Compartment Model of COVID-19 Epidemic Process in Ukraine

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Abstract
The paper presents a compartment model of the dynamics of the incidence of the new coronavirus (COVID-19). An approach to the construction of SIR models is shown. The SIR-F model for the COVID-19 epidemic process in Ukraine has been built. Morbidity data provided by the Center of Public Health of the Ministry of Health of Ukraine. The morbidity was analyzed, the assessment of the stay of people in public places before and during quarantine was carried out. Based on the simulation results, the predicted incidence of COVID-19 in Ukraine for 10 and 60 days was calculated. The research implementation results enhance the efficiency of management decisions to ensure the biosafety of the population and the development of scientifically based strategies for anti-epidemic and preventive measures. The results obtained in this study expand the possibilities for making correct decisions by administrators who determine strategies in the health care of countries.

Keywords 1
Public Health, Epidemic Process, Epidemics Control, Intelligent Information Technologies, Decision Support System, Machine Learning, Simulation.

1. Introduction

The coronavirus infection COVID-19, which began in late 2019 in China, Wuhan, has spread beyond its borders and captured most of the countries of the world [1]. The World Health Organization has assessed the emergence of this virus as a threat to the entire population of the planet, as a disease of international importance, and declared the COVID-19 pandemic [2]. An effective vaccine has not yet been created, there is no specific treatment for the disease, severe forms of infection are registered, which can be fatal, it is very important to choose the most effective, efficient and cost-effective strategy for combating coronavirus, taking into account the peculiarities of public health of a particular country [3], its economic, material and personnel potential.

Health systems in most countries were overwhelmed. There were not enough hospital beds, beds in Intensive Care Units, health-care workers, Personal Protective Equipment (PPE), ventilators, medical devices, and other medical supplies [4].

Patient treatment protocols were often revised and improved, which affected both the patient's treatment results and the epidemic situation.

The development of vaccines, which are obtained using different technologies, has become an additional tool for mitigating the epidemic. Vaccination began in Israel, European countries, the USA, etc. [5] However, vaccines are not yet available for the entire population of the world. In the face of a vaccine shortage, each country uses its vaccination methods. Most countries, first of all, began to vaccinate risk groups – the elderly, medical workers, etc. What vaccine will give the best epidemiological effect? Which contingents will be the best tactic to contain the pandemic? What

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measures will reduce disease severity and the case fatality rate? The answers to these and other questions have not yet been received.

All forecasting models have different initial assumptions and use historical data differently. Models based on well-grounded theoretical understanding and available evidence are critical to formulating viable observational policies, but shifts in distribution can lead to systematic false predictions [6-9].

As a matter of fact, COVID-19 has followed specific patterns which are basically related to the dynamic contagion of the pandemic. When the pandemic occurs, different methods of surrogation measures are implemented to detect and evaluate these infective diseases [10-11]. Any epidemic in a state or country has occurred with another aspect of magnitude including time, specifically changing weather periods and spread of the epidemic over these periods, and also exhibited as nonlinear in the environment. To monetarize these nonlinear compelling changes, investigators have focused on designing such nonlinear systems in order to describe the abruptness of infective diseases [12-13]. Thus, mathematical models like Susceptible Infective Recovered (SIR) are introduced for analyzing the epidemics. Experiments help to understand and analyze the main drivers of the epidemic [14], for example, the intensity of communication between people, their crowding, etc., which makes it possible to develop and implement measures aimed at eliminating or weakening this driver [15].

It is impossible to get answers to all questions, to correctly assess and predict the development of the situation from only observations. Mathematical modeling can help, on the one hand, identify and understand the main driving forces behind the spread of the disease and, on the other hand, evaluate the most effective measures to contain a pandemic for the specific conditions of a particular country, city, area [16], and also enable governments and health systems promptly to provide healthcare institutions with the necessary resources, to develop business tactics, the existence of the population, and to correct preventive and control measures [17].

