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Article

Systems dynamics approach for modelling South Africa's response to COVID-19: A "what if" scenario

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Abstract

Background: Many countries in the world are still struggling to control COVID-19 pandemic. As of April 28, 2020, South Africa reported the highest number of COVID-19 cases in Sub-Sahara Africa. The country took aggressive steps to control the spread of the virus including setting a national command team for COVID-19 and putting the country on a complete lockdown for more than 100 days. Evidence across most countries has shown that, it is vital to monitor the progression of pandemics and assess the effects of various public health measures, such as lockdowns. Countries need to have scientific tools to assist in monitoring and assessing the effectiveness of mitigation interventions. The objective of this study was thus to assess the extent to which a systems dynamics model can forecast COVID-19 infections in South Africa and be a useful tool in evaluating government interventions to manage the epidemic through 'what if' simulations.

Design and Methods: This study presents a systems dynamics model (SD) of the COVID-19 infection in South Africa, as one of such tools. The development of the SD model in this study is grounded in design science research which fundamentally builds on prior research of modelling complex systems.

Results: The SD model satisfactorily replicates the general trend of COVID-19 infections and recovery for South Africa within the first 100 days of the pandemic. The model further confirms that the decision to lockdown the country was a right one, otherwise the country's health capacity would have been overwhelmed. Going forward, the model predicts that the level of infection in the country will peak towards the last quarter of 2020, and thereafter start to decline.

Conclusions: Ultimately, the model structure and simulations suggest that a systems dynamics model can be a useful tool in monitoring, predicting and testing interventions to manage COVID-19 with an acceptable margin of error. Moreover, the model can be developed further to include more variables as more facts on the COVID-19 emerge.

Introduction

The coronavirus pandemic is a world-catastrophic event which has unpredictably put the entire world to a halt.[1,2] Tracking its genesis, many patients with pneumonia of unknown etiology emerged in Wuhan City, China, in December 2019.[3] Severe Acute Respiratory Syndrome Coronavirus 2' (SARS-CoV-2) was confirmed as the causative agent of 'Coronavirus Disease 2019' or COVID-19. As of April 28, 2020, the virus had spread to more than 213 countries, with a record of 2,883,603 cases and 198,842 deaths.[4] It became a looming threat to the African continent given the incidence trends and the underlying vulnerable healthcare systems.[5] Evidence across most countries have shown that, it is vital to monitor the progression of such outbreaks and assess the effects of various public health measures, such as lockdown on mass gatherings, extra-ordinary personal hygiene, social distancing measures in real-time and protective clothing.

The systems dynamics model presented in this paper attempt to broaden the understanding of South Africa's epidemic interventions using the "what if" scenario. The main objective of this study was to assess the extent to which a systems dynamics model can forecast the COVID-19 infections in South Africa and be a useful tool in evaluating government interventions to manage the epidemics through 'what if' simulations. The model simulates infections, deaths and recovery in light of the various strategic intervention measures based on various assumptions.

Essentially the paper attempts to broadly answer three questions, namely: i) Can a system dynamics model predict the South African trend of COVID-19 spread, in particular the levels of infection, death, and recovery? ii) When is the expected infection peak period? iii) Based on model simulations, can South Africa's COVID-19 interventions be justified and what does this mean going forward? The model presented provides the feedback processes based on the various interventions employed by the South African government in response to the pandemic.

Significance for public health

The paper offers a nuance in the realm of uncertainty through prediction of infectious diseases, which could assist national authorities in decision making through a multidisciplinary approach of systems dynamics.

COVID-19 intervention strategies

In recognising the fact that COVID-19 is a new virus and there is currently no vaccine and it might take at least 18 months to develop, countries around the world have implemented public health measures to control transmissions.[6-10] According to Fong *et al*.[6] and Anderson *et al*.[11] these measures assist in slowing down the spread of infectious disease, delaying the time of peak infection, buying time for healthcare systems preparation and development of vaccines.

