Mathematical modelling of the dynamics and containment of COVID-19 in Ukraine

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***Abstract*— The COVID 19 epidemic has already posed serious challenges to the population and resulted in high rates of trauma and death worldwide epidemic. In this project we target Ukraine with a population of 44 million and a developed country in Europe. Using datas and available parameters that separate clinical signs of disease Previous and next. We include boundaries of age specific disease and matric age and specific area to constitute contacts. We exhibit that the report is able to supply numerical specification and distribution of cases of casualties and death, and we came to the conclusion that works done by avoiding the contacts are better at lowering the burden of disease than lowering school contacts.**

I. Introduction

The first cases of the novel Corona Virus (Covid-19) were first registered in China's Wuhan province, and as a result of human trafficking, the number of infected people increased rapidly, forcing Wuhan to enter a strong key. Since then, the disease was announced by the World Health Organization (WHO) on March 11, 2020 and has spread rapidly around the world, infecting all countries and still taking many lives in its positive course. To prevent the spread of this deadly disease and to provide effective treatment or antidepressant, many countries have followed China and introduced locks, bans and suspensions of all normal daily activities, such as school closures, workplaces and the like. The introduction of analysed measures of social imprisonment using statistical models has shown their effectiveness in reducing the spread of COVID-19.

The infection of COVID-19 is caused by the SARS-CoV-2 virus, which is highly transmitted by the respiratory tract, and the main symptoms are dry cough, high fever, and no smell or taste. Some carriers are not fully balanced, and estimates suggest that the number of equals could be more than 50-75% 10.11. The severity of the disease varies according to age, and most deaths occur in people over the age of 65, or older who already have pre-existing conditions. Challenges to controlling the distribution of COVID-19 include infection of its height, as well as more serious cases requiring intensive treatment to comply with the need for air conditioning COVID-19 incubation period of about 5.5 days, but can be 14 days, and this varies between individuals. Recent studies suggest that as viral infections become more common , people with both symptomatic and asymptomatic infections are equally in danger, asymptomatic carriers have the same potential to infect as that of a normal symptomatic carrier.

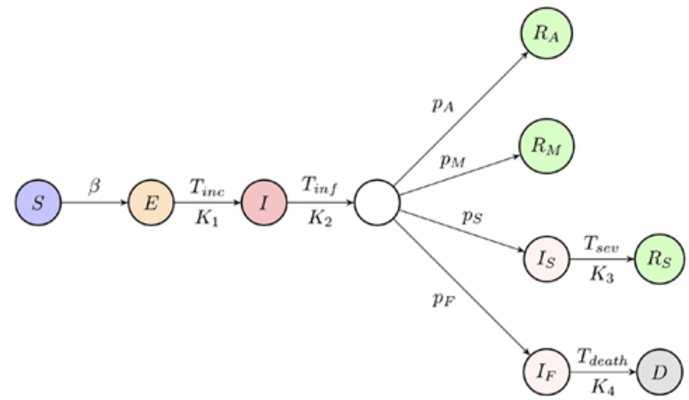

Fig. 1 Model of disease transmission illustrating how the compartments are linked by arrows, letters above/below arrows indicate how the compartments are connected, and circles represent the compartments. It is likely that a few of the pairs were confused with each other. For instance, both the first element of each pair - T_{inc} - describes the period of time spent in an illness and the second element of each pair describes the stages of the distribution of that period.