The research aims to develop a compartment model of the COVID-19 epidemic process using statistical data of COVID-19 in Ukraine.

2. SIR model

The SIR (Susceptible, Infected, Recovered) model [18] is the basis for describing the spread of infectious diseases and was proposed in the 1920s by Scottish epidemiologists Anderson Kermack and William McKendrick. According to SIR model, the population is divided into three groups: susceptible (S), infected (I) and those who have recovered (R). Over time, transitions $S \rightarrow I$ (infection) and $I \rightarrow R$ (recovery or death) are possible. Today there is a whole family of models developed on the basis of SIR models. The SIR-based models are based on the idea that the studied population is divided into compartments (clusters) and assumptions about the nature and rate of transmission from one compartment to another. Diseases that confer immunity have a compartmental structure different from diseases without immunity, and are most often described by ordinary differential equations (which are deterministic), but models with a stochastic (random) structure, which are more realistic, but much more difficult to analyze, can also be used [19].

The three categories are interrelated with one another and with parameters due to the following equations: Rate of change of Susceptible Population is given by:

$$\frac{dS}{dt} = -\beta * I * S \tag{1}$$

Rate of Infected Population change is given by:

$$\frac{dt}{dt} = \beta * I * S - \gamma * I \tag{2}$$

Rate of Recovered Population change is given by:

$$\frac{dR}{dt} = \gamma * I \tag{3}$$

where β is the pathogen contagion rate and γ is the recovery rate.

3. Simulation of COVID-19 epidemic process

The developed model allows us to investigate the dependance of COVID-19 epidemic process dynamics and antiepidemic countermeasures. The purpose of such experiments is to find out which factors influence the dynamics the most.

We have expanded classic SIR model with state "F". SIR-F parameter estimation is applied to dynamics of COVID-19 epidemic process in time subsets to determine the effects of measures. To investigate infection rate and recovery rate S-R trend analysis has been provided.

Analysis of the incidence of the new coronavirus shows that all infected areas can be divided into two clusters: with a growth factor greater than one, and a growth factor less than one. In the developed model, the growth factor was calculated using the following formula.

$$\text{Growth Factor} = \frac{\Delta \mathrm{C}_n}{\Delta \mathrm{C}_{n-1}} \tag{4}$$

in which C is the number of confirmed cases.

The rapid spread of the disease, the congestion of hospitals and the lack of information about the new coronavirus infection lead to the death of some patients before the diagnosis of the disease. Therefore, the number of deaths is added to those infected: "S + I → Fatal + I. And SIRF model is described by following equations:

$$\begin{aligned} \mathrm{S} \xrightarrow{\beta I} \mathrm{S}^* &\xrightarrow{\alpha_1} \mathrm{F} \\ \mathrm{S}^* &\xrightarrow{1-\alpha_1} \mathrm{I} \xrightarrow{\gamma} \mathrm{R} \\ &\quad\;\; \mathrm{I} \xrightarrow{\alpha_2} \mathrm{F} \end{aligned} \tag{5}$$

in which S is susceptible people, S^* is confirmed and uncategorized cases, I is infected and categorized cases, R is recovered people, F is dead because of infection, α_1 is mortality rate of $S*$, α_2 is mortality rate of I [1/min], β is contact rate [1/min], γ is recovery rate [1/min],

The model can be described by ordinary differential equation (6)

$$\begin{aligned} \frac{\mathrm{d}S}{\mathrm{d}T} &= -N^{-1}\beta SI \\ \frac{\mathrm{d}I}{\mathrm{d}T} &= N^{-1}(1-\alpha_1)\beta SI - (\gamma+\alpha_2)I \\ \frac{\mathrm{d}R}{\mathrm{d}T} &= \gamma I \\ \frac{\mathrm{d}F}{\mathrm{d}T} &= N^{-1}\alpha_1\beta SI + \alpha_2 I \end{aligned} \tag{6}$$

