# The Spread of COVID-19

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# Chapter 1

# Introduction

## 1.1 The data

For this project, we use COVID-19 data provided by Johns Hopkins University (updated daily), as well as data from the world bank with demographic information. More specifically, we use daily records of total confirmed infection cases (or cumulative number of cases), total number of fatalities (or cumulative number of deaths) per country starting from 2020-01-22 until 2020-04-05. The dataset, downloaded on 2020-04-06, contains 12,975 observations and 13 variables (country, iso3c, date, confirmed, deaths, population, land_area_skm, pop_density, pop_largest_city, gdp_capita, life_expectancy, region, income).

**Special credits**: This project has been developed as part of the dsfba course and many thanks to professor Thibault Vatter and his assistants for their contributions.

Furthermore, the repository for this project can be found here.

## 1.2 A note on Epidemiological Models

Today's epidemiological models are mostly described by so called ***SIR***-like models (see details in Martcheva, 2015, pp.9–12). In this class of models, the population is divided into three groups:

- *(**S**)usceptible* — people, might get infected;
- *(**I**)nfectious* — people, who carry the infection and can infect others;
- *(**R**)ecovered/(**R**)emoved* — people, who have already recovered from the disease and got immunity.

The SIR model is a system of ordinary nonlinear differential equations. In this homework, we focus on the following *logistic* model (see Batista, 2020, pp. 2;

Martcheva, 2015, pp. 35–36):

$$\frac{dC(t)}{dt} = r\,C(t) \cdot \left[1 - \frac{C(t)}{K}\right],$$

where $C(t)$ is the accumulated number of cases at time $t$, $r$ is the growth rate (or infection rate), and $K$ is the final size of epidemic. Let $C_0$ be the initial number of cases: in other words, at time $t = 0$, assume that there was $C_0$ accumulated number of cases. The solution of the *logistic* model is

$$C(t) = \frac{K \cdot C_0}{C_0 + (K - C_0)\,\exp(-r\,t)},$$

which looks like a scaled *logit* model in econometrics.

## 1.3 This project

Because we only have access to the confirmed cases that are reported, we use those figures as a proxy for the total number of cases, with the understanding that they almost surely underestimates the actual number of interest. In what follows, we do a preliminary exploration of the data. We then use the *logistic* model to analyze the spread of **COVID-19** and try to predict the final number of accumulated confirmed cases for every country. More specifically, we

- start by focusing on modelling the spread in Switzerland;
- then apply the same approach to every country in the dataset.

# Chapter 2

# Exploratory data analysis

## 2.1 Description of the state of the spread

We fisrt provide a high level description of the state of the spread. In particular, including the:

- the number of days that have passed since the first confirmed case/death,
- the current stage for confirmed cases/deaths/mortality (i.e., ratio of deaths to confirmed cases).

*Note*: Please do note that most of the plots in this section, as well as some of the final plots in the the "many models" section, are interactive, hence, in order to see the built-in legend(for each country) you would have to scroll over the lines/bars.

**Comment**: Most of the current news is based on the absolute values of the confirmed cases and deaths per country, therefore we have decided to start our analysis by plotting them. However, since the sizes of the countries can differ quite a lot, we thought that it was best to have a look at the confirmed cases and deaths per country relative to their population to build a better picture.

We can see that by taking their size into account, the situation for some countries changes, more specifically we can see that the curve for the countries in the region of East Asia and Pacific is flatter when taking into account the size of the population, same for North America, while, on the other hand, the curves for countries in Europe and Central Asia are way steeper. This makes sense as, generally, countries in Europe are smaller, therefore a high absolute value would mean a higher percentage of the population, while in North America and Asia, where the countries have larger populations, the absolute values will correspond to a lower percentage.

What is evident is that for both confirmed cases and deaths, the situation that

is the most worrying is the one in Europe and Central Asia. It is perhaps more interesting to zoom on this area to gain a better understanding.

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**Comment**: Once we focus on Europe and Central Asia, we can notice that the countries with the highest increase are San Marino, Andorra and Luxembourg. As we can see from the table, for the three countries, the population does not exceed a milion people, hence they are fairly small countries. Consequently, as we mentioned already before, this means that the emergence of every new case corresponds to a bigger increase of the percentage of the affected population, which is larger relative to the countries with larger populations.

After looking at Europe and Central Asia, we can move on to analyze the current situation for all the countries in the world.

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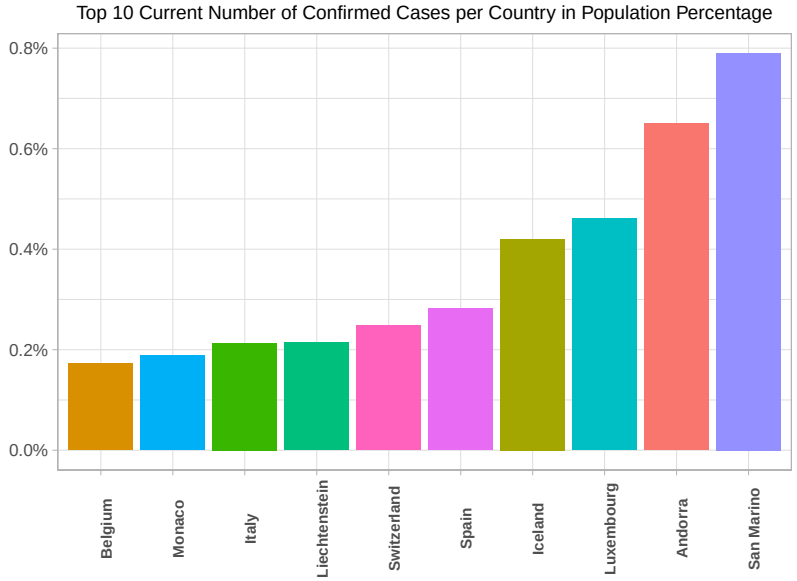


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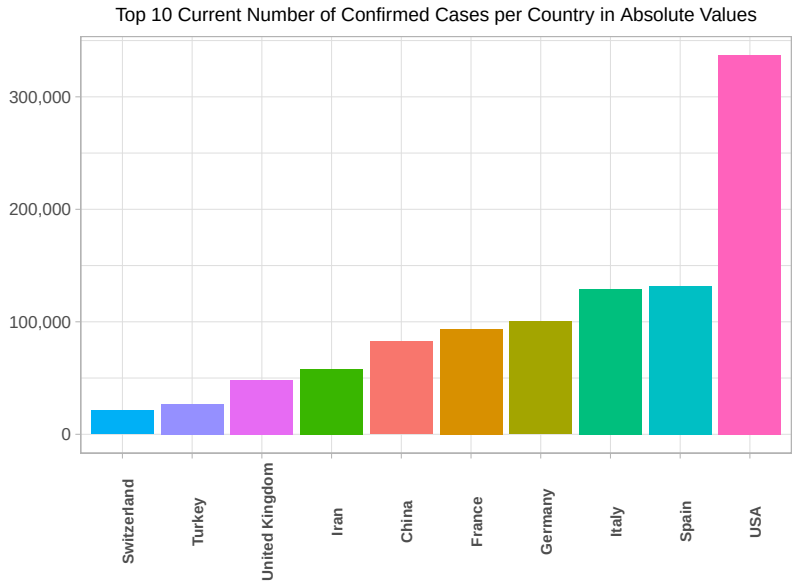
| The Population per Country in Europe and Central Asia (from smallest to largest) | |
|---|---|
| country | population |
| San Marino | 33,671 |
| Liechtenstein | 35,994 |
| Monaco | 38,682 |
| Andorra | 77,006 |
| Iceland | 353,574 |
| Luxembourg | 607,728 |
| Montenegro | 622,345 |
| Cyprus | 1,189,265 |
| Estonia | 1,320,884 |
| Latvia | 1,926,542 |
| Slovenia | 2,067,372 |
| North Macedonia | 2,082,958 |
| Lithuania | 2,789,533 |
| Albania | 2,866,376 |
| Armenia | 2,951,776 |
| Bosnia and Herzegovina | 3,323,929 |
| Moldova | 3,545,883 |
| Georgia | 3,731,000 |
| Croatia | 4,089,400 |
| Ireland | 4,853,506 |
| Norway | 5,314,336 |
| Slovakia | 5,447,011 |
| Finland | 5,518,050 |
| Denmark | 5,797,446 |
| Kyrgyzstan | 6,315,800 |
| Serbia | 6,982,084 |
| Syria | 6,982,084 |
| Bulgaria | 7,024,216 |
| Switzerland | 8,516,543 |
| Austria | 8,847,037 |
| Belarus | 9,485,386 |
| Hungary | 9,768,785 |
| Azerbaijan | 9,942,334 |
| Sweden | 10,183,175 |
| Portugal | 10,281,762 |
| Czechia | 10,625,695 |
| Greece | 10,727,668 |
| Belgium | 11,422,068 |
| Netherlands | 17,231,017 |
| Kazakhstan | 18,276,499 |
| Romania | 19,473,936 |
| Uzbekistan | 32,955,400 |
| Poland | 37,978,548 |
| Ukraine | 44,622,516 |
| Spain | 46,723,749 |
| Italy | 60,431,283 |
| United Kingdom | 66,488,991 |
| France | 66,987,244 |
| Turkey | 82,319,724 |
| Germany | 82,927,922 |
| Russia | 144,478,050 |

| Confirmed Cases per Country in Absolute Values | |
|---|---|
| country | confirmed |
| USA | 337,072 |
| Spain | 131,646 |
| Italy | 128,948 |
| Germany | 100,123 |
| France | 93,773 |
| China | 82,602 |
| Iran | 58,226 |
| United Kingdom | 48,436 |
| Turkey | 27,069 |
| Switzerland | 21,100 |
| Belgium | 19,691 |
| Netherlands | 17,953 |
| Canada | 15,756 |
| Austria | 12,051 |
| Portugal | 11,278 |
| Brazil | 11,130 |
| Korea, South | 10,237 |
| Israel | 8,430 |
| Sweden | 6,830 |
| Australia | 5,687 |
| Norway | 5,687 |
| Russia | 5,389 |
| Ireland | 4,994 |
| Czechia | 4,587 |
| Denmark | 4,561 |
| Chile | 4,471 |
| Poland | 4,102 |
| Romania | 3,864 |
| Malaysia | 3,662 |
| Ecuador | 3,646 |
| India | 3,588 |
| Philippines | 3,246 |
| Pakistan | 3,157 |
| Japan | 3,139 |
| Luxembourg | 2,804 |
| Saudi Arabia | 2,402 |
| Peru | 2,281 |
| Indonesia | 2,273 |
| Thailand | 2,169 |
| Finland | 1,927 |
| Serbia | 1,908 |
| Mexico | 1,890 |
| Panama | 1,801 |
| United Arab Emirates | 1,799 |
| Dominican Republic | 1,745 |
| Greece | 1,735 |
| South Africa | 1,655 |
| Qatar | 1,604 |
| Iceland | 1,486 |
| Colombia | 1,485 |
| Argentina | 1,451 |
| Algeria | 1,320 |