Research evidence has shown that public health measures were successful in treating the 1918 Spanish flu, SARS epidemic in 2003 and Ebola in 2014.[10] Improved control of COVID-19 outbreak in Wuhan, China was credited to public health measures interventions.[12] Public health interventions include social distancing; quarantine, lockdowns, isolation[10] implemented in combination with personal, hand and respiratory hygiene.[13]

The main common COVID-19 mitigation strategies used by countries all over the world have been encouraging personal hygiene, social distancing in public space, locking down the country and active testing of the citizenry. These strategies are briefly expounded in the following section.

Personal hygiene

COVID-19 is transmitted through respiratory droplets, close contact with an infected person and contact with contaminated surfaces.[14,15] COVID-19 virus has been detected in patient rooms (bed rail, table, chair, light switch and floor), toilet (door handle, bowl, surface, hand rain and sink), soles of medical personnel and trash cans in hospital wards with infected people.[16,17] The above information supports the need for, hand and respiratory hygiene and use of personal protective equipment (PPE). The following measures are recommended: regular washing of hands with soap and water or with an alcohol-based sanitizer, avoiding touching eyes, nose and mouth, and covering mouth and nose with bent elbow or tissue, disposing of used tissue immediately and wearing of a face mask.[18] To prevent the shortage of medical masks for medical personnel in South Africa, the use of cloth face mask was recommended for consideration by the general public.

Social distancing and effective quarantine

Social distancing attempts to slow the spread of virus transmission by maintaining a physical distance between people and reducing social interactions.[19-22] Since COVID-19 is transmitted by respiratory droplets, people are required to be in certain proximity for it to spread.[9] Furthermore, research has shown that even asymptotic people can transmit COVID-19.[23-25] Thus, social distancing reduces transmission of COVID-19.[9,24] Social distancing measures comprise of keeping physical distance between people (keeping 1 meter apart between people), closure of schools, universities and workplaces, limiting public transportation, cancellation of mass gatherings, closure of non-essential workplaces, limiting the number of shoppers in shops, and limiting close contact with people outside the households.[9,20,26] Literature has shown that social distancing played a substantial role in containing the spread of COVID-19 outbreak in China.[27,28] Although social distancing has shown to be effective in slowing the spread of COVID-19, Anderson *et al*.[11] argues that compliance is of utmost importance for social distancing to be effective. A study by Ferguson *et al*.[21] shows that lifting social distancing measures which are currently in place most countries without a vaccine might result in the second wave of peak infection. It is therefore recommended that social distancing measures be in place until a vaccine is found and is accessible to all people around the world.

Quarantine is regarded as one of the oldest and most effective methods for controlling communicable disease outbreaks.[29] Quarantine is defined as confinement and restriction of movement of people who are alleged to have been exposed to a contagious disease but are not yet showing symptoms either because they did not get infected or are still in incubation period.[9,10,30-33] In contrast, isolation is the movement restriction of confirmed infected people either at home or designated facilities.[9] It may be an individual or group either at home or designated facility, voluntary or mandatory.[9,30,32] Quarantine and isolation are more effective in reducing the spread of COVID-19 when done at a designated facility than at home.[34] It is recommended that contacts of COVID-19 patients be quarantined for at least 14 days from the last day they were exposed to an ill patient.[35] Quarantine is most effective when detection is swift, and contacts can easily be traced within a short period.[9,10] However, like social distancing, it does not work if people are not adhering. Well-timed information on the dos and don'ts while in quarantine plays an important role in educating people and may therefore increase adherence.[33] In addition, sufficient supplies of food, medication and other essentials should be provided to all quarantines to improve adherence.