For non-dimensional model we set $(S,I,R,F)= N\times(x,y,z,w)$ and $(T,\alpha_1,\alpha_2,\beta,\gamma) = (\tau t,\theta,\tau^{-1}\kappa,\tau^{-1}\rho,\tau^{-1}\sigma)$. This model can be described as (7).

$$\begin{aligned} \frac{\mathrm{d}x}{\mathrm{d}t} &= -\rho xy \\ \frac{\mathrm{d}y}{\mathrm{d}t} &= \rho(1-\theta)xy - (\sigma+\kappa)y \\ \frac{\mathrm{d}z}{\mathrm{d}t} &= \sigma y \\ \frac{\mathrm{d}w}{\mathrm{d}t} &= \rho\theta xy + \kappa y \end{aligned} \tag{7}$$

where

$$0 \le (x, y, z, w, \theta, \kappa, \rho, \sigma) \le 1$$
$$1 \le \tau \le 1440 \quad (8)$$

Reproduction number can be defined as

$$R_0 = \rho(1-\theta)(\sigma+\kappa)^{-1} = \beta(1-\alpha_1)(\gamma+\alpha_2)^{-1} \quad (9)$$

Performance results of model (7) are shown at figure 1.

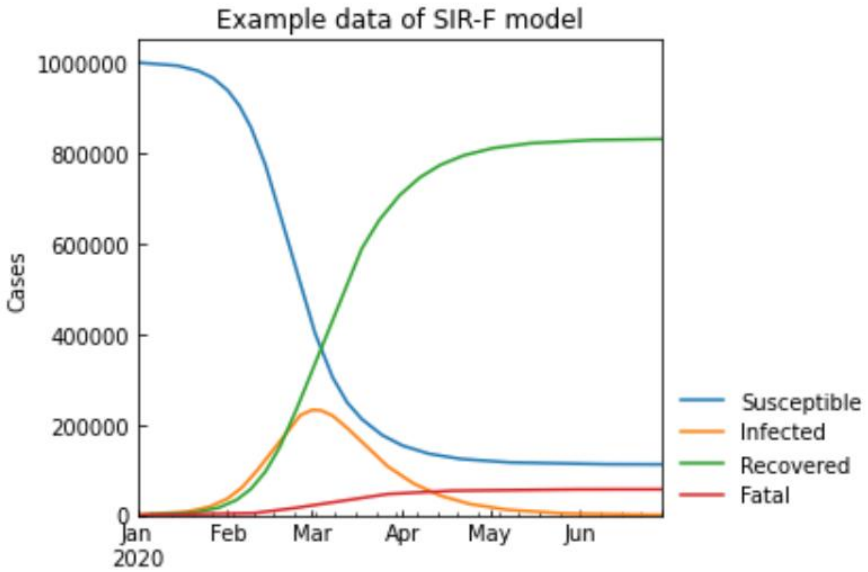

Figure 1: Example of non-dimensional SIR-F model.

Now we perform Susceptible-Recovered trend analysis for actual data of COVID-19 incidence in Ukraine. The plot of the S-R trend is shown in figure 2.

