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The Use of Mathematical Models Describing the Spread of Covid-19 in Strategic State Security Management

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Abstract:

Purpose: *The security system of each country should be capable of identifying and eliminating potential threats. However, such events' variety and unpredictability make it impossible to be ready for each scenario, should one materialize. Situations posing a national security threat require that effective actions be undertaken, including risk prevention and mitigation of its effects. Decisions must be taken responsibly and competently. However, they also must be taken quickly, as time is a key factor in any emergency. Extreme caution must be exercised, as citizens' lives and health may depend on the strategic level decisions. Therefore, any instruments to support the decisions, enabling the best choices to be made, are very much desirable. Knowledge of the scale of the phenomenon and its evolution is particularly useful and important here. It is easier to fight an opponent knowing their strengths and potential.*
Design/Methodology/Approach: *To know required, mathematical models may be constructed describing the phenomenon in question and its development over time. This paper presents and compares mathematical models describing the SARS-Cov-2 virus's evolution in four EU countries (Poland, Germany, Great Britain, and Italy).*
Findings: *The ability to describe the evolution of the pandemic in mathematical terms and rely on the results of such modeling in strategic state security management. The results obtained were compared with the actions taken in the countries in question.*
Practical Implications: *Furthermore, the importance of reliable information in making crucial decisions on the national level and achieving the appropriate degree of citizen security was emphasized.*

Keywords: *SARS-Cov-2, strategic management, state security, crisis situations, mathematical modeling, pandemic.*

JEL codes: *C13, C20, I10, I18, I19.*

Paper Type: *Research in Security Studies.*

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1. Introduction

The first SARS-CoV-2 infection cases were found at the end of 2019 in a Chinese town (Wuhan). By the end of January 2020, the epidemic spread throughout China and beyond its borders. The scale of the threat caused the World Health Organization (WHO) to declare a pandemic on 11 March 2020. At that time, the coronavirus was already present in over 110 countries. 4,300 thousand deaths evidenced the seriousness of the threat to each country's security it caused. Over 121,500 people were infected at that time [12]. The challenge was primarily to implement efficient, appropriate, and relevant actions to combat the epidemic risks and consequences, develop procedures, and have adequate medical staff and protective measures.

In addition to the lethal effects of the spread of SARS-CoV-2, its negative impact on the global economy is also significant. As a result of the decline in China's economic activity and other closely related Asian economies, global supply chains, which also include EU and US companies, were disrupted. In addition, the sharp reduction in the activity of citizens, resulting from the fear of infection, as well as the tightening of administrative measures (e.g., cancellation of mass events, movement restrictions) resulted in a drastic reduction in demand in such industries as tourism, transport (especially air transport), catering and entertainment [4, 29]. All this also affected investment moods, deteriorating them. Therefore, at the beginning of March, the stock exchanges in the EU and the USA, Asia, and Australia recorded the worst results since the financial crisis in 2008. [30].

Lower consumption and thus, the limited flow of goods affect the value of GDP, and therefore mechanisms to stimulate the economy are necessary. Strong embedding in international business, economic, and energy structures is also an important factor in shaping each state's security. Effective counteracting the slowdown in the global economy resulting from the coronavirus outbreak and assessing the potential losses associated with the pandemic will depend primarily on the pandemic's duration, which is unknown in the current situation. Prolonged uncertainty increases the likelihood of a recession, and therefore methods and tools that can indirectly, through their effective application at the level of strategic management, reduce it are desirable. Hence the popularity of mathematical models predicting the development of the epidemic over time in the literature. However, the information key's availability to combat Covid-19 may be limited, and the data disseminated may be incomplete or unreliable. This is particularly limiting in the case of country-specific benchmarking. Therefore, it is a natural challenge to quickly verify and adapt existing techniques to effectively and efficiently reproduce new measurements and try to reduce the impact of their quality on the final modeling result.

In recent years, we have observed a dynamic growth of interest in the area of so-called data science. This is facilitated by the intensive development of tools (IT systems), enabling the generation, recording, and archiving large data resources. But it is also the result of increased awareness of the need for greater access to knowledge, arising from the processing of resources already accumulated and those for which real-time analysis and inference is necessary. This knowledge is particularly important in management systems, transport, and energy sectors and has recently played a major role in health security. The coronavirus pandemic and the related challenges of strategic management and national security are currently a thematic area where data processing plays a key role. A huge amount of medical information is currently being recorded and collected, including the number of cases, duration of hospitalization, the number of screening tests performed, and the number of people quarantined. In parallel, knowledge is acquired about epidemiologically relevant social behavior, e.g., about the intensity of human contact and the movement of healthy people and carriers of the virus. The efficient processing of these data and the effective application thereof are the basis for taking appropriate decisions and actions to limit the spread of the epidemic and eliminate its social and economic consequences.

In the search for the best mathematical models which faithfully reproduce the course of the epidemic and at the same time allow to forecast its development, solutions known from time series analysis used in econometrics, signal analysis, or engineering prediction are tested [1, 18, 19, 20]. They shall be verified according to the quality and quantity of the epidemiological data collected and the reference to the purpose of the analysis or forecast. In the paper [24], two data modeling techniques were analyzed – polynomial and autoregressive time series representations – based on the number of cases in England and the USA. Purely mathematical considerations, with no reference to the practical possibilities of using the results obtained, e.g., inference for crisis management purposes, were the study's subject. There is also extensive literature describing the application of Bayesian sequential and adaptive estimation dynamics to identify and predict objects of different classes' behavior. In this context, the authors of the paper [6] attempt to transfer some of its key achievements to epidemiology, showing that it is possible to reliably estimate and predict the epidemiological situation based on daily public records, which are likely to be considered uncertain or imprecise. The method proposed can be used to estimate the variables specific to infection and recovery and track and predict the epidemiological curve with satisfactory accuracy, as confirmed by observations from the Lombardy region in Italy and the USA. In the scenarios presented, the average absolute percentage error is below 5% in the 7-day forecast and around 10% when the forecast horizon is 14 days.

