensional plot and (b) two dimensional plot. The portion above the lines signify $R_0 > 1$ while below the lines indicate that $R_0 < 1$. Table 1 gives the values used for other parameters.

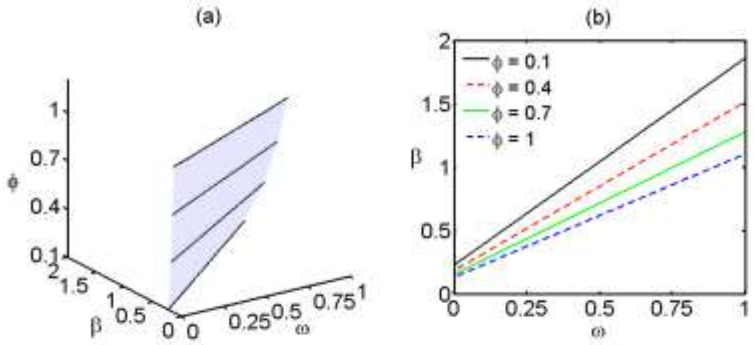

Figure 3: Stability region of the model for varied values of β, ω and ϕ shown in (a) three dimensional plot and (b) two dimensional plot. The portion above and below the lines signify $R_0 > 1$ and $R_0 < 1$ respectively. The values for other parameters used are stated in Table 1.

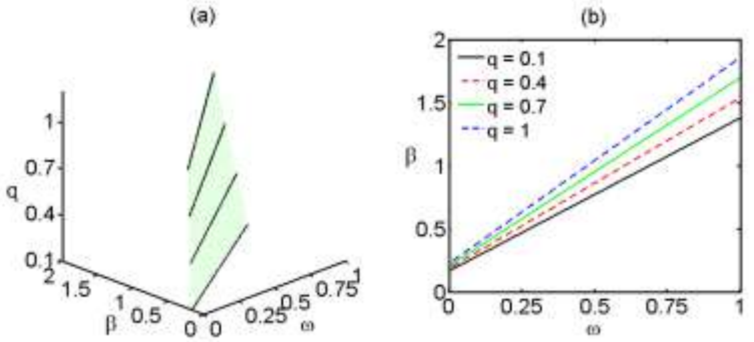

Figure 4: Stability region of the model for varied values of β, ω and q shown in (a) three dimensional plot and (b) two dimensional plot. The portion above the lines indicate $R_0 > 1$ while below the lines is obtained when $R_0 < 1$. Table 1 gives other parameter values used.

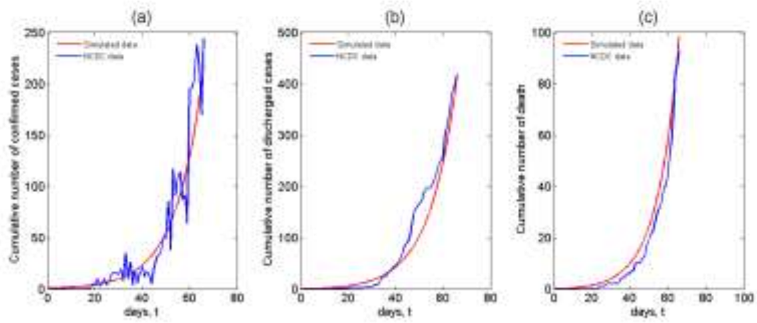

Figure 5: The curves for COVID-19 real data as extracted from NCDC situation reports fitted with the dynamics of the model for the cumulative number of (a) confirmed, (b) discharged (recovered) and (c) death cases. The parameter values used are defined in Table 1.

Consequently, the dynamics of the model for the spread of COVID-19 with $R_0 > 1$ (that is, the endemic state) and with $R_0 < 1$ (the disease-free steady state) is given in Figures 6 and 7 respectively. While the outcome estimating the epidemic peak of COVID-19 in Nigeria is shown in Figure 8.

