Professional paper

MATHEMATICAL MODELS IN DIFFERENT POTENTIAL CRISIS SITUATIONS

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Abstract: *According to the Danish mathematician Ole Skovsmose, there are at least three connections between mathematics and crises: mathematics picturing a crisis, mathematics constituting a crisis and mathematics formatting a crisis. In this paper we explain and further explore the three relationships of mathematics and crisis in disease spread and cyber security. Regarding mathematical models, the emphasis is on differential equations which we explain in simple language and show how they are connected to our reality by the use of concrete examples in economics, epidemiology (disease spread) and climate change. Altogether, the aim of this paper is to show and convey to the wider audience how mathematics and crisis are connected and how mathematics, through differential equations, embodies relationships, dynamics and changes of the objects from different areas of the real world, with an emphasis on crises situations.*

Key words: *mathematics picturing a crisis, mathematics constituting a crisis, mathematics formatting a crisis, mathematical models, differential equations*

1. INTRODUCTION

Crises represent complex and dynamic phenomena that evolve over time. Whether they involve the outbreak of infectious diseases, the advancement of climate change, or economic instability, they are influenced by numerous interacting factors. Comprehending and forecasting their trajectories is imperative for effective intervention and serves as a cornerstone of sound policy-making.

Mathematics today, on the other hand, is an unavoidable tool in almost all areas of science and technology of everyday life. Not only that it is unavoidable, but it has become essential in modelling dynamical phenomena of real-life situations. Today new interdisciplinary fields of science are rapidly evolving like mathematical biology, mathematical chemistry, mathematical economy, mathematical physics, mathematics for computer science, etc. The fields also help mathematics to evolve - many mathematical approaches got developed precisely because of challenges in its applications. Motivated by working at our University of Applied Sciences Velika Gorica, where we have both undergraduate and graduate modules that educate students about crisis management, we started investigating how mathematics is involved to crises at some deeper levels. We started exploring how mathematics models potential crisis situations.

The relationship between mathematics and crisis was investigated thoroughly by the Danish mathematician Ole Skovsmose (Skovsmose, 2021). According to him, there are at least three connections between mathematics and crises: *mathematics picturing a crisis, mathematics constituting a crisis* and *mathematics formatting a crisis.* We discuss them thoroughly in chapter 2.

We reviewed books and papers from different areas where crisis might emerge, like *epidemiology (disease spread), climate changes and economy (and finances)* and *cyber security* to see which methods are used here. Among many others, we find that the common method used in mathematical models in these three areas are *differential equations* (see for example Brauer et al., 2008; Zhang, 2005; MacKenzie, 2007; Hryshchuk, 2021). Differential equations are often used to describe everyday dynamical processes, i.e. processes that change in time, like processes in the above four mentioned areas, and interactions of factors that are a part of these processes. In chapter 3 we explain differential equations in simple language. In chapters 4, 5 and 6 we first explain how economics, disease spread and climate change are associated with crisis situations. After that, we examine how differential equations are connected to these areas by showing one example of differential equations or a system of differential equations in each area. We show how differential equations are connected to the real world situations and how they can be used to predict future states and hence prevent or better handle crisis situations.

2. RELATIONSHIP BETWEEN MATHEMATICS AND CRISIS

According to the Danish mathematician Ole Skovsmose, there are at least three connections between mathematics and crises: *mathematics picturing a crisis, mathematics constituting a crisis and mathematics formatting a crisis* (Skovsmose, 2021). The first mentioned relationship is due to mathematics picturing different parts of our reality, and hence crises, using its models. A mathematical model is an abstract representation of a real-world system expressed through mathematical concepts and mathematical language. The purpose of mathematical modelling is to simplify complex processes and systems to better understand them, predict their future behaviour, optimize decisions, observe patterns and trends, explore different scenarios, etc. Mathematical models use mathematical formulas, equations, graphs or other mathematical structures. For instance, in disease spread, mathematical models can show how an illness moves through a population, helping us understand the possible impact of prevention strategies (Brauer et al., 2008). In cybersecurity, models help visualize how digital attacks might spread through networks or identify weak points in a system (Hryshchuk, 2021).