Ferrari *et al.* [5] proposed an approach based on the Susceptible – Infectious – Recovered (SIR) extended epidemiological model of the COVID-19 epidemic, concerning regionally specific populations densities, was used to test the impact of contact tracing applications in numerous variants. Based on Italy and Spain's data, scenarios differing in basic contact indicators, density, links, and percentage of application users from a given population were simulated. The results show that tracing people's contacts through applications can improve the effectiveness of isolation, helping to mitigate the epidemic's effects. However, regional differences in population density may make this tool-less effective in areas with higher density.

The aim of the research work described in [4], similar in concept to the SIR model, was to estimate the effects of implementing selected governmental intervention measures to mitigate the spread of the Covid-19 epidemic. A process model based on a compartmental epidemiological framework Susceptible – Infected – Recovered – Dead (SIRD) was used. According to its authors, the analysis of case data using such a model has an advantage over purely phenomenological approaches as the SIRD model's parameters can be calibrated using prior knowledge. This approach can be used to investigate how government interventions have affected the Covid-19 transmission rate and mortality during the epidemic.

The WHO database of publications concerning COVID-19 as of the end of July 2020 has over 55,000 publications in various thematic areas [15]. This includes publications on data processing. Latif et al. in paper [16] attempted to systematize current scientific and research activities related to data science in the field of epidemiology, which, together with the collected and daily updated data, can be used for further work on the spread of COVID-19 in the context of mitigation strategies. The authors [24] pay special attention to the emerging typical challenges and traps observed in the analyzed thematic area, resulting, among others, from the limited amount of available information and the related risk of forecasting error resulting from the lack of representativeness of the research sample and overfitting of the real state by a mathematical model. Therefore, it should be stressed that the mathematical models being constructed are flawed, which is an obvious risk in all research papers. In addition, the rapid development and nature of the epidemic situation encourage conscious and unconscious mistakes, the consequences of which can be serious, for example, when a forecast is used by people who are not familiar with the specifics of research to decide on the degree of social distancing. Therefore, it is considered a key challenge to balance the necessity and need for well-documented and reproducible research results with an awareness of how they can influence strategic management policies and actions [16].

Analyses carried out by EndCoronavirus (ECV) organization established on 29 February 2020 to combat coronavirus and to end the pandemic as soon as possible, indicate [11] that based on the number of daily confirmed infection, all countries of the world can be divided into three groups: countries that have mitigated the course of the epidemic by effectively extinguishing emerging outbreaks of coronavirus cases, those with a clear downward trend in the number of new cases, and countries where the number of new cases is still increasing or decreasing slightly. Given the above, the article analyzes four selected countries from the most vulnerable group – the third one. Poland, Great Britain, Germany, and Italy were selected. The current epidemic situation and actions are taken, such as introducing travel restrictions, imposing the obligation to wear protective masks, or maintaining social distance (isolation), were characterized. The number of coronavirus tests performed in each country was also presented. Moreover, a mathematical model was proposed for each of them, estimating the distribution of pandemic duration and the total number of cases. The total and the daily number of infections for scaled distributions: log-normal, Weibull, Gompertz, and Gamma were presented. For this purpose, data on the spread of Covid-19, published by the Humanitarian Data Exchange platform, from the beginning of the epidemic until 2 August 2020, was used. [9].

2. Model Specification

Biological phenomena, which also include the development of infection, may be interpreted as the life cycle of the product on the market or reliability tests of components and devices for which it is possible to distinguish clear phases [23, 31]. In most cases, the phases of introduction (growth), maturity and decline are identified [22, 28]. This makes the dynamics of the spread of infectious disease predictable to some extent. In the introductory phase, the number of infected people increases exponentially. This is due to the population's susceptibility to infection. Theoretically, each person infected with the virus passes it on to two others and then, assuming an infinite population, the number of people infected after two weeks will be over 8,000, and after three weeks already a billion. In reality, however, such a surge will not last long, due to the limited number of people susceptible to infection. In addition, herd immunity is developed meaning that less and less people will get infected over time (the number of potential carriers of the virus is decreasing because most of them are either infected or immune). This way, the development of the epidemic goes into a phase of slowdown – maturity. In the last – third (declining) phase, there are no new infections, patients recover, develop immunity and the epidemiological wave distinguishes.

The dependence presented above means that mathematical models, in which the independent variable influencing the number of cases is the duration of the pandemic, play a key role in understanding the course of the epidemic and developing strategies to stop the rapid spread of infectious diseases.
Let τ be a random variable that describes the duration of the pandemic. In fact, we observe a sequence {x_i }_(1≤i≤n)where x_i represents the total number of cases until i. At the time of the end of the pandemic, Markov's moment is unknown. The only information available is: P(τ≤∞)=1 and the realization of sequence {x_i }_(1≤i≤n). Observing the disease prevalence from moment i to moment j we assume:

$$aP(i \leq \tau \leq j) = x_j - x_i, \tag{1}$$

where a indicates the total number of cases during the pandemic (not known) and $\lim_{n\to\infty} x_n = a$. Therefore, when observing the sequence $\{x_i\}_{1\leq i\leq n}$, it is necessary to estimate both the distribution of pandemic duration and the total number of cases. Distribution of random variable τ will be modeled using log-normal, Weibull, Gompertz and Gamma distributions [8, 16, 25] (belonging to the family of exponential distributions). $T = min\{k \in N: aP(\tau \leq k) > a - \varepsilon\}$ value, where $\varepsilon > 0$ and the value $\varepsilon \in N$ means the maximum allowable number of cases which will not cause further development of the epidemic.