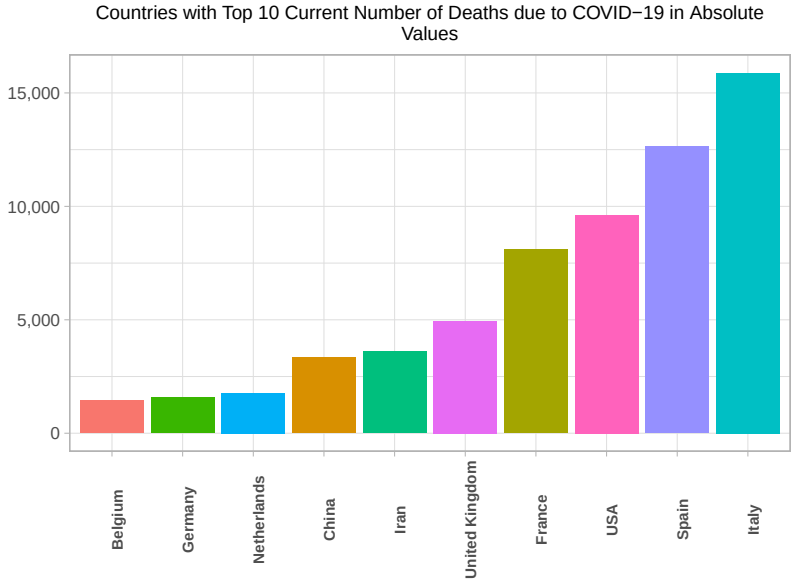
| Confirmed Cases per Country in Percentage | |
|---|---|
| country | % Confirmed |
| San Marino | 0.79% |
| Andorra | 0.65% |
| Luxembourg | 0.46% |
| Iceland | 0.42% |
| Spain | 0.28% |
| Switzerland | 0.25% |
| Italy | 0.21% |
| Liechtenstein | 0.21% |
| Monaco | 0.19% |
| Belgium | 0.17% |
| Austria | 0.14% |
| France | 0.14% |
| Germany | 0.12% |
| Norway | 0.11% |
| Portugal | 0.11% |
| Ireland | 0.10% |
| Netherlands | 0.10% |
| USA | 0.10% |
| Israel | 0.09% |
| Denmark | 0.08% |
| Estonia | 0.08% |
| Iran | 0.07% |
| Sweden | 0.07% |
| United Kingdom | 0.07% |
| Qatar | 0.06% |
| Malta | 0.05% |
| Slovenia | 0.05% |
| Bahrain | 0.04% |
| Canada | 0.04% |
| Cyprus | 0.04% |
| Czechia | 0.04% |
| Panama | 0.04% |
| Armenia | 0.03% |
| Brunei | 0.03% |
| Croatia | 0.03% |
| Finland | 0.03% |
| Latvia | 0.03% |
| Lithuania | 0.03% |
| Montenegro | 0.03% |
| North Macedonia | 0.03% |
| Serbia | 0.03% |
| Turkey | 0.03% |
| Antigua and Barbuda | 0.02% |
| Australia | 0.02% |
| Barbados | 0.02% |
| Bosnia and Herzegovina | 0.02% |
| Chile | 0.02% |
| Dominican Republic | 0.02% |
| Ecuador | 0.02% |
| Greece | 0.02% |
| Korea, South | 0.02% |
| Mauritius | 0.02% |

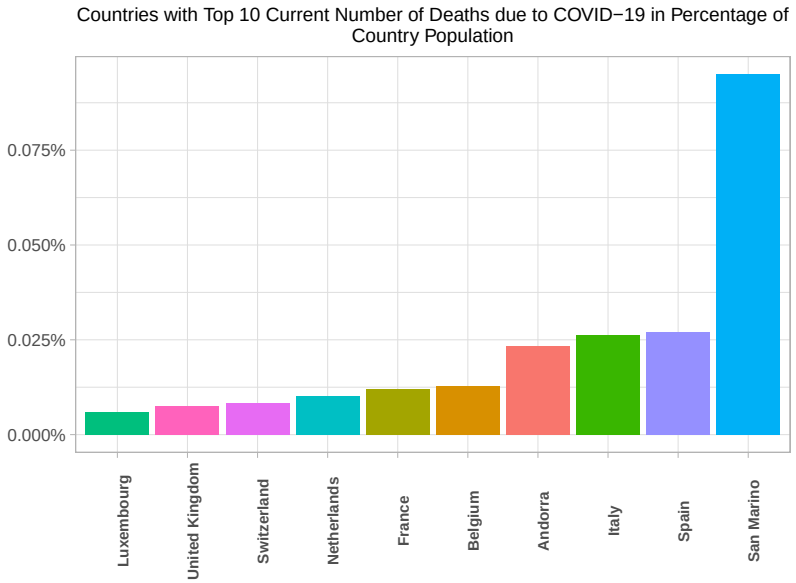



**Comment**: Thanks to these graphs (showing only the countries with the 10 highest percentage and absolute values in terms of confirmed cases) and the tables (showing all the countries), we can see that actually the situation changes quite a lot if we consider the percentage of the population or the absoulte values. In any case, as to 2020-04-06, we can see that, in absoulte values, the countries with the most confirmed cases are the USA, Spain and Italy, while in percentage the oustanding ones are San Marino and Andorra. Again, this is probably due to the difference in size of these countries. The USA are especially outstanding with regards to the number of confirmed cases, which is somehow a confirm of the news we hear everyday, and the fact that their president didn't take the situation very seriously from the beginning.

| Deaths per Country (in descending order) | |
|---|---|
| country | deaths |
| Italy | 15,887 |
| Spain | 12,641 |
| USA | 9,619 |
| France | 8,093 |
| United Kingdom | 4,943 |
| Iran | 3,603 |
| China | 3,333 |
| Netherlands | 1,771 |
| Germany | 1,584 |
| Belgium | 1,447 |
| Switzerland | 715 |
| Turkey | 574 |
| Brazil | 486 |
| Sweden | 401 |
| Portugal | 295 |
| Canada | 259 |
| Austria | 204 |
| Indonesia | 198 |
| Korea, South | 183 |
| Ecuador | 180 |
| Denmark | 179 |
| Ireland | 158 |
| Algeria | 152 |
| Philippines | 152 |
| Romania | 151 |
| India | 99 |
| Poland | 94 |
| Peru | 83 |
| Dominican Republic | 82 |
| Mexico | 79 |
| Egypt | 78 |
| Japan | 77 |
| Greece | 73 |
| Norway | 71 |
| Morocco | 70 |
| Czechia | 67 |
| Iraq | 61 |
| Malaysia | 61 |
| Serbia | 51 |
| Israel | 49 |
| Pakistan | 47 |
| Panama | 46 |
| Russia | 45 |
| Argentina | 44 |
| Ukraine | 37 |
| Luxembourg | 36 |
| Australia | 35 |
| Colombia | 35 |
| Chile | 34 |
| Hungary | 34 |
| Saudi Arabia | 34 |
| San Marino | 32 |

| Deaths per Country relative to the population | |
|---|---|
| country | % deaths |
| San Marino | 0.095% |
| Spain | 0.027% |
| Italy | 0.026% |
| Andorra | 0.023% |
| Belgium | 0.013% |
| France | 0.012% |
| Netherlands | 0.010% |
| Switzerland | 0.008% |
| United Kingdom | 0.007% |
| Luxembourg | 0.006% |
| Iran | 0.004% |
| Sweden | 0.004% |
| Denmark | 0.003% |
| Ireland | 0.003% |
| Liechtenstein | 0.003% |
| Monaco | 0.003% |
| Portugal | 0.003% |
| USA | 0.003% |
| Austria | 0.002% |
| Germany | 0.002% |
| Albania | 0.001% |
| Bahamas | 0.001% |
| Bosnia and Herzegovina | 0.001% |
| Canada | 0.001% |
| Cyprus | 0.001% |
| Czechia | 0.001% |
| Dominican Republic | 0.001% |
| Ecuador | 0.001% |
| Estonia | 0.001% |
| Finland | 0.001% |
| Greece | 0.001% |
| Guyana | 0.001% |
| Iceland | 0.001% |
| Israel | 0.001% |
| Mauritius | 0.001% |
| North Macedonia | 0.001% |
| Norway | 0.001% |
| Panama | 0.001% |
| Romania | 0.001% |
| Serbia | 0.001% |
| Slovenia | 0.001% |
| Trinidad and Tobago | 0.001% |
| Turkey | 0.001% |
| Afghanistan | 0.000% |
| Algeria | 0.000% |
| Angola | 0.000% |
| Antigua and Barbuda | 0.000% |
| Argentina | 0.000% |
| Armenia | 0.000% |
| Australia | 0.000% |
| Azerbaijan | 0.000% |
| Bahrain | 0.000% |




**Comment**: The situation of the deaths due to COVID-19 is a little bit different from the one of the confirmed cases. The country with the most deaths in absoulte values is Italy, followed by Spain and the USA, while in percentage the highest value is the one of San Marino, followed not very closely by Spain and

Italy. This indicates that the fatality of the COVID-19 has been severe in both Italy and Spain which has caused both countries to have very high values boths in absolute terms as well as relative to their populations, while for San Marino the worrying high value is again mainly due to the fact that the country is really small and it has a small population (33671 inhabitants and 266 deaths due to COVID-19 as to 2020-04-06).