The first case of COVID-19 in Ukraine was confirmed on the 3rd March 2020. A week later, the Cabinet introduced a countrywide quarantine, which went into effect on the 12th March 2020. Despite quarantine restrictions, the number of COVID-19 cases continued to rise quite rapidly, and on the 25th March 2020, the number of confirmed COVID-19 cases in Ukraine exceeded 100. The majority of these infected cases came from abroad, and the early COVID-19 progression was similar to that of Sweden and Poland, albeit with some delay. Further, more strict, restrictions were introduced on the 6th April 2020, including the closure of schools, universities. shopping malls, fitness facilities. Public transport was reduced to an absolute minimum across the country to minimise inter-regional transmissions, and face masks became obligatory in all public places. The early introduction of lockdown slowed the disease progression, with estimated doubling time of cases going from 8 days to 11 days in the week 28 April to 5 May, and the most infected regions, including Kyiv and Chernivtska region, showed that the infection rate doubled to 10 days during this time frame. Next week, COVID-19 cases in Ukraine increased to 13 from 11 days prior, indicating that this outbreak was showing a rapid slow down if lockdown measures were followed. As of May 12, 2020, the first restrictions easing will occur, and further restrictions will follow on May 22nd, 2020. The number of confirmed cases of COVID-19 in Ukraine is 52, 043, with 1345 deaths, as of 10th July 2020. The number of confirmed cases has steadily and significantly increased since the middle of June 2020, and then slowed down in the first 2 weeks of July 2020.

We use a modified age-structured compartmental SEIR framework to analyze the dynamics of the COVID-19 epidemic in Ukraine. The modifications are designed to take into account the presence of asymptomatic carriers, the different types of clinical progression once someone has been infected, hospitalisation requirements, and the severity of hospital interventions. This was based on the assumption that anyone who had recovered from COVID 19 would be immunized against the virus throughout the remaining epidemic. A model parameterized with official data from the Ministry of Health of Ukraine is based on a distribution of incubation and recovery times, as well as confirmatory data from the ministry. Our study also examines the impact of a variety of lockdown types on the number of cases and deaths of COVID-19 in Ukraine and provides a short-term forecast of the future dynamics of COVID-19.

II. Results

A. Mathematical model.

A compartmental SEIR-type model that takes into account the distribution of each characteristic time as well as the country's population structure has been developed. These studies build on earlier models of COVID-19 dynamics in the UK by Blyuss and Kyrychko and COVID-19 dynamics in Ukraine by Brovchenko. Associated with each group are the susceptible individuals, those exposed to the disease and those infected with the disease. During the infective period, "asymptomatic carriers" will simply recover without ever showing any signs of the disease, thus moving to the compartment of asymptomatic recovered individuals (RA) (t), while individuals with mild symptoms will also move toward the recovered class RM (t). After the same period, a proportion of pH-affected individuals require hospitalization. Under Davies et al., this assumption is further supported. Of these individuals, pS moves to a new compartment IS(t) that contains individuals with severe disease, who are expected to recover from infection during hospitalization, and then move to the recovered compartment RH(t). In the remaining proportion, pF, a period of hospitalization will occur, and then death will require the transition to compartment D(t). Fig. 1 illustrates the model compartment transitions, while Methods provides information about the model itself.

TABLE 1

Age-group (years)	% Asymptomatic cases, p_A (%)	% Hospitalised cases, p_H (%)	Case fatality ratio, p_F (%)
0 to 4	45.8	19.3	0.002
5 to 9	46.9	12.4	0.002
10 to 14	46.3	10.5	0.10
15 to 19	43.1	13.3	0.34
20 to 24	42.3	14.6	0.11
25 to 29	39.3	14.4	0.11
30 to 34	40	15.2	0.36
35 to 39	36.4	17	0.43
40 to 44	35.6	21.7	0.92
45 to 49	35.5	23.5	1.27
50 to 54	33.2	28.3	1.76
55 to 59	30.2	33.3	2.77
60 to 64	28.7	36.7	3.70
65 to 69	28.5	41.6	5.95
70 to 74	28.2	45.5	8.44
75 to 79	26.4	50.8	11.25
80+	27	52.9	18.2

$$C_{ij} = a_1 C_{ij}^{school} + a_2 C_{ij}^{work} + a_3 C_{ij}^{other} + a_4 C_{ij}^{home}, \quad i,j = 1....16$$

