Covid-19 Spread Simulation based on control measures in UAE

محاكاة انتشار فايروس كوفيد 19 طبقا للتدابير الوقائية المتبعة في الامارات العربية المتحدة

by

AMER YASEEN

Dissertation submitted in fulfilment

of the requirements for the degree of

MSc INFORMATICS

at

The British University in Dubai

May 2021

DECLARATION

I warrant that the content of this research is the direct result of my own work and that any use made in it of published or unpublished copyright material falls within the limits permitted by international copyright conventions.

I understand that a copy of my research will be deposited in the University Library for permanent retention.

I hereby agree that the material mentioned above for which I am author and copyright holder may be copied and distributed by The British University in Dubai for the purposes of research, private study or education and that The British University in Dubai may recover from purchasers the costs incurred in such copying and distribution, where appropriate.

I understand that The British University in Dubai may make a digital copy available in the institutional repository.

I understand that I may apply to the University to retain the right to withhold or to restrict access to my thesis for a period which shall not normally exceed four calendar years from the congregation at which the degree is conferred, the length of the period to be specified in the application, together with the precise reasons for making that application.

Signature of the student

Abstract

By February 2021, the total number of reported COVID-19 cases are over 110 million with 2.4 million death cases. In response to that, governments all over the world have imposed a variety of control measures including travel ban, lockdowns, events cancellation and closure of workspace and schools. In addition, continuous monitoring, contacts tracing and increasing the testing capacity were applied in most of the countries. With continuous growth of spread momentum, more strict rules are applied causing unprecedented disruption for society and economy.

In this thesis, a SEIR compartmental model is proposed and developed by python-based program in order to analyze the virus transmission between different model compartments. The program executes the standard SEIR model differential equations over time under different combinations of control measures in order to examine their effectiveness on the virus development.

Three control measures were discussed and analyzed in this thesis which namely are closure of schools, closure of universities and limitation of business capacity. Results show that if schools get closed, then the number of infections will surge rapidly starting from day 100 and reach a peak of 5% of population at day 150. Similarly, closing the universities will cause the number of infections to start surging at day 70 and reach a peak of 7% of population at day 120. Finally, forcing all employees to work remotely from home will lead to flattening the infection curve. Results show also that if we set the effectiveness value of control measure to 45%, then infections curve will get flattened and hence keep the infection rate under control.

Finally, an optimized policy of control measures is proposed which will not only control the virus infection rate, but also will minimize the unnecessary control measures and keep the infected population below the capacity of the healthcare system.

نبذة مختصرة

بحلول فبراير 2021 ، بلغ العدد الإجمالي لمصابي كوفيد 19 مليون و المبلغ عنها أكثر من 110 ملايين مع 2.4 مليون حالة وفاة. و نتيجة لذلك ، فرضت الحكومات في جميع أنحاء العالم مجموعة من التدابير الوقائية بما في ذلك حظر السفر وتقييد الحركة وإلغاء المناسبات وإغلاق أماكن العمل والمدارس. بالإضافة إلى ذلك ، تم تطبيق التعقب الحراري و المراقبة المستمرة وتتبع المخالطين وزيادة عدد الاختبارات في معظم البلدان. و كلما زاد زخم انتشار الفايروس ، يتم تطبيق قواعد أكثر صرامة مما تسبب في اضطراب غير مسبوق للمجتمع والاقتصاد.

في هذه الأطروحة ، تم اقتراح وتطوير نموذج المجموعات الوبائي SEIR بواسطة برنامج قائم على لغة البرمجة بايثون و الذي يهدف لدراسة كيفية انتقال الفيروس بين شرائح المجتمع المختلفة. يقوم البرنامج بتنفيذ المعادلات التفاضلية لنموذج SEIR في ظل مجموعات مختلفة من التدابير الوقائية من أجل تقييم فعاليتها في الحد من انتشار الفيروس مع مرور الوقت.

تمت مناقشة وتحليل ثلاثة تدابير وقائية وهي إغلاق المدارس وإغلاق الجامعات والحد من سعة العمل. تظهر النتائج أن إغلاق المدرسة سيؤدي الي ارتفاع عدد الاصابات وصولا للقمة عند 5% من مجموع السكان في اليوم المائة و الخمسون. كما سيؤدي إغلاق الجامعات لوصول عدد الاصابات الى 7% من مجموع السكان في اليوم السبعين. أخيرًا ، سيؤدي إجبار جميع الموظفين على العمل عن بُعد إلى تسوية منحنى الاصابات و السيطرة على الوباء لكنه اجراء غير عملي و غير قابل للتطبيق بسبب اثاره الكارثية على الاقتصاد . تشيرالنتائج أيضًا الى أنه إذا قمنا بتحديد فعالية الاجراءات بقيمة 45٪ ، فسيتم ايضا تسوية منحنى العدوى وبالتالي ابقاء معدل الإصابة تحت السيطرة.

أخيرًا ، تم اقتراح خطة محسّنة و متغيرة لإجراءات الوقاية التي لن تتحكم فقط في معدل الإصابة بالفيروس ، بل ستقلل أيضًا من التدابير الوقائية غير الضرورية و ستبقي عدد المصابين تحت الحدود الاسيتيعابية لنظام الرعاية الصحية.

Acknowledgements

all praises are to Allah for bestowing me with the strength, knowledge, ability and opportunity to undertake this research and to persevere and complete it satisfactorily. without his blessings, this achievement would not have been possible.

First of all, I would like to express my sincere gratitude to my supervisor, Professor Sherief Abdallah, for his time and guidance throughout the whole dissertation project. I have learned a lot from him on the topic of data science and simulation. I would also like to thank all my teachers in the Master's program for their continuous support and motivation.

Last but not the least, I would like to pay the warmest tribute to my beloved wife Wisam and my kids Yazan, Tala, Leen and Mohammad whose love, patience and support made it possible for me to persist in my studies.

Table of Contents

List of Figures

List of Tables

1. Introduction

The first cases of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) were identified in Wuhan, China in December 2019. Within few days, the virus has spread to all other China provinces. The first case outside China was reported in Thailand in 13th January 2020. By end of January 2020, the total number of confirmed cases was 7818 where China has the majority of cases while 82 cases are reported in different 18 countries. At this point, WHO has officially declared the virus outbreak as a Public Health Emergency International Concern ((WHO) 2020b).

COVID-19 has peaked in China during the last week of January 2020 and then has rapidly declined paving the road for eliminating the virus. However, the virus has started to form a huge wave in Europe, USA and Africa. By end of June 2020, the total number of reported cases are over 10 million with half million death cases ((WHO) 2021a) . At the time of writing this report, the latest update from WHO reports over 110 million cumulative cases and over 2.4 million deaths since the beginning of the pandemic ((WHO) 2021c).

COVID-19 is not the first human to human disease which outbreaks in such a wide range. In 2002, a virus called Acute Respiratory Syndrome Coronavirus (SARS-CoV) has emerged and spread across 37 countries. Similarly, Middle East Respiratory Syndrome Corona Virus (MERS-CoV) has spread in 2012 across 27 countries. (Yadav & Renu Verma 2020)

COVID-19 virus is mainly transferred between individuals as a result of close contact, through very small droplets produced while talking, sneezing or coughing. Such droplets are commonly found in the airspace surrounding infected people or on the ground or surfaces leaving these places contaminated. Touching these contaminated surfaces is another way of transmitting the virus (CDC 2020). The infected human commonly becomes infectious three days after the onset of symptoms which include fever, coughing, smell loss, breath difficulty and fatigue. In some cases, symptoms might include acute respiratory distress syndrome and pneumonia ((WHO) 2021b). The time between infection and onset of symptoms is called incubation period and might range from two to fourteen days with an average of five days (Li, Guan, et al. 2020). To reduce the probability of spreading the virus, it is recommended to maintain hygiene and social distancing habits including hand washing, wearing face masks and self-isolation whenever suspected ((WHO) 2021b). Governments and authorities all over the world have imposed a variety of control measures like travel ban, lockdowns, events cancellation and closure of workspace and schools. In addition, continuous monitoring, contacts tracing and increasing the testing capacity was applied in most of the countries. With continuous growth of spread momentum, more strict rules were applied causing unprecedented disruption for society and economy ((WHO) 2020a). Authorities had to cancel all sports, social and political events (CNBC 2020). Panic buying and shortage of supply was also noticed in different parts of the world (bbc 2020). Around 850 million students worldwide were affected (UNESCO 2020).

a. Problem Statement

To control the pandemic, it is very important to understand the dynamics of virus transmission and to analyze the effect and usefulness of different control policies (Yousefpour, Jahanshahi & Bekiros 2020). Dynamic Transmission models were widely implemented attempting to identify the most influential factors that affect the spread behavior. Hence, producing accurate predictions and determining the proper effective control measures that keep the pandemic under control (Guan et al. 2020).

The government in United Arab Emirates is implementing an intensive scanning and testing strategy in order to identify and isolate COVID-19 cases at early stages. When a new case is detected, a quarantine period of 14 days is imposed (Moonesar et al. 2020) . In addition, mask wearing was imposed at public places at the early stage of the pandemic. Social distancing culture was promoted and educated across all layers of the society. Starting march 8^{th} 2020, the ministry of education started the closure of educational institutes including schools and universities until the online learning was fully adopted across the whole country. The coherent technological infrastructure was leveraged to facilitate working and learning from home to reduce the contact rate in the society. By end of march 2020, shopping centers were closed and all sports events were postponed. Furthermore, all inbound and outbound airline passenger flights were suspended (Portal 2020).

According to (Meters 2021), the number of Covid-19 has reached 413,332 cases in the UAE as of 5th March 2021 as shown in the following Figure.

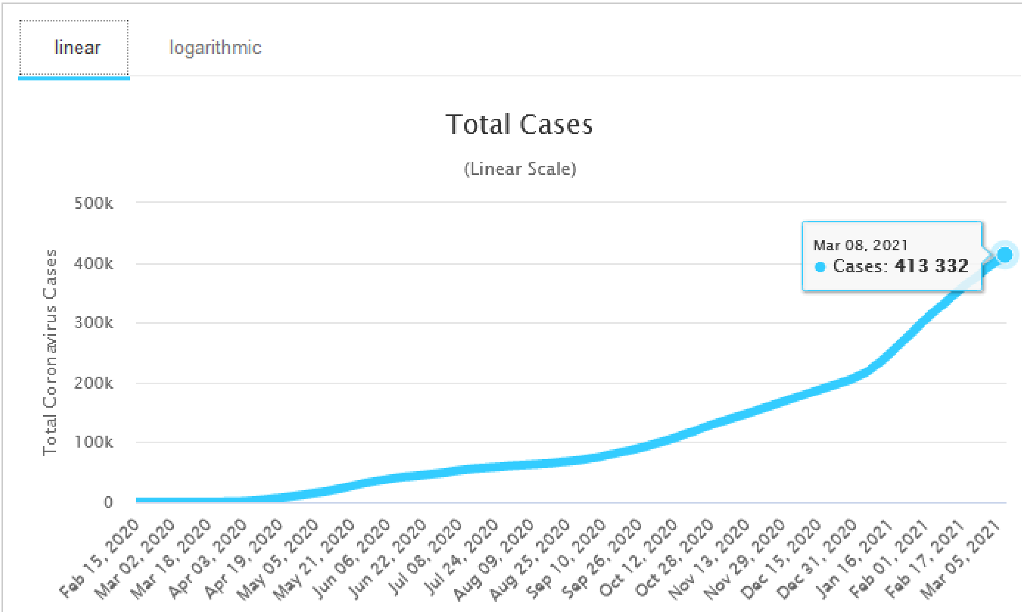


Figure 1 Covid-19 cases in UAE

In 2020, the daily number of cases was fluctuating between 200 and 1500 with average of 1000 daily cases. In contrast, the number of cases in 2021 has suddenly surged to reach between 3000 and 4000 cases a day. However, the number of cases was steadily decreasing in February until the time of writing this report in March 2021 as shown in the following daily chart.