Stopping mass gatherings and effects of lockdown

Mass gatherings can be defined as any occasion either organised or spontaneous that attracts a sufficient number of people to strain the planning and response resources of the community, city or nations hosting the event.[36] Examples of mass gatherings include sporting events such as Olympics, concerts, political rallies, conferences, religious gatherings and cruise ships. Over the years mass gatherings have shown to be the sources of infectious diseases which have spread globally[37] and respiratory disease are the most common infections transmitted during mass gatherings.[38] Mass gathering poses several health risks such as importation of infectious diseases, amplification of transmission during events and international spread of disease.[39] Cancellation or suspension of mass gathering is critical to pandemic mitigations.[36] Main augments for cancellation or postponement of mass gatherings during the pandemic is that main public health measures for infectious disease without vaccine usually focus on personal hygiene and social distancing, and are challenging to carry out at mass gatherings.[38] Examples of mass gatherings where outbreaks occurred include cruise ships, church gatherings and funerals. An outbreak of COVID-19 was reported from Princess Diamond cruise ship off the coast of Japan and 17 % (617) of the 3700 passengers and crew were confirmed positive.[40] A church gathering in Bloemfontein, South Africa where there were five international visitors who later tested positive led to 61 cases of COVID-19 in Bloemfontein.[41] Several cases in provinces such as Free State, Kwa-Zulu Natal, and Northern Cape were traced to church gathering. In Eastern Cape Province, South Africa, nearly 200 cases were traced to 3 funerals.[42] Of the three funerals, one was attended by East London Department of Correctional Service employee and led to nearly 80 cases in prison.[42] Many countries around the world such as China, India, Germany, Italy, France, Poland, United Kingdom, New Zealand including South Africa have imposed restrictive mass quarantine or what is known as lockdown as the most important controlling measure to fight the spread of COVID-19.[43-45] Lockdowns have been the most effective strategies to fight COVID-19.[46] Duration of lockdown varies and ranges from 2-4 weeks or more. South Africa entered into its first 21 days of lockdown from the 26th of March to 16th April, 2020.[44] The government then adopted a risk-adjusted strategy as a way of managing infections in the country. On the 9th of April, the lockdown was extended for an additional two weeks until the 30th of April 2020 and was to be lifted out in phases.[47] As part of lockdown, all businesses were expected to be closed except for those offering essential services. The police and soldiers were deployed to carry out patrols. Violation of lockdown carried a penalty. Since the 1st of May, the country has moved to level 4 and eased some of the lockdown restrictions.[47] While lockdown may help in curbing the spread of COVID-19, it has significant social, economic,[48] environmental[49,50] and physiological impacts.[51] For example, a lockdown for 1.5 months in the UK cost 3.5 % of its GDP.[48] Lockdown in Wuhan, China led to reduced production of automobile parts and reduced production in countries relying on them for supply such as Japan.[52] Research shows than 5 million people lost their jobs in China between January and February 2020.[48] And it is expected to occur in other countries including South Africa as more business are closing because of lockdown. Preliminary results from a study by the Human Sciences Research Council (2020) on the impacts of lockdown revealed that during the lockdown, 26 % of the respondents had no money to purchase food. Furthermore, 43% -63 % of people were no longer employed, thus, they were unable to pay debts and other necessities.

Testing

As of 11th May 2020, South Africa had conducted 356,067 tests, with 10652 positive confirmed cases and 206 mortalities.[47] About 4357 patients had recovered from the virus resulting in 6,089 active cases. At the time of this writing Western Cape Province had the highest number of cases followed by Kwa-Zulu Natal (KZN) and Gauteng with 3,908, 722 and 702 active cases, respectively. Although testing is vital in understanding the pandemic and developing intervention strategies, alone it will not help in stopping the spread of COVID-19, it should be part of the strategy.[53] The testing strategy should include rapid diagnosis followed by a quick and efficient testing with immediate isolation and rigorous contact tracing and self-isolation of all presumed close contacts. A model by Hellewell *et al.*[54] showed that for a reproduction number of 2.5, 80% of the contacts would need to be traced to control 90% of the outbreaks. Contact tracing can be quick when the number of cases is still low, but when they increase dramatically, it becomes labour intensive and can overload public health systems.[55] A number of digital apps are available for contact tracing, although they are not widely implemented due to ethical considerations.[56] Such apps can collect real-time data such as individual location, health status and movements. For the testing strategy to be successful testing centres should be widely available and easily accessible.[57] However, when demand surpasses the capacity, testing strategy may be infective.[18]

The South African context of modelling COVID-19 spread

South Africa has not been spared from this pandemic as it recorded its first case on the 5th of March 20 and has witnessed an upsurge of 4,793 confirmed cases and a death toll of 90 by the 27th of April 2020.[47] Figure 1 illustrates the spatial distribution of cases and recoveries across the country with the Western Cape being the epicenter of the epidemic, followed by Gauteng and KZN respectively. Although the recovery statistics provide an encouraging scenario of the government's efforts in reducing the spread, the future is still uncertain given the increasing infections. COVID-19 is a classic example of how modern-day society grapples with uncertainty.