Now we look at the percentage of deaths over the confirmed cases per country.

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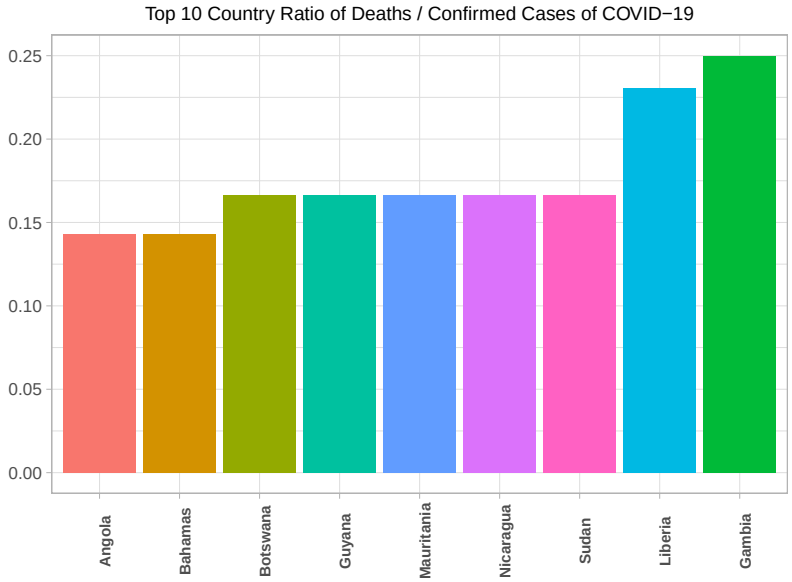
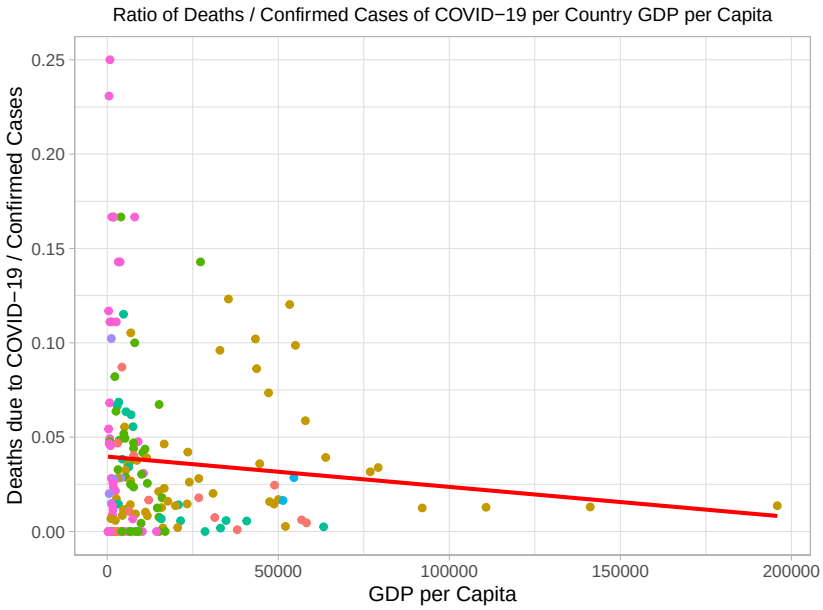



**Comment**: The countries with the highest percantage are Gambia and Liberia, these values are mainly due to the fact that there are only 4 and 13 cases of COVID-19 respectively, as to 2020-04-06, so, following the same reasoning as before, an increase of one victim here means a high increase in the ration of percentage over the confirmed cases. This opens an interesting discussion of whether this ratio is related to the GDP (a way to measure how rich the country is) or not. That is why we decided to plot the gdp against this ratio to see if there is any kind of correlation between the two variables.

| Ratio of Deaths/Cases per Country | |
|---|---|
| country | ratio |
| Gambia | 0.250 |
| Liberia | 0.231 |
| Guyana | 0.167 |
| Mauritania | 0.167 |
| Nicaragua | 0.167 |
| Sudan | 0.167 |
| Botswana | 0.167 |
| Angola | 0.143 |
| Bahamas | 0.143 |
| Cabo Verde | 0.143 |
| Italy | 0.123 |
| San Marino | 0.120 |
| Congo (Kinshasa) | 0.117 |
| Algeria | 0.115 |
| Congo (Brazzaville) | 0.111 |
| Zimbabwe | 0.111 |
| Mali | 0.111 |
| Syria | 0.105 |
| Bangladesh | 0.102 |
| United Kingdom | 0.102 |
| Suriname | 0.100 |
| Netherlands | 0.099 |
| Spain | 0.096 |
| Indonesia | 0.087 |
| France | 0.086 |
| Honduras | 0.082 |
| Belgium | 0.073 |
| Morocco | 0.069 |
| Togo | 0.068 |
| Trinidad and Tobago | 0.067 |
| Egypt | 0.066 |
| Bolivia | 0.064 |
| Iraq | 0.063 |
| Iran | 0.062 |
| Sweden | 0.059 |
| Libya | 0.056 |
| Albania | 0.055 |
| Niger | 0.054 |
| Jamaica | 0.052 |
| Ecuador | 0.049 |
| Burkina Faso | 0.049 |
| El Salvador | 0.048 |
| Gabon | 0.048 |
| Haiti | 0.048 |
| Dominican Republic | 0.047 |
| Philippines | 0.047 |
| Ethiopia | 0.047 |
| Hungary | 0.046 |
| Tanzania | 0.045 |
| Venezuela | 0.044 |
| Brazil | 0.044 |
| Greece | 0.042 |




**Comment**: This economic indicator could be a proxy for the ability of the country to afford the medical emergence and to have a state-of-the-art healthcare system so that they are ready to deal with the alarming situation. However, it is not the only thing to take into account, the size of the country and the regulations taken by the government have also an impact (as we have seen earlier). As we can see here, it is not always the case to have a correlation between GDP and the ratio of deaths due to COVID-19 and the number over the confirmed cases.

We then decided to look at the evolution of the expansion of the virus, by considering the first confirmed case and the first death due to COVID-19 per country.

*Note*: Please note as the dataset has the first recording for China starting from 22/01/2020, **this is far away from the reality as the first cases were already announced in December**, hence the first Chinese confirmed case is not found the dataset and we have decided for the integrity of our exploratory analysis to ignore it. The same holds for countries such as Japan and Thailand who on the 22nd of January had 2 confirmed cases and not only 1, however, this may be because there were 2 people diagnosed at once or it is an accumulation over time however for simplicity we assumed the latter.

**Comment**:Considering only the countries for which we have the first confirmed case, the first country to have had a confirmed case of COVID-19 is, surprisingly, the US, the 22nd of January, and the day after Singapore, which is probably due to the high economic and business exchange with the other Asian countries. As we can see, the first countries were mainly in the South-Easth Asia, North

| Timeline of First Case per Country | | |
|---|---|---|
| date | country | region |
| 2020-01-22 | Korea, South | East Asia & Pacific |
| 2020-01-23 | Singapore | East Asia & Pacific |
| 2020-01-27 | Cambodia | East Asia & Pacific |
| 2020-01-30 | Philippines | East Asia & Pacific |
| 2020-02-28 | New Zealand | East Asia & Pacific |
| 2020-03-09 | Brunei | East Asia & Pacific |
| 2020-03-10 | Mongolia | East Asia & Pacific |
| 2020-03-19 | Fiji | East Asia & Pacific |
| 2020-03-20 | Papua New Guinea | East Asia & Pacific |
| 2020-03-22 | Timor-Leste | East Asia & Pacific |
| 2020-01-27 | Germany | Europe & Central Asia |
| 2020-01-29 | Finland | Europe & Central Asia |
| 2020-01-31 | Sweden | Europe & Central Asia |
| 2020-02-01 | Spain | Europe & Central Asia |
| 2020-02-04 | Belgium | Europe & Central Asia |
| 2020-02-25 | Croatia | Europe & Central Asia |
| 2020-02-25 | Switzerland | Europe & Central Asia |
| 2020-02-26 | Georgia | Europe & Central Asia |
| 2020-02-26 | Greece | Europe & Central Asia |
| 2020-02-26 | North Macedonia | Europe & Central Asia |
| 2020-02-26 | Norway | Europe & Central Asia |
| 2020-02-26 | Romania | Europe & Central Asia |
| 2020-02-27 | Denmark | Europe & Central Asia |
| 2020-02-27 | Estonia | Europe & Central Asia |
| 2020-02-27 | Netherlands | Europe & Central Asia |
| 2020-02-27 | San Marino | Europe & Central Asia |
| 2020-02-28 | Belarus | Europe & Central Asia |
| 2020-02-28 | Iceland | Europe & Central Asia |
| 2020-02-28 | Lithuania | Europe & Central Asia |
| 2020-02-29 | Ireland | Europe & Central Asia |
| 2020-02-29 | Luxembourg | Europe & Central Asia |
| 2020-02-29 | Monaco | Europe & Central Asia |
| 2020-03-01 | Armenia | Europe & Central Asia |
| 2020-03-02 | Andorra | Europe & Central Asia |
| 2020-03-02 | Latvia | Europe & Central Asia |
| 2020-03-03 | Ukraine | Europe & Central Asia |
| 2020-03-04 | Liechtenstein | Europe & Central Asia |
| 2020-03-04 | Poland | Europe & Central Asia |
| 2020-03-06 | Serbia | Europe & Central Asia |
| 2020-03-06 | Slovakia | Europe & Central Asia |
| 2020-03-08 | Moldova | Europe & Central Asia |
| 2020-03-11 | Turkey | Europe & Central Asia |
| 2020-03-15 | Uzbekistan | Europe & Central Asia |
| 2020-03-22 | Syria | Europe & Central Asia |
| 2020-02-26 | Brazil | Latin America & Caribbean |
| 2020-02-28 | Mexico | Latin America & Caribbean |
| 2020-03-01 | Dominican Republic | Latin America & Caribbean |
| 2020-03-03 | Argentina | Latin America & Caribbean |
| 2020-03-03 | Chile | Latin America & Caribbean |
| 2020-03-06 | Colombia | Latin America & Caribbean |
| 2020-03-06 | Costa Rica | Latin America & Caribbean |
| 2020-03-06 | Peru | Latin America & Caribbean |