The density functions of the selected distributions take the form:
–for Log-normal distribution:

$$f(t,b,c)=\begin{cases}\frac{1}{\sqrt{2\pi}tc}\exp\left(-\frac{(lnt-b)^2}{2c^2}\right), & t\geq 0,\\ 0, & t<0.\end{cases} \tag{2}$$

–for Weibull distribution:

$$f(t,b,c)=\begin{cases}\frac{b}{c}\left(\frac{t}{c}\right)^{b-1}\exp\left(-\left(\frac{t}{c}\right)^{b}\right), & t\geq 0,\\ 0, & t<0.\end{cases} \tag{3}$$

–for Gompertz's distribution:

$$f(t,b,c)=\begin{cases}c\exp(bt)\exp\left(\frac{-c}{b}\left(e^{bt}-1\right)\right), & t\geq 0,\\ 0, & t<0.\end{cases} \tag{4}$$

–for Gamma distribution:

$$f(t,b,c)=\begin{cases}\frac{t^{b-1}\exp\left(\frac{-t}{c}\right)}{c^b\Gamma(b)}, & t\geq 0,\\ 0, & t<0.\end{cases} \tag{5}$$

where

$$\Gamma(s)=\int_0^\infty z^{s-1}\exp(-z)dz$$

The cumulative distribution function for each distribution is defined as:

$$F(t)=P(\tau<t)=\int_0^t f(s,b,c)ds \tag{6}$$

and $F(\infty)=1$

The mathematical task is to estimate the total number of cases in a given country $a>0$ by observing the daily incidence increments $\{y_i\}_{1\leq i\leq n}$, where $y_i=\Delta x_i=x_i-x_{i-1}$ and $x_0=0$.

If we take $F_a(t)=aF(t)$ then $F_a(\infty)=a$ and the value

$$h(t,a,b,c)=a\int_{t-1}^t f(s,b,c)ds \tag{7}$$

for $t>0$ is the predicted number of cases in $(t-1,t]$ range.

The method of least squares will be used to determine a,b,c parameters, so we solve the task:

$$\min_{a,b,c\geq 0}\sum_{t=1}^n\left(y_t-h(t,a,b,c)\right)^2 \tag{8}$$

By solving the task (8), we will estimate a, b, c parameters estimators. The predicted number of cases will by denoted by $\hat{a}$ value and, depending on the density function used (for log-normal f, Weibull, Gompertz and Gamma distribution) in formula (7), values $\hat{b}$ and $\hat{c}$ denote estimators of unknown parameters of density function.

According to formula (7), the expected number of infections in the following k days amounts to:

$$\sum_{t=n+1}^{n+k} h\left(t, \hat{a}, \hat{b}, \hat{c}\right)$$

3. Analysis of Covid-19 cases in Poland

In Poland, the first case of Covid-19 infection was confirmed on 4 March 2020 [13]. The experience of other countries led to the first restrictions being introduced quite quickly. As soon as on 10 March, all mass events were canceled, following the recommendations of the WHO to take radical measures to limit the spread of coronavirus. Simultaneously, the efforts were made to seal the borders by creating sanitary points at all border crossing points and extending the scope of controls, especially at the eastern borders, i.e., Ukraine, Belarus, Russia Lithuania. Then, on 12 March, when the infection was confirmed in only 25 people, it was decided to close schools, nurseries, and kindergartens, and switch to remote education. At the same time, the activities of cultural institutions: theaters, philharmonic halls, museums, cinemas, as well as art schools were suspended.

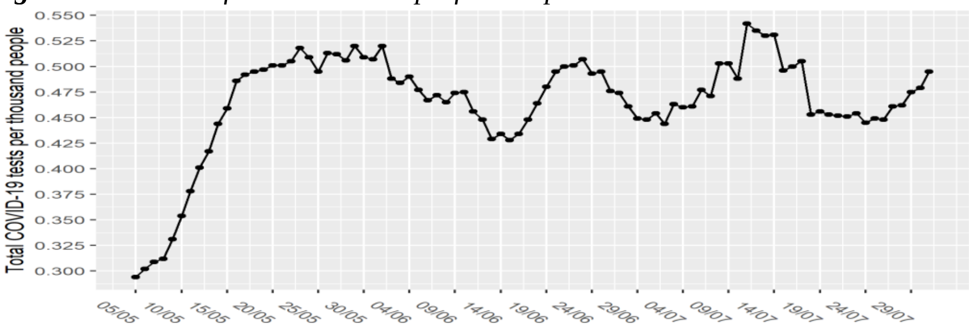
As of 15 March, Poland's borders were closed to air and rail traffic, and passport controls were introduced at all land borders. Only workers and citizens of Poland were allowed to enter the country, but a 14-day quarantine was imposed on them. In addition, restrictions on public gatherings were tightened by banning state and religious meetings of over 50 people. Compliance with all prohibitions and restrictions imposed was subject to inspection, and those who did not comply were fined. Further, stricter restrictions were introduced as of 25 March. It prohibited gatherings of more than 2 people and introduced restrictions on public transport, reducing the maximum number of passengers per vehicle/wagon to half of all seats.

