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Using System Dynamics approach as decision support tool in fighting against pandemic

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Abstract

The COVID-19 outbreak hit all countries and all mankind with unexpected initial force. This forced decision-makers at all levels, both among the rulers and managers of the private sector, to make decisions that had been atypical so far. As a last resort, in order to minimize the number of cases and ultimately the number of victims, the rulers were forced to introduce further lockdowns. Unfortunately, such activities have severely limited economic activity, contributing to the economic slowdown. Thus, the rulers are forced to make difficult decisions on how much to protect health and how much to protect the economy. In this paper, using the method of systems dynamics and epidemic development models, we present how to predict its course and how to support decision-makers in assessing the current and future situation. The paper describes how to use well known epidemic spread model called SIR (Susceptible-Infected-Recovered) together with System Dynamics methodology and simulation tool JOptisim. The methodology that was choosen, allows modelers to easily extend basic SIR model by new variables depending on modeler needs. In presented example the cost of hospitalization was the variable which was added to the basic model. Using the proprietary JOptisim tool, which has implemented RADU5 numerical procedure, allows authors to validate developed model and achieve accurate simulation results. The paper consists of three sections. The first one is the general introduction to possibilities of predicting epidemic spread and the second one describes briefly the System Dynamics methodology. In the last section it is explained how to choose equations for some of the variables of the model using nonlinear regression methods implemented in R language when real data is available.

Keywords: simulation; system dynamics; decision support systems; epidemics modeling

1. Introduction

Phenomena related to the spread of diseases have always accompanied mankind and, unfortunately, they have usually claimed huge numbers of victims, e.g. the plague epidemic in the fourteenth century or the Spanish flu epidemic in the early twentieth century.

With the development of mathematical sciences, models have begun to emerge that make it possible to predict the spread of diseases. Technological development, in turn, meant that these models began to be implemented on calculating machines, and then software was created that enabled relatively fast simulation and modeling of various scenarios of the development of the situation.

Universal models for predicting the epidemic spread were developed at the beginning of the 20th century by Kermack and McKendrick in 1927 and took into account the division of the population into susceptible, infected and recovered people.

Hence, these models have the popular names: SI (taking into account only the division into susceptible and infected) and SIR (taking into account the division into susceptible, infected and recovered).

2. Brief introduction to System Dynamics

Since the models originally introduced by Kermack and McKendrick are based on differential equations, this way of notation is usually difficult to understand by non-mathematicians.

To make models of this type more useful and more widely used in practice, in the 1950s, MIT Professor Jay Forrester developed a methodology for dynamic modeling of the so-called System Dynamics.

In this methodology, differential variables are represented by the so-called stocks and algebraic variables by flows (inflows or outflows) which could be controlled by other external variables (algebraic) or constants. The epidemic spread model can be presented in System Dynamics notation as in Figure 1.

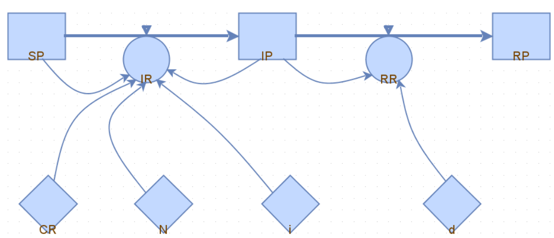

Figure 1. SIR model in System Dynamics notation

where:

SP – represents susceptible population,

IP – represents infected population,

RP – represents infected population,

CR – Contact Rate between people

N – Population size

i – Infectiousness of a disease

d – Mean recovery time

IR – Infection rate

RR- Recovering rate

Having prepared the model in such a way, its transformation into the form of differential equations is performed, which are solved with the use of appropriate numerical procedures. In the easiest case it can be the Euler or RK-4 method with a fixed step, and in the more difficult case the method with a variable step of integration. In the article presented in this article, all simulations were carried out in the proprietary JOptisim software, in which the advanced RADAU5 method is implemented. It enables solving not only systems of differential equations (ODE), but also systems of differential-algebraic equations (DAE) with the so-called index 3. However, this article does not focus on the details of the numerical methods used, but on the use of the System Dynamics approach as a decision support tool.

The essence of the System Dynamics methodology is not to understand existing mathematical models but to understand the surrounding reality by discovering relations between objects existing in it, and then a relatively simple transformation of these relations into mathematical formulas.