Modelling is an important way of simplifying a complex reality but to the extent that one can still get plausible insights on a phenomenon of interest and on how to influence it. Specific to South Africa, there are a number of models that have been referred to, in the country's projection of COVID-19 spread, explanation of ramifications thereof and justifying interventions. These models, however, have not been out in the public domain, hence there is a limit to which they can be engaged for knowledge purposes, among other aspects. This study adds to the existing models for COVID-19 spread for South Africa. The unique aspect of this model is that it is in the public domain for review, and improvement if need be.

Design and Methods

The study adopted Peffers *et al.* [59] framework on design science research. Fundamentally this builds on prior research of mental modelling of uncertainty and complex systems. The research design also involved targeted collection of secondary data as published by the NICD South Africa. In addition, the study also adopted the Standard SEIR (Susceptible, Exposure, Infective, and Recovery) Model. The basic structure of the model structure is based on the modified system dynamics model of epidemic spread first developed by Kermack and McKendrick in 1927[60] customised to the South African situation. A reinforcing feedback loop is responsible for causing exponential growth in the number of infected people. Essentially the SEIR model was built on the basic premise that, when no vaccine is available, the isolation of diagnosed infectives, social distancing and hygiene are the only control measures available.

Model assumptions

- Pandemic is in a short period of time; hence the population remains constant.
- We also assume that the N mixes homogeneously, regardless of demographics (age, gender where they live or work) or any other behaviour traits that the individuals might have. Proportionality of rates is applied due to homogeneity.
- Rate of increase of infected is proportional to the contacts between infective and susceptible (manner in which the disease is transmitted). In this case we assume that when susceptible come in contact with an infected person there is a probability r=0.8 of transmission per contact.

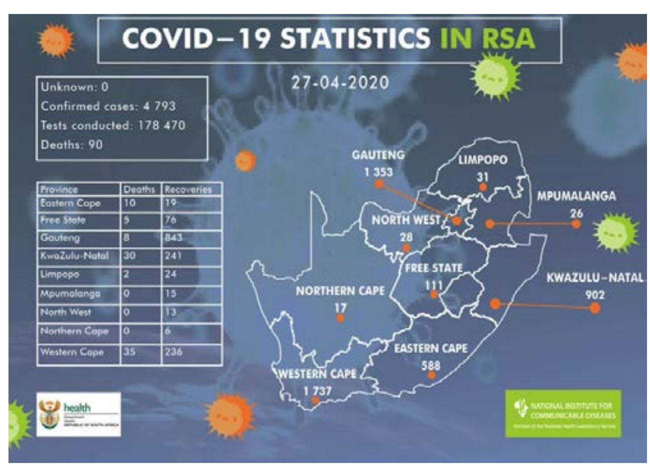

Figure 1. Map showing the spatial distribution of COVID cases in South Africa.[58]

- Lack of infectiousness during the incubation period (14 days)
- There is a constant rate either death or recovery
- There is no re-infection for those who have recovered.

The set of differential equations adopted have thus been summarized follows:

$$\begin{cases} \frac{dS}{dt} = \cdots \dots\dots \quad \dots . -r\,\frac{S(t)I(t)}{N} \\ \frac{dE}{dt} = r\,\frac{S(t)I(t)}{N} - (\mu+\epsilon)E(t) \\ \frac{dI}{dt} = \epsilon E(t) - (\gamma+\alpha+\mu)I(t) \\ \frac{dR}{dt} = \quad \dots\dots\dots . \gamma I(t) - \mu R(t) \end{cases}$$

Moreover,
$N = S + E + I + R \leq N_0$
Initial conditions for the population are *S (0), E (0), I (0),* and *R (0)*

Description of system variables

Variable	Description
S	Stock of susceptible individuals
E	Stock of exposed individuals who are infected-infectious
I_i	Stock of infected with interventions
I_{wi}	Stock of infected without interventions
R_d	Stock of removed population by death
R_r	Stock of removed population by recovery