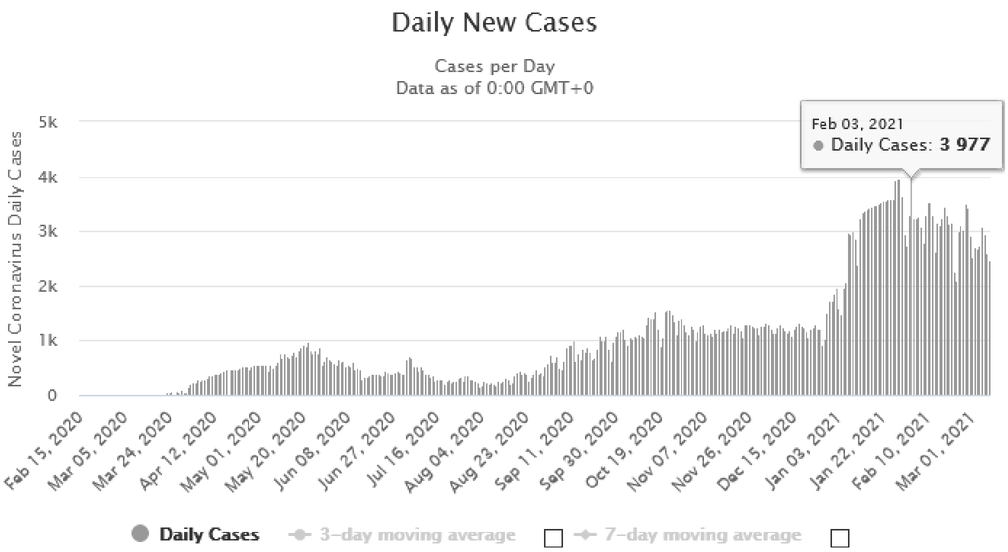


Figure 2 Covid-19 Daily cases in UAE

Two main strategies of non-pharmaceutical interventions (NPI) were identified for controlling the spread of the pandemic which namely are mitigation and suppression. Mitigation strategy aims to slow down the spread of the disease by protecting the elderly and reducing the social contact channels and hence, reducing the peak load on healthcare system and protecting the individuals at risk (Walker et al. 2020). On the other side, suppression aims to reverse the growth rate of the epidemic by applying more intensive measures that can reduce the infection rate and maintain a low level of new cases. (Robinson, Sullivan & Shogren 2020). In both strategies, mathematical models are used to assess the effectiveness of different preventive measures and to simulate the growth of the COVID-19 cases across the population. One crucial outcome of these models is to predict the number of infections over time based on different model parameters which in role are directly influenced by the implemented control measures (Panovska-Griffiths 2020). Therefore, mathematical modeling is considered a powerful tool to understand the dynamics of the virus infection under different scenarios given that a good health care system is in place which holds minimum level of treatment capacity. (Rubin & Crowe 2020).

b. Research Questions

Following are the main research questions that are addressed and discussed in this thesis:

- How computer based sequential simulation can be used to evaluate the impact of COVID-19 interventions in UAE?
- What is the optimal dynamic control policy that can set the COVID-19 pandemic under control in UAE using computer based dynamic optimization?

c. Contribution

In this research, differential equations of the SEIR model are simulated by a python-based sequential simulation code in order to study the COVID-19 infection transmission between different population groups. The simulation will execute the standard SEIR model differential equations under different settings of interventions to examine their impact on the virus development over time. The purpose is to simulate the COVID-19 growth in the United Arab Emirates and to mathematically assess the impact of the various control measures in real time scenarios. The simulation program receives the implemented control measures as input, calculates the effectiveness factor of each and solve various model differential equations in order to figure out the number of infected and infectious population. Finally, it trends the development of pandemic curves showing how value changes over time. In addition, the program implements dynamic optimization to find out an ideal policy of interventions which can set the pandemic under control without stressing the economy and the society. I believe identifying such optimized policies and evaluating the impact of interventions either separately and when combined together would be very beneficial for the healthcare authorities while planning for the pandemic control response strategies.

To the best of my knowledge, the approach of sequential simulation and dynamic optimization of the COVID-19 virus development based on the demographic analysis in UAE was not done before. Hopefully, this work can add a value and support decision making authorities in future planning of public health response strategies.

The summarized contributions of this thesis are as follow

- Demographic analysis of UAE population based on age categories in order to figure out how each age category contributes to the spread of the COVID-19 pandemic.
- Using sequential simulation of differential equations to simulate the COVID-19 development in UAE under different control measures.
- Using dynamic optimization in python to find a typical optimized policy of control measures that when applied, it will not only control the virus infection rate, but also will minimize the unnecessary control measures. Moreover, such dynamic policy should keep the infected population below the capacity of the healthcare system.

d. Scope

Various control measures can affect the spread of COVID-19 virus and contribute in controlling the virus spread. However, only three control measures are examined in this thesis which namely are closure of schools, closure of universities and business staff capacity. Reasons of excluding other factors like airports closure, lockdown and others are lack of supporting data needed for estimating the effectiveness of such control measures.

e. Organization of Thesis

The rest of this thesis is organized as follows. Chapter 2 provides a literature review about previous work in the COVID-19 simulation field and different models that were implemented. Chapter 3 illustrates the details of both SIR and SEIR models and how they differ. It also highlights the reason of choosing SEIR model as a basis of the implemented simulation program. Chapter 4 explains the methodology used to design, develop and run the simulation model. Chapter 5 provides a detailed discussion and analysis about the simulation results. Lastly, Chapter 6 concludes the results of model simulation and highlights suggestions for future development and enhancements.

2. Literature Review

The main goal of studying and simulating the COVID-19 spread is to understand the dynamics of the virus and identify the main influential factors that affect its spread. With such understanding, we will be able to make predictions and evaluate the effectiveness of control measures and strategies including and not limited to lockdown, social distancing, thermal scanning, and closure of business and schools (Holmdahl, Buckee & Phil 2020). Due to the unprecedented severity of the virus, a massive effort was paid and plenty of researches were conducted trying to understand the dynamics of the virus and how it reacts under varying circumstances. Out of these researches, many papers have focused on evaluating the effectiveness of control measures. Some studies have focused on a single intervention while others have attempted to evaluate the effectiveness of multiple control measures especially when implemented in parallel.

(Yang et al. 2020) demonstrated that travel ban could avoid around 13600 cases and delay the virus outbreak by 3 days. Similarly, around 540,000 cases could be avoided in China due to travel ban restrictions (Tian et al. 2020). In Europe, travel ban has reduced the number of cases by 10% (Linka et al. 2020). In France, it reduced the reproduction factor R_0 from 3.3 to 0.5. (Kucharski et al. 2020) show that average reproduction number (R_o) has decreased from 2.35 to 1.05 one week after imposing travel restriction in Wuhan on 23rd Jan 2020. (Abdollahi et al. 2020) shows that extending the school closure from 3 to 16 weeks can reduce the students contact rate by 60% to 80% and hence, reducing the overall pandemic spread rate by 7% to 13% in Canada. (Sarkar et al. 2020) concludes that scanning and early detection of infected individuals can reduce the overall reproduction factor R_0. Furthermore, (Ndaïrou et al. 2020) believe that isolating infected individuals is the most critical measure. (Bouchnita & Jebrane 2020) shows that early wearing of masks and washing hands can hold the pandemic under control and fatten the infection growth. (Sun et al. 2020) show that if the lockdown was delayed two more days in Shanxi, China, the total number of cases would have been three times as the current scale of cases

Other studies show the significance of comprehensive control strategies. (Tian et al. 2020) shows that control measures have helped to avoid 96% of the cases in China. In Italy, control measures could avoid 700,000 cases. In Germany and Indonesia, virus transmission rate was reduced (Wirawan & Januraga 2020). Similarly, effective reproduction number was reduced from 2.9 to 0.98 in Santa Clara, California (Childs et al. 2020). (Harb & Harb 2020) shows that lowering contact factor and increasing medication factor can slow down the spread of virus. (Rohith & Devika 2020) demonstrated a strategy that could reduce the reproduction rate from 2.5 down to 1 by applying high testing rate, community awareness campaigns, social gathering restrictions and travel ban. (Annas et al. 2020) promotes scanning and early detection of infected individuals which can hold the spread rate under control. (Okuonghae & Omame 2020) shows that if at least 55% of the population abide to social distancing regulation and wear masks in public places, the pandemic has no chance to spread any more. (Zhang et al. 2020) and (Abdollahi et al. 2020) agree that that most critical measures in China and Canada respectively are temperature scanning in public areas, early hospital admission working remotely from home and attending online schools. (Li, Yang, et al. 2020) show that If the control measures were applied 5 days earlier, the total number of infections would have been reduced by 42% compared to current value. (Madewell et al. 2020) promote Schools Closure, Public Transport Limitation, Social Distancing as the main factors that affect the growth rate of the virus.

Dynamic models were used to understand how the SRS-CoV-2 virus spreads and how it reacts to different assumptions and non-pharmaceutical interventions (Holmdahl, Buckee & Phil 2020). Various types of models were implemented with an attempt to forecast and trend the future evolution of the infection under different assumptions and a variety of preventive measures. The common goal among these models is to identify the most significant interventions and preventive measures that governments can apply in order to keep the pandemic under control and mitigate the virus infection rate. However, the virus is still spreading in a very fast pace and the course of the epidemic could not predicted so far even with the best modelling efforts (Guan et al. 2020).

As observed, most of the disease statistical simulation models are based on the Susceptible, Infected, Recovered (SIR) model (Petard 1938) . The other extended predictive models are based on SEIR model (Hethcote 2000).

In this paper, various studies were identified which demonstrate different COVID-19 simulation models and conduct comprehensive assessment of different intervention measures applied in different parts of the world. The main purpose of measures assessment is to identify the most influential measures that affect the momentum of virus spread and reduce the infection/death rate. Majority of these models are variants of either SIR (Susceptible – Infected - Recovered) or SEIR (Susceptible -Exposed– Infected - Recovered) dynamic models. A tradeoff between simplicity and realism is involved in all presented models. Several preventive measures are promoted and found very effective in controlling the virus spread. However, modelling remains useful in exploring scenarios rather than making precise predictions about the virus dynamics (Holmdahl, Buckee & Phil 2020).