Mathematics constituting a crisis means that some reality processes that can end in critical situations do not exist without mathematical algorithms, like making transactions and decisions on the stock markets today. The crisis can happen due to misreadings and misusings of mathematics or maybe due to not understanding the process enough and hence not applying the appropriate models and approaches in specific situations. In disease management, if decision-makers rely on flawed models or misunderstood data, this can lead to poor responses that make the situation worse. In cybersecurity, many systems depend on complex algorithms for protection. If these are broken or misused, they can create vulnerabilities or even trigger large-scale security failures.

The third role where we say that mathematics formats a crisis is about how mathematics forms the view on crisis situations and hence forms how we approach and take action in these situations. The way a problem is represented mathematically influences how serious we believe the crisis is and what kind of solutions we consider. In public health, graphs or statistics can strongly influence how people perceive the urgency of a disease outbreak. In cybersecurity, models can determine how much attention is given to certain threats over others.

3. DIFFERENTIAL EQUATIONS IN GENERAL

Today, more mathematical methods and tool are combined, both qualitative and quantitative, to create a unique appropriate approach to a specific interdisciplinary problem for which a solution is being sought. Differential equations are just one of them. Some of the other tools are machine learning, Markov Chains, linear programming, Monte Carlo simulations, graph theory, cryptography, game theory, etc.

Differential equations of the first order are mathematical equations that connect (unknown) mathematical functions and their first derivatives, i.e. their rates of change. They tell us how fast a quantity that is being observed changes. Higher order differential equations incorporate derivatives of higher order and they and they show how is a quantity changing, how is the change itself changing, etc. Differential equations are used to predict future states and understand better how these processes work and hence prevent potential crisis situations. They belong to quantitative methods where one is interested more why and how some phenomenon works. There are many types of differential equations. Often, processes that are modelled with differential equations are very complex and cannot be represented with just one differential equation but with a system of differential equations. Also, often it is not a simple job to find a solution for these equations. We will not go deep into the theory of differential equations, yet our goal is to provide some simple explanations which a wider non-mathematical audience would, hopefully, understand.

Starting with some assumptions of the phenomenon that is being modelled, differential equation or a system of differential equations is being constructed. Differential equations could be seen as rules that show how dynamical processes are changing over time and they describe interactions of factors that are a part of these processes. Differential equations are often used in situations when one is interested in how *one or more quantities change over time.* They express how *rates of change of these quantities* are behaving. The aim is to find the formula (function) for this *quantity* dependent on time. Why? Because if we plug inside the formula a specific point in time in the future, we get the *future prediction* of the amount of this quantity. With this information we can take action and prevent or better handle crisis situations.

To conclude, we said that the quantity that is being observed is in a mathematical way being connected with its rate of change through mathematical structures and mathematical language. Some other factors can also be incorporated inside this connection. We can obtain this quantity (expressed as a mathematical function), how it behaves in time, analytically or numerically. This is exactly the setting with differential equations: we know how ‘something’ (the quantity) is changing, and from this we obtain this ‘something’.

4. ECONOMICS AND CRISIS

The economy and crises are deeply interconnected, each influencing the other's trajectory. Economic conditions can precipitate crises, while crises can, in turn, reshape economic landscapes.

Economic downturns often exacerbate social and political tensions. The 2008 financial crisis, for instance, triggered widespread unemployment - peaking at 10% in the U.S. - and led to global austerity measures that fuelled public discontent and political instability (Cassidy, 2018). One of the most striking examples was Greece, where the sovereign debt crisis led to a 25% decline in GDP and a surge in unemployment. The government's austerity measures, such as public sector layoffs and cuts to pensions and healthcare, led to mass protests and a shift in the political landscape (Nelson, 2017; BBC News, 2015; Tzortzinis, 2015). Financial crises, such as currency devaluations or banking collapses, can have cascading effects on both domestic and global economies. The Asian financial crisis of 1997 and the global financial crisis of 2008 serve as pertinent examples where financial turmoil led to widespread economic downturns, increased unemployment, and long-term developmental challenges (Investopedia, 2021).

On the other hand, crises in general can profoundly affect economic systems. The COVID-19 pandemic disrupted global supply chains, leading to economic contractions worldwide. In the United States, the pandemic-induced recession resulted in the loss of over 22 million jobs in early 2020, highlighting the economy's vulnerability to health crises (Bureau of Labor Statistics, 2021). The World Bank noted that the pandemic triggered the largest global economic crisis in over a century, exacerbating inequalities within and across countries (World Bank, 2022)

Environmental challenges, particularly those related to climate change, pose significant risks to economic stability. The increasing frequency and intensity of natural disasters strain infrastructure, disrupt agricultural productivity, and necessitate substantial financial resources for recovery and adaptation. These events can lead to long-term economic setbacks, especially in vulnerable regions (Intergovernmental Panel on Climate Change [IPCC], 2021).