America and some countries in Europe. Interestingly, we can notice a sort of temporary void before the real boom of the virus, between the first days of February and mid-February. This could be probably due to the fact that the coutries had to develop a way to test the virus, plus, once it started to spread it has been hard to stop, so once some countries started to confirm the first case, the closest countries were quick to follow. The latest to confirm the first case of the virus has been South Sudan on the 2020-04-05.

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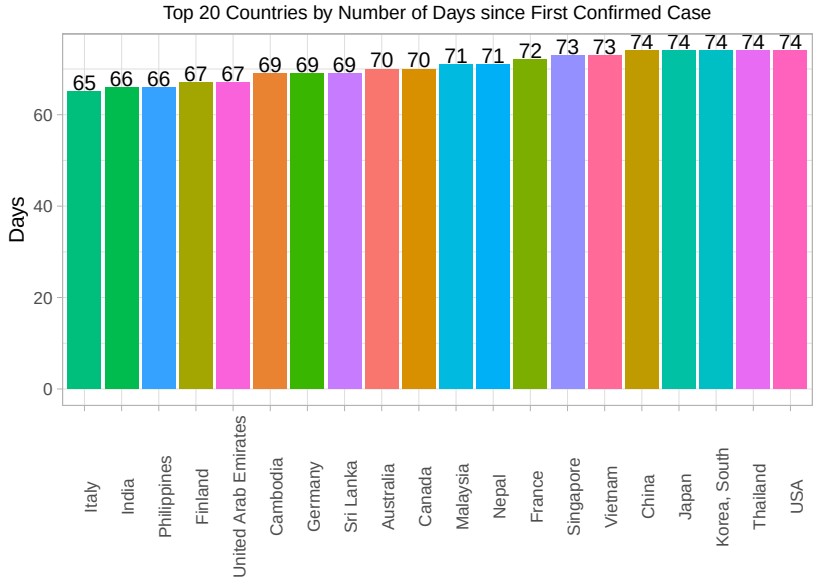
**Comment**: Regarding the first death due to COVID-19, the first country (again not considering China) announcing the first fatality due to the virus is on the 2020-02-02 in the Philippines, followed more than 10 days after by Japan and then France. Here the void between the countries, especially before March, is even more evident, and we can see that in March there is an exponential increase of the first deaths due to the virus. In general, the countries with the first fatalities are in the East Asia and Pacific area, with the exception of France.

Following, the graph of the number of days since the first confirmed case and first fatality due to COVID-19 per country.

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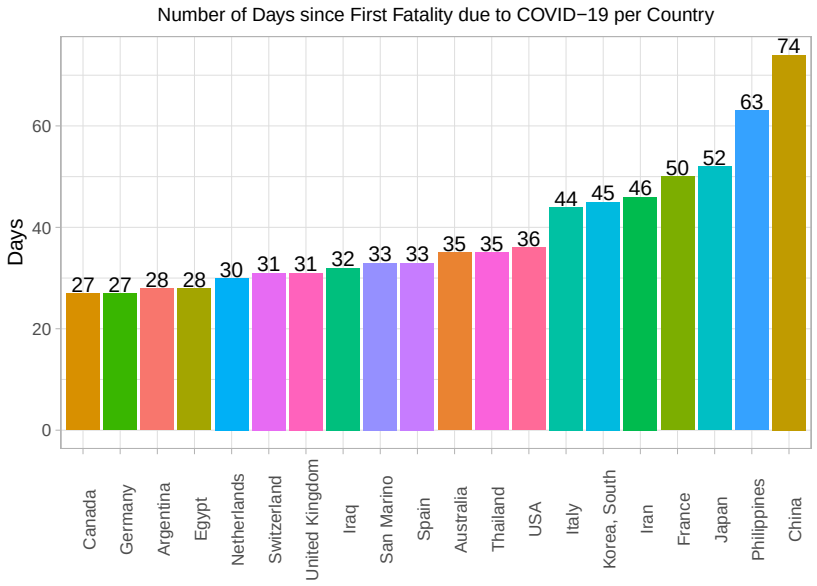
| Timeline of First Death due to COVID-19 per Country | | |
|---|---|---|
| date | country | region |
| 2020-02-02 | Philippines | East Asia & Pacific |
| 2020-02-13 | Japan | East Asia & Pacific |
| 2020-02-15 | France | Europe & Central Asia |
| 2020-02-20 | Korea, South | East Asia & Pacific |
| 2020-02-21 | Italy | Europe & Central Asia |
| 2020-02-29 | USA | North America |
| 2020-03-01 | Australia | East Asia & Pacific |
| 2020-03-01 | Thailand | East Asia & Pacific |
| 2020-03-03 | San Marino | Europe & Central Asia |
| 2020-03-03 | Spain | Europe & Central Asia |
| 2020-03-05 | Switzerland | Europe & Central Asia |
| 2020-03-05 | United Kingdom | Europe & Central Asia |
| 2020-03-06 | Netherlands | Europe & Central Asia |
| 2020-03-08 | Argentina | Latin America & Caribbean |
| 2020-03-08 | Egypt | Middle East & North Africa |
| 2020-03-09 | Canada | North America |
| 2020-03-10 | Lebanon | Middle East & North Africa |
| 2020-03-10 | Morocco | Middle East & North Africa |
| 2020-03-11 | Albania | Europe & Central Asia |
| 2020-03-11 | Bulgaria | Europe & Central Asia |
| 2020-03-11 | Greece | Europe & Central Asia |
| 2020-03-11 | India | South Asia |
| 2020-03-11 | Indonesia | East Asia & Pacific |
| 2020-03-11 | Ireland | Europe & Central Asia |
| 2020-03-11 | Panama | Latin America & Caribbean |
| 2020-03-11 | Sweden | Europe & Central Asia |
| 2020-03-12 | Algeria | Middle East & North Africa |
| 2020-03-12 | Austria | Europe & Central Asia |
| 2020-03-12 | Guyana | Latin America & Caribbean |
| 2020-03-12 | Poland | Europe & Central Asia |
| 2020-03-13 | Azerbaijan | Europe & Central Asia |
| 2020-03-13 | Sudan | Sub-Saharan Africa |
| 2020-03-13 | Ukraine | Europe & Central Asia |
| 2020-03-14 | Denmark | Europe & Central Asia |
| 2020-03-14 | Luxembourg | Europe & Central Asia |
| 2020-03-14 | Slovenia | Europe & Central Asia |
| 2020-03-15 | Hungary | Europe & Central Asia |
| 2020-03-16 | Bahrain | Middle East & North Africa |
| 2020-03-16 | Guatemala | Latin America & Caribbean |
| 2020-03-17 | Brazil | Latin America & Caribbean |
| 2020-03-17 | Dominican Republic | Latin America & Caribbean |
| 2020-03-17 | Iceland | Europe & Central Asia |
| 2020-03-17 | Portugal | Europe & Central Asia |
| 2020-03-17 | Turkey | Europe & Central Asia |
| 2020-03-18 | Bangladesh | South Asia |
| 2020-03-18 | Burkina Faso | Sub-Saharan Africa |
| 2020-03-18 | Cuba | Latin America & Caribbean |
| 2020-03-18 | Moldova | Europe & Central Asia |
| 2020-03-18 | Slovakia | Europe & Central Asia |
| 2020-03-19 | Costa Rica | Latin America & Caribbean |
| 2020-03-19 | Croatia | Europe & Central Asia |
| 2020-03-19 | Jamaica | Latin America & Caribbean |

| Number of days since the first confirmed case | |
|---|---|
| country | days passed |
| China | 74 days |
| Japan | 74 days |
| Korea, South | 74 days |
| Thailand | 74 days |
| USA | 74 days |
| Singapore | 73 days |
| Vietnam | 73 days |
| France | 72 days |
| Malaysia | 71 days |
| Nepal | 71 days |
| Australia | 70 days |
| Canada | 70 days |
| Cambodia | 69 days |
| Germany | 69 days |
| Sri Lanka | 69 days |
| Finland | 67 days |
| United Arab Emirates | 67 days |
| India | 66 days |
| Philippines | 66 days |
| Italy | 65 days |
| Russia | 65 days |
| Sweden | 65 days |
| United Kingdom | 65 days |
| Spain | 64 days |
| Belgium | 61 days |
| Egypt | 51 days |
| Iran | 46 days |
| Israel | 44 days |
| Lebanon | 44 days |
| Afghanistan | 41 days |
| Bahrain | 41 days |
| Iraq | 41 days |
| Kuwait | 41 days |
| Oman | 41 days |
| Algeria | 40 days |
| Austria | 40 days |
| Croatia | 40 days |
| Switzerland | 40 days |
| Brazil | 39 days |
| Georgia | 39 days |
| Greece | 39 days |
| North Macedonia | 39 days |
| Norway | 39 days |
| Pakistan | 39 days |
| Romania | 39 days |
| Denmark | 38 days |
| Estonia | 38 days |
| Netherlands | 38 days |
| San Marino | 38 days |
| Belarus | 37 days |
| Iceland | 37 days |
| Lithuania | 37 days |

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**Comment**: From the tables above, wan see that the countries that have had the first case of COVID-19 confirmed were the USA and South Korea, and interestingly, as we already saw before, there is a gap between Belgium and Egypt of 10 days and onther one of almost a week between Beligum and Lebanon, and from then on the spread has been increasing exponentially. In general, these graphs and tables are just a confirmation of what we have seen before.