Papers reviewed in this research are divided in the following sections according the underlying simulation model.

a. SIR based models

(Sarkar et al. 2020) proposed an extended form of SIR model called SARIIqSq which segregates the population into six different groups which namely are Susceptible, Asymptomatic infected, Infected, Isolated-infected, Recovered and Quarantined susceptible. Sensitivity analysis had promoted six main significant parameters of the model which namely are pandemic transmission probability, Susceptible quarantine rate, entire population contact rate, clinical symptoms rate for asymptomatic individuals, asymptomatic Infected recovery rate, and infected recovery rate. Results show that reducing the contact rate between susceptible and infected groups by quarantining susceptible group can reduce the reproduction number R_0, and hence controlling the pandemic spread rate. Results show also that pandemic can be effectively controlled by applying both social distancing and contact tracing.

(Harb & Harb 2020) implemented a variant of SIR (susceptible, Infected, Recovered) model trying to analyze the impact of controlling parameters on the virus spread. The main studied model parameters are contact factor between individuals, virus transmission factor, initial infected and health medication factor which reflects the capability and capacity of the medical infrastructure. Simulation results show that lowering the contact factor and increasing the medication factor can slow down the spreading of the virus. However, and since the medication factor cannot be improved immediately in real life scenarios, a more focus should be paid to lower the contact factor in order to keep the pandemic under control. Moreover, the study shows that the number of deaths decrease drastically with an increased health medication factor.

(Ndaïrou et al. 2020) proposed a compartmental model as variant of the classical SIR model which classifies the population to Susceptible [S], Infected[I], Recovered[R], Super Spreaders[P], Hospitalized[H] and Fatality[F]. Authors have computed the reproduction number R_0 and investigated the sensitivity analysis to find out that the most critical parameter to the model is the rate at which the exposed people become infected and hence, the recommendation is to emphasis applying the quarantine policies and isolation procedures.

b. SEIR based models

In (Rohith & Devika 2020), a Slide Mode Control numerical simulation was applied on their SEIR model. The purpose of simulation is to study the impact of various governmental control measures on the spread rate of COVID-19 in India. Different settings and combinations of control measures were simulated and the virus reproduction rate was computed for each. A weighted aggressiveness value was assigned for different controls. The complete lockdown is the most aggressive control measure and was given 100% while lower values are assigned to other more relaxed measures like testing rate, community awareness campaigns, social gathering restrictions and travel ban. The result consists of a strategy that could reduce the reproduction rate from 2.5 down to 1 which is an acceptable rate that would keep the virus spread under control. The strategy suggests to start with high strict control measures during the early stage of the pandemic until the curve of new cases get flattened and then start reducing the measures gradually over time in order to gain the confidence of public and keep the pandemic under control. The study also shows that keeping the strict measures after reaching an acceptable value of reproduction number R_0 is ineffective and will achieve a negligible effect compared to the huge economic deterioration that will result from maintaining a strict mode for a long time.

(Annas et al. 2020) have constructed a SEIR model which aims to analyze the effect of isolation and vaccination on the COVID-19 virus spread in Indonesia. Generation matrix method was used to calculate the basic reproduction number. Simulation results provide a short-term estimate of the number of infected cases in Indonesia. Results also show that isolation measures can slow down the spread rate while vaccination can speed up the COVID-19 healing.

(Djaoue et al. 2020) have formulated an extended version of SEIR model where the population in Cameroon was divided into 10 groups which namely are Susceptible, Asymptomatic infected, Moderate Infected, Seriously Infected, Quarantined Infected, Confined Partially, confined totally, Latent individual, Quarantined and Recovered. Susceptible group are those who can catch the virus by any mean of transmission like droplets generated while sneezing or speaking or droplets left on surfaces. Partially confined differs than susceptible group by having movement constrains where they are allowed to visit only certain shops and essential locations. Latent individuals are those who are held under quarantine because they interacted and communicated with infected people. Infected are those who are spreading the virus in the surrounding environment freely without constraints or being quarantined. Some of model parameters are assumed at fixed values while others are estimated. The rate of change over time for each group is then simulated using differential equations. The aim of the model is to evaluate the effect of control strategies applied in Cameroon including lockdown, scanning and testing and imposing masks. Sensitivity analysis was applied on the model to evaluate the significance of different model parameters. Results show that the virus spread rate is highly affected by the asymptomatic infectious population. Also, results indicate that virus transmission is greatly influenced by isolation such as isolating 80% of exposed population will cause the disease to disappear in 100 days. Similarly, scanning and testing have a major impact on the virus spread where identifying and isolating 95% of infected people will hold the pandemic under control in 90 days.

(Okuonghae & Omame 2020) have proposed a variant of SEIR model to simulate and forecast the virus infections over time for different level of control measures. The model splits the total population into different groups which namely are Susceptible, exposed, asymptomatic infectious, symptomatic infectious, detected infectious and recovered.

Simulation results show that if at least 55% of the population abide to social distancing regulation and wear masks in public places, the pandemic has no chance to spread any more.

(Zhang et al. 2020) have implemented an integrated solution of agent based SEIIR model on Shenzhen city, Guangdong Province, China for the period of Jan 1 until Feb 16. The model splits population into Susceptible, Exposed, Asymptomatic Infectious, Infectious not hospitalized, and Recovered. The model is designed to analyze the effectiveness of the preventive measures set taken by the government which namely are: delay of hospital admission since symptoms onset, public places temperature scanning, testing arrivals, imposing masks, Hubei province arrivals quarantine, closing schools, work from home and home quarantine for asymptomatic individuals. Results show that the most important measures to prevent the virus spread in Shenzhen are the early hospital admission after symptoms onset, quarantine of arrivals coming from Hubei province, and home quarantine of symptomatic individuals. Results also suggest the best time to quarantine arrivals from Hebei province is the period of Jan 10 to Jan 17 which represents an early stage of the pandemic. The ideal time for local preventive measure is the period of Jan 15 to Jan 22. If all individuals are immediately hospitalized after symptoms onset, the local infections could have been reduced by 50%. If temperature scanning in public places applied since Jan 15, the 67 % of overall infections could have been prevented. If 2 weeks quarantine was imposed on arrivals from Hubei province, the number of infections could have been reduced by 86%. Working from home and attending schools online since Jan 22^{nd}, could avoid 70% of infections. If all individuals worn mask in public areas since Jan 22^{nd}, 67% of infections could have been avoided.

(Yadav & Renu Verma 2020) have designed a mathematical fractional order derivative model which is based on a concept called Caputo-Fabrizio fractional derivative. Aim of the model is to investigate the transmission dynamics for the COVID-19 in Wuhan, china. Methodology of the Model is to segregate the population into different categories which are Susceptible, Exposed, Infected and Recovered. Then virus concentration is calculated at different points of time by means on mathematical differential equations. The model positivity analysis was performed using the theorem of mean value. Results show that count of infected cases has decreased after implementing lockdown and social distancing which promotes the significance of preventive governmental measures.

(Ahmad et al. 2020) have built a sophisticated mathematical fractional order model to investigate the COVID-19 transmission behavior against different values of fractional order. Authors believe that classical mathematical models cannot achieve the desired degree of accuracy in diseases modeling. So, the solution would be implementing fractional differential equations. The model segregates the population to eight groups which are Susceptible, Infected, Exposed, Symptomatic infectious, super spreaders and infectious asymptomatic. Authors first simulate the model based on the real data, then compare results of different fractional order values with real value of infection and death rates. Results show that a fractional order of 0.97 will lead to a perfect match between simulation and real data model.

c. Agent Based Models

(Abdollahi et al. 2020) have designed and implemented an agent-based simulation model to assess the impact of preventive measures imposed by the Canadian government in Ontario on the spread momentum of the pandemic. The two main measures that were evaluated are the school closure and self-isolation of symptomatic cases. The model was parameterized with Ontario population grouped by age. In addition, the contact pattern among each group and between different age groups were considered in the model. Simulation results show that extending the school closure from 3 to 16 weeks can reduce the students contact rate by 60% to 80% and hence, reducing the overall pandemic spread rate by 7% to 13%. Similarly, the ICU admission rate was reduced by 3% to 6%. In addition, simulation results show that applying school closure in parallel to 20% of self-isolation can reduce the virus spread rate even further by 6% to 9%. Authors believe that simulation results reflect the significance of social distancing especially when combined with other preventive measures.

(Kaxiras & Neofotistos 2020) suggests a model that can explain the multiple waves that were observed in the real data of many countries. Authors have used both agent-based simulation and multi wave modeling, then fitted the real infection data along with few more parameters on the model. Authors believe that such fitting represent an evidence that the virus dynamics can be successfully shaped as a series of epidemic waves. Data from 18 countries were analyzed and relevant parameters were calculated. Results show that imposing social distancing measures at the early stage of the pandemic has a significant impact on the growth rate of infected cases. For example, if the social distancing was imposed 20 days earlier on a population of 10 million, the number of current infections will reduce from 8.7 million down to 93,000 cases only.

(Bouchnita & Jebrane 2020) have proposed a multi agent framework to assess the effectiveness of non-pharmaceutical measures applied by the government in Morocco. In multi agent model, each individual is represented by an agent which communicates and interacts with other individuals and the surrounding environment. Motion of each individual is described by what is called social force model. The model simulates the virus spreading between individuals in a closed population environment which includes 250 symptomatic individuals moving around randomly in an area of 250 m^2. In this experiment, virus transmission is possible by either the direct contact between individuals or through touching contaminated solid surfaces by infected individuals. Results show that sudden solutions that might cause public panic will boost the spreading of virus even if social distancing rules are imposed and followed. Model shows also that maintaining a social distance of one meter between individuals is not enough to prevent the virus transmission from one person to another in crowded areas. In addition, model reveals the high infection rate caused by asymptomatic individuals who are infectious but didn't develop any symptoms. Identifying such cases by public areas scanning and intensive testing strategy will control such issue. Purification and disinfection of surfaces in public areas has also a significant effect on reducing the transmission rate of the virus. Finally, the study concludes that early wearing of masks and washing hands can hold the pandemic under control and fatten the infection growth.

d. Mathematical Models

(Kucharski et al. 2020) have developed a stochastic transmission model in order to estimate the dynamics of virus and how it changed over time during January and February 2020. Data of coronavirus cases in Wuhan and other international cases originated from Wuhan were fed into the model. Then, probability that newly identified cases might cause an outbreak in other areas was calculated. Calculations results show that average reproduction number (R_o) has decreased from 2.35 to 1.05 one week after imposing travel restriction in Wuhan on 23rd Jan 2020. Same calculations were applied to other similar locations and it was found that if there are at least four new cases introduced, then the probability that infection will spread and cause an outbreak is higher than 50%.

(Sun et al. 2020) presented a dynamic model to evaluate the effectiveness of lockdown and travel restrictions applied on Wuhan. The model is based on differential equations. Values of model parameters were estimated using Markov Chain Monte Carlo simulations. Results show that if the lockdown was delayed two more days in Shanxi Province, the total number of cases would be three times as the current scale of cases.