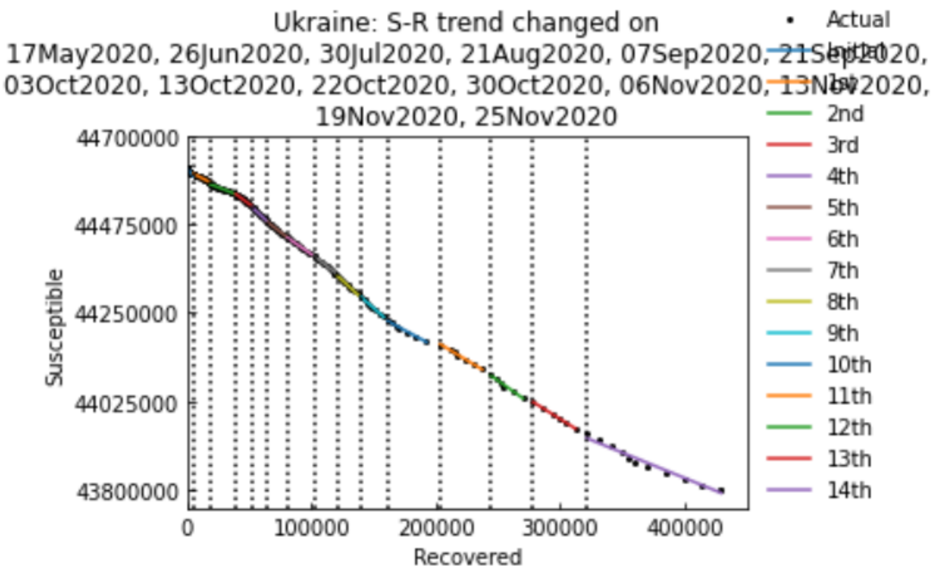

Figure 2: The trend of COVID-19 confirmed cases and recovered cases in Ukraine based on COVID-19 and population datasets.

We assume that morbidity by novel coronavirus infection in Ukraine have four dates of its dynamics changes.

4. Scenarios of COVID-19 epidemic process dynamics in Ukraine

Now we investigate COVID-19 data in Ukraine (figure 3). Data for further simulation was given by the Center of Public Health of the Ministry of Health of Ukraine.

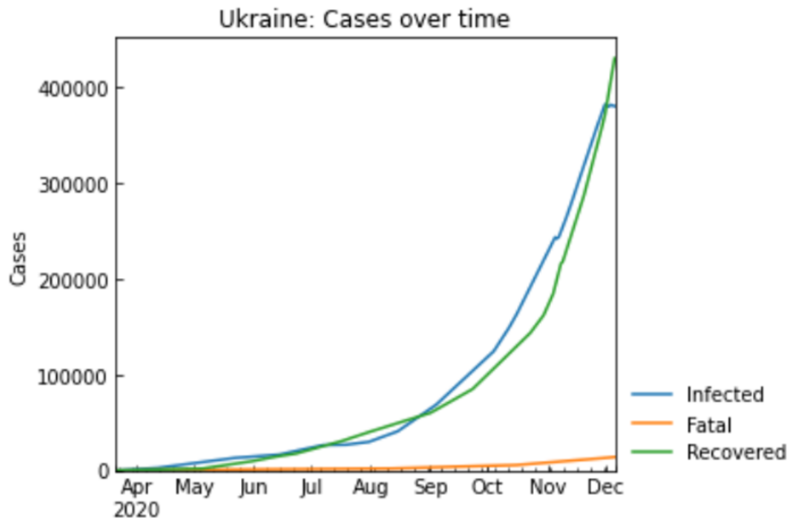

Figure 3: Ukraine cases over time.

Let's apply dates of COVID-19 dynamics changes to our model, and build SIRF model started from the date each stage starts. Figure 4 shows different phases of the COVID-19 epidemic process in Ukraine.

	Type	Start	End	Population
0th	Past	21Mar2020	16May2020	44622516
1st	Past	17May2020	25Jun2020	44622516
2nd	Past	26Jun2020	29Jul2020	44622516
3rd	Past	30Jul2020	20Aug2020	44622516
4th	Past	21Aug2020	06Sep2020	44622516
5th	Past	07Sep2020	20Sep2020	44622516
6th	Past	21Sep2020	02Oct2020	44622516
7th	Past	03Oct2020	12Oct2020	44622516
8th	Past	13Oct2020	21Oct2020	44622516
9th	Past	22Oct2020	29Oct2020	44622516
10th	Past	30Oct2020	05Nov2020	44622516
11th	Past	06Nov2020	12Nov2020	44622516
12th	Past	13Nov2020	18Nov2020	44622516
13th	Past	19Nov2020	24Nov2020	44622516
14th	Past	25Nov2020	06Dec2020	44622516

Figure 4: Different phases in Ukraine.