Restrictions are also applied to pedestrians. It was established that up to two people could walk together, and they must maintain a distance of at least 1.5 m (except for the closest family members). The number of people taking part in religious ceremonies was limited to 5. The strictest restrictions were introduced as of 1 April, prohibiting children and young people under 18 from staying in public without adult supervision. Parks, boulevards, beaches were closed, access to forests was banned. Hair, beauty, and tattoo saloons were forced to close. Restrictions on shops and service outlets were introduced, limiting the number of customers to three times the available cash registers. For the sake of the elderly, all supermarkets and service outlets were to open from 10 a.m. to 12 p.m. only for people over 65 years of age. Employees in each store were equipped with personal protective equipment, and customers were forced to wear protective gloves while shopping. As of 9 March, an obligation to wear masks in public places was introduced, extended on 20 April to a general obligation to cover the mouth and nose.

The Ministry of Health announces the official information on the number of tests performed in Poland. Initial problems in diagnosing the virus's presence and a small number of tests were related to several issues. The first was the worldwide shortage of tests and the questionable quality of some products. The second problem was the limited capacity of state laboratories, so private facilities were quickly involved in testing. In addition, these difficulties were accompanied by a lack of knowledge about how to take and store the sample (swab), resulting in it often being unsuitable for testing.

In April 2020, about 0.3 tests per thousand inhabitants were performed in Poland. This value grew until the end of May, reaching the level of 0.5 test per thousand inhabitants, and this level is maintained until today, as shown in Figure 1.

***Figure 1**. Number of Covid-19 tests performed per thousand inhabitants in Poland*



Source: *Own creation.*

A mathematical model was constructed for Poland to estimate the distribution of pandemic duration and total confirmed infections. The results of fitting the total and the daily number of cases for the scaled log-normal Weibull, Gompertz, and Gamma distributions are presented in Table 1. The parameters' values were obtained using the least-squares method and the value of the objective function for the task (8).

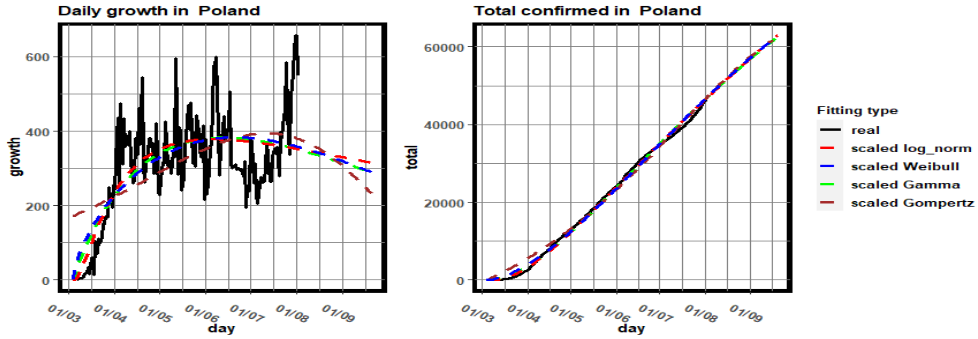
***Table 1**. Estimated parameters and Sum of Squared Errors*

	a	b	c	SSE
scaled log_norm	243686.90	6.11	1.25	1396088
scaled Weibull	96138.99	1.64	192.97	1564587
scaled Gompertz	70192.47	0.01	0.00	2033853
scaled Gamma	109428.20	1.93	108.60	1501414

Source: *Own creation.*

Table 1 shows that a better fitting is obtained for scaling the log-normal distribution, as evidenced by the lowest value of the SSE. Chart 2 shows fitting of daily growth of new infections and fitting of total confirmed infections.

***Figure 2**. Fitting of total confirmed infections and daily growth of new infections for Poland*



***Source:** Own creation.*

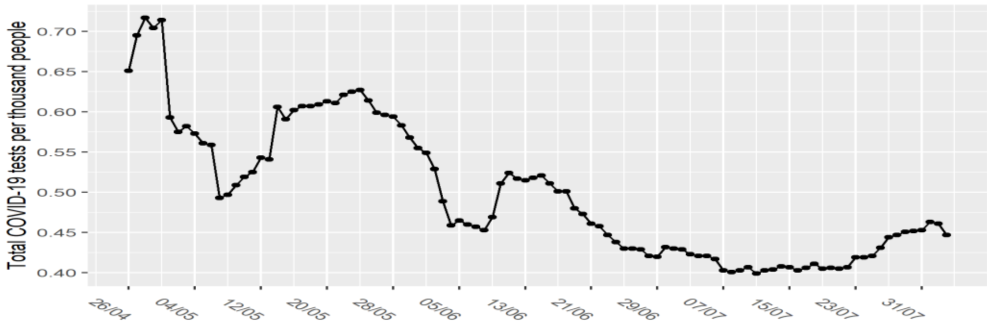
4. Analysis of Covid-19 Cases in Italy

In Italy, the first case of coronavirus infection was reported on 31 January 2020. On 1 February, a state of emergency was declared in Italy, and air traffic with the People's Republic of China was blocked. On 21 February, there was increased growth of new infections in the town of Codogno in Lombardy, which was quickly locked down, gradually followed by neighboring areas so that on 8 March, the whole of Lombardy became the 'red zone,' including Milan and 11 adjacent provinces, hoping that this would prevent the spread of the epidemic. Unfortunately, on 10 March, the whole country was included in such a zone, urging the residents to stay in their homes. On the next day – 11 March – commercial and restaurant activities were suspended. The drastic development of the epidemic, especially in Northern Italy, resulted in further restrictive recommendations on society's function.