(Li, Yang, et al. 2020) designed a model for COVID-19 transmission based on the gaussian distribution theory. Model results show a high match with real data of the studied countries including India, China, Iran and South Korea. Results also show that the most significant factors on the virus spread are the basic reproduction factor R_0, incubation period, and infection rate. Finally, the paper attempts to answers some selective questions which if answered, will give insights about the transmission dynamics of the virus. As per the model results, the first infection case in Hubei should have occurred in Nov 24th. The infection rate has decreased from 3.8 to 0.5 and then to 0.1 after locking down Wuhan and closing the state's community respectively. The average incubation period is 6 days. Model shows also that If the control measures were applied 5 days earlier, the total number of infections would have been reduced by 42% compared to current value. Such results reflect the significance of control interventions on the virus momentum and its spread rate.

e. Machine Learning Models

(Deng 2020) demonstrates the use of multivariate deep learning model which can estimate the transmission parameters of the pandemic. Estimated parameters are then fed into a variant of SEIR model to predict the virus dynamics and infection timeframe. The model splits the population into Susceptible, Exposed, Infected, recovered, Quarantined, Isolated and Deceived groups. Two deep learning approaches were applied which are the standard neural networks and the advanced recurrent neural networks long short-term memory RNNLSTM. Constructed models were used to train the existing virus records in order to predict the future development of infection and death records. Model results indicate that a peak has already formed and the virus will start to die out in the united states during mid of August 2020.

(Madewell et al. 2020) have reused a previously developed agent based artificial intelligence simulation model called EnerPol in order to examine the development of COVID-19 in Switzerland. All possible virus transmission between individuals along with governmental interventions were loaded into the model. The main governmental Interventions that were examined are Schools Closure, Public Transport Limitation, Social Distancing and others. Results show that there will be 720 deaths and 73,300 recovered cases out of 83,300 infected cases during the period of 22nd February until 11th April 2020. Results also show that 42% of the swiss population would have been infected if the governmental interventions were not applied. Simulation results warn also that relaxation of the interventions level before initiating a national vaccination campaign might lead to another wave of virus spreading.

3. Compartmental models in epidemiology

SIR and SEIR are two of the most commonly implemented compartmental models in the domain of infectious disease spreading (Guan et al. 2020). SIR model splits the population into three compartments which namely are Susceptible(S), Infected(I) and Removed(R) (Petard 1938). Following diagram depicts the population flow along with the flow rate of each among the three compartments.

Figure 3 SIR Compartmental Model

Population flow between model compartments can be described by the following differential equations

$$\frac{d(S)}{dt} = -\beta \frac{S}{N} * I$$

$$\frac{d(I)}{dt} = \beta \frac{S}{N} * I - yI$$

$$\frac{d(R)}{dt} = yI$$

$$\beta = y * R0$$

$$y = \frac{1}{\varepsilon}$$

In above equations, βrepresents the infection transmission rate and it controls transmission from Susceptible compartment to the Infected compartment. y represents the recovery rate which is reciprocal to the mean recovery period Ɛ and it controls transmission from Infected to Recovered compartment.

As can be noticed, the SIR model ignores the fact that some viruses including COVID-19 have a period of time before the infected individual shows symptoms and becomes infectious. That period of time is called incubation period. Hence, there was a necessity for extending the SIR model to count for this special infection behavior. Such extended model is called SEIR.

SEIR is an extended version of the classical SIR model which incorporates an additional compartment called Exposed(E) (Hethcote 2000). The compartment 'Susceptible' represents the whole population of individuals who are prone to catch the virus by any mean of transmission like droplets produced while sneezing or speaking or droplets left on contaminated surfaces. The 'Exposed' compartment represents the individuals who have recently caught the virus but still in the incubation period and hence, not infectious yet. The 'Infected' compartment are individuals who are infectious and spreading the virus in the surrounding environment. Finally, the compartment 'Removed' represents the Individuals who are already removed from infected group by either recovery or death. Following transfer diagram shows the different model compartments along with flow rate among them.

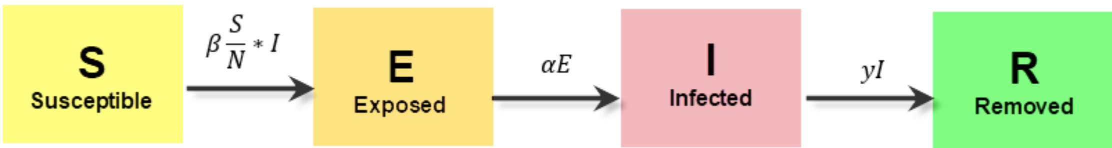
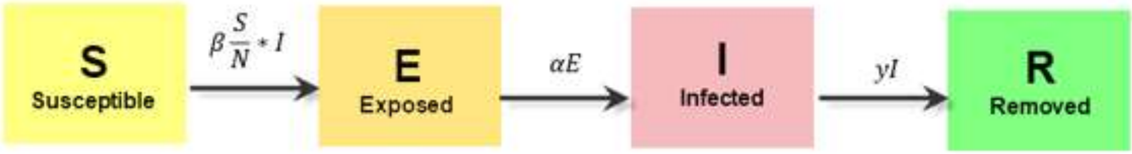


Figure 4 SEIR Compartmental Model

The transmission between the aforementioned compartments can be represented by the following differential equations.



$$\frac{\mathrm{d}(S)}{\mathrm{d}t} = -\beta \frac{S}{N} * I$$

$$\frac{\mathrm{d}(E)}{\mathrm{d}t} = \beta \frac{S}{N} * I - \alpha E$$

$$\frac{\mathrm{d}(I)}{\mathrm{d}t} = \alpha E - yI$$

$$\frac{\mathrm{d}(R)}{\mathrm{d}t} = yI$$

β is called the infection transmission rate and controls the flow from Susceptible to Exposed group. α represents the mean infectious rate and it is reciprocal of the incubation period. y represents the mean recovery rate and it is reciprocal of the infectious period. N represents the total population.

4. Methodology

In this chapter, the design of the implemented compartmental model will be explained in details including the differential equations, model parameters and constants. Also, model simulation along with initial simulation parameters are explained. Finally, a demographic overview of UAE population is conducted in order to derive the effectiveness of different control measures.

a. Model Design

In this paper, an extended susceptible, exposed, infected and removed (SEIR) compartmental model is implemented for simulating the pandemic spread in the United Arab Emirates. The model is adapted from (Malkov 2020) where the total population is initially split into different disease states which namely are susceptible(S), latent(L), infectious(I) or removed(R). However, further calculations are applied to the model to reflect the various interventions and preventive measures implemented by the government in order to reduce the infection transmission rate and keep the pandemic under control.

The following diagram illustrates the modified compartmental SEIR model along with population transmission rate between different compartments.

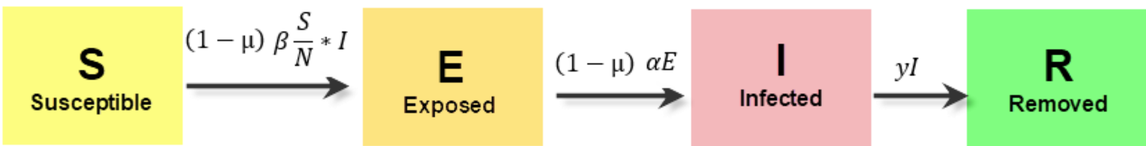


Figure 5 Context diagram of COVID-19 SEIR Model

In the proposed model, susceptible group represents the entire population of UAE. All individuals in this group are subject to catch the virus. Exposed state represents the Individuals who have caught the virus already but they are still in the incubation period. Infected are the Individuals who have caught the virus and became infectious. Finally, removed group represents the Individuals who are already removed from infection domain by either recovery or by death.

Susceptible population transforms to Exposed state when they get in contact with infectious individuals at a transmission rate of β multiplied by $(1-\mu)$. μ represents the effectiveness percentage of control measures with value range of 0 and 1. Zero means there are no control measures implemented while One represents the most strict and effective set of control measures. When a full set of control measures is implemented. The value of $1-\mu$ leads to Zero and hence, no more infections will occur. On the contrary, when no measures are implemented, then the maximum value of infections will occur.

Similarly, population move from 'Exposed' compartment to 'Infected' at a rate of $(1-\mu)\ \alpha E$ where α represents the mean infectious period and is the reciprocal of the incubation period. According to the literature, the incubation period equals in average 5.2 days (Li, Guan, et al. 2020) (Wang et al. 2020) (Imai et al. 2020). So, the rate of transfer from Exposed to Infected (α) is assumed to equal 1/5.2.

Finally, the flow from 'Infected' to 'Recovered' occurs at a rate of yI where y is the reciprocal of the recovery period and represents the recovery rate. According to literature, the average recovery period is 18 days (Chen et al. 2020) (Wang et al. 2020). Hence, a value 1/18 is used as a value for y in the model.

At any point of time, the total population(N) can be formulated as follows:

$N = S(t) + E(t) + I(t) + R(t)$

Furthermore, transition of population between different model compartments can be summarized by the following differential equations:

$$\frac{d(S)}{dt} = -(1-\mu)\,\beta\frac{S}{N} * I$$

$$\frac{d(E)}{dt} = \beta\frac{S}{N} * I - (1-\mu)\,\alpha E$$

$$\frac{d(I)}{dt} = (1-\mu)\,\alpha E - yI$$

$$\frac{d(R)}{dt} = yI$$

$\beta = y * R_0 = \frac{1}{18} * 2.5 = 0.138$

$y = \frac{1}{infectious\ period} = \frac{1}{18} = 0.055$

$\alpha = \frac{1}{incubation\ period} = \frac{1}{5.2} = 0.192$

R_0 is called the basic reproduction number and it represents the number of individuals an infected individual can transfer the virus to during his course of infection. According to the literature, the average value of the basic reproduction number is 2.5 (Zhuang et al. 2020)(Musa et al. 2020)(Abdollahi et al. 2020) (Linka, Peirlinck & Kuhl 2020) (D’Arienzo & Coniglio 2020).

The following table lists the different model parameters along with meaning of each.

Parameter	Description	Value
β	Virus Transmission Rate. The rate at which infected individual communicates with others and transmit the disease.	0.138
α	Rate at which Exposed individuals get infectious	1/5.2
y	Recovery rate which is the reciprocal of the recovery period	1/18
μ	Effectiveness of control measures	variable

Table 1 SEIR Model Parameters

b. Model Simulations

Initial parameters are configured for the simulation model to run, as listed in the following table

Parameter	Description	Value
Population	The total population of UAE	9.8 M
Duration	Duration of simulation in days	365
Initial Number of infections	Initial Number of Exposed cases	100

Table 2 Simulation tool parameters

Effectiveness of control measures μ is a significant parameter and represents the impact of all implemented control measures combined together including closure of schools, closure of universities, business shutdown, social distancing, and others. The more control measures get applied, the higher the value of μ and vice versa.

In this research, a python-based simulation program is developed as an extension of (Apmonitor 2020). Firstly, the original program parameters were changed to fit the population conditions of United Arab Emirates. Then, the program input parameters were changed to calculate the control measures effectiveness based on the demographic analysis conducted in this thesis instead of the original fixed values.