## 2.2 Worldwide map

We then produce a worlwide map of the **COVID-19** spread at the latest date available in `covid19_data` for each country, and describe what we see.

We will use the `ggplot2` package particularly two useful commands of

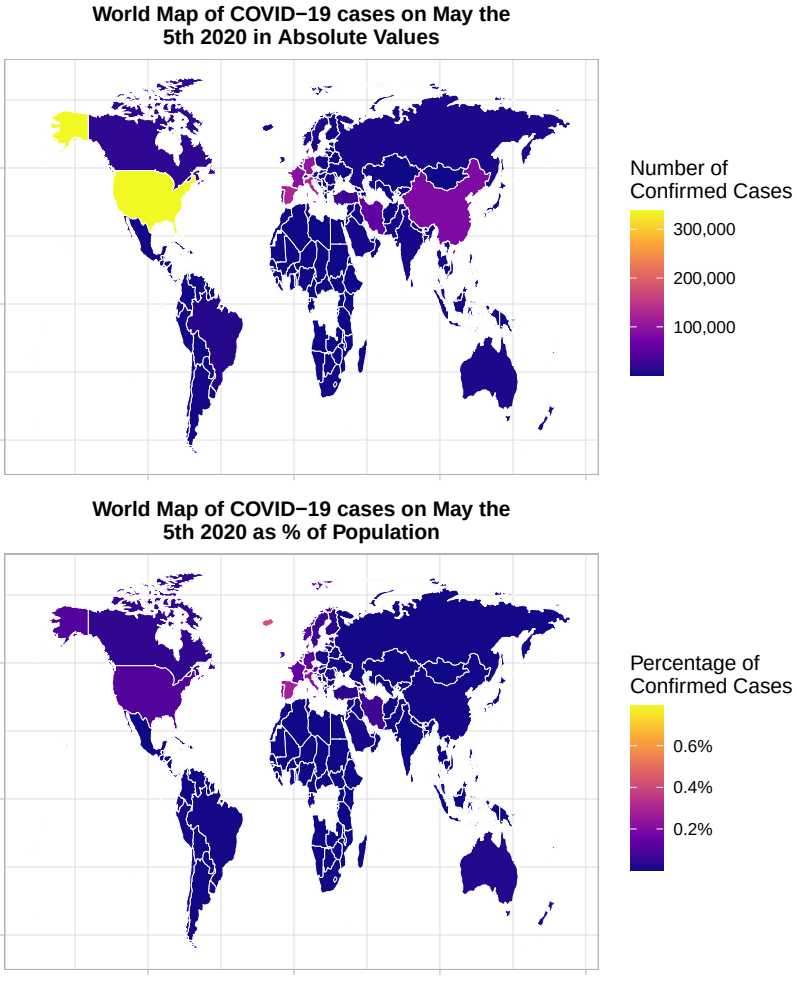
- `map_data()` to retrieve a map,
- and `geom_map()` to draw a map on a plot.

We then use `expand_limits` to make sure we display the whole map of the world.

```
#> Warning in left_join(end_confirmed, world_map, by = "country"): Each row in `x` is expected to
#> i Row 1 of `x` matches multiple rows.
#> i If multiple matches are expected, set `multiple = "all"` to
#>   silence this warning.
#> Warning: Using `size` aesthetic for lines was deprecated in ggplot2 3.4.0.
```

| Number of days since the first death | |
|---|---|
| country | days passed |
| China | 74 days |
| Philippines | 63 days |
| Japan | 52 days |
| France | 50 days |
| Iran | 46 days |
| Korea, South | 45 days |
| Italy | 44 days |
| USA | 36 days |
| Australia | 35 days |
| Thailand | 35 days |
| San Marino | 33 days |
| Spain | 33 days |
| Iraq | 32 days |
| Switzerland | 31 days |
| United Kingdom | 31 days |
| Netherlands | 30 days |
| Argentina | 28 days |
| Egypt | 28 days |
| Canada | 27 days |
| Germany | 27 days |
| Lebanon | 26 days |
| Morocco | 26 days |
| Albania | 25 days |
| Belgium | 25 days |
| Bulgaria | 25 days |
| Greece | 25 days |
| India | 25 days |
| Indonesia | 25 days |
| Ireland | 25 days |
| Panama | 25 days |
| Sweden | 25 days |
| Algeria | 24 days |
| Austria | 24 days |
| Guyana | 24 days |
| Poland | 24 days |
| Azerbaijan | 23 days |
| Sudan | 23 days |
| Ukraine | 23 days |
| Denmark | 22 days |
| Ecuador | 22 days |
| Luxembourg | 22 days |
| Norway | 22 days |
| Slovenia | 22 days |
| Hungary | 21 days |
| Iceland | 21 days |
| Bahrain | 20 days |
| Guatemala | 20 days |
| Brazil | 19 days |
| Dominican Republic | 19 days |
| Malaysia | 19 days |
| Portugal | 19 days |
| Turkey | 19 days |

```
#> i Please use `linewidth` instead.
#> This warning is displayed once every 8 hours.
#> Call `lifecycle::last_lifecycle_warnings()` to see where this
#> warning was generated.
#> Warning in left_join(end_confirmed, world_map, by = "country"): Each row in `x` is expected to
#> i Row 1 of `x` matches multiple rows.
#> i If multiple matches are expected, set `multiple = "all"` to
#>   silence this warning.
```




**Comment**: We can see that the countries with the most cases are the USA, Spain and Italy (warmer colors), in absolute values. In percentage the highest values are still in Europe, (Island, Spain, Switzerland and Italy are the one the

warmest colors). This is perfectly in line with what we have seen up to now.

## 2.3 Data selection and alignment

To compare the speed of the infection spread between countries, we need to "align" the data. In other words, we model the epidemic using equivalent "starting conditions" for every country. To do that, we filter the data so that the number of confirmed cases (in any country) is greater or equal to the maximal number of confirmed cases at the first day of a specific country.

Let $C_{d,i}$ be the number of accumulated confirmed cases on day $d$ for country $i$. Let country $k$ be the one such that it had the highest number of reported cases on the first day in the dataset, that is $C_{1,k} \geq C_{1,i}$ for any other $i$. Find $k$ and discuss.

From `covid19_data`, extract a new table `covid19_data_filtered`:

- Select only the countries $i$, which on some day $d_{0,i}$ have $C_{d_{0,i},i} \geq C_{0,k}$. We will call this time $d_{0,i}$ a day-zero for country $i$. In the next sections, we model $C_i(t) = C_{d_{0,i}+t,i}$, that is the spread of the epidemic in country $i$ with $t$ representing "event days". Remember, for every country the day-zero is, in general, different. However, when a country entered the epidemic stage, we are only interested in number of days that has passed from the date of entry (i.e. day-zero).
- First, we remove countries who are left with less than two weeks of data, i.e. we keep those countries whose number of days that has passed from the day-zero of this country is 14 or more.
- Then we create a new column called `t` representing the number of days from the day-zero of this country.
- Finally, we create a new column called `confirmed_1e5pop` representing the number of confirmed cases per 100,000 habitants. This is useful in order to compare how the spread of the epidemic differs between countries relative to their population.

Furthermore, we will aim to answer the following three questions:

- Which countries are left in `covid19_data_filtered`?
- What is the state of the spread there?
- What is the relationship between `t` and `confirmed_1e5pop`?

**Comment**: K is China, with 548 cases, 17 deaths on the 2020-01-22.

**Comment**: The countries left in `covid19_data_filtered` are Australia, Austria, Belgium, Brazil, Canada, Chile, China, Czechia, Denmark, Ecuador, Finland, France, Germany, Greece, Iceland, Indonesia, Iran, Ireland, Israel, Italy, Japan, Korea, South, Luxembourg, Malaysia, Netherlands, Norway, Pakistan, Poland, Portugal, Romania, Saudi Arabia, Spain, Sweden, Switzerland, Thailand, Turkey, United Kingdom, USA.

| Date in Which Countries Entered an Epidemic Situation | |
|---|---|
| country | date |
| China | 2020-01-22 |
| Korea, South | 2020-02-23 |
| Italy | 2020-02-27 |
| Iran | 2020-02-29 |
| France | 2020-03-06 |
| Germany | 2020-03-06 |
| Spain | 2020-03-08 |
| USA | 2020-03-09 |
| Japan | 2020-03-10 |
| Norway | 2020-03-11 |
| Switzerland | 2020-03-11 |
| Denmark | 2020-03-12 |
| Sweden | 2020-03-12 |
| Belgium | 2020-03-13 |
| Netherlands | 2020-03-13 |
| United Kingdom | 2020-03-13 |
| Austria | 2020-03-14 |
| Malaysia | 2020-03-16 |
| Australia | 2020-03-18 |
| Canada | 2020-03-18 |
| Brazil | 2020-03-19 |
| Czechia | 2020-03-19 |
| Ireland | 2020-03-19 |
| Portugal | 2020-03-19 |
| Israel | 2020-03-21 |
| Luxembourg | 2020-03-21 |
| Pakistan | 2020-03-21 |
| Turkey | 2020-03-21 |
| Chile | 2020-03-22 |
| Ecuador | 2020-03-22 |
| Finland | 2020-03-22 |
| Greece | 2020-03-22 |
| Iceland | 2020-03-22 |
| Poland | 2020-03-22 |
| Thailand | 2020-03-22 |
| Indonesia | 2020-03-23 |
| Romania | 2020-03-23 |
| Saudi Arabia | 2020-03-23 |

**Comment**: We can see which countries were the first ones to reach China's situation; South Korea the 23rd February (almost a month after China), Italy the 27th February and Iran the 29th of February. The evolution of the situation in the countries that reached the state of China is given by the graph above. One of the biggest concerns is the situation in the US that seems to be growing exponentially and having no intention to slow, while in China the curve has flattened a lot following the regulations introduced by the government. Nevertheless, we do have to mention that the potential lack of transparency by the Chinese government could also explain this flat curve which falls beyond the scope of this analysis.