On 23 February, the Venice Carnival and other mass events were canceled, schools and universities, and playgrounds and parks were closed. As of 8 March, a ban on collective events, including religious ceremonies, such as funerals or weddings, was introduced. The sports competition could only be held without the participation of the public. Restrictions on restaurants' operation were also introduced – they could stay open until 6 p.m., and customers had to be seated 1m apart. Violation of the quarantine rules could result in 3 months' imprisonment. Further restrictions were successfully introduced in the period from 11 to 21 March. All stores (except for grocery ones and pharmacies), restaurants, and service outlets were closed; outdoor recreation was banned, and the industry's functioning was restricted. Wearing masks in the initial stage was only a recommendation; however, the vast majority of Italians (over 90% [14]) wore them. Such an obligation was first introduced in Lombardy on 5 April. In Italy as a whole, wearing a mask became mandatory as of 4 May.
Official data on the number of tests performed are made available by the Ministry of Health of the Italian Republic and collected by the Department of Civil Protection. Unfortunately, they are not of high quality. For the selected dates, the results for

individual regions are missing, and therefore they are not included in the total number of tests performed for the whole country. Also, delays result from reporting, which may be as much as 3-4 days [10]. Nevertheless, according to the information provided, the highest number of tests per one thousand inhabitants was performed at the end of April (0.72 tests per one thousand inhabitants on 28 April). Then there was a decrease in this value, and now it remains at the level of around 0.45 (Figure 3).

***Figure 3**. Number of Covid-19 tests performed per thousand inhabitants in Italy*



***Source:** Own creation.*

A mathematical model was also constructed for Italy to estimate the distribution of pandemic duration and total confirmed infections. The total and the daily number of infections for the scaled log-normal Weibull, Gompertz, and Gamma distributions are presented in Table 2. The parameters' values were obtained using the least-squares method and the value of the objective function for the task (8).

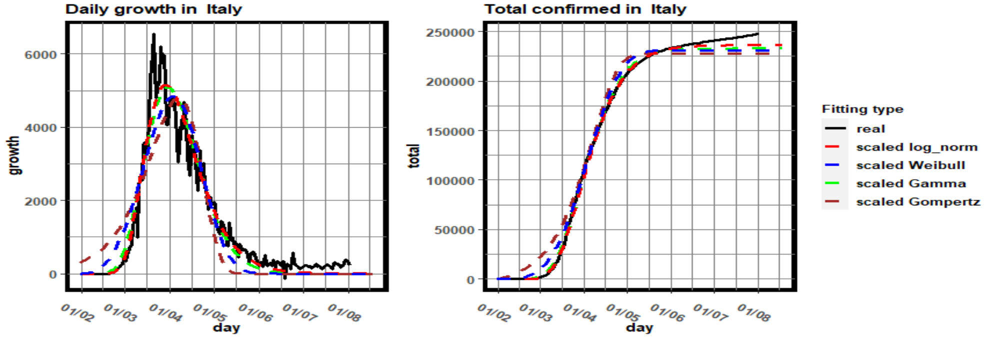
***Table 2**. Estimated parameters and Sum of Squared Errors*

	a	b	c	SSE
scaled log_norm	236384.9	4.16	0.30	28802100
scaled Weibull	231226.9	3.77	68.94	65799217
scaled Gompertz	228107.8	0.06	0.00	109367473
scaled Gamma	232946.3	11.88	5.50	36117225

***Source:** Own creation.*

Table 2 shows that a better fitting is obtained for scaling the log-normal distribution. Chart 4 shows the fitting of new infections' daily growth and the fitting of total confirmed infections.

Figure 4. *Fitting of total confirmed infections and daily growth of new infections for Italy*



Source: *Own creation.*

5. Analysis of Covid-19 Cases in Great Britain

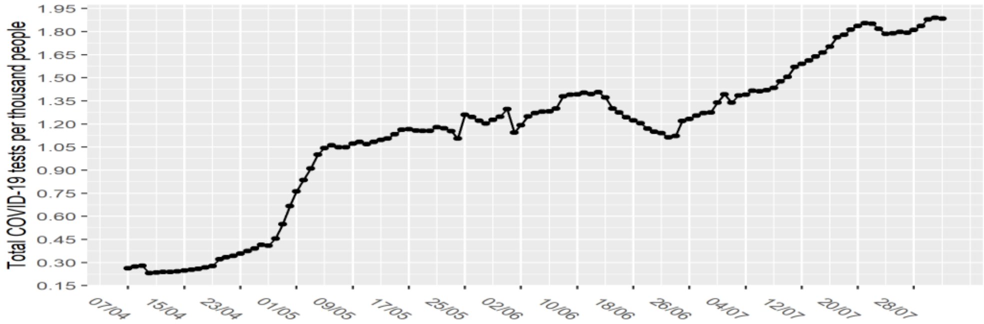
The first coronavirus case in Great Britain was detected on 31st January, the first death from Covid-19 took place on 5 March, but for a long time, the British government did not want to take radical steps to stem its spread. It was only recommended that citizens stay at home and only leave in emergencies, resulting in crowds on British streets. While European countries were closing bars, restaurants, stores, schools, and borders, the British officials recommended washing hands and staying at home if coughing.

Such an attitude resulted from the adopted strategy to develop "herd immunity" by getting even 60 – 80 percent of the population infected. It was assumed that this would take place in a supervised manner over a long period of time. This approach was based on the assumption that pandemic can be managed in a controlled way and that infections cannot be avoided. The conviction that the vast majority of the population will not develop severe symptoms or complications. The infection was to be mainly transmitted to young, healthy, and strong people. The number of people in the society that could be infected would gradually reach its peak value and create a natural barrier against the further spread of the epidemic.