Multiple simulation trials with different values of the control measures effectiveness μ will be executed to examine the impact of implemented control measures on the pandemic development. Mainly, three modes will be simulated which are: without NPI, strict NPI and varying NPI. The purpose of both "without" and "strict" modes is to set the lower and upper boundaries for the virus development in terms of number of infections and peak time duration. The varying NPI mode is actually the main interest of this research in which the infection progress will be simulated and illustrated by sliding up or sliding down the level of control measures. Typically, results of this trial are expected to oscillate between the lower and upper bounds as we increase or decrease the level of control measures.

i. Model Simulation without NPI

In this trial, the pandemic development will be observed under the absence of all COVID-19 non-pharmaceutical interventions. This scenario represents the normal life scenario prior to the existence of COVID-19 where no social distancing rules apply. As a result, the transmission rate of virus is at the high side. To simulate this situation, the value of control measures μ is set to zero. Trial simulation result is depicted in the following graph.

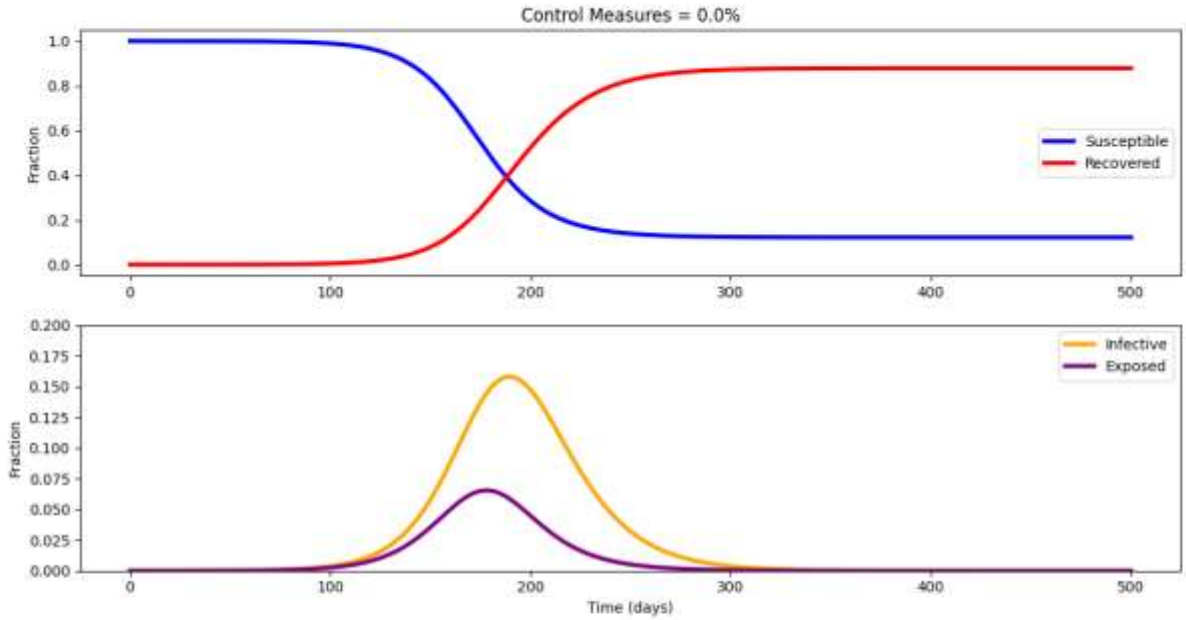


Figure 6 COVID-19 Infection trend with 0% Control Measures

ii. Model Simulation with maximum NPI

In this scenario, the highest value of control measures is applied. In other words, the strictest social distancing rules are imposed. Hence, all the interaction connections between infected and susceptible individuals are shut down and there is no chance for the infection to spread in the community. As a result, the pandemic will die out immediately as shown in the following graph.

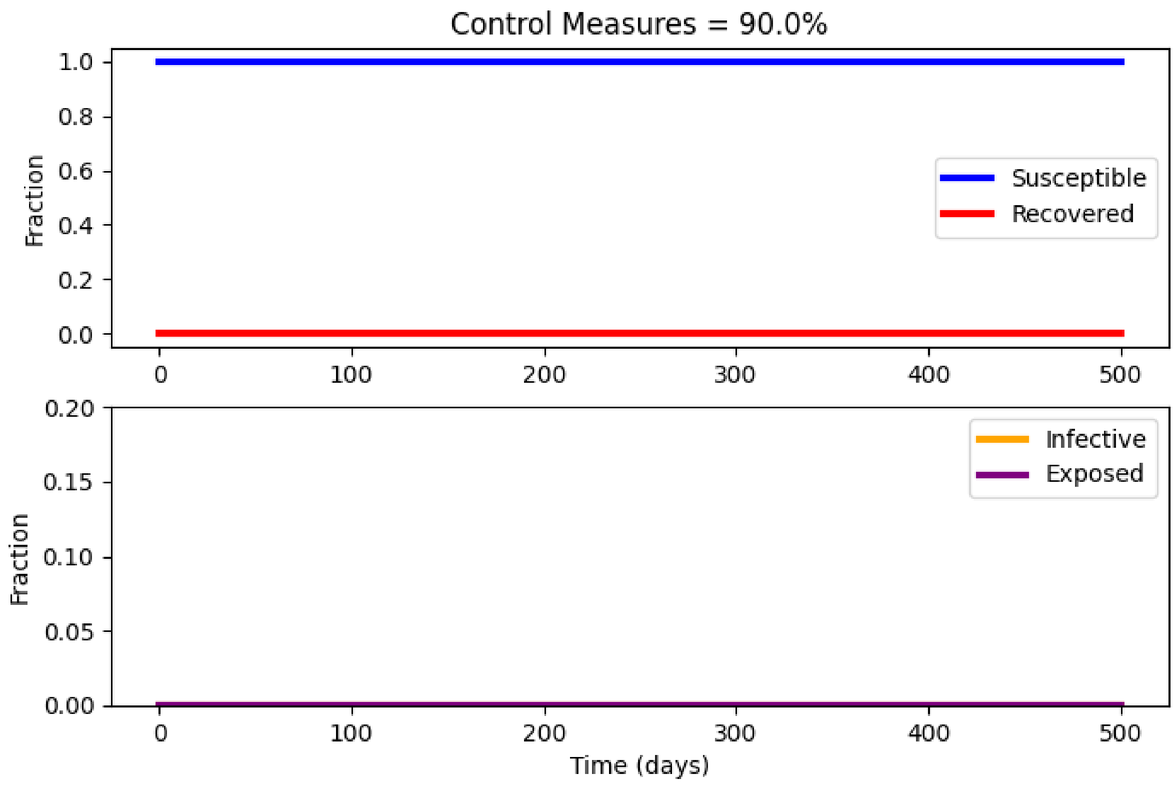


Figure 7 COVID-19 Infection trend with 90% Control Measures

iii. UAE Demographic overview

In this section, the demographic statistics of UAE will be analyzed in order to derive a mapping between the model μ value and the implemented control measures. To achieve that, each control measure will be examined and assigned a weight based on the percentage of associated population with respect to the total population of the UAE.

As a beginning, the demographic statistics of UAE across different age groups are fetched and recorded from (Globalmediainsight.com 2021) (Wikipedia 2020). Following bar chart depicts the UAE population grouped by age.

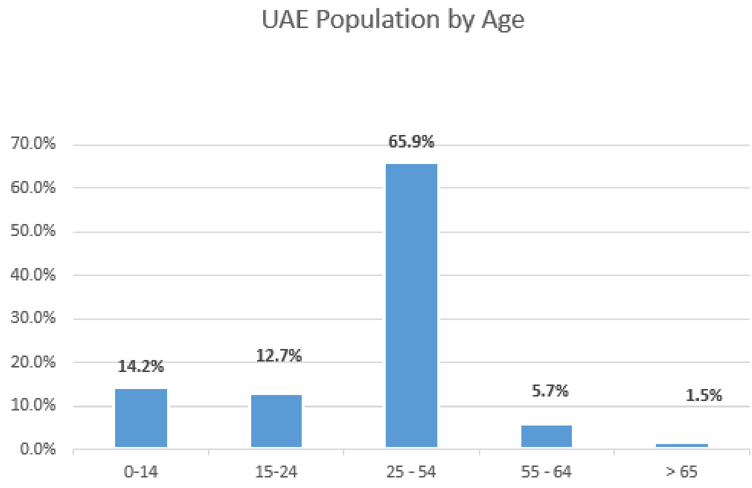


Figure 8 UAE population by Age

Then, population of each group will be broken down to different control measures based on age as per the following criteria:

1. population of each age group is distributed across different control measures like schools, universities and workspace. Distribution is based on either available official data or estimated by Author when data is absent.
2. Population of each control measure is calculated as the summation of population across all age groups for each control measure.
3. Percentage of the total summation is calculated with respect to the total population.

Consequently, population (P) of the age group (0-14) is 1,391,600. Assuming equal distribution of population across the ages, population of each year would be P/14 which equals to 99,400. In UAE, children start attending nurseries at the age of 4 years (MOE 2021). This suggests that the remaining 11 segments out of the total 14 segments will be attending schools. Hence, the percentage of population in Schools at the age group of (0-14) is 11/14 which is equivalent to 79% of the total group population. For the same group, there is no chance to have university students or workers due to age restrictions. Hence, the percentage of these categories 0%.

Similarly, population of the age group (15-24) is 1,244,600. Assuming equal distribution of population across all the ages, population of each year would be P/10 which equals to 124,460. In UAE, students start attending universities by age of 19. This suggests that 4 segments out of 10 will be attending schools. The next four segments of age which are 19, 20, 21 and 22 belong to university control measure group. Finally, the last 2 segments which are people at age of 23 and 24 are assumed workers. Hence, the population distribution is 40%, 40% and 20% for schools, universities and workplace control measure groups subsequently.

In UAE, the unemployment rate for 2020 is 2.45% (Statista 2020). So, population of age group (25 – 54) is split into 97.5% as employed and 2.5% as unemployed. The age group (55-64) is divided into 50% employed and 50% unemployed because the retirement age is 60. Finally, the (above 65) age group is divided into 90% unemployed while 10% employed.

Following table lists the population distribution among different age and control measures groups.

	0-14	15-24	25 - 54	55 - 64	> 65	Total
Population %	14.2%	12.7%	65.9%	5.7%	1.5%	100%
Population count	1,391,600	1,244,600	6,458,200	558,600	147,000	9,800,000
Children at Home %	3/14	0%	0%	0%	0%	
Children at Home Count	298,200	0	0	0	0	298,200
Schools Students %	11/14	4/10	0%	0%	0%	
Schools Students Count	1,093,400	497,840	0	0	0	1,591,240
High Edu. Students %	0%	4/10	0%	0%	0%	
High Edu. Students Count	0	497,840	0	0	0	497,840
Employed %	0%	2/10 (20%)	97.5%	50%	10%	
Employed Count	0	248,920	6,296,745	279,300	14,700	6,839,665
Unemployed %	0%	0%	2.5%	50%	90%	
Unemployed Count	0	0	161,455	279,300	132,300	573,055

Table 3 UAE Population distribution based on age

5. Results and Discussion

Model simulation without implementing any control measures is depicted in Figure 6 which shows that the number of infections will drastically increase after day number 100. The number of cases will keep surging until day number 190 where infection curve reaches its max at the value of 16% of population which equals 1,600,000 cases. The capacity of Health care system in UAE is 60 doctors and nurses per 10,000 persons which equals 0.6 % (Sector 2015). This means that the whole healthcare system will be overwhelmed and fully occupied on day number 100 leaving no chance to admit new patients and hence leading to an imminent failure in the overall health care system. Obviously, this is an imaginary and undesirable scenario which should not happen in any country. But it represents the lower boundary of the pandemic development when no control measures are implemented.