Parameters	Description
r	Probability of disease transmission per contact
ϵ	Rate of progression from exposed to infectious (the reciprocal is the incubation period)
α	Transition rate of exposed to infected class
Υ	Rate of recovery of quarantined to the recovered
μ	Virus-induced average death rate
R_0	$\frac{r}{\alpha}$

The analytical solution using system dynamics is thus denoted as follows:

Initial values of the model

Parameter	S	r	ϵ	A	Υ	μ
Value	$57{,}78 \times 10^6$	0.8	0.071	0.4	0.78	0.012

The model structure as depicted on Figure 2 comprise of 5 major stocks namely Susceptible, Exposure, Infections Deaths and Recoveries.

Results

The results presented essentially revolve around the three key questions which this paper attempts to respond to. The first part is a response to the extent to which COVID-19 spreads in South Africa. Essentially the focus has been to determine the number of infections and recovery before and after the government interventions, *i.e.* the lockdowns.

Can a system dynamics model predict the South African trend of COVID-19 spread, in particular, the levels of infection, death, and recovery?

The model simulation of infections and recovery before government interventions referred in this study as the *Business As Usual Scenario* indicated that by the 23rd day since the first recorded case of COVID-19, South Africa had approximately 1,187 infected people denoted as infectives on Figure 3. The simulated recoveries' by then were very low far much less than the cumulative 30 people.

The model depicted a similar trend for recoveries and infections over the first simulated phase as shown on Figure 3. In spite of the similar trajectory the estimated figures during the first month are slightly lower than the actual recorded figures as indicated on Figure 2 with last date infections record of 1,187 and 1,210, respectively. The recovery by then were relatively few as indicated on Figure 2 for the actual in comparison with the simulated results. The model satisfactorily depicted the trend, and this was validated using regression curves for the simulated data *vs* the actual recordings shown on Figure 4.

When is the expected peak period?

As shown on Figure 5 the model suggests that infections peak will be experienced around 130 days post the interventions which is around August 2020. The level of infections will skyrocket to over 2 million people while the exposed population will be much higher within the first 100 days. While recoveries will be growing cumulatively over time the levels of mortality will also rise with an anticipated zenith of around 16,000 deaths.

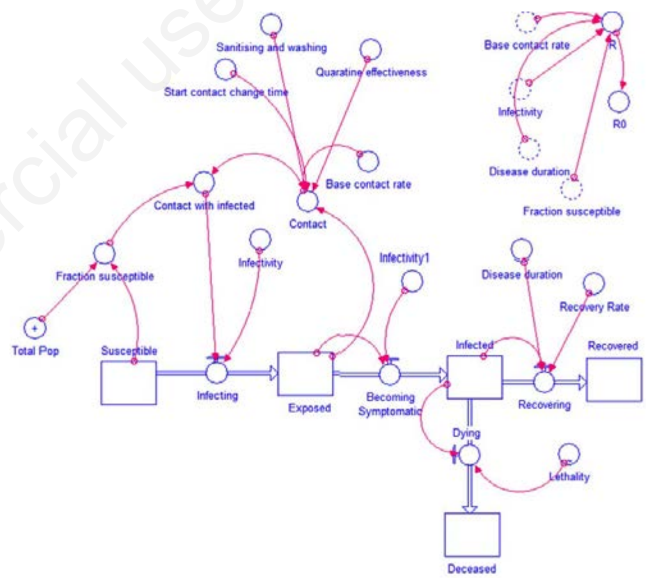

Figure 2. Standard SEIR Model used in the study.

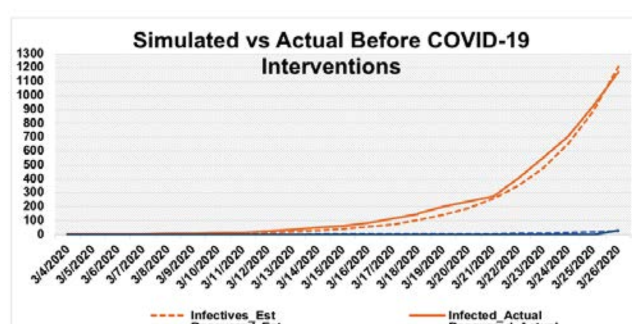

Figure 3. Simulated *vs* recorded infections and recovery before lockdown (*Business as Usual Scenario*).