Such decisions aimed to try to maintain the functioning of the economy at a fairly stable level. Despite the government's disrespectful stance, increased public vigilance was observed. As of 13 March, the organizers canceled or suspended most of the major sporting and cultural events, and the companies directed their employees to work remotely from home. By that time, the shortages of some goods, in particular medicines, toilet paper, and long-life foods such as pasta and rice, started to occur. It was not until the end of March, when the number of deaths exceeded 100 people, that the government decided to reduce public transport (17 March), close schools across the country, and start online learning (20 March). A few days later (23 March), a complete social lockdown was introduced. In Great Britain, wearing masks in public places was for a long time only a recommendation, not an obligation, and it was not until 15 June that it was ordered to cover mouth and nose on public transport. As of 8

June, a mandatory two-week quarantine for persons entering Great Britain was introduced. The number of tests currently performed per thousand inhabitants in Great Britain is the highest of all the countries studied and amounts to 1.88. A clear upward trend is also visible (Figure 5).

***Figure 5**. Number of Covid-19 tests performed per thousand inhabitants in Great Britain*



***Source:** Own creation.*

A mathematical model was also constructed for Great Britain to estimate the distribution of pandemic duration and total confirmed infections. The total and the daily number of infections for the scaled log-normal Weibull, Gompertz, and Gamma distributions are presented in Table 3. The parameters' values were obtained using the least-squares method and the value of the objective function for the task (8).

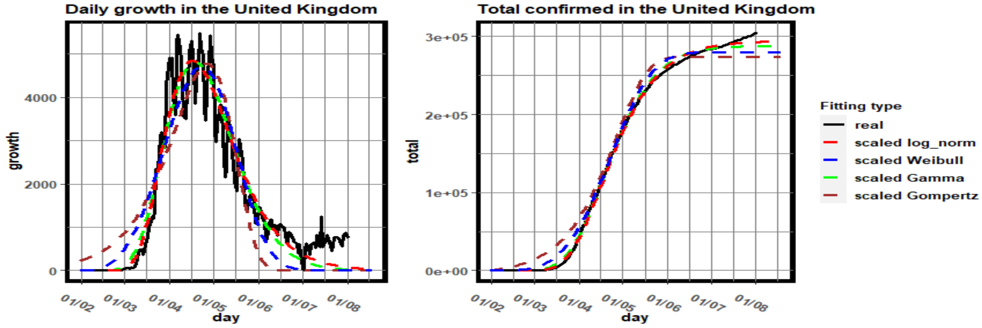
***Table 3**. Estimated parameter and Sum of Squared Errors*

	a	b	c	SSE
scaled log_norm	294205.5	4.43	0.30	39568021
scaled Weibull	279908.5	3.95	89.51	78443224
scaled Gompertz	273812.5	0.05	0.00	121493944
scaled Gamma	287711.1	12.07	7.10	47355337

***Source:** Own creation.*

Table 3 shows that a better fitting is obtained for scaling the log-normal distribution. Chart 6 shows fitting of daily growth of new infections and fitting of total confirmed infections.

***Figure 6**. Fitting of total confirmed infections and daily growth of new infections for the United Kingdom*



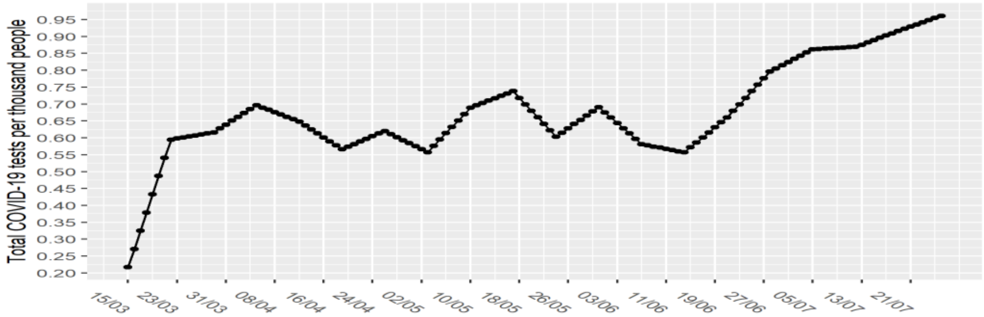
***Source:** Own creation.*

6. Analysis of Covid-19 Cases in Germany

The first case of the SARS-CoV-22 virus in Germany was confirmed on 7 January. The first measures were taken on 27 February, when the crisis staff was set up. The initial decisions on increased precautions were taken, especially concerning the control of persons arriving in the country. As of 2 March, the gradual cancellation of mass events began, but formal decisions in this respect were not announced until a week later. On 16 March, it was decided to close down schools and kindergartens in some lands, and public transport in Germany's capital was restricted. The next day – March 17 – Chancellor Angela Merkel called on the Germans to cancel their holidays at home and abroad while banning them from gathering in churches, mosques, and synagogues. Playgrounds and some stores were closed except supermarkets, banks, offices, post offices, and petrol stations. Hair and beauty salons, building materials stores, and laundries could still operate. The opening time of restaurants and cafés was limited to 6 p.m., while hotels could only operate for non-tourist purposes.

A few days later, on 22 March, restrictions were introduced so that people could move around the streets of German cities, keeping a distance of 1.5 m from other pedestrians. Hair, beauty, tattoo, and massage salons and restaurants were completely closed (in the case of restaurants only allowing for the sale of take-away and delivery meals). Clubs, discos, theaters, operas, concert halls, museums, fairs, galleries, cinemas, amusement parks, zoos, casinos, and all sports facilities were closed. In addition, it was ordered to limit contacts with other people to the necessary minimum. In all workplaces, hygiene rules were imposed on both employees and customers. As of 10 April, a mandatory 14-day house quarantine for people returning to Germany was introduced. The obligation to wear masks in Germany has never been introduced at the federal level. Such orders are left to the Land authorities. The first decisions in this respect were made in Saxony on 20 April, and on 22 April, Bremen was the last German Land to announce an order to cover the mouth and nose. As shown in Figure 7, the number of tests performed in Germany per thousand inhabitants shows an increasing trend. The current number is 0.96, which is the second (after Great Britain) result among the analyzed countries.