As shown in Fig. 2. A gamma distribution with an integer shape parameter was applied, and the maximum likelihood estimator, implemented in the MATLAB gamfit function, provided the fitting results. An analysis of hospitalisation data suggests that the longer tail of the Tsev distribution is, very likely, artificial, indicating that our fit may be even better than what can be seen in this figure. A similar gamma distribution for incubation and infectious periods has been found in studies of epidemiological data for COVID-19 cases in other countries. In the current model, the distributions are represented as multiple stages with the same mean period. In the absence of clinical data on Tinf distribution, it was assumed gamma distribution with five stages, as suggested by Davies et al.Since population structure is known to have a major effect on disease transmission, as manifested by significant differences in age-specific hospitalisation and mortality rates, we have divided each compartment into sixteen 5-year age groups spanning from 0 until 75+. To model interactions between individuals in different age groups, we have used a contact matrix

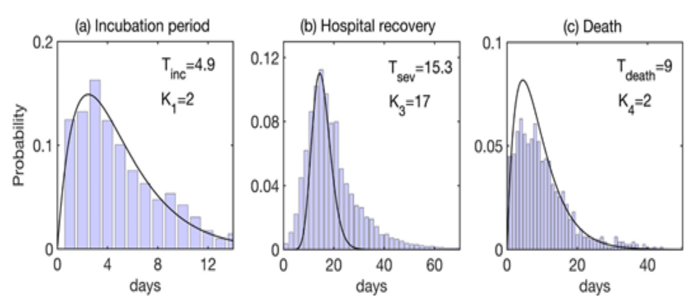

Fig. 2

B. Dynamics of epidemic spread.

As in recent models of COVID-19 in other countries, we looked at the dynamics of the spread of SARS-CoV-2 by varying coefficient values a1,...,a4 for different contributions to a mixing matrix (1). In Hubei province, where the first cases of SARS-CoV-2 virus had been reported, early observations also suggested reductions in the number of cases as a result of different intervention measures. During the simulation, which begins on 25 March 2020, the number of confirmed cases of COVID-19 will reach 100 for the first time in Ukraine. We modelled school closures and university closures by setting a1 = 0, and we modelled nurseries and playgrounds by setting $C_{11}^{other} = 0$. All other coefficients were set to a1 = a2 = 0.4 (significantly reduced interactions in 'work' and 'other' compartments), while a4 remained constant throughout. As of 6 April 2020, new government guidance introduced a shielding for self-isolation for over-60s, so our matrices for workers and other categories have been reduced by another 50%. Nursery schools opened on May 25, 2020, with social distancing requirements, and on June 1, 2020, gyms, schools, and universities were allowed to open, with very limited services, represented by setting a1 =1 and setting C_{11}^{other} to 30% of baseline. On the 5th of June 2020, a restriction on self-isolation of over-60s was lifted, along with restrictions on the opening of cafes, restaurants, etc., A subsequent simulation gave the values a1 = 0.1, a2 =a3 = 0.6, a4 =1.

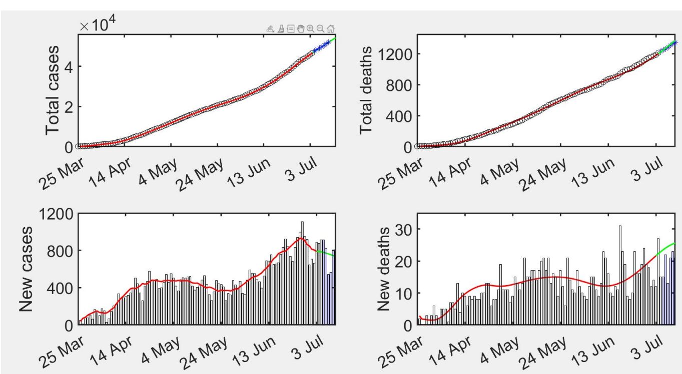

Fig. 3 The total number of cases and deaths, as well as the number of cases and deaths each day. A black circle indicates actual data, a red line indicates a simulation of the model, a green line indicates a projection based on the simulation, and a blue star indicates the latest data. Data is taken from.