The System Dynamics methodology provides for the creation of the so-called casual loop diagrams (CLD's) containing the most important elements of the modeled reality and the relationships between them. Relationships have their own direction and nature, which can be positive or negative. The positive nature means that the elements in relation to each other behave in harmony, and the negative character means that the elements that are related to each other behave in the opposite way. For the SIR epidemic model, the CLD diagram looks like as presented in Figure 2. The CLD contains three balancing loops (also known as negative feedback): SP ↔ IR, IP ↔ IR, IP ↔ RR, which force the system to seek a stable state.

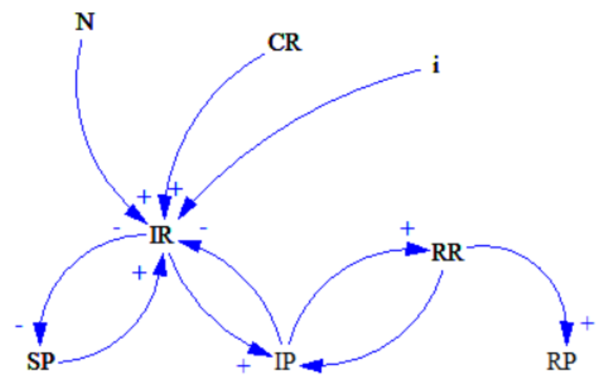

Figure 2. Casual Loop Diagram of SIR model

Another advantage of using the methodology is that it can be easily modified with additional elements of the existing generic models. Such modifying example is described in the further section of the article.

3. Verification of the SIR model, estimation and calibration of parameters

In each model, its key elements are the parameters and their values, which determine the behavior of the modeled system and the trajectory of individual variables. An important step before performing the simulation is the selection of appropriate values so that the model reflects the modeled reality as accurately as possible, which contributes to the development of more accurate forecasts.

In the first phase of the COVID-19 epidemic, estimating the parameters of existing models appeared to be very difficult as little was known about the behavior of the virus itself, its contagiousness and its curability. Only on the basis of the data collected on an ongoing basis, it was possible to estimate the above parameters and on this basis to make key decisions, in particular related to limiting movement and limiting contacts.

As part of the research started in the first quarter of 2020, the following research problems were defined:

1) whether the existing universal models of epidemic development, in particular SIR, are capable of modeling the development of the epidemic related to the COVID-19 virus,
2) whether at the current stage of knowledge (Q1 2020) it is possible to select model parameters in such a way as to reflect the course of the epidemic,
3) whether undertaken actions related to limiting contacts were justified.

In order to solve the above problems, authors used the SIR model transformed to System Dynamics notation in the JOptisim tool. Next, the real data of epidemic spread in Germany and Austria in the first quarter of 2020 was gathered. These two countries were chosen as countries where as countries where the virus was observed quite early and quick decisions were taken to prevent the epidemics. Further, data from Poland, as country which coped quite well with pandemic were gathered. Basing on gathered data with help of nonlinear regression methods implemented in R language, estimation of model parameters was carried out.

As mentioned above, in the first wave of the pandemic, the knowledge about the behavior of the virus was not fully known. Consequently some assumptions had to be made in order to calibrate the model. Based on the collected data and information appearing in the media space, authors assumed that the probability of infection with a virus is 20%, which corresponds to the value of 0.2 for the "i" parameter in the SIR model.

Subsequently, based on the collected data, in accordance with the formula:

$$CR = \frac{IR}{i * SP * \left(\frac{IP}{N}\right)} \qquad (1)$$

the CR (Contact Rate) parameter was determined for each day of the epidemic.

Having determined the values of the CR parameter, in the second step, the approximating function was selected using the nonlinear regression method based on the least squares method. The equations of the function with the mean square error value are presented in formula (2) for Austria and (3) for Germany while the trajectories of the approximating function and the values of calculated CR parameters are presented in the Figures 3 and 4.