Economic disparities can lead to social unrest, particularly when large segments of the population feel marginalized. The 2014 Brazilian economic crisis, marked by a significant GDP contraction, was accompanied by widespread protests and political turmoil, culminating in the impeachment of President Dilma Rousseff (Watts, 2016; Romero, 2016).

Geopolitical tensions and conflicts can lead to economic sanctions, trade disruptions, and fluctuations in global markets. For example, the Russian invasion of Ukraine not only caused humanitarian crises but also led to significant disruptions in global energy supplies, contributing to a broader energy crisis and economic instability in various regions (International Energy Agency [IEA], 2022).

Despite the challenges, economies often demonstrate resilience. Post-crisis periods can lead to structural reforms and innovation. Several nations have undertaken significant financial and structural reforms following economic downturns, leading to improved growth prospects.

4.1. DIFFERENTIAL EQUATIONS IN ECONOMICS

In this chapter we show one of the simplest examples of differential equations, an example that incorporates only the notion of proportionality between two parts of the equation. The notion from economics at hand is the GDP - final markets money value of all countries products in a year. This quantity will be denoted with X and it is dependent on time t. To simplify, instead of saying GDP, we will just refer to it as a money value, since it can be any other money value at some point in time. Often, if one does not know from which assumption to start building a model, a differential equation, we can start from proportionality if it seems logical. Here it would mean the following: the more money we have, the faster it will change, i.e. the amount of money X and its rate of change, denoted with $\frac{dX}{dt}$ are proportional. $\frac{dX}{dt}$ is actually the derivative of quantity X. Proportionality means that one quantity is obtained by multiplying the other by some constant, here the constant (parameter) is denoted with k. The equation is the following:

$$\frac{dX}{dt} = kX$$

where k could be referred to as the growth rate, one chooses it with accordance of the problem (Zhang, 2005). The solution X to equation (1) is an exponential function. If we plug inside the exponential solution a future point in time t, we get the amount X in the future point in time, i.e. we predict future states.

If we check our new data on the amount of money in some point in time and it coincides with our exponential function as the solution, we are done with the model. If not, maybe the parameter k is off, we can play with that. If we see that that is also not enough, we either start with a new model or incorporate new factors in the model. The exponential function has no upper boundary so it seems that the amount of money can rise and can grow indefinitely which is not realistic. To avoid that, we can plug in the model a new part of the equation that ensures the upper boundary of the wanted quantity of money, here being GDP. Then test the model again with new data. And so on, until we are satisfied with the model and how it predicts our quantity in time X.

5. EPIDEMIOLOGY AND CRISIS

Historically, major outbreaks of infectious diseases have led to significant mortality, economic downturns, and social disruption, with pandemics reshaping societies. In the 14th century, the Black Death caused massive depopulation, resulting in severe labor shortages that triggered significant economic and social transformations. (Jedwab, Johnson, & Koyama, 2022)

The 1918 influenza pandemic, known as the Spanish Flu, infected about a third of the global population, and its effects extended beyond health, influencing economies and societies during and after World War I. (Spinney, 2017)

Most recently, the COVID-19 pandemic has led to significant global health and economic crises. This pandemic triggered recessions, disrupted supply chains, and exposed vulnerabilities in healthcare systems worldwide. (Berger, Karakaplan, & Roman, 2023)

Analysing the mentioned past events, it is evident that epidemics and pandemics are among the most potent triggers of complex crises. They begin as health emergencies, but their impacts rapidly extend into economic, political, and social domains, profoundly affecting societies, economies, and global stability. Some of the identified impacts include health system overload, economic shocks, social and psychological crises, and political consequences. Hospitals become overwhelmed, routine care is disrupted, and mortality rates climb not only from the disease itself but also from secondary issues left untreated. Lockdowns, travel restrictions, and supply chain disruptions reduce economic output, employment, and investment. Prolonged restrictions, isolation, and loss of livelihoods lead to rising mental health issues, social unrest, and political instability. Public trust in institutions may erode when responses are perceived as inadequate or inconsistent. This also ties into the political consequences – it potentially triggers leadership changes, civil disobedience, or institutional reform.