This figure shows the results of numerical simulations of the model (2) using parameter values from Table 1. Although many challenges have been associated with accurate and timely collection and reporting of cases and deaths, the results of the study are in good agreement with actual data, despite all of the problems associated with obtaining short-term predictions using the model. Dynamically, one observes a plateau-like region from mid-April to the end of May 2020. While the total number of cases and deaths has continued to rise over the past year, the number of new cases and deaths each day has remained relatively stable.

In terms of epidemiology, this is explained by the fact that Ukraine rather went into quarantine as early as the middle of March, when the number of confirmed cases was still very small, and the quarantine largely remained in place until May. 2 months later, however, it became difficult to justify maintaining lockdown rules and they began to be relaxed. These include allowing people over 60 to leave their houses (before, they were expected to shield themselves and not leave their homes except for emergencies), operating public transport again, and resuming work at cafes, restaurants, gyms, etc. Lockdown restrictions were lifted, which resulted in a marked increase in mixing between people, with many not adhering to social distancing guidelines, and, as has been observed in many other countries, the number of cases and deaths has continued to grow. In many Ukrainian towns and cities, transportation is mainly provided by shuttle taxis. Because the number of shuttle taxis is limited, these taxis often take large numbers of passengers, resulting in people being squeezed into tight spaces for an extended period of time.

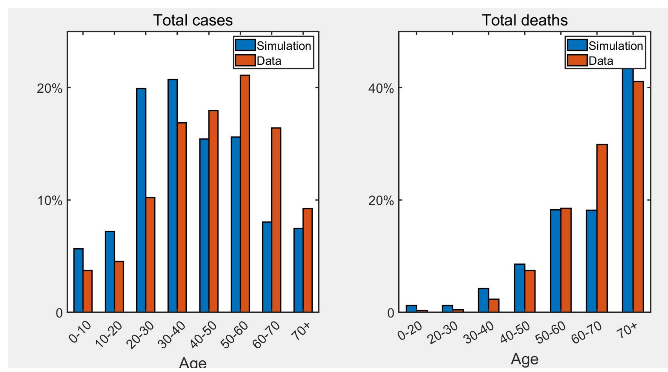

Fig. 4 According to the data and the simulation of model (2), age distribution of COVID-19 cases and deaths on 10 July 2020. Statistics from the beginning of July suggest that existing social distancing measures appear to be working, with new cases decreasing over this period.

A similar pattern to what has been observed elsewhere, there are very few deaths among the young and their numbers increase with age, as shown in Figure 4. The proportion of deaths among people 50-60 years of age is already quite high (around 20%) with the highest morbidity occurring in the 60-70 age bracket, and the lowest among older age groups (24% in 70-80, and 17% in 80+). One possible reason is that women have a life expectancy of 76.7 years and men 66.7 years, indicating that the 60-70 age group is very likely to suffer from a variety of illnesses, and COVID-19 has made matters worse in this regard. A larger proportion of deaths among the 80+ group may be attributable to the fact that despite having the highest age-specific case fatality rate, this group is the smallest in terms of actual number of people. Moreover, deaths among the 40–50 age group account for around 7% of the total death rate, whereas in many other countries, this distribution is much lower. This could be due to the co-morbidities among people in this age group that result in a higher death rate. The number of confirmed cases appears to be highest among those of working age, though around 10%

of cases have been registered in children and young adults under 20. Though rates of child deaths are very low, they are still not negligible, and recent outbreaks in nurseries and schools highlight the need to maintain social distance in these settings, where there is naturally a high level of interaction between children. Importantly, the case and death distributions for both groups appeared to have stabilized by mid-April. Subsequent increases in cases and deaths do not seem to have changed this distribution, which indicates that cases and deaths in each group are only growing proportionally. Figure 4 shows that despite qualitative similarities, there are some discrepancies between simulated and observed age distributions of cases and deaths. Many reasons could be attributed to this: the mixing matrices were constructed using household survey data, but they may not accurately reflect Ukrainian population mixing; there are notable differences in population structure and mixing in different regions of Ukraine; and there may be issues with the collection and reporting of cases and deaths. However, our model proves valuable in delivering accurate predictions for COVID-19 dynamics, particularly from the perspective of the impact of age groups and population structure on the disease's spread.