Now we compare developed model results for estimating SIR-F parameters (fig. 5).

Start	End	Population	ODE	Rt	theta	kappa	rho	sigma	tau	1/gamma [day]	1/beta [day]	1/alpha2 [day]	alpha1 [-]	RMSLE	Trials	Runtime
21Mar2020	16May2020	44622516	SIR-F	9.38	0.053485	0.000306	0.118545	0.011660	1440	85	8	3269	0.053	1.113574	2335	3 min 0 sec
17May2020	25Jun2020	44622516	SIR-F	1.42	0.018904	0.000331	0.033987	0.023179	1440	43	29	3020	0.019	0.041658	2414	3 min 1 sec
26Jun2020	29Jul2020	44622516	SIR-F	1.40	0.000030	0.000742	0.031474	0.021714	1440	46	31	1348	0.000	0.036582	2536	3 min 0 sec
30Jul2020	20Aug2020	44622516	SIR-F	2.13	0.000950	0.000642	0.039359	0.017855	1440	56	25	1557	0.001	0.011399	2605	3 min 0 sec
21Aug2020	06Sep2020	44622516	SIR-F	2.96	0.016276	0.000040	0.039649	0.013148	1440	76	25	25202	0.016	0.007697	589	0 min 40 sec
07Sep2020	20Sep2020	44622516	SIR-F	2.31	0.000653	0.000641	0.034232	0.014180	1440	70	29	1560	0.001	0.006341	461	0 min 30 sec
21Sep2020	02Oct2020	44622516	SIR-F	1.91	0.000632	0.000594	0.033945	0.017168	1440	58	29	1683	0.001	0.008020	430	0 min 30 sec
03Oct2020	12Oct2020	44622516	SIR-F	2.42	0.000116	0.000555	0.035225	0.013983	1440	71	28	1802	0.000	0.008084	1138	1 min 20 sec
13Oct2020	21Oct2020	44622516	SIR-F	2.63	0.000143	0.000645	0.033013	0.011887	1440	84	30	1551	0.000	0.008609	441	0 min 30 sec
22Oct2020	29Oct2020	44622516	SIR-F	2.33	0.000488	0.000526	0.033804	0.013963	1440	71	29	1901	0.000	0.011670	168	0 min 10 sec
30Oct2020	05Nov2020	44622516	SIR-F	1.97	0.001450	0.000568	0.039280	0.019386	1440	51	25	1759	0.001	0.010275	2819	3 min 0 sec
06Nov2020	12Nov2020	44622516	SIR-F	1.70	0.001455	0.000747	0.040128	0.022843	1440	43	24	1338	0.001	0.010660	167	0 min 10 sec
13Nov2020	18Nov2020	44622516	SIR-F	1.91	0.000488	0.000526	0.039288	0.020069	1440	49	25	1901	0.000	0.013201	159	0 min 10 sec
19Nov2020	24Nov2020	44622516	SIR-F	1.65	0.000785	0.000557	0.040129	0.023683	1440	42	24	1796	0.001	0.009750	330	0 min 20 sec
25Nov2020	06Dec2020	44622516	SIR-F	1.38	0.000775	0.000446	0.038976	0.027794	1440	35	25	2240	0.001	0.016523	2290	2 min 50 sec

Figure 5: Comparing estimate SIR-F parameters.

A national lockdown was implemented in Ukraine from 13th of March, 2020. A national lockdown affected on g_s and c. Let's assume that people started to meet each other less with the lockdown for 19%. Now we estimate g_s before 13th of March (fig. 6).