Alternative scenario: model simulation with interventions (lockdown, hygiene, social distancing)

As shown on Figure 5, the model suggests that the peak of infections would have been experienced much earlier around day 80, which is around June 2020. Infections level could have risen to nearly 2.5 million. Deaths on the other hand would surge to over 50000 deaths. Lastly an exponential increase in recoveries is also expected under this scenario. To validate the model regression curves were developed comparing the simulated results with the actual recorded cases. The next section provides the regression curves for infections, recoveries and deaths.

Discussions

Can a SEIR model adapted using systems dynamics be able to predict infection spread of COVID-19?

Despite the needed room for improvement, the systems dynamics model presented has been able to depict the general trend of infections. The model adds value to the body of knowledge on transmission dynamic models, which are an important initial step towards understanding emerging infectious disease such as COVID-19.[61] The feedback loops between key variables point towards the heterogeneity of infectiousness. This view point is mindful of the model's major underlying assumptions, such as lack of infectiousness during the incubation period and the net effect of government interventions to flatten the curve COVID-19. Similar to SARS, which was characterised by a number of super-spreaders in which most people infect two to three others, the risk of established local transmission with a single imported case is considerably higher.[61] This could assist in explaining the burgeoning rate of infections especially when the lockdown phase in South Africa was lifted. Similarly, Kucharski[62] ascertained that chains of transmission might not take off initially and might require up to four imported cases to establish transmission. Social distancing thus remains a great plausible action which the South African government undertook to delay and minimise the spread.

The differences in figures between simulated cases and the actual

While the first few weeks of the simulation reflects generally low figures compared to the actual recorded cases and later on the simulated infections become relatively higher compared to the actual cases. The two contrasting scenarios demonstrate that in one crucial respect, though, these simulations are not perfect predictors of reality. Specific to system dynamics modelling, more weight is put in replicating trends rather than point accuracy.[63]

This study argues that while the recorded cases may not necessarily translate to the exact total number of cases experienced in the country, the r squares indicated on Figure 6 points to the ability of the designed model to satisfactorily predict the infection trend for South Africa. The relatively lower figures at the beginning few weeks could possibly be explained by the patient zero effect. The model started simulating from the week of the first recorded infection, yet a number of people could have already been exposed and some infected but not recorded or reported by then. The patient zero effect was envisaged weeks later with traced 39 patients and 80 staff linked to the hospital had been infected, and 15 patients died in Kwa-Zulu Natal South Africa.[64] Thus the model may still have had the lag for incubation of possible cases in those few weeks.

Unaccounted for figures may help explain the relatively higher estimates compared to the actual recordings. Like many other countries in the world South Africa may not have the full capacity for testing let alone reporting of all the cases related to COVID-19. As such a large number of people may have remained unaccounted for. This corroborates the WHO[18] acknowledgement that testing strategy can be threatened when demand surpasses the capacity. In addition, the disparity in figures could also be explained by the sheer inability of the model to provide the exact figures given the

Figure 4. Simulated infections, exposure, recoveries and deaths.

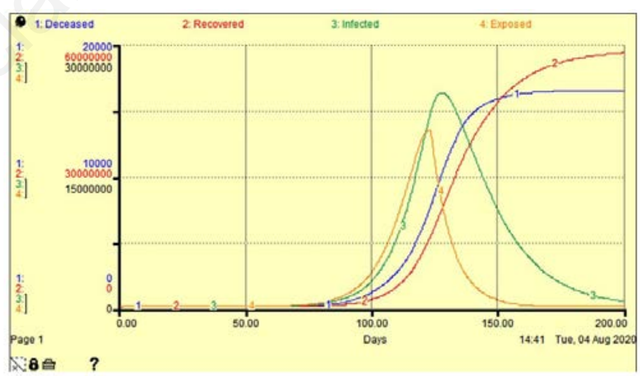

Figure 5. Simulated infections, exposure, recoveries and deaths ***(Infection peak period with limited interventions).***