C. Longer-term forecast and containment

In the long-term, figure 5 contrasts the prevalence of disease transmission rates in the baseline set at their peak on 10 July 2020 with scenarios where the rates are uniformly increased by 10% or 20% in all age groups over a period of two weeks. According to the data from the first ten days of July, the number of new cases has been declining rapidly, resulting in a further decrease in new cases and deaths (with deaths slightly lagging behind), and slower growth rates for total cases and deaths. Disease transmission for almost all age groups increases by 10%, and, with the planned return to school on 1 September 2020 (though with social distancing measures in place, so as to set a1=0.6), this increases the number of cases and deaths by Autumn. The hypothetical scenario of increasing the transmission rate by 20% can result in a very significant increase in cases and deaths that could even surpass those that occurred during the first epidemic wave -- should the remaining restrictions be removed and lead to a substantial increase in cases and deaths over the next few months. Leaving quarantine restrictions in place may undermine social distance and disease control measures.

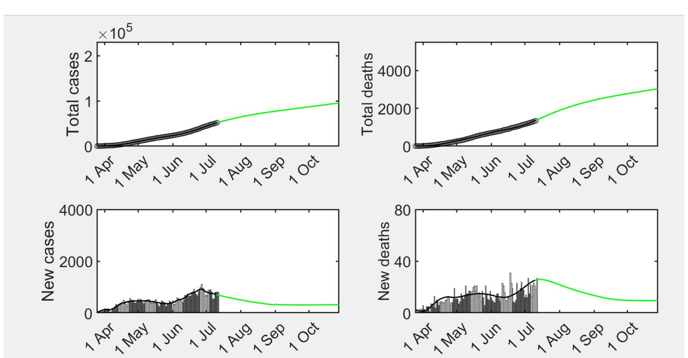

Fig. 5 Longer-term forecast of epidemic dynamics of model (2) continuing with an overall transmission rate β as of 10 July 2020 (green)

On the 1st September of each year, when school in Ukraine begins, there would be a 30% reduction in contacts between school groups. Under the second scenario, the contacts for people older than 60 are reduced by 50%, which corresponds to a previous policy of shielding in place from April 6 to June 6, 2020. We find that the reduction in school contacts is more efficient in reducing both daily and overall cases than that of the restriction in school contacts, but it has much less impact on the number of total and daily deaths, and we find even greater results when a longer period of time is considered. Our results can be explained by the fact that young people have significantly more contacts than older people and a 30% decrease in contacts at work could further spread the illness. The last scenario we consider is a reduction in contacts by 50% among work contacts. This scenario results in the absolute reduction in daily cases as well as total cases, but interestingly, it also results in a reduction in total deaths over time, as an overall reduction is also resulted from a smaller number of daily deaths. There is a causal link between mortality among 40-60-year-olds and a decrease in the infection rate they can spread to older people, suggesting that promoting work from home and reducing work contacts could be most effective at controlling the spread of disease in Ukraine and minimising disease burden. Working from home was associated with lower rates of COVID-19 in Hong Kong. This finding is consistent with earlier observations that working at home contributed to the increase in early cases.