$$y = -1{,}296516 + 3{,}91699 * e^{-0{,}01756407*x} \qquad (2)$$

$$y = 0{,}415247 + 8{,}408425 * e^{-0{,}1029*x} \qquad (3)$$

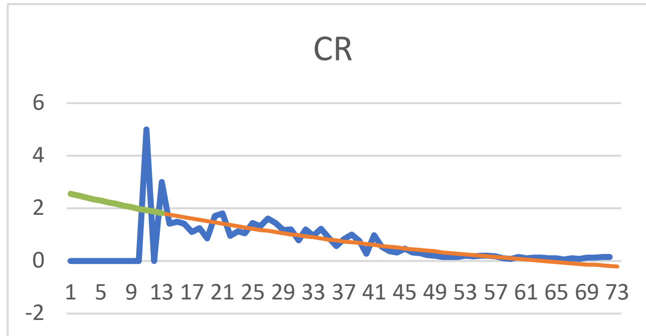

Figure 3. Determined CR values with its approximating function for Austria case

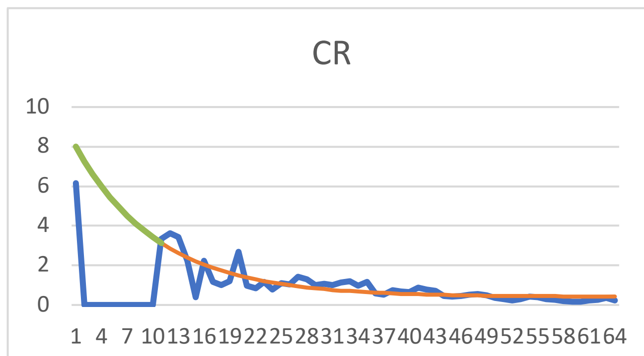

Figure 4. Determined CR values with its approximating function for Germany case

In the next step, the value of the approximating function was entered into the model. Additionally, other calibration parameters were introduced in the model, the values of which were determined manually on the basis of a series of simulation experiments. The complete model which includes death rate and some additional parameters (for simplifing some equations) is presented in Figure 5.

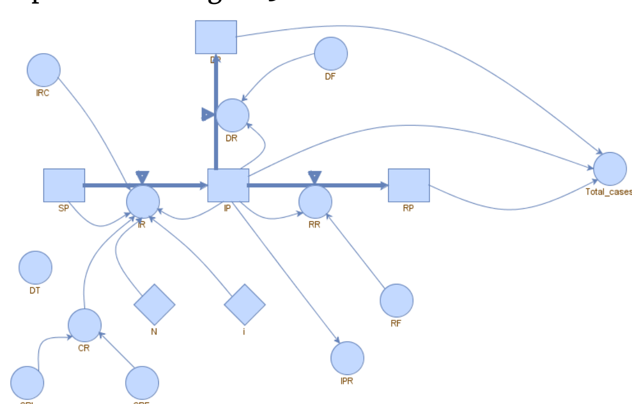

Figure 5. Model of epidemic spread created in JOptisim

As a result, a forecast was obtained for the total number of cases in a short period of time. Forecast and real values are presented in Figures 6 – 8.

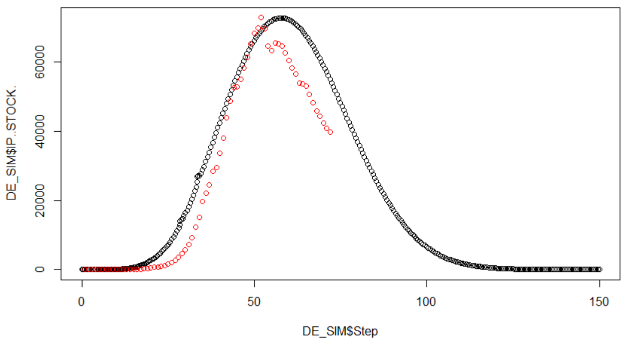

Figure 6. Infected population (red -real data, black – simulation and forecast) for Germany case

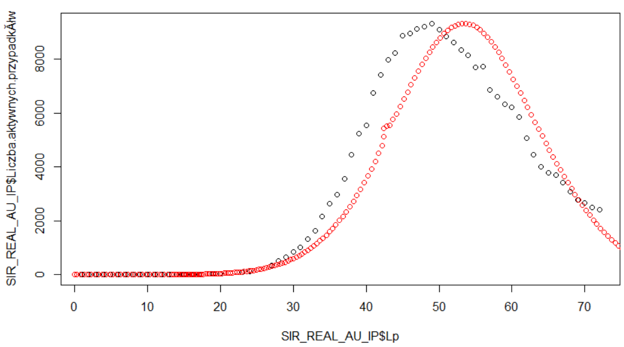

Figure 7. Infected population (red – simulation and forecast, black – real data) for Austria case