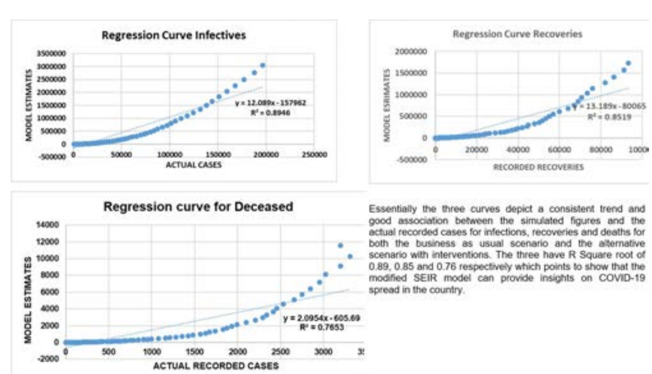

Figure 6. Simulated ***vs*** **actual recorded regression curves.**

inherent assumptions and constant rates that have been imputed to run the simulations. Despite these variations the model still provides a good idea of the trend in infections, recovery and mortality thereof. However, simulations are not COVID-19, and these simulations vastly oversimplify the complexity of real life.[65]

When was the peak expected and what could have been the alternative scenario had the government not intervened?

According to this model at the time of this writing, the peak is yet to be experienced. Had it not been the government's interventions, in particular social distancing and the risk adjusted lockdown strategy the peak period would have been experienced earlier during the peak of winter. The net effect of government intervention has thus been the peak delay and is thus anticipated to occur during the second half of the year 2020 giving an allowance for better preparedness. One of the greatest threats posed by COVID-19 has been the tremendous pressure on the health care systems. Countries such as Spain, Italy and the US have witnessed enormous pressure on hospitals to support the influx of people with severe disease, and such countries have experienced high levels of mortality.

Model limitations

In this study, we acknowledge some limitations in the model. Among these is the: i) The homogeneous mixing which can lead to an overestimation of the final pandemic size and the magnitude of the interventions needed to stop the pandemic. ii) The model attempts to simulate and predict South Africa's covid situation in view of the lack of suitable data and the uncertainty of the different parameters, namely, the variation of the degree of isolation and social distancing as a function of time, the initial number of exposed individuals and infected people, the incubation and infectious periods, and the fatality rate. This paper underscores the school of thought which affirms that "All models are wrong, but some are useful".

Conclusions

Tools such as the adapted SEIR model using systems dynamics can predict infection spread of COVID-19. Such tools provide valuable insights to decision makers through understanding the course of the epidemic in especially the levels of infections, recoveries, and deaths. Had it not been the government's interventions, in particular social distancing and the risk adjusted lockdown strategy the peak period would have been experienced earlier during the peak of winter. Developing models such as the SD presented in this paper can be crucial for anticipating resource requirements particularly during the peak of the epidemic. Planning and level of preparedness remain crucial cornerstones for a sound disaster risk of strategy for pandemics such as COVID-19 and thus systems dynamics model can assist with informed decision making. Although the South African government's response strategy can be commendable and justified given the fairly low mortality rates recorded, thus far, in comparison to many developed countries, the country still needs better tools of prediction and analysis to support it in the next phase of similar pandemics. A systems dynamics model is one of such needed tools.

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Key words: COVID-19, systems dynamics; SEIR.

Contributions: All the authors contributed to a review of COVID-19 response strategies, SEIR model modification, systems dynamics model design and development (building assumptions, model parameterisation, model simulations- scenario building, model validation) discussion, comparing with South African (COVID-19 statistics), revision of manuscript, critical review, finalisation of manuscript. All the authors have read and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

Conflicts of interests: The authors declare that they have no competing interests, and all authors confirm accuracy.

Ethics approval: Not applicable.

Disclaimer: The model has been built based on assumptions and the limited available accessible data which could be used by the authors.

Significance for public health: The paper offers a nuance in the realm of uncertainty through prediction of infectious diseases, which could assist national authorities in decision making through a multidisciplinary approach of systems dynamics.

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