III. Discussion

An analytical model for COVID-19 for Ukraine has been developed and tested in this paper, which combines realistic distributions of characteristic times and population ages, as well as age-specific mixing patterns, as well as the implications of several lockdown scenarios. The results suggest that both the number of infections and deaths will continue to increase rapidly in the near future. Current trend suggests that Ukraine has experienced the problem observed in many other countries: a lockdown was introduced very early into the outbreak, when the numbers of infected people were still relatively small, and then after 2–3 months, it was necessary to start lifting lockdown restrictions to reduce societal tensions and support the economy, but since by this point the prevalence was much higher, this quickly resulted in the high level of growth of new cases. After a short initial transient, age distributions by mid-April 2020 settled into stationary patterns after a short initial transient, with more cases/deaths having almost no impact on these patterns. While the highest proportion of deaths in most countries occurs among elders, nearly 50% of deaths in Ukraine occur among the age group of 50-70, which can be partially attributed to shorter life expectancy, but can also be related to comorbidities that result in disease and death. Other worrying observations may also be explained by co-morbidities and generally poorer health, such as worryingly high mortality rates among younger age groups (compared with other places), such as 40–50, and even 30–40 years, respectively, in contrast to hardly any deaths elsewhere.

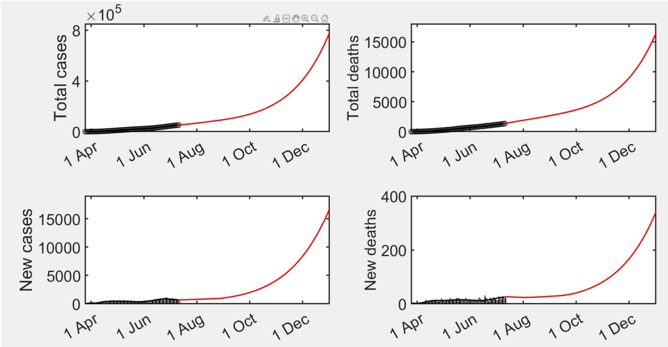

Fig. 6 Modelling the effects of different quarantine strategies. Red line indicates the baseline forecast for a 20% increased transmission rate without any quarantine measures

We have examined the possible influences of different lockdown scenarios on the case and death numbers if the Ukraine crisis worsens in the short term. Our studies showed that reducing mixing among children and young adults of the same age group had the greatest impact on reducing cases, whereas shielding over-60s would have a lesser effect on reducing cases, but be significantly more effective in reducing deaths. Intriguingly, a moderate drop in contacts among the working-age population is associated with the biggest drop in both cases and deaths. This suggests that encouraging working at home whenever possible, eliminating travel by crowded public transport, and pushing hard for social distancing/prevention would significantly decrease cases in the longer run, thus reducing the amount of overload on hospitals, as well as reducing death rates. Figure 5 provides forecasts for the first half of October 2020 under the assumption that disease transmission rates will increase by 20%. Actual data for that first half suggests the model has good predictive ability. On average, there were just under 4,000 new cases per day on average and 215,000 confirmed cases at the end of October. The actual figures exceeded that slightly, with just under 5,000 cases over a week and 265,451 confirmed cases on 12 October 2020. On 12 October 2020, both the forecasted daily mortality rate and the actual number of deaths have been corrected to 75 and 5,100, respectively, showing qualitative agreement.