The overall outcome of the model analysis indicate that COVID-19 will continue to spread in Nigeria since $R_0 > 1$ unless it is reduced such that $R_0 < 1$ then it will eventually die out from the population. Figures 2 to 4 gave the pictorial representation of the stability regions with each indicating the respective regions for the stable and unstable/not feasible steady states of the model with respect to the various values of R_0. These results were affirmed by the dynamics of the model shown in Figures 6 and 7 respectively for the endemic and disease-free states.

The numerical results portrayed the same argument with equation (2). Even though there is no direct effect of δ on R_0, it aids in the recovery of I_s. The increment/decrease in β causes a corresponding increment/decrease in

R_0. Similarly, as $\phi \to 1$, the value of R_0 increases and it decreases when $\phi \to 0$. But R_0 increases when $\omega, p, q \to 0$ and decreases when $\omega, p, q \to 1$. Thus demonstrating the influence of aware in reducing susceptibility and the impact of reducing the symptomatic infective by prompt administration of medical assistance respectively as regard the spread of COVID-19. Figure 5 shows the outcome of fitting the model with the data for the cumulative number of confirmed, discharged (recovered) and death cases of COVID-19 in Nigeria within the period considered for this research. The estimated transmission rate is obtained as $\beta = 1.575$ and the basic reproduction number is obtained using equation (2) as $R_0 = 1.904$. The occurrence of the estimated epidemic peak is approximately 216 days from 29th February, 2020 which implies 1st October, 2020 and the disease is expected to gradually die out after about 330 days (Figure 8).

4. Conclusion

Based on the model analysis, the disease will reach its peak in about five months from now with so many infective cases of COVID-19 if no further strict measures are put in place to control the contact rate of the populace. Basically, since the transmission of the virus is greatly enhanced by close contact with infective individuals, it is therefore recommended that social distancing be highly enforced within the lockdown period. This is to reduce, to the lowest minimum, the value of β thus causing a corresponding reduction in R_0 and possibly eliminate the spread of COVID-19 within minimal days.

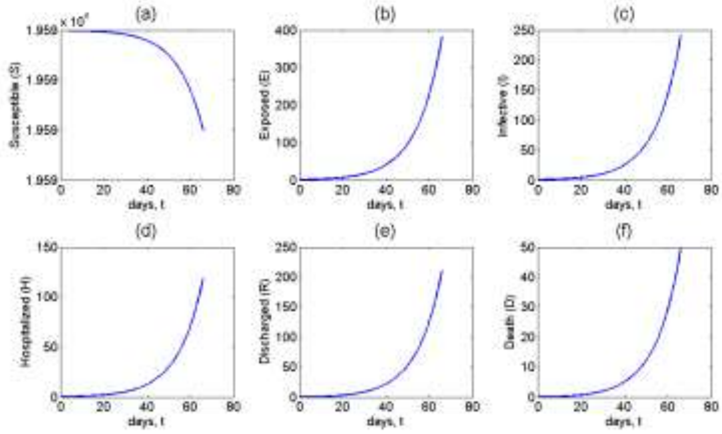

Figure 6: Dynamics of the model equation for the endemic state shown in (a)-(f) for each of the population class respectively. The parameter values used are as defined in Table 1, $R_0 = 1.904$.

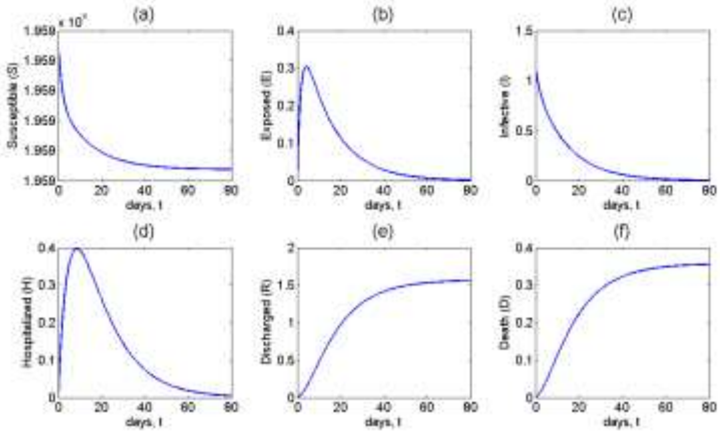

Figure 7: Dynamics of the model equation for the disease-free steady state using $\beta = 0.35$ with other parameter values defined in Table 1, $R_0 = 0.4231$. The respective population class is captured in (a)-(f).