Figure 7. *Number of Covid-19 tests performed per thousand inhabitants in Germany*



Source: *Own creation.*

A mathematical model was also constructed for Germany to estimate the distribution of pandemic duration and total confirmed infections. The total and the daily number of infections for the scaled log-normal Weibull, Gompertz, and Gamma distributions are presented in Table 4. The parameters' values were obtained using the least-squares method and the value of the objective function for the task (8).

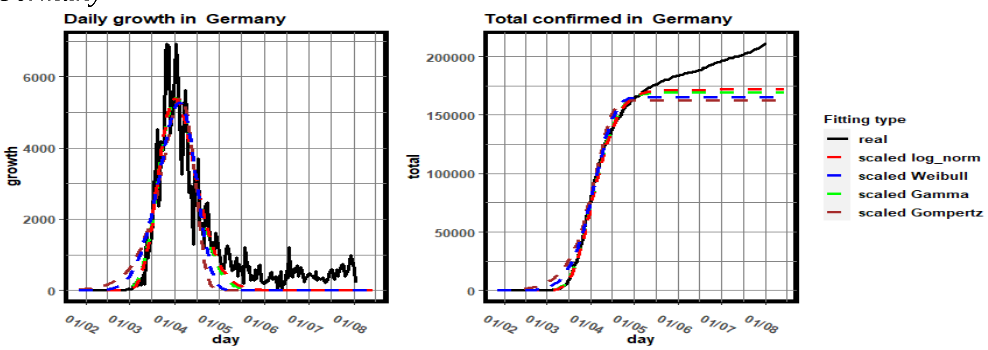
Table 4. *Estimated parameters and Sum of Squared Errors*

	a	b	c	SSE
scaled log_norm	171740.0	4.22	0.19	63493452
scaled Weibull	165402.3	6.00	70.28	95667005
scaled Gompertz	162337.4	0.09	0.00	115835299
scaled Gamma	169216.1	28.82	2.37	67899360

Source: *Own creation.*

Table 4 shows that a better fitting is obtained for scaling the log-normal distribution. Chart 8 shows fitting of daily growth of new infections and fitting of total confirmed infections.

Figure 8. *Fitting of total confirmed infections and daily growth of new infections for Germany*



Source: *Own creation.*

7. Conclusions

Understanding the nature of the epidemiological threat allows us to develop effective crisis management strategies. Although the general nature of the spread of infectious diseases is similar, each virus has its own specificity, resulting from its multiplication rate and impact on the infected organism. The most important and effective weapon in the fight against infectious diseases is vaccines. They reduce the number of susceptible people in the population, thus limiting the spread of the virus. However, in the case of the analyzed Covid-19 pandemic, the vaccine has not yet been invented, so all methods conducive to reducing the number of infected people, including restrictions imposed on society, are imposed on society desirable.

They should be introduced at the state authorities' strategic level, preferably in orders and prohibitions, rather than suggestions and guidelines. The life and health of citizens and the total number of pandemic victims may depend on the speed and effectiveness of such decisions. The most important activities in this area include introducing travel restrictions, imposing the obligation to wear protective masks, or maintaining social distance (isolation). The number of coronavirus tests performed is also important as it reflects the real scale of the threat. The article describes four countries' above-mentioned measures: Poland, Italy, Great Britain, and Germany. The desired support in making decisions in this area is knowledge of the threat's expected scale and duration. It is enhanced by constructing mathematical models that identify and predict the infection's development over time.

Therefore, a model estimating the pandemic duration and the total number of infections was proposed for each analyzed country. The best fit of the disease curve was obtained using a scaled log-normal distribution, as evidenced by the obtained values of Sum of Squared Errors; however, it should be stressed that such prediction concerns single epidemic waves. In the case of successive waves or the level of oscillation (flattening) of new infections in formula (7), a combination of linear distributions should be used. Also, the model's development needs to be updated and corrected on an ongoing basis, also due to the specificity of collecting results on infections, which, due to delays and errors, may not accurately reflect the situation in the country concerned.

SARS-CoV-2 is a new coronavirus, not yet fully understood, so every day, there are new reports from scientists, clinicians, and state institutions in this area. Numerous scientific studies help to bring closer the moment when we can talk about winning the pandemic fight and give a chance to save lives. The characteristics of activities carried out in individual countries, and the proposed mathematical models presented in this article are also part of this global fight.

References:

Brown, R.G. 1957. Exponential smoothing for predicting demand. Operations Research, 5, 145-145.

Brown, R.G. 2004. Smoothing, forecasting and prediction of discrete time series. Courier Corporation.

Chakraborty, A., Chen, J., Desvars-Larrive, A., Klimek, P., Tames, E.F., Garcia, D., Hornsmeyer, L., Kaleta, M., Lesser, J., Reddish, J., Pinior, B., Wahcs, J., Turchin, P. 2020. Aanalyzing Covid-19 Data using SIRD Models. medRxiv preprint.

Endcoronavirus.ro. 2020. A Multi- Disciplinary Effort to Eliminate Covid-19. Retrieved from: https://www.endcoronavirus.org.

Ferrari, A., Santus, E., Cirillo, D., Ponce-de-Leon, M., Ferretti, M.T., Chadha, A.S., Mavridis, N., Valencia, A. 2020. Simulating SARS-CoV-2 epidemics by region-specific variables and modelling contact tracing app containment. medRxiv preprint.