	Age_first	Age_last	Period_of_life	School	Office	Others	Portion
0	0	2	nursery	3	0	0	0.029017
1	3	5	nursery school	4	0	1	0.030672
2	6	10	elementary school	5	0	1	0.056309
3	11	13	middle school	5	0	1	0.032996
4	14	18	high school	6	0	1	0.047233
5	19	25	university/work	3	3	1	0.070750
6	26	35	work	0	6	1	0.148973
7	36	45	work	0	5	1	0.156723
8	46	55	work	0	5	1	0.134502
9	56	65	work	0	5	1	0.135738
10	66	75	retired	0	0	4	0.093840
11	76	85	retired	0	0	3	0.051272
12	86	95	retired	0	0	2	0.011974

Figure 6: Reduction of ρ and measures taken in Ukraine.

Simulation shows that the average time people go out without lockdown is 5,8 days. Now we estimate g_s after national lockdown (fig. 7). Simulation shows that after lockdown average time susceptible people go out is 0,8 days.

	Age_first	Age_last	Period_of_life	School	Office	Others	Portion
0	0	2	nursery	0	0	0.0	0.029017
1	3	5	nursery school	0	0	0.2	0.030672
2	6	10	elementary school	0	0	0.2	0.056309
3	11	13	middle school	0	0	0.2	0.032996
4	14	18	high school	0	0	0.2	0.047233
5	19	25	university/work	0	1	0.2	0.070750
6	26	35	work	0	1	0.2	0.148973
7	36	45	work	0	1	0.2	0.156723
8	46	55	work	0	1	0.2	0.134502
9	56	65	work	0	1	0.2	0.135738
10	66	75	retired	0	0	0.2	0.093840
11	76	85	retired	0	0	0.2	0.051272
12	86	95	retired	0	0	0.2	0.011974

Figure 7: Simulation data after lockdown.

Now we build forecasts of COVID-19 morbidity using that parameters for one week (fig. 8, 9).

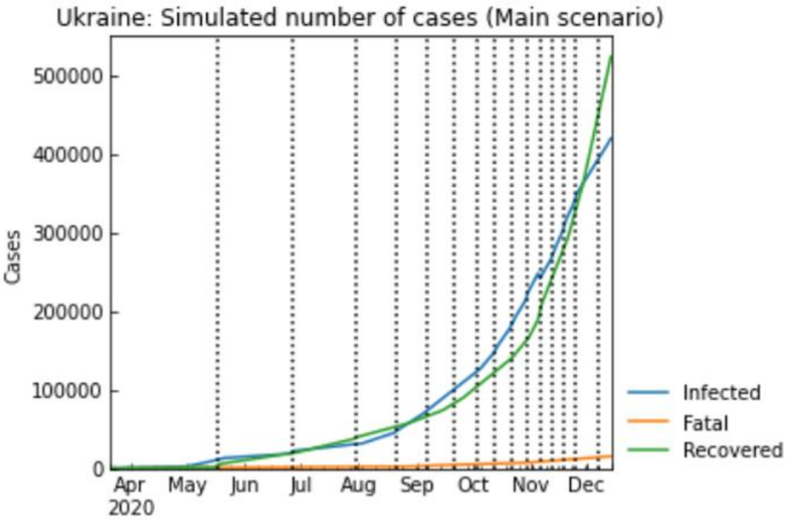

Figure 8: Plot of forecasted cases of COVID-19 in Ukraine for one week.

	Date	Confirmed	Fatal	Infected	Recovered
262	2020-12-08 00:00:00	864619	14150	395132	455337
263	2020-12-09 00:00:00	879794	14339	399081	466374
264	2020-12-10 00:00:00	895116	14530	403064	477522
265	2020-12-11 00:00:00	910584	14723	407081	488780
266	2020-12-12 00:00:00	926201	14918	411132	500151
267	2020-12-13 00:00:00	941968	15114	415219	511635
268	2020-12-14 00:00:00	957886	15313	419340	523233

Figure 9: Numerical values of forecasted cases of COVID-19 in Ukraine for one week.

Simulation of COVID-19 cases in Ukraine for 60 days showed worse accuracy (fig. 10, 11).