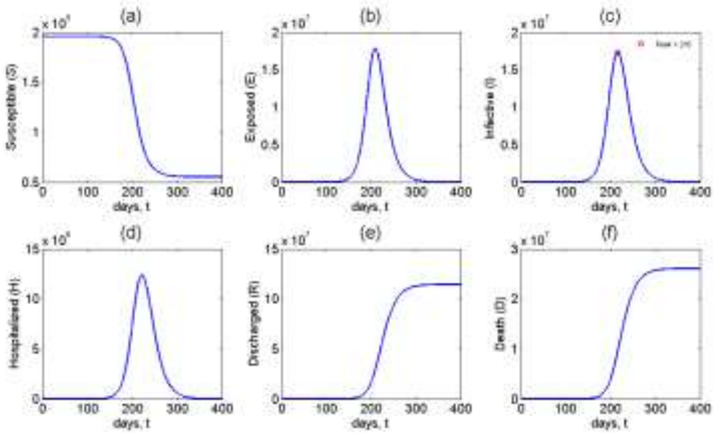

Figure 8: Dynamics of the model showing the epidemic peak of COVID-19 in Nigeria with (a)-(f) presenting the various population classes respectively. The same parameter values defined in Table 1 were used.

The study therefore advocates for speedy and dramatic respond of all authorities concern in each State of the Federation including FCT to contend with the rapid spread of the disease. The provision of all required health care facilities and equipment for arresting the current state of the nation by each State is highly necessary and recommended. Furthermore, since awareness facilitates the reduction in susceptibility which reduces the spread of the virus, implementing more awareness campaign especially in rural areas and enforcing closure of all inter-state borders to prevent the transition of COVID-19 among States cannot be overemphasized. These measures are also recommendable to other countries with similar transmission dynamics for onward implementation.

References

Agaba, G.O., Kyrychko, Y.N. and Blyuss, K.B. (2017). Mathematical model for the impact of awareness on the dynamics of infectious diseases. *Mathematical Biosciences*, **286**,22-30.

Arcede, J.P., Caga-anan, R.L., Mentuda, C.Q. and Mammeri, Y. (2020). Accounting for Symptomatic and Asymptomatic in a SEIR-type model of COVID-19. [Online] Available: arXiv:2004.01805v1 [q-bio.PE] (Apr 3, 2020).

Chen, T., Rui, J., Wang, Q., Zhao, Z., Cui, J. and Yin, L. (2020a). A mathematical model for simulating the phase-based transmissibility of a novel coronavirus, *Infectious Diseases of Poverty*, https://doi.org/10.1186/s40249-020-00640-3.

Chen, Y., Cheng, J., Jiang, Y. and Liu, K. (2020). A Time Delay Dynamical Model for Outbreak of 2019-nCoV and the Parameter Identification. [Online] Available: arXiv:2002.00418v1 [q-bio.PE] (Feb 2, 2020).

Choi, S. and Moran, K. (2020). Estimating the reproductive number and the outbreak size of COVID-19 in Korea, *Epidemiol Health*, **42**: e2020011, 2020, https://doi.org/10.4178/epih.e2020011.

Kucharski, A.J., Russell, T.W., Diamond, C., Liu, Y. Edmunds, J., Funk, S. and Eggo, R.M. (2020). Early dynamics of transmission and control of COVID-19: A mathematical modelling study, *Lancet Infect Dis*, https://doi.org/10.1016/S1473-3099(20)30144-4.