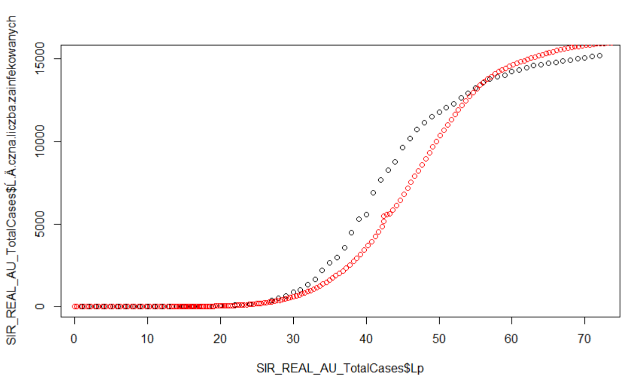

Figure 8. Total number of infections (red – simulation and forecast, black – real data) for Austria case

As it can be seen, the results between the forecast and the real trajectories for both Germany and Austria case, as well as the Total Cases and Active Cases variables are very similar. It means that the proposed model and the method of selecting parameters were both correct.

According to the adopted assumptions, if the restrictions are maintained for a longer period, the pandemic in these two countries should reduce its scope quite quickly.

However, due to the spring and summer period and in order to counteract the stagnation in the economy, decisions were made to introduce relaxation, which again increased the development of the pandemic.

This moment can be seen very well on the example of Poland, where the epidemic has been minimized for a long time and, according to the prepared forecast, it could be brought totally under control. However, during the so-called long weekend of May, it was decided to loosen the restrictions, which caused the epidemic to gain momentum again. It is shown in Figure 9.

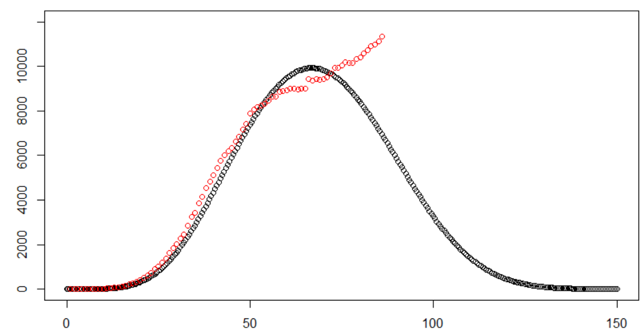

Figure 9. Loosing restrictions at inflection point Poland made increase of active cases (red – real date, black – simulation and forecast)

4. Extending the model, prediction of additional parameters

After the holiday season in 2020, the so-called second wave of the pandemic forced governments to reconsider their decisions to introduce lockdowns. Based on the previous experience, these decisions were unwelcome by the public, but the gains and losses related to the introducing or not introducing restrictions had to be reassessed.

Because on the basis of the research carried out in the first quarter, it could be concluded that it was possible to calibrate and use the SIR model, and thus to make a prognosis of the epidemic development.

In the fourth quarter of 2020, before the imposing restrictions, authors of the paper slightly modified the previous model and applied hospitalizations of patients with a more severe course of the disease. The model took into account the 14 days of a mean time of hospitalization and the hospitalization factor 0.2 what means that 20% of infected need to hospitalized. Daily hospitalization cost was set to PLN 100 which similar to real cost of hospitalization. The described model is presented in Figure 10.

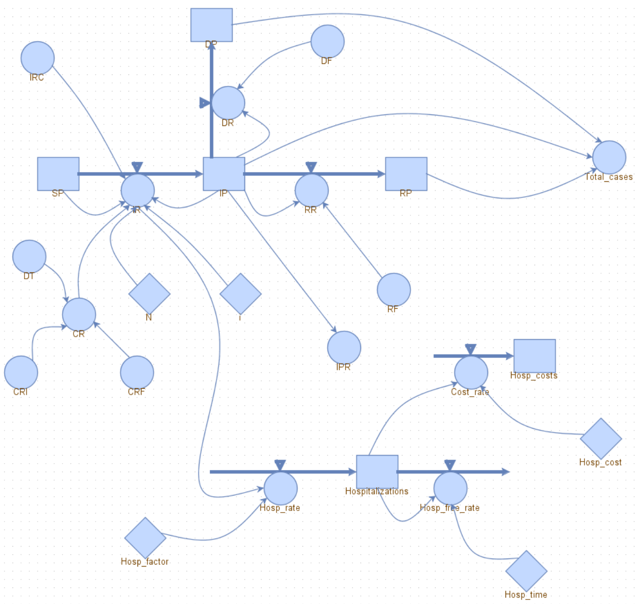

Figure 10. SIR model with applied hospitalizations

On this basis, forecasts were made, estimating not only the number of potential cases, but also the number and, above all, the costs of hospitalizations.