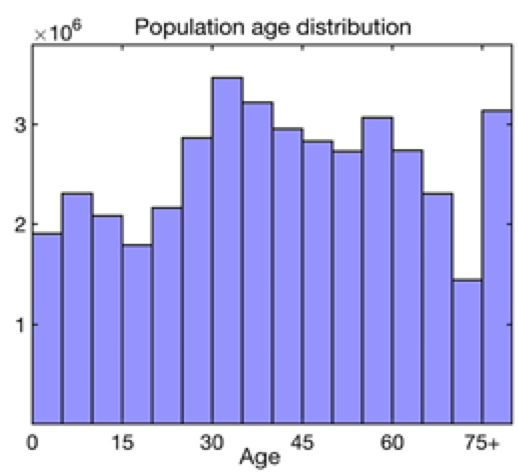

Fig. 7 Population age distribution in Ukraine

The results of this paper have the potential to be extended in more directions. One such extension would be to create up-to-date and reasonably accurate mixing matrices for different types of contacts and different age groups in Ukraine. There is an opportunity to address this through surveys that would reveal patterns of contacts, travel habits, shopping patterns, etc., in a similar fashion to the household survey that has been implemented since February 2020 in the UK for an analogous project33. It would be possible to estimate contact matrices that provide the best fit for observed data by using simulation results and short-term forecasts coupled with the model. Another related issue is the fact that Ukraine is the sixth largest country by population in Europe by size, and there is a lot of variation in terms of population structure, transportation modes, work patterns, etc, which obviously imposes a significant effect on the rate of spread of disease there. A local survey in this respect would allow one to model the dynamics of the local spreading much more accurately. In addition to a COVID-19 epidemic, we are currently experiencing an associated "infodemic", which has resulted in many people not believing in coronavirus and, as a consequence, not following safety guidelines, such as wearing face masks. Obviously, this only exacerbates the epidemic and makes it more difficult to contain. Another direction, in which our model could be improved is to include the spread of disease awareness and compliance into a model, which would also allow us to analyse different ways how to best target awareness campaigns. Last but not least, an important challenge for any mathematical model of epidemics is the reliability of the data on which the model is built. Similar to many countries, it is already known in the specific context of COVID-19 in Ukraine that there are some delays in collecting and reporting data, and that improving this would have a positive impact on improving the parameterization of the model, which would increase its predictive value. Testing for SARS-CoV-2 is currently being performed within WHO guidelines of 10–30 tests per confirmed case, so Ukraine is well within this benchmark of adequate testing, though improving testing capabilities might help reduce risk of disease outbreak.

IV. Parameter Estimation

Asymptomatic and hospitalized rates were calculated using age-stratified parameters, and case fatality ratios were obtained directly from the Public Health Center of the Ministry of Health of Ukraine (Table 1), and are provided as table 1 in this report.

BRN (Basic Reproduction Number) for the model (2) is CijNi/Nj (eigenvalue) times the βTinf. The effective reproduction number has been approximated to the BRN due to susceptibility of the population. Data of one full cycle of COVID-19 infection from European countries indicate seroprevalence between 5-10%. Dynamics of the following day is simulated using the β value obtained from the number of new infections of the present day. Our ability to closely monitor changes in transmission associated with the introduction and lifting of quarantines made it possible for us to track disease transmission very closely. At day 30 after the start of the simulation, the death rate was proportionally scaled to 0.046 by taking the sum of diverse pF values for each age group, and subsequently it was kept constant for the rest of the simulation. Initially, a population of 25 people was selected for the simulation. As of March 2020, 100 confirmed COVID-19 cases had been reported.

V. Conclusion

Our research focuses on developing and testing a statistical model for COVID-19 in Ukraine with a particular emphasis on practical distributions of characteristic times, population age structures, and age-specific mixing trends, as well as effects of various lockdown scenarios. We anticipate a steady rise in the number of illnesses, as well as a rapid rise in the number of deaths, over the next few years. After a brief initial transient, the age distributions of cases and deaths have stabilised by mid-April, with concurrent rise in cases/deaths having virtually no impact on these distributions. In Ukraine, one particular problem is the lack of current and relatively reliable mixing matrices for various types of contacts and age ranges. This may be approached with surveys that elucidate touch trends, as well as travel to work/shopping preferences, and so on, in a manner comparable to the household sample that has been contacted in the UK since March 2020 for a similar work. A statistical model of epidemics is incomplete without reliable data; ensuring this is one of the most difficult challenges offered by such models. In the particular sense of COVID-19 in Ukraine, as in many other countries, there are still established delays in data collection and reporting, and enhancing this will result in more accurate parameterization of the model, thereby increasing its predictive ability. Ukraine currently performs 14.9 SARS-Cov-2 tests per confirmed case, which is well within the WHO-recommended guideline of 10-30 tests per confirmed case as a baseline for appropriate testing, though expanding testing ability further may better detect and trace cases faster, reducing the potential for disease transmission. And all of the data used in this analysis can be prescribed form via the platform of Ukraine's Ministry of Health's Public Health Center, with all boundary conditions included in the manuscript's text.

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