Kuniya, T. (2020). Prediction of the Epidemic Peak of Coronavirus Disease in Japan, 2020, *J. Clin. Med.*, **9**, 789, doi:10.3390/jcm9030789.

Li Y, Wang B, Peng R, Zhou C, Zhan Y, Liu Z, *et al*. (2020). Mathematical Modeling and Epidemic Prediction of COVID-19 and Its Significance to Epidemic Prevention and Control Measures. *Ann Infect Dis Epidemiol*., **5**(1), 1052.

Lin, Q., Zhao, S., Gao, D., Lou, Y., Musa, S.S., Wang, M.H., Cai, Y., Wang, W., Yang, L. and He, D. (2020). A conceptual model for the coronavirus disease 2019 (COVID-19) outbreak in Wuhan, China with individual reaction and governmental action, *International Journal of Infectious Diseases*, **93**(2020), 211–216, https://doi.org/10.1016/j.ijid.2020.02.058.

Meng, W. and Jingtao, Q.I. (2020). A deterministic epidemic model for the emergence of COVID-19 in China, *medRxiv preprint*, doi: https://doi.org/10.1101/2020.03.08.20032854.

Nigeria Centre for Disease Control (NCDC), COVID-19 Situation Reports S/N:001 to 66 (2020). [Online] Available: www.covid19.ncdc.gov.ng (May 5, 2020).

Rocklöv, J., Sjödin, H. and Wilder-Smith, A. (2020). COVID-19 outbreak on the Diamond Princess cruise ship: estimating the epidemic potential and effectiveness of public health countermeasures. *Journal of Travel Medicine*, taaa030, https://doi.org/10.1093/jtm/taaa030.

Sahafizadeh, E. and Sartoli, S. (2020). Estimating the reproduction number of COVID-19 in Iran using epidemic modeling, *medRxiv preprint*, doi: https://doi.org/10.1101/2020.03.20.20038422.

Tang, B., Wang, X., Li, Q., Bragazzi, N.L., Tang, S., Xiao, Y. and Wu, J. (2020). Estimation of the Transmission Risk of the 2019-nCoV and Its Implication for Public Health Interventions. *J. Clin. Med.*, **9**, 462, doi:10.3390/jcm9020462, www.mdpi.com/journal/jcm.

Tian, J., Wu, J., Bao, Y., Weng, X., Shi, L., Liu, B., Yu, X., Qi, L. and Liu, Z. (2020). Modeling analysis of COVID-19 based on morbidity data in Anhui, China, *Mathematical Biosciences and Engineering*, **17**(4): 2842–2852. DOI: 10.3934/ mbe.2020158.

Traini, M.C., Caponi, C. and De Socio, G.V. (2020). Modelling the epidemic 2019-nCoV event in Italy: a preliminary note, *medRxiv preprint*, doi: https://doi.org/10.1101/2020.03.14.20034884.

Wang, W., Chen, Y., Wang, Q. Cai, P., He, Y., Hu, S., Wu, Y, Huang, Z. and Wang, W. (2020). Transmission dynamics of SARS-COV-2 in China: impact of public health Interventions, *medRxiv preprint*, doi: https://doi.org/10.1101/2020.03.24.20036285.

World Bank, United States Census Bureau (2020). [Online] Available: www.census.gov/glossary/#term_Populationestimates (April 24, 2020).

World Health Organization (WHO), Coronavirus disease 2019 (COVID-19): Situation Reports 1 to 83 (2020). [Online] Available: https://www.who.int, (April 13, 2020).

Zhang, R, Li, M. and Zhao, K. (2020). Impact of Wuhan's Epidemic Prevention Policy on the Outbreak of COVID-19 in Wuhan, China, THELANCET-D-20-02744, preprint. [Online] Available: https://ssrn.com/abstract=3548759 (April 13, 2020).