Conversely, figure 7 shows the pandemic development when all control measures are implemented. In such scenario, schools, universities, businesses and all public places are shutdown. Travel is banned. Transport is under strict control. Hence, connectivity channels between society members are totally shutdown. Hence, members of the susceptible group will not get in contact with infected persons and as a result, the infections curve will tend to zero resulting in a rapid end of the pandemic. This scenario is also theoretical and hard to implement due to the economical disaster that will result. However, it sets an upper boundary to our simulation model.

Based on the population distribution listed in Table 3, children at home represents 3% only of the population while students at schools represent 16%. High school students represent 5%. Employed people represent 70% while un-employed people represent 6% of the population. Hence, employed people represent the majority of population and hence, is expected to have the highest impact on virus transmission when restrictions apply to this group of population. The following pie chart shows the main population groups along with percentage of each.

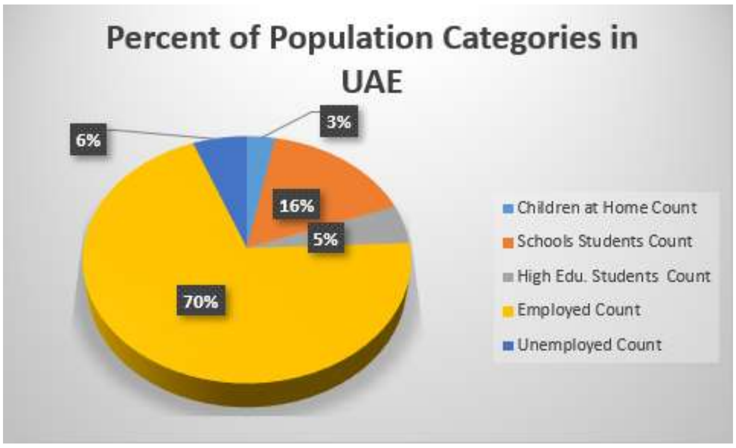


Figure 9 Percentage of population categories in UAE

In the following sections, the impact of restricting each of the aforementioned groups on the virus transmission will be examined in order to find out a compromised response plan which can set the pandemic under control with minimal social and economic disruption.

The main population categories that will be examined in this paper are students at schools, students at universities and workers at workspace. These three categories represent 90% of the population. The remaining 10% belong to children at home and unemployed people. These two categories will be ignored because there is no enough data on how these could participate in virus spreading compared to people of other categories who meet and communicate in schools, universities and work places. In addition, the minimum control measure value in the model is assumed to be 10% representing the mandate of face masks and minimum social distancing.

a. Impact of Schools

Closing all schools while leaving universities and work places open will lead to control measure value of 26%. As per the simulation results, 2% of population will get infected during the first 100 days. After then, the number of infections will surge rapidly and reach the peak of 5% of population at day 150 which is extremely high compared with the maximum healthcare capacity. Hence, closure of schools alone will not be sufficient to stop the virus spread or keep it under control. It should be combined with other control measures to achieve a more reasonable result.

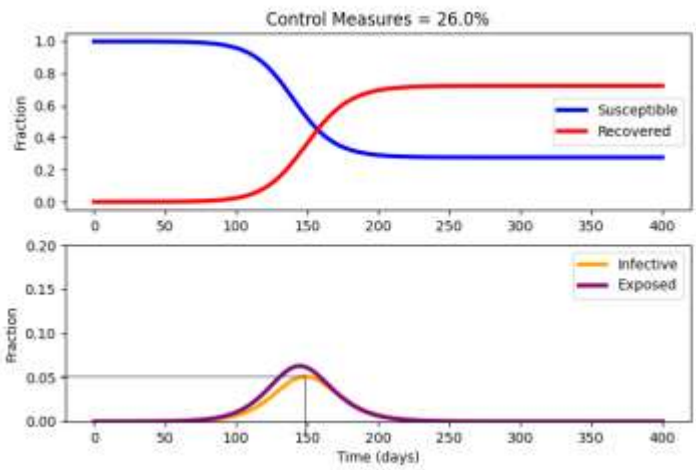


Figure 10 Impact of Schools Closure on virus spreading

b. Impact of Universities

Closing all universities while leaving schools and work places open will lead to control measure value of 15%. As per the simulation results, 1% of population will get infected during the first 60 days. After then, the number of infections will surge rapidly and reach 7% of population at day 120 which is extremely high compared with the maximum healthcare capacity. So similar to the closure of schools, closure of universities alone will not be sufficient to stop the virus spread or keep it under control. It should be combined with other control measures to achieve a more reasonable control over the pandemic.

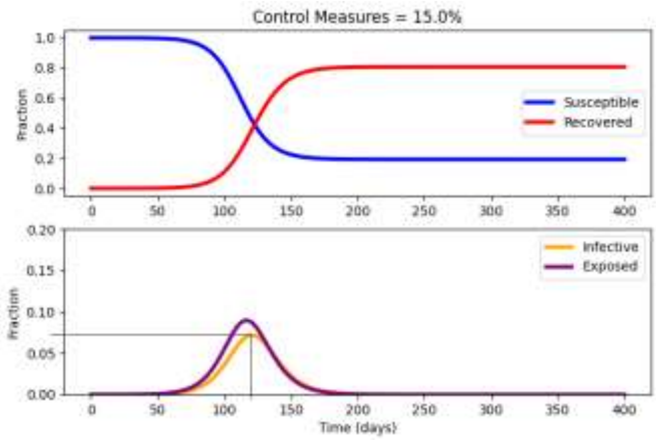


Figure 11 Impact of universities closure on virus spreading

c. Impact of Employed people

Forcing all employees to work remotely from home while keeping schools and universities open will lead to a control measure value of 79%. Such high value would be enough to keep the infections count under control. However, this is not a practical solution because working remotely does not suit the majority of businesses where physical attendance of staff is a must for the business to run. Hence, closing businesses 100% is not foreseen possible and can lead to catastrophic impact on economy and society. Hence, a compromised solution consisting of multiple control measures with adequate level of restriction on each will be examined in the following sections.

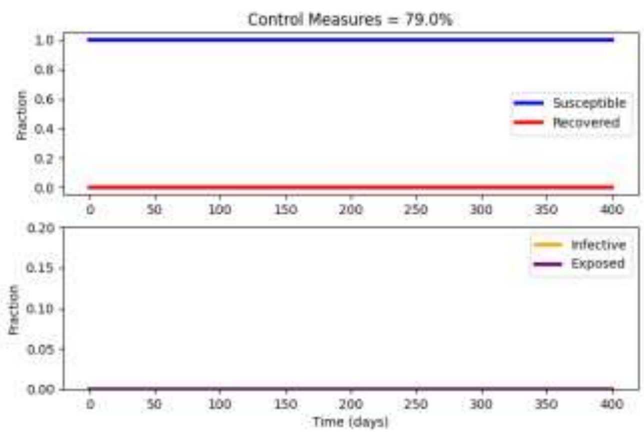


Figure 12 Impact of 100% closure of work space on virus spreading

d. Minimum safe level of control measures

In this section, the value of control measures μ will be slid up and down in order to observe and find the suitable value that should give a proper control over the virus infection rate.

As a beginning, a fixed value is assigned to μ that if further increased, the virus infection will break out. After multiple trials with different values of μ, it was found that if we set it below than 45% then the infection curve will surge causing the susceptible population count to decline rapidly. Following chart depicts the infection behavior with a value of 45% for the control measures effectiveness factor μ.

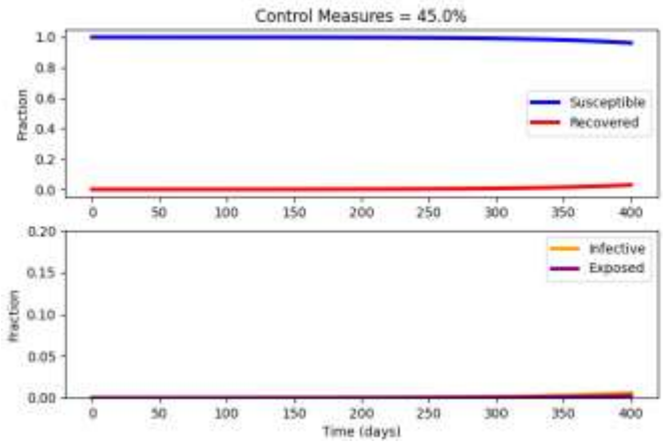


Figure 13 Infection trend with 45% Control Measures

Setting the value to 45% will flatten the infections curve and hence keep the infection rate under control.

The target value of 45% can be achieved by implementing multiple control measure simultaneously. For example, social distancing and masks gives 10%. Closure of schools increases the value 26%. Closure of universities will add 5% leading to total value of 31%. Reducing the business staff capacity to 20% will add a value of 14% leading to a total of 45%. Many other combinations of control measures are possible to reach the same level of effectiveness.

e. Control Measures Optimization

As concluded in previous sections, there is no single control measure that is able to control the pandemic development by itself. Hence, the aim of this section is to solve an optimization problem that can suggest a typical optimized policy of control measures that when applied, it will not only control the virus infection rate, but also will minimize the unnecessary control measures. Moreover, such optimized policy should keep the infected population below the capacity of the healthcare system.

As mentioned earlier, the capacity of Health care system in UAE is 60 doctors and nurses per 10,000 persons which equals 0.6 % of the total population (Sector 2015). However, the country has implemented a surge in the capacity of Healthcare as a response to the rising cases of COVID-19 (economictimes 2021). Since the amount of increase in healthcare system capacity is not officially defined, author will assume a 0.9 % overall capacity of healthcare system.

The optimization model will watch the healthcare system capacity and ensure that number of infected individuals will not exceed the specified capacity. On the other hand, the optimizer will also try to reduce the control measures over time as possible without violating the health care capacity constraint.

The following chart shows the result of optimization trial.