**Comment**: We can see that these two variables are positively correlated with one another, especially for Luxembourg and Iceland, while, on the other hand, for China is not at all the case. However, this make sense, since China is the reference country and it was already in the epidemic situation and was the first to take measurement to stop the expansion of the healthcase crisis.

# Chapter 3

# Modeling the spread of COVID-19 in a single country

## 3.1 The logistic model in R

Using the filtered dataset, we study the spread of COVID-19 with the logistic model. Letting $C_i(t) = C_{d_{0,i}+t,i}$, the model for country $i$ can be expressed as:

$$C_i(t) = \frac{K_i \cdot C_i(0)}{C_i(0) + (K_i - C_i(0)) \exp(-R_i\, t)}$$

The goal is to find the final number of cases $K_i$ and the infection rate $R_i$. We implement this in R using the following function:

```r
# here, we assume that data is a data frame with two variables
#  - t: the number of event days
#  - confirmed: the number of confirmed cases at time t
logistic_model <- function(data) {
  data <- data %>% arrange(t)
  C_0 <- data$confirmed[1]
  C_max <- data$confirmed[nrow(data)]
  nls(
    formula = confirmed ~ K / (1 + ((K - C_0) / C_0) * exp(-R * t)),
    data = data,
    start = list(K = 2 * C_max, R = 0.5),
    control = nls.control(minFactor = 1e-6, maxiter = 100)
  )
```

```
}
```

Notice:

- We use the nonlinear least square method `stats::nls` to fit the unknown parameters.
- In R, the formula above is `confirmed ~ K / (1 + ((K - C_0)/C_0) * exp(-R * t))`.
- As starting point $(K_0, R_0)$ for the optimiser, we set $R_0 = 0.5$ and $K_0 = 2\,C(t^*)$, where $t^*$ is the latest information about accumulated confirmed cases.
- We further set the `control` argument as `nls.control(minFactor = 1e-6, maxiter = 100)`.

## 3.2 The logistic model applied to data from Switzerland

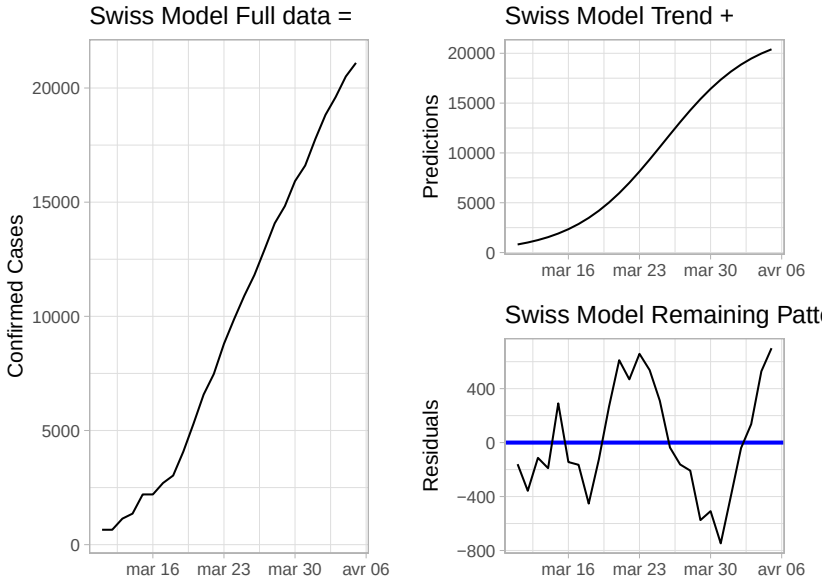
From `covid19_data_filtered`, extract a table `covid19_ch` which corresponds to data for Switzerland. Then:

- We use the function above to fit the logistic model for Switzerland
- We describe its output (fitted parameters, `broom::tidy()` might be useful here)
- We discuss the goodness-of-fit.
- We plot the fitted curve, as well as observed data points.
- And finally, we present the predictions of the model. What is the estimated final size of the epidemic and infection rate in Switzerland?

We will start by presenting the data we own for the model we want to describe.

```
#> Warning: Using `size` aesthetic for lines was deprecated in ggplot2 3.4.0.
#> i Please use `linewidth` instead.
#> This warning is displayed once every 8 hours.
#> Call `lifecycle::last_lifecycle_warnings()` to see where this
#> warning was generated.
```

| term | estimate | std.error | statistic | p.value |
|---|---|---|---|---|
| K | 22253.429 | 345.696 | 64.4 | 0 |
| R | 0.227 | 0.002 | 96.3 | 0 |




**Comment**: In general we can see that there is an increasing trend for the confirmed cases of COVID-19 in Switzerland (which does not come as a surprise). The trend seems to follow quite well the pace of the observations, and the residuals seems to focus around zero, with some variation, especially towards the end of March.

**Comment**: we can see that the two parameters found are both statistically significant and both positively correlated to the independent variable.