The simulation result is presented in Figure 11 - 13.

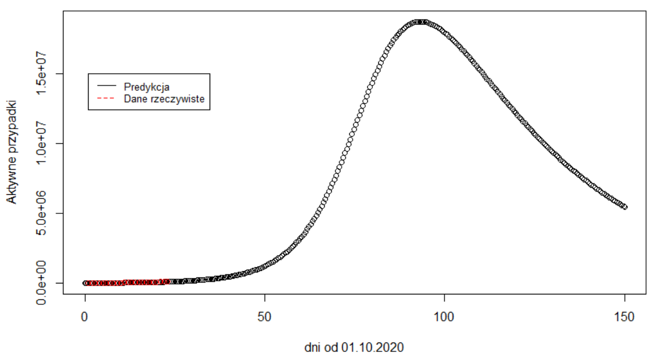

Figure 11. Active cases during the second wave in Poland without imposing restriction (red – real data, black – simulation and forecast)

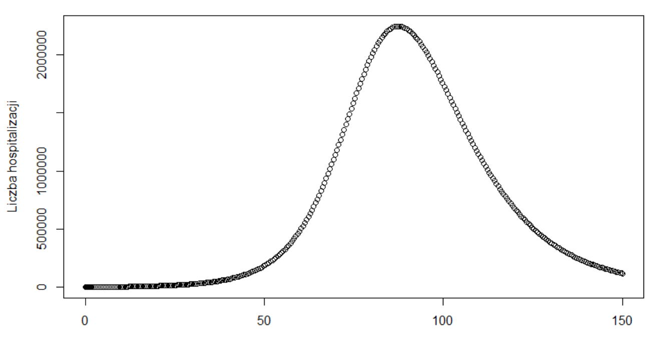

Figure 12. Predicted hospitalization during the second wave in Poland without imposing restriction (black – simulation and forecast)

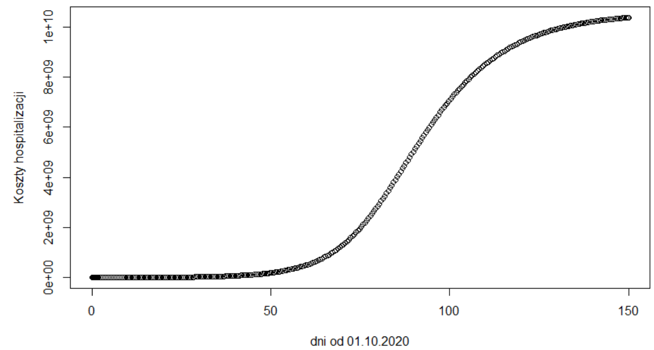

Figure 13. Predicted hospitalization costs during the second wave in Poland without imposing restriction (black – simulation and forecast)

As it can be seen, if no restrictions were introduced, based on the data on the growing number of cases, it could be expected within a few months of a sudden increase in the number of patients and a sudden increase in the number of hospitalizations.

Forecast indicated that the total number of active cases would reach to 15 milion (Figure 11), the necessary hospitalizations in a short period of time (approx. 5 months) would be 2 million people (Figure 12), and the total cost of hospitalization during only 5 month would approach to PLN 10 billion (Figure 13).

In practice, hospitalization of such a large number of people would be impossible, so that a significant proportion of patients would not have a chance of being cured. Moreover, an additional expenditure of this order in a short period of time could disturb the continuity of financing the health service. As a result, the simultaneous occurrence of these two factors (too many required hospitalizations and its rapidly growing costs) could realistically lead to a paralysis of long-term health care, and thus a breakdown of the country's security.

5. Conclusions

Based on the conducted research, it can be stated with certainty that the generic epidemic models developed at the beginning of the 20th century are still possible to use. In addition, having data on the course of the disease, it is relatively easy to estimate parameters and prepare an epidemic development forecast.

In addition, having a model prepared in the System Dynamics methodology, it is possible to easily extend it by additional element. The results of the simulations performed provide a real basis for making difficult decisions.

Further researches will focus on developing **JOptisim** tool and applying methods od for automatic calibration of the parameters of the model. To achieve this goal the optimal control theory is planned to be used.

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