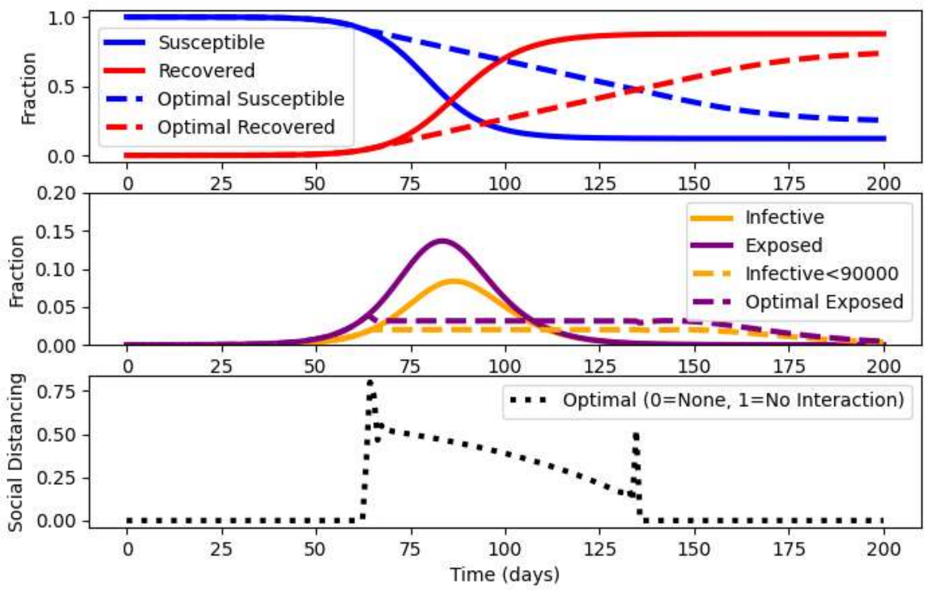


Figure 14 Control Measures optimization

The chart consists of three sections. The upper section shows number of susceptible and recovered population. The section in the middle shows the infected and exposed population. Finally, the last section which is the social distancing section shows the implementation plan of optimized control measures over time. The solid lines on the graph represent the count of cases without any control measures while the dotted lines represent the optimized number of cases when suggested social distancing plan is implemented.

The results suggest to apply two waves of strict control measures. The first wave starts on day 60 and remains for a week at a high value of 75%. After then, the control measures can be reduced gradually over the following 100 days until reaching down to 25%. Second wave starts on day 160 for another week with a high value of control measures. Then control measures can be removed. Starting from day 170, the pandemic starts to fade out with majority of population get recovered. Both waves start with a high value of 75% which means that multiple control measures shall be applied at the same time. Wide range of settings and control measures combinations can be implemented. For example, to achieve a value of 75% of control measures, government can achieve 10% of control measures by imposing the basic social distancing rules including face mask mandate. Also closure of schools and universities will roughly add a value of 21%. Finally, reducing workspace capacity to 30% can achieve additional 49% leading to a total of 80%.

6. Conclusion and Future Work

In this chapter, simulation results are concluded with main findings highlighted. In addition, answers of research questions are discussed. Finally, suggested future work is included in the last section.

a. Conclusion

To control the pandemic, it is very important to understand the dynamics of virus transmission and to analyze the effect and usefulness of different control policies. Mathematical modeling is considered a powerful tool to understand the dynamics of the virus infection under different scenarios.

In this thesis, a SEIR model was implemented using a python-based simulation program in order to study the virus transmission between different model compartments. The program implements sequential simulation to execute the standard differential equations of SEIR model under different settings of control measures in order to examine their impact on the virus development over time. The purpose is to analyze the COVID-19 growth in the United Arab Emirates and to mathematically assess the impact of the various interventions. The simulation program receives the implemented control measures as input, calculates the effectiveness factor of each. Finally, it trends the development of pandemic curves over time demonstrating the effect of each control measure.

With respect to research questions of this thesis, three research questions were discussed and answered as follow:

- How computer based sequential simulation can be used to evaluate the impact of COVID-19 interventions in UAE?

  Differential equations of SEIR compartmental model were executed over time using python sequential simulation program. Three control measures were considered and analyzed which namely are Closure of schools, closure of universities and business staff capacity. Simulation results show that if schools get closed, then the number of infections will surge rapidly starting from day 100 and reach a peak of 5% of population at day 150. Similarly, closing the universities will cause the number of infections to start surging at day 70 and reach a peak of 7% of population at day 120.

Finally, forcing all employees to work remotely from home will lead to flattening the infection curve. Results show also that if we set the effectiveness value of control measure to 45%, then infections curve will get flattened and hence keep the infection rate under control.

- What is the optimal dynamic control policy that can set the COVID-19 pandemic under control in UAE using computer based dynamic optimization?

  As concluded in this thesis, there is no single control measure that is able to control the pandemic development by itself. In the Control Measures Optimization section, an optimized policy of control measures was found using dynamic optimization which suggests to impose two waves of strict control measures. The first wave starts on day 60 and remains for a week at a high value of 75%. After then, the control measures can be reduced gradually over the following 100 days all the way down to 25%. Second wave starts on day 160 for another week with a high value of control measures. Then control measures can be removed. Starting from day 170, the pandemic starts to fade out with majority of population get recovered. Both waves start with a high value of 75% which means that multiple control measures shall be applied at the same time. As suggested by results, implementing such policy will not only control the virus infection rate, but also will minimize the unnecessary control measures and keep the infected population below the capacity of the healthcare system.

b. Future Work

As a future work, it is suggested to analyze and measure the effectiveness of imposing the face mask mathematically rather than assuming a fixed value of 10%. This will depend on the availability of official data but will lead to more accurate results.

In addition, more control measures can be studied and analyzed including travel ban, shopping centers restrictions, lockdown and events cancellation. The more control measures analyzed, the more realistic and accurate the model will be.

Finally, when official data becomes available, it is suggested to extend the SEIR compartmental model to add two important population flows between model compartments. The first one is the population flow from Recovered compartment to Susceptible. This reflects the fact that recovered people are not immune 100% and can catch the virus again. The second one is population flow from Susceptible to Recovered as a result of vaccination. But again, this would require official data to estimate flow rates especially when different vaccines with different efficacies are used.

References

(WHO), W. H. O. (2020a). *Impact of COVID-19 on people's livelihoods, their health and our food systems* [online].Available at: https://www.who.int/news/item/13-10-2020-impact-of-covid-19-on-people%27s-livelihoods-their-health-and-our-food-systems.

(WHO), W. H. O. (2020b). *WHO Timeline - COVID-19* [online]. [Accessed 27 February 2021]. Available at: https://www.who.int/news/item/27-04-2020-who-timeline---covid-19.

(WHO), W. H. O. (2021a). *Coronavirus disease (COVID-19) Weekly Epidemiological Update and Weekly Operational Update* [online]. [Accessed 10 March 2021]. Available at: https://www.who.int/emergencies/diseases/novel-coronavirus-2019/situation-reports.

(WHO), W. H. O. (2021b). *Covid 19 Symptoms* [online]. [Accessed 10 March 2021]. Available at: https://www.who.int/health-topics/coronavirus#tab=tab_3.

(WHO), W. H. O. (2021c). *Weekly epidemiological update - 23 February 2021* [online]. [Accessed 27 February 2021]. Available at: https://www.who.int/publications/m/item/weekly-epidemiological-update---23-february-2021.

Abdollahi, E., Haworth-Brockman, M., Keynan, Y., Langley, J. M. & Moghadas, S. M. (2020). Simulating the effect of school closure during COVID-19 outbreaks in Ontario, Canada. *BMC Medicine*. BMC Medicine, vol. 18(1), pp. 1–8.

Ahmad, S., Ullah, A., Al-Mdallal, Q. M., Khan, H., Shah, K. & Khan, A. (2020). Fractional order mathematical modeling of COVID-19 transmission. *Chaos, Solitons and Fractals*. Elsevier Ltd, vol. 139, p. 110256.

Annas, S., Sanusi, W., Side, S., Sanusi, W. & Side, S. (2020). Journal Pre-proof.

Apmonitor. (2020). *COVID-19 SEIR Simulation* [online].Available at: https://apmonitor.com/pdc/index.php/Main/SimulateCOVID19.

bbc. (2020). *Coronavirus: The psychology of panic buying* [online]. [Accessed 10 March 2021]. Available at: https://www.bbc.com/worklife/article/20200304-coronavirus-covid-19-update-why-people-are-stockpiling.

Bouchnita, A. & Jebrane, A. (2020). A hybrid multi-scale model of COVID-19 transmission dynamics to assess the potential of non-pharmaceutical interventions. *Chaos, Solitons and Fractals*. Elsevier Ltd, vol. 138.

CDC. (2020). *COVID-19 Overview and Infection Prevention and Control Priorities in non-US Healthcare Settings* [online].Available at: https://www.cdc.gov/coronavirus/2019-ncov/hcp/non-us-settings/overview/index.html.

Chen, N., Zhou, M., Dong, X., Qu, J., Gong, F., Han, Y., Qiu, Y., Wang, J., Liu, Y., Wei, Y., Xia, J., Yu, T., Zhang, X. & Zhang, L. (2020). Epidemiological and clinical characteristics of 99 cases of 2019 novel coronavirus pneumonia in Wuhan, China: a descriptive study. *The Lancet*. Elsevier Ltd, vol. 395(10223), pp. 507–513.

Childs, M. L., Kain, M. P., Kirk, D., Harris, M., Couper, L., Nova, N., Delwel, I., Ritchie, J. & Mordecai, E. A. (2020). The impact of long-term non-pharmaceutical interventions on COVID-19 epidemic dynamics and control. *medRxiv*, vol. 22.

CNBC. (2020). *Coronavirus grinds the sports world to a halt: Here's what's canceled* [online]. [Accessed 10 March 2021]. Available at: https://www.cnbc.com/2020/03/12/the-sports-world-grinds-to-a-halt-amid-the-coronavirus-outbreak.html.

D'Arienzo, M. & Coniglio, A. (2020). Assessment of the SARS-CoV-2 basic reproduction number, R0, based on the early phase of COVID-19 outbreak in Italy. *Biosafety and Health*. Elsevier B.V., vol. 2(2), pp. 57–59.

Deng, Q. (2020). Dynamics and development of the COVID-19 epidemic in the United States: A compartmental model enhanced with deep learning techniques. *Journal of Medical Internet Research*, vol. 22(8), pp. 1–12.

Djaoue, S., Guilsou Kolaye, G., Abboubakar, H., Abba Ari, A. A. & Damakoa, I. (2020). Mathematical modeling, analysis and numerical simulation of the COVID-19 transmission with mitigation of control strategies used in Cameroon. *Chaos, Solitons and Fractals*. Elsevier Ltd, vol. 139.

economictimes. (2021). *Dubai 'surges' health care capacity as virus cases spike* [online].Available at: https://economictimes.indiatimes.com/news/international/uae/dubai-surges-health-care-capacity-as-virus-cases-spike/articleshow/80867954.cms.

Globalmediainsight.com. (2021). *UNITED ARAB EMIRATES POPULATION STATISTICS (2021)* [online]. [Accessed 6 March 2021]. Available at: https://www.globalmediainsight.com/blog/uae-population-statistics/.

Guan, J., Wei, Y., Zhao, Y. & Chen, F. (2020). Modeling the transmission dynamics of COVID-19 epidemic: a systematic review. *Journal of Biomedical Research*, vol. 34(6), pp. 422–430.

Harb, A. M. & Harb, S. M. (2020). Corona COVID-19 spread - a nonlinear modeling and simulation. *Computers and Electrical Engineering*. Elsevier Ltd, vol. 88(April), p. 106884.

Hethcote, H. W. (2000). The Mathematics of Infectious Diseases ∗, vol. 42(4), pp. 599–653.

Holmdahl, I., Buckee, C. & Phil, D. (2020). Can and Cannot Tell Us, pp. 2020–2022.