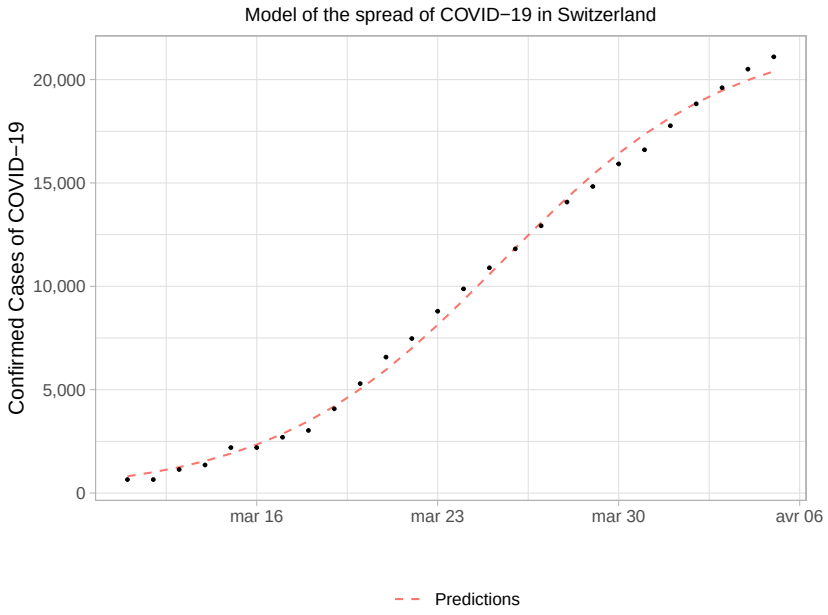
Now, we will discuss the goodness of fit of the model by comparing it to a null model having the confirmed case explained by a constant variable.

```
#>
#> Call:
#> glm(formula = confirmed ~ 1, data = covid19_ch)
#>
#> Coefficients:
#>             Estimate Std. Error t value   Pr(>|t|)
#> (Intercept)     9650       1370    7.04 0.00000022 ***
#> ---
#> Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
#>
```

```
#> (Dispersion parameter for gaussian family taken to be 48822367)
#>
#>     Null deviance: 1220559163  on 25  degrees of freedom
#> Residual deviance: 1220559163  on 25  degrees of freedom
#> AIC: 537.1
#>
#> Number of Fisher Scoring iterations: 2
#> Analysis of Variance Table
#>
#> Model 1: confirmed ~ K/(1 + ((K - C_0)/C_0) * exp(-R * t))
#> Model 2: confirmed ~ 1
#>   Res.Df Res.Sum Sq Df      Sum Sq F value              Pr(>F)
#> 1     24    4200305
#> 2     25 1220559163 -1 -1216358858    6950 <0.0000000000000002 ***
#> ---
#> Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

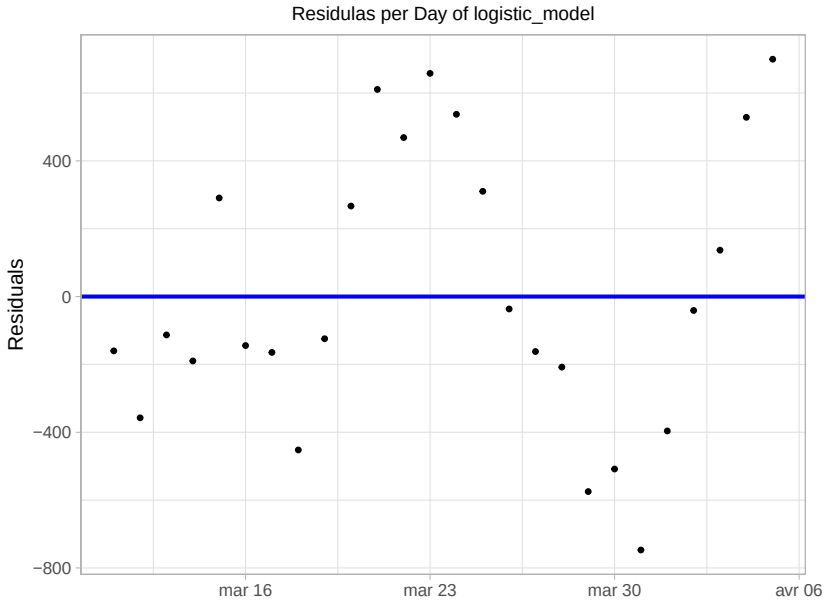
**Comment**: The ANOVA results shows that the hypothesis that the two models have the same effect can be reject are 0.1% (since the p-value is lower than 0.001). Moreover, we also calulate the MAPE to measure the accuracy of the prediction of the model. Having a MAPE of 0.08, we can say that the model is fairly good, being the error small.

We then plot the fitted curve and the observations.




**Comment**: As we can see the predictions are following quite well the observations, meaning that the model is working quite well. However, it is woth

mentioning that the model is fitted on the whole datasets, which could lead to some form of overfitting, not having a separation in training and test set, meaning that once dealing with new data, the prediction ability of the model could decrease quite a lot.




The residuals from the plot tell us that many actual numbers were lower than the predicted ones, however this is not too far off from zero, and it is rather expected that the model overpredicts at this point; the number of cases to be higher as the confirmed does not mean that all the people have been identified and due to the limitations in number of testing kits, perhaps more are infected than our data shows.

Eventually, the prediction the estimated final size of the epidemic and infection rate in Switzerland is $2.04 \times 10^4$.

# Chapter 4

# Modeling the spread of COVID-19 worldwide

In this section, we fit the logistic model to every country in the `covid19_data_filtered` dataset.

## 4.1 Fitting the logistic model to every country

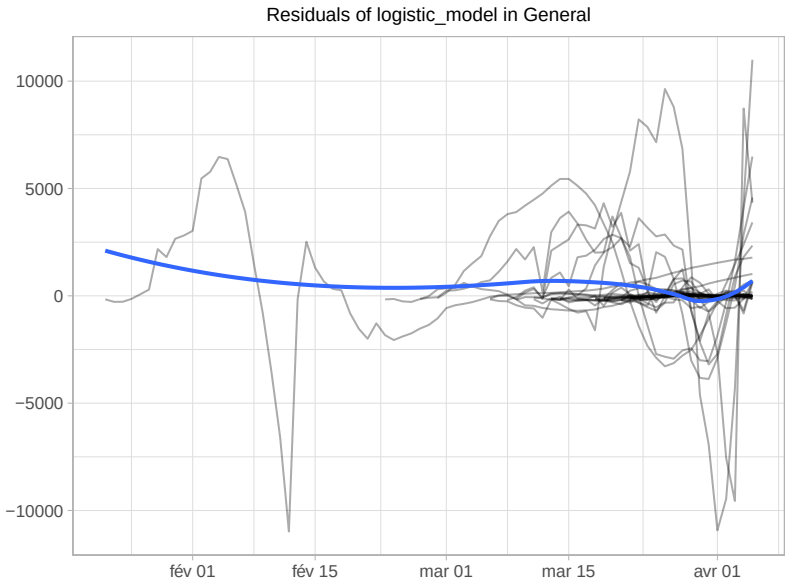
Here we make use of the nested data, list-columns and `logistic_model` to fit the logistic model to every country in the dataset. Because, for some countries, the optimization method might not converge, we will use the `possibly()` function to see which ones fail and which ones succeed. Now one may wonder, for which country does the optimization fail ?

First, let's fit the logistic model to every country and have a look at which one are not converging.

The countries for which the optimization fails are the following:

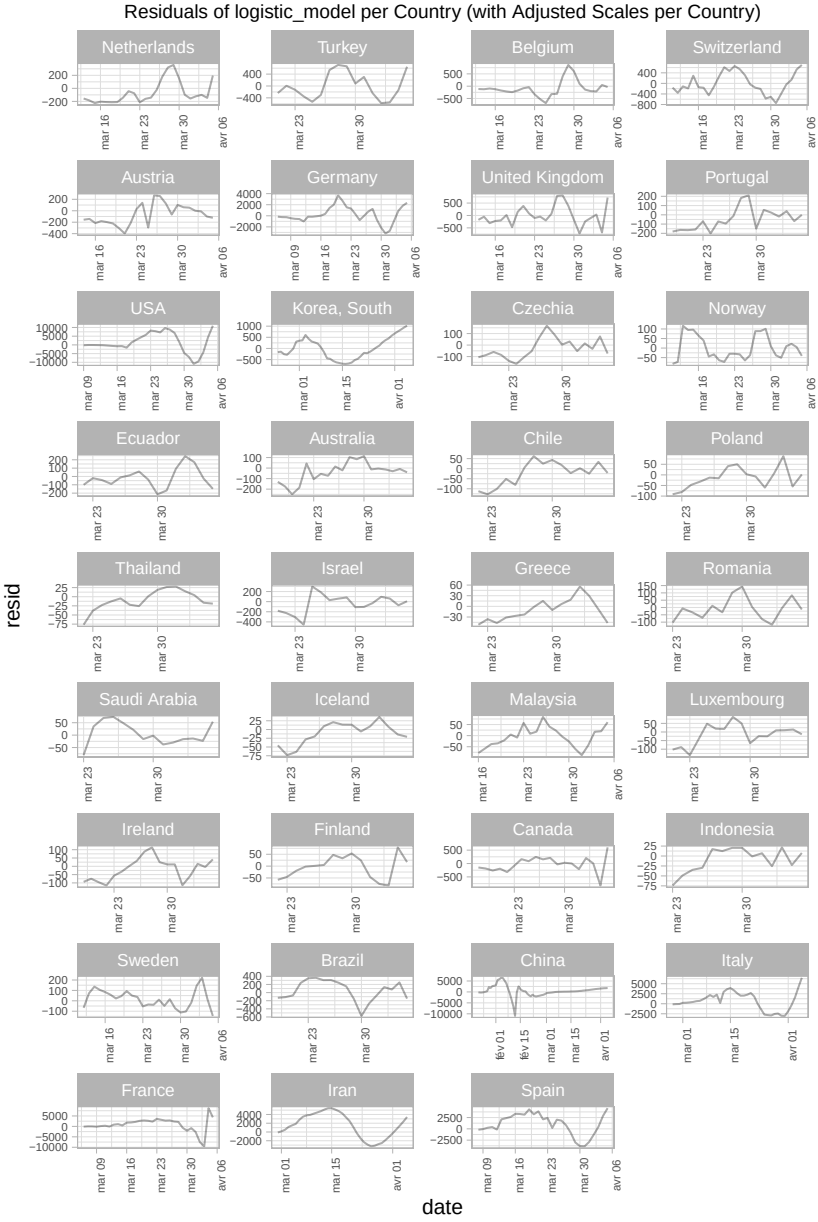
Denmark, Japan, Pakistan

We will also assess the goodness-of-fit of the logistic model in the various countries. Lets plot the residuals per country to have a look at the general trend of the residual in the model.

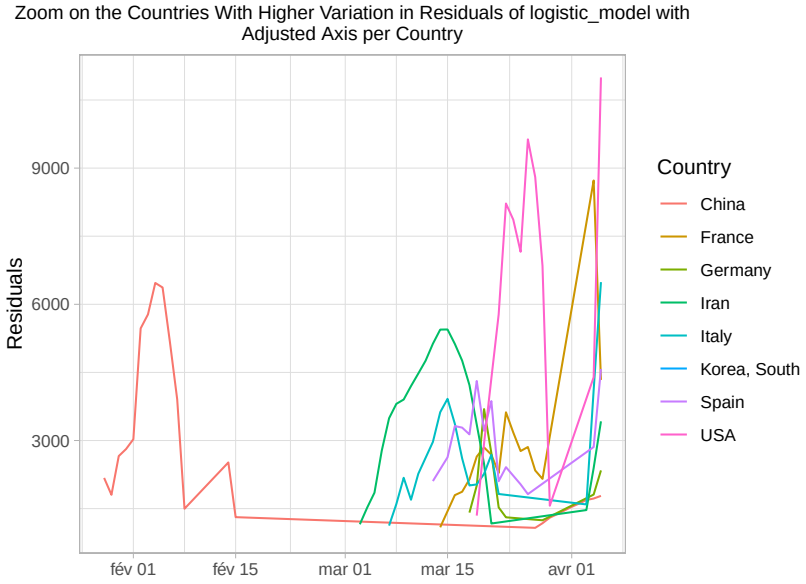



**Comment**: As we can see, the residuals seem to be quite close to zero, especially towards the end of the timeline (end of March, beginning of April), while at the beginning we can see some more distance from zero (given by the fact that the only country present in the dataset at that time is China, being the only one already in an epidemic situation). From the moment in which more countries join the dataset, we can see that the accuracy of the model increase, hence the residuals decrease and are closer to zero.

Let's plot the residual per country to have a better look, and then we will zoom on the countries with the highest values of the residuals (meaning that they are the ones for which the model has a lower accuracy in the predictions).




*Note:* The axis are for this graph `Residual of logistic_model per country` and the one below has been adjusted for each country in order to be able to see better the different distributions.




**Comment**: As we can see the countries for which the model has the highest values for the residuals are China, France, Germany, Iran, Italy, South Korea, Spain and the USA. This does not come as a susprise, actually, since in the EDA part of our analysis, we have seen that they are the countries with the highest exponentiality in terms of absolute values of the confirmed cases (especially the US), while for China, as already mentioned, the residuals are higher at the beginning of the timeline, being the only country in the dataset, since we are considering only the countries in an epidemic situation.

We would like to also have also a score which shows the goodness-of-fit of the model for each country, however according to the (Burnham and Anderson, 2002, pp. 80), it is mentioned that **AIC cannot** be used for models with different number of observations (and also different datasets) as we see in the table below.