Gaglione, D., Braca, P., Millefiori, S.M., Soldi, G., Forti, N., Marano, S., Willett, P.K., Pattipati, K.R. 2020. Adaptive Bayesian Learning and Forecasting of Epidemic Evolution – Data Analysis of the COVID-19 Outbreak. IEEE Access.

Hastie, T., Tibshirani, R., Friedman, J. 2009. The elements of statistical learning. Springer-Verlag New York Inc.

HDX. 2020. Novel Coronavirus (COVID-19) Cases Data. Retrieved from: https://data.humdata.org/dataset/novel-coronavirus-2019-ncov-cases.

Hellwig, Z. 1993. Elementy rachunku prawdopodobieństwa i statystyki matematycznej. Państwowe Wydawn. Naukowe.

James, G., Witten, D., Hastie, T., Tibshirani, R. 2013. An introduction to statistical learning. Springer-Verlag GmbH.

Koronacki, J., Mielniczuk, J. 2009. Statystyka dla studentów kierunków technicznych i przyrodniczych. Wydawnictwa Naukowo-Techniczne.

Kozłowski, E., Kowalska, B., Kowalski, D., Mazurkiewicz, D. 2019. Survival Function in the Analysis of the Factors Influencing the Reliability of Water Wells Operation. Water Resources Management; 33(14), 4909-4921.

Kozłowski, E., Mazurkiewcz, D., Kowalska, B., Kowalski, D. 2018. Application of multidimensional scaling method to identify the factors influencing on reliability of deep wells. In: Burduk A., Chlebus E., Nowakowski T., Tubis A. (eds) Intelligent Systems in Production Engineering and Maintenance. ISPEM. Advances in Intelligent Systems and Computing, 835, 56-65.

Kozłowski, E., Mazurkiewicz, D., Żabiński, T., Prucnal, S. 2020. Machining sensor data management for operation-level predictive model. Expert Systems with Applications; 159,1-22.

Latif, S., Usman, M., Manzoor, S., Iqbal, W., Qadir, J., Tyson, G., Castro, I., Razi, A., Boulos, M.N.K., Weller, A., Crowcroft, J. 2020. Leveraging Data Science To Combat COVID-19: A Comprehensive Review. TechRxiv. Preprint.

Liu, D., Wang, S., Tomovic, M.M. 2020. Degradation modeling method for rotary lip seal based on failure mechanism analysis and stochastic process. Eksploatacja i Niezawodnosc – Maintenance and Reliability; 22(3), 381-390.

Liu, Y, Wang, Y., Fan, Z., Houz, Zhang, S, Chen, X. 2020. Lifetime prediction method for MEMS gyroscope based on accelerated degradation test and acceleration factor model. Eksploatacja i Niezawodnosc – Maintenance and Reliability, 22(2), 221-231.

Ministerstwo Zdrowia. 2020. Pierwszy przypadek koronawirusa w Polsce. Retrieved from: https://www.gov.pl/web/zdrowie/pierwszy-przypadek-koronawirusa-w-polsce.

Nandi, A.K. 2020. Data Modeling With Polynominal Representations and Autoregressive Time-Series Representations, and Their Connections.

Our World Data. 2020. Coronavirus (COVID-19) TestingStatistics and Research. Retrieved from: https://ourworldindata.org/coronavirus-testing#italy.

Pap, P. 2020. Italia - Włosi pokochali maseczki. Retrieved from: https://www.poradnikzdrowie.pl/aktualnosci/wlochy-pokochali-maseczki-aa-2fo7-LToZ-EhCE.html.

Ross, S.M. 1997. Introduction to probability models. Academic press.

Shammi, M., Bodrud-Doza, M., Islam, A.R.M.T., Rahman, M.M. 2020. Strategic assessment of COVID-19 pandemic in Bangladesh: comparative lockdown scenario analysis, public perception, and management for sustainability. Environment, Development and Sustainability, 1-44.

Shumway, R.H., Stoffer, D.S. 2017. Time series analysis and its applications: With r examples. Springer.

Sun, B., Li, Y., Wang, Z., Li, Z., Xia, Q., Ren, Y., Feng, Q., Yang, D., Qian, C. 2020. Physics-of-failure and computer-aided simulation fusion approach with a software system for electronics reliability analysis. Eksploatacja i Niezawodnosc – Maintenance and Reliability, 22(2), 340-351.

Ułanowicz, L, Jastrzębski, G, Szczepaniak, P. 2020. Method for estimating the durability of aviation hydraulic drives. Eksploatacja i Niezawodnosc – Maintenance and Reliability, 22(3), 557-564.

Wenzel, M., Stanske, S., Lieberman, M.B. 2020. Strategic responses to crisis. Strategic Management Journal.

WHO. 2020. Global research on coronavirus disease (COVID-10). Retrieved from: https://www.who.int/emergencies/diseases/novel-coronavirus-2019/global-research-on-novel-coronavirus-2019-ncov.

WHO. 2020. WHO announces COVID-19 outbreak a pandemic. Retrieved from: https://www.euro.who.int/en/health-topics/health-emergencies/coronavirus-covid-19/news/news/2020/3/who-announces-covid-19-outbreak-a-pandemic.

Wnukowski, D. 2020. Konsekwencje epidemii koronawirusa dla gospodarki UE.

Zaharia, S.M. 2019. The methodology of fatigue lifetime prediction and validation based on accelerated reliability testing of the rotor pitch links. Eksploatacja i Niezawodnosc – Maintenance and Reliability, 21(4), 638-644.