Imai, N., Dorigatti, I., Cori, A., Riley, S. & Ferguson, N. M. (2020). Report 1: Estimating the potential total number of novel coronavirus (2019-nCoV) cases in Wuhan City, China. *Imperial College London COVID-19 Response Team*, (January), pp. 1–7 [online].Available at: doi: https://doi.org/10.25561/77150.

Kaxiras, E. & Neofotistos, G. (2020). Multiple epidemic wave model of the COVID-19 pandemic: Modeling study. *Journal of Medical Internet Research*, vol. 22(7).

Kucharski, A. J., Russell, T. W., Diamond, C., Liu, Y., Edmunds, J., Funk, S., Eggo, R. M., Sun, F., Jit, M., Munday, J. D., Davies, N., Gimma, A., van Zandvoort, K., Gibbs, H., Hellewell, J., Jarvis, C. I., Clifford, S., Quilty, B. J., Bosse, N. I., Abbott, S., Klepac, P. & Flasche, S. (2020). Early dynamics of transmission and control of COVID-19: a mathematical modelling study. *The Lancet Infectious Diseases*, vol. 20(5), pp. 553–558.

Li, L., Yang, Z., Dang, Z., Meng, C., Huang, J., Meng, H., Wang, D., Chen, G., Zhang, J., Peng, H. & Shao, Y. (2020). Propagation analysis and prediction of the COVID-19. *Infectious Disease Modelling*. Elsevier Ltd, vol. 5, pp. 282–292.

Li, Q., Guan, X., Wu, P., Wang, X., Zhou, L., Tong, Y., Ren, R., Leung, K. S. M., Lau, E. H. Y., Wong, J. Y., Xing, X., Xiang, N., Wu, Y., Li, C., Chen, Q., Li, D., Liu, T., Zhao, J., Liu, M., Tu, W., Chen, C., Jin, L., Yang, R., Wang, Q., Zhou, S., Wang, R., Liu, H., Luo, Y., Liu, Y., Shao, G., Li, H., Tao, Z., Yang, Y., Deng, Z., Liu, B., Ma, Z., Zhang, Y., Shi, G., Lam, T. T. Y., Wu, J. T., Gao, G. F., Cowling, B. J., Yang, B., Leung, G. M. & Feng, Z. (2020). Early Transmission Dynamics in Wuhan, China, of Novel Coronavirus–Infected Pneumonia. *New England Journal of Medicine*, vol. 382(13), pp. 1199–1207.

Linka, K., Peirlinck, M. & Kuhl, E. (2020). The reproduction number of COVID-19 and its correlation with public health interventions. *Computational Mechanics*. Springer Berlin Heidelberg, vol. 66(4), pp. 1035–1050.

Linka, K., Peirlinck, M., Sahli Costabal, F. & Kuhl, E. (2020). Outbreak dynamics of COVID-19 in Europe and the effect of travel restrictions. *Computer Methods in Biomechanics and Biomedical Engineering*. Taylor & Francis, vol. 23(11), pp. 710–717.

Madewell, Z. J., Yang, Y., Jr, I. M. L., Halloran, M. E. & Dean, N. E. (2020). NOTE: This preprint reports new research that has not been certified by peer review and should not be used to guide clinical practice. 1. *medRxiv*, pp. 1–13.

Malkov, E. (2020). Simulation of coronavirus disease 2019 (COVID-19) scenarios with possibility of reinfection. *Chaos, Solitons and Fractals*. Elsevier Ltd, vol. 139, p. 110296.

Meters, W. (2021). *Covid-19 UAE cases* [online]. [Accessed 10 March 2021]. Available at: https://www.worldometers.info/coronavirus/country/united-arab-emirates/.

MOE. (2021). *MOE Admission* [online]. [Accessed 8 March 2021]. Available at: https://u.ae/en/information-and-services/education/school-education-k-12/joining-k-12-education/stages-and-streams-of-school-education.

Moonesar, I. A., Hussain, M., Gaafar, R. & Suliman, D. (2020). Rapid Response: Informing United Arab Emirates' Response to the COVID-19 Pandemic., (April), p. 55.

Musa, S. S., Zhao, S., Wang, M. H., Habib, A. G., Mustapha, U. T. & He, D. (2020). Estimation of exponential growth rate and basic reproduction number of the coronavirus disease 2019 (COVID-19) in Africa. *Infectious Diseases of Poverty*. Infectious Diseases of Poverty, vol. 9(1), pp. 1–6.

Ndaïrou, F., Area, I., Nieto, J. J. & Torres, D. F. M. (2020). Mathematical modeling of COVID-19 transmission dynamics with a case study of Wuhan. *Chaos, Solitons and Fractals*, vol. 135.

Okuonghae, D. & Omame, A. (2020). Journal Pre-proof.

Panovska-Griffiths, J. (2020). Can mathematical modelling solve the current Covid-19 crisis? *BMC Public Health*. BMC Public Health, vol. 20(1), pp. 1–3.

Petard, H. (1938). A Contribution to the Mathematical Theory of Big Game Hunting. *The American Mathematical Monthly*, vol. 45(7), p. 446.

Portal, U. gov. (2020). *Primary governmental efforts to contain COVID-19* [online].Available at: https://u.ae/en/information-and-services/justice-safety-and-the-law/handling-the-covid-19-outbreak/government-efforts-to-contain-covid-19.

Robinson, L. A., Sullivan, R. & Shogren, J. F. (2020). Do the Benefits of COVID-19 Policies Exceed the Costs? Exploring Uncertainties in the Age–VSL Relationship. *Risk Analysis*, (March).

Rohith, G. & Devika, K. B. (2020). Dynamics and control of COVID-19 pandemic with nonlinear incidence rates. *Nonlinear Dynamics*. Springer Netherlands, vol. 101(3), pp. 2013–2026.

Rubin, J. E. & Crowe, S. E. (2020). Annals of internal medicine®. *Annals of Internal Medicine*, vol. 172(1), pp. ITC1–ITC14.

Sarkar, K., Khajanchi, S., Nieto, J. J., Khajanchi, S. & Nieto, J. J. (2020). Journal Pre-proof.

Sector, T. U. A. E. H. (2015). The Health Care Sector. *The Sector Strategist*, pp. 51–71.

Statista. (2020). *UAE Enemployment* [online]. [Accessed 8 March 2021]. Available at: https://www.statista.com/statistics/297778/uae-unemployment-rate/.

Sun, G. Q., Wang, S. F., Li, M. T., Li, L., Zhang, J., Zhang, W., Jin, Z. & Feng, G. L. (2020). Transmission dynamics of COVID-19 in Wuhan, China: effects of lockdown and medical resources. *Nonlinear Dynamics*, vol. 101(3), pp. 1981–1993.

Tian, H., Liu, Y., Li, Y., Wu, C. H., Chen, B., Kraemer, M. U. G., Li, B., Cai, J., Xu, B., Yang, Q., Wang, B., Yang, P., Cui, Y., Song, Y., Zheng, P., Wang, Q., Bjornstad, O. N., Yang, R., Grenfell, B. T., Pybus, O. G. & Dye, C. (2020). The impact of transmission control measures during the first 50 days of the COVID-19 epidemic in China. *medRxiv*, vol. 642(May), pp. 638–642.

UNESCO. (2020). *Half of world's student population not attending school: UNESCO* [online]. [Accessed 10 March 2021]. Available at: https://en.unesco.org/news/half-worlds-student-population-not-attending-school-unesco-launches-global-coalition-accelerate.

Walker, P. G., Whittaker, C., Watson, O., Baguelin, M., Ainslie, K. E. C., Bhatia, S., Bhatt, S., Boonyasiri, A., Boyd, O., Cattarino, L., Cucunubá, Z., Cuomo-Dannenburg, G., Dighe, A., Donnelly, C. A., Dorigatti, I., Van Elsland, S., Fitzjohn, R., Flaxman, S., Fu, H., Gaythorpe, K., Geidelberg, L., Grassly, N., Green, W., Hamlet, A., Hauck, K., Haw, D., Hayes, S., Hinsley, W., Imai, N., Jorgensen, D., Knock, E., Laydon, D., Mishra, S., Nedjati-Gilani, G., Okell, L. C., Riley, S., Thompson, H., Unwin, J., Verity, R., Vollmer, M., Walters, C., Wang, W., Wang, Y., Winskill, P., Xi, X., Ferguson, N. M. & Ghani, A. C. (2020). Report 12: TheThe Global Impact of COVID-19 and Strategies for Mitigation and Suppression. *Imperial College COVID-19 Response Team*, vol. March(June), p. 19 [online].Available at: https://doi.org/10.25561/77735%0Adoi.org/10.25561/77735.

Wang, H., Wang, Z., Dong, Y., Chang, R., Xu, C., Yu, X., Zhang, S., Tsamlag, L., Shang, M., Huang, J., Wang, Y., Xu, G., Shen, T., Zhang, X. & Cai, Y. (2020). Phase-adjusted estimation of the number of Coronavirus Disease 2019 cases in Wuhan, China. *Cell Discovery*. Springer US, vol. 6(1), pp. 4–11.

Wikipedia. (2020). *Demographics of the United Arab Emirates* [online].Available at: https://en.wikipedia.org/wiki/Demographics_of_the_United_Arab_Emirates#Sex_ratio.

Wirawan, A. & Januraga, P. P. (2020). Forecasting COVID-19 Transmission and Healthcare Capacity in Bali, Indonesia. *Journal of Preventive Medicine and Public Health*, vol. 53(3), pp. 158–163.

Yadav, R. P. & Renu Verma. (2020). A numerical simulation of fractional order mathematical modeling of COVID-19 disease in case of Wuhan China. *Chaos, Solitons and Fractals*. Elsevier Ltd, vol. 140.

Yang, Z., Zeng, Z., Wang, K., Wong, S. S., Liang, W., Zanin, M., Liu, P., Cao, X., Gao, Z., Mai, Z., Liang, J., Liu, X., Li, S., Li, Y., Ye, F., Guan, W., Yang, Y., Li, F., Luo, S., Xie, Y., Liu, B., Wang, Z., Zhang, S., Wang, Y., Zhong, N. & He, J. (2020). Modified SEIR and AI prediction of the epidemics trend of COVID-19 in

China under public health interventions. *Journal of Thoracic Disease*, vol. 12(3), pp. 165–174.

Yousefpour, A., Jahanshahi, H. & Bekiros, S. (2020). Optimal policies for control of the novel coronavirus disease (COVID-19) outbreak. *Chaos, Solitons and Fractals*. Elsevier Ltd, vol. 136, p. 109883.

Zhang, N., Cheng, P., Jia, W., Dung, C. H., Liu, L., Chen, W., Lei, H., Kan, C., Han, X., Su, B., Xiao, S., Qian, H., Lin, B. & Li, Y. (2020). Impact of intervention methods on COVID-19 transmission in Shenzhen. *Building and Environment*. Elsevier Ltd, vol. 180(May), p. 107106.

Zhuang, Z., Zhao, S., Lin, Q., Cao, P., Lou, Y., Yang, L., Yang, S., He, D. & Xiao, L. (2020). Preliminary estimates of the reproduction number of the coronavirus disease (COVID-19) outbreak in Republic of Korea and Italy by 5 March 2020. *International Journal of Infectious Diseases*. International Society for Infectious Diseases, vol. 95, pp. 308–310.