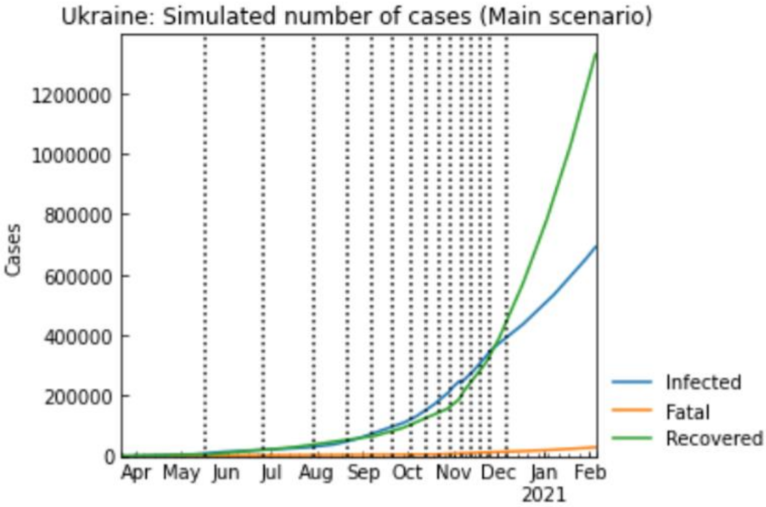

Figure 9: Plot of forecasted cases of COVID-19 in Ukraine for 60 days.

	Date	Confirmed	Fatal	Infected	Recovered
315	2021-01-30 00:00:00	1897917	27163	654987	1215767
316	2021-01-31 00:00:00	1922465	27476	660934	1234055
317	2021-02-01 00:00:00	1947219	27791	666920	1252508
318	2021-02-02 00:00:00	1972184	28110	672946	1271128
319	2021-02-03 00:00:00	1997358	28431	679011	1289916
320	2021-02-04 00:00:00	2022745	28755	685116	1308874
321	2021-02-05 00:00:00	2048344	29082	691261	1328001

Figure 10: Numerical values of forecasted cases of COVID-19 in Ukraine for 60 days.

5. Conclusions

Based on SIR models, we saw that more parameters can be included and we are capable to do more complicated calculations spontaneously by the easiness of implementing and operating on the actual datasets as the input. That means the complexity of SIR models didn't disturb the easiness of applying it, also it gave a more reliable forecasting output which was exactly what we expected. These models have the ability to forecast the trend not only based on single parameters but including a mix of them and considering the interactions of some and illustrating the result through diagrams and tables. In the last part of implementing this model, we saw that we could have a view of the effect of new medicines on the trend as an external parameter. This shows that SIR models have the capability of adding more parameters as the input and showing their influence on the output which might be practical for further studies. Thus, the results have more credit to rely on for making further investigations and even decisions.

Our research has shown that the SIR model can be used to assess the contribution of various factors to the development of the epidemic. On the one hand, experiments help to understand and analyze the main drivers of the epidemic, for example, the intensity of communication between people, their crowding, etc., which makes it possible to develop and implement measures aimed at eliminating or weakening this driver. On the other hand, experiments with the model make it possible to evaluate the effectiveness of a particular preventive measure aimed at mitigation of the epidemic. For example, what percentage of the population should be vaccinated in order to reduce the reproductive number, which categories of the population should be vaccinated in the first order to reduce the incidence of the population, the effectiveness of masks, the effectiveness of hand rub, etc. The results obtained in this study expand the possibilities for making correct decisions by administrators who determine strategies in the health care of countries.

Based on the predictions we have developed using the approach we have developed, healthcare administrators can timely set the required number of hospital beds, medical personnel, ventilators, and other necessary resources. It should be taken into account that in experiments with the model it is possible to estimate when, for what period of time and in what volume one or another measure should be introduced. For example, how effective will the weekend quarantine, or adaptive quarantine, or complete knockdown be, if it is entered in a specific period of time.

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