## 4.2 Fitted parameters and long-term predictions

We then describe the fitted parameters (i.e., the final size and the infection rates), both on a per-country basis and some aggregate numbers (e.g., total size of the epidemic over all considered countries). Furthermore, we study the evolution (say for $t$ from 0 to 50) of the predictions of the number of confirmed cases from our models. Similarly as was discussed in the last sub-section of the exploratory data analysis, the number of confirmed cases per 100,000 habitants is also important to understand how specific countries are managing the spread of the epidemic. Thus, we predict the evolution of this number (i.e., by dividing our predictions for confirmed cases by the population size) and discuss.

| Number of observations per country | |
|---|---|
| country | observations |
| Australia | 19 |
| Austria | 23 |
| Belgium | 24 |
| Brazil | 18 |
| Canada | 19 |
| Chile | 15 |
| China | 75 |
| Czechia | 18 |
| Ecuador | 15 |
| Finland | 15 |
| France | 31 |
| Germany | 31 |
| Greece | 15 |
| Iceland | 15 |
| Indonesia | 14 |
| Iran | 37 |
| Ireland | 18 |
| Israel | 16 |
| Italy | 39 |
| Korea, South | 43 |
| Luxembourg | 16 |
| Malaysia | 21 |
| Netherlands | 24 |
| Norway | 26 |
| Poland | 15 |
| Portugal | 18 |
| Romania | 14 |
| Saudi Arabia | 14 |
| Spain | 29 |
| Sweden | 25 |
| Switzerland | 26 |
| Thailand | 15 |
| Turkey | 16 |
| USA | 28 |
| United Kingdom | 24 |

We will do the aforementioned using the following functions:

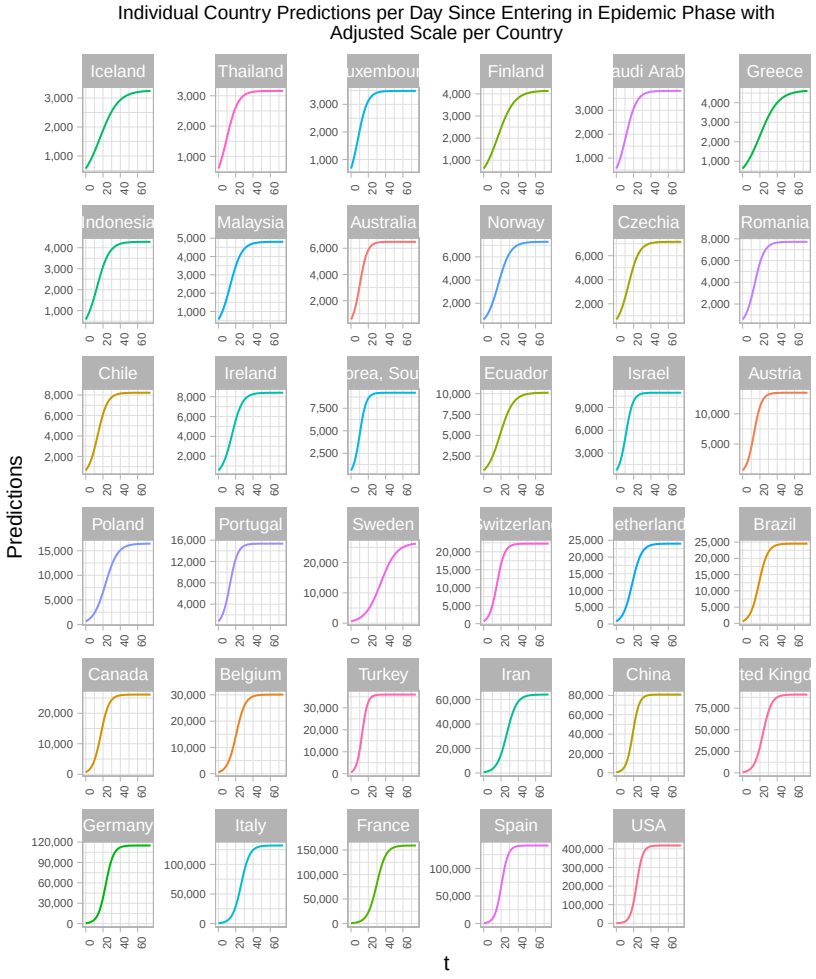
- Format the fitted parameters using `broom::tidy()`.
- For the long-term predictions, we use `data = data.frame(t = 0:50)` in `add_predictions()`.

First we can see the parameters of the various models for each countries.

*Note:* Please do note that we have rounded our results to 2 decimal places.

**Comment**: It doesn't come as a surprise the fact that they vary quite a lot.

Now let's look at the prediction per country.

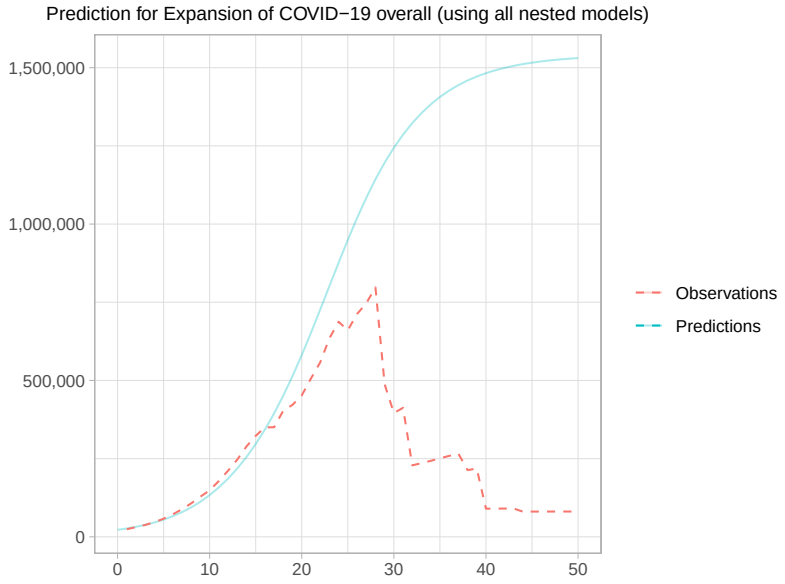



**Comment**: We can see that the countries with the highest absolute values are

| Fitted parameter per Country | | |
|---|---|---|
| country | K | R |
| Australia | 6490 | 0.229 |
| Austria | 13475 | 0.227 |
| Belgium | 30106 | 0.192 |
| Brazil | 24528 | 0.194 |
| Canada | 26125 | 0.209 |
| Chile | 8226 | 0.178 |
| China | 80822 | 0.263 |
| Czechia | 7156 | 0.159 |
| Ecuador | 10116 | 0.131 |
| Finland | 4143 | 0.105 |
| France | 159261 | 0.185 |
| Germany | 114953 | 0.222 |
| Greece | 4636 | 0.093 |
| Iceland | 3258 | 0.094 |
| Indonesia | 4284 | 0.141 |
| Iran | 63936 | 0.175 |
| Ireland | 8411 | 0.167 |
| Israel | 10943 | 0.242 |
| Italy | 131962 | 0.201 |
| Korea, South | 9220 | 0.265 |
| Luxembourg | 3488 | 0.179 |
| Malaysia | 4802 | 0.148 |
| Netherlands | 24000 | 0.184 |
| Norway | 7300 | 0.143 |
| Poland | 16456 | 0.141 |
| Portugal | 15335 | 0.219 |
| Romania | 7725 | 0.180 |
| Saudi Arabia | 3811 | 0.159 |
| Spain | 141690 | 0.259 |
| Sweden | 26528 | 0.109 |
| Switzerland | 22253 | 0.227 |
| Thailand | 3162 | 0.151 |
| Turkey | 36048 | 0.311 |
| United Kingdom | 90683 | 0.201 |
| USA | 417895 | 0.280 |

the US, Spain, Germany, France and Italy (over a 100'000 of final confirmed cases predicted). This is in line with what we have found in the EDA part of our analysis.

In order to look at the aggregated sum, we can either use the logistic model on the filtered data and calculate new coefficients as we did with the swiss model but now applied to all countries and the second approach is to do it by region to use the fitted parameters of each country (nested) which makes more sense.




**Comment**: We can see that up to the 28th period the aggregated model predicts well however after that we do not have observations for most of the countries so it does not make sense to look at the observed values.

*Note*: Please do note that that the highest "t" belongs to China which is about 75 periods and therefore we have decided to extend our model to also include the all these dates. However, please do keep in mind that the 50th period the observation is mainly representative of predictions for China.

We can also do the aggregated sum for all countries only for the first 50 periods (because afterwards we do not have observed data points for almost all countries hence the observations naturally goes down). This model is a better one because it takes into account all the different coefficients rather than assigning the same one to all the countries.

*Note*: In the graph below, Please feel free to scroll over the country to see which one is contributing the most.

**Comment**: In terms of regions, we see the highest increase for North America

due to the predicted increase for the US, followed by Europe & Central Asia, Italy, Spain and France among many and lastly, East Asian & Pacific with the most predicted cases for China.

Furthermore, referring back to the per-country predictions, we can also calculate the same for cases per 100,000 habitants displayed by the interactive plot below.

**Comment**: We can see that Iceland (green line) and Luxembourg (blue line) will have the highest number of confirmed cases per 100,000 habitants which is same as what we saw previously in the section of exploratory data analysis. This is due to their small populations and their infection numbers will be far larger than the countries that follow like Spain, Switzerland Belgium.

# Bibliography

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