On the other hand, some existing crises can become fertile ground for infectious diseases. Armed conflicts force populations into overcrowded, unsanitary conditions with limited access to healthcare, accelerating the spread of diseases. For instance, the ongoing civil war in Sudan has led to the resurgence of diseases like malaria, cholera, and measles among displaced populations lacking access to clean water and medical care. (Hassan, Abuassa, & Ibrahim, 2025)

Poverty is closely linked to higher rates of infectious diseases—limited access to healthcare, inadequate housing, and poor nutrition weaken immune systems and increase vulnerability to infections. (Siddique, Haynes, Kulkarni, & Li, 2023)

In many cases, epidemics and crises create a self-reinforcing feedback loop—one triggers the other, worsening the initial conditions. Once again, a great example was set during the COVID-19 pandemic: the pandemic triggered an economic crisis, which then impacted vaccination campaigns and responses to other health threats like measles and polio. (WHO, 2020)

The spread of infectious diseases is not merely a medical issue; it reflects broader systemic vulnerabilities. From overwhelmed healthcare systems to disrupted economies and displaced populations, epidemics do not occur in isolation—they evolve within crises and often help to shape them. Understanding this relationship is crucial for breaking the cycle and fostering sustainable crisis preparedness.

5.1. DIFFERENTIAL EQUATIONS IN DISEASE SPREAD

To show a little more complex example, we chose a well known SIR model (Brauer et al., 2008). Here we have a system of three differential equations with quantities S, I and R:

$$\frac{dS}{dt} = -\beta SI$$
$$\frac{dI}{dt} = \beta SI - \gamma I \qquad (2)$$
$$\frac{dR}{dt} = \gamma I$$

where S stands for number of susceptible (healthy) people, I is the number of infected people and R the number of recovered (removed) people. In this set are people that can no longer infect others or be infected. They cannot spread disease or get ill again. This includes deceased people as well. Parameters here are β as the infection rate and γ as the recovery rate.

And again, expressions (derivatives) $\frac{dS}{dt}$, $\frac{dI}{dt}$ and $\frac{dR}{dt}$ denote rates of change of respectively S, I and R.

To explain the first equation in (2) we have the following. The amount of healthy people changing (decreasing) in a point in time, for instance in the first day, is equal to the number of healthy ones S meeting the number of infected ones I at time t, so S times I if all the healthy would meet all the infected. This is not realistic so there is the β parameter. People from group S meeting people from group I gets them infected by some probability. If healthy get infected, they transfer to the group of the infected ones I. The minus sign in $-\beta \boldsymbol{SI}$ represents a decrease in the number of healthy people S.

The third equation is as follows. The rate of change of the recovered ones is proportional to the amount of infected ones with the proportionality parameter γ being the recovery rate. In other words, the more infected ones, the faster the group of the recovered ones R will change since the infected ones are transferred to their group when recovered.

And finally the second equation, how fast the infected ones change is the sum of the βSI (here we have a plus sign since the amount of infected ones is increasing by this term since they transferred from the group of the healthy ones) and $-\gamma I$ (the minus sign is here since the recovered ones are transferring from group I to group R, i.e. the number of infected is decreasing by this term).

It is not such a trivial thing to find a solution for S, I and R. There is no analytical solution for any of the three quantities, i.e., there is no 'nice' formula to express them, yet solutions are found in approximate forms (Barlow and Weinstein, 2020). But when we find solutions, again, we can use the equations to step forward in time, by plugging in some point in time, predicting how many people will be infected, sick, or recovered on each day and hence apply measures to prevent or calm down a crisis situation.

This is one of the simplest models for disease spread. It is also used in other fields. For instance, it is used to model how rumors are spread (Hatzivelkos and Golubić, 2019). Furthermore, today's models are much more complex. But this one is often a starting point to understand and construct other models.

6. CLIMATE CHANGE AND CRISIS

Climate change and crises are closely interconnected, with each one affecting and intensifying the other in complex ways. This relationship is evident in several areas, including humanitarian emergencies, economic instability, and geopolitical tensions.

One of the most noticeable manifestations of climate change is through extreme weather events. In April 2025, a severe storm system swept across the Mississippi Valley in the United States, resulting in catastrophic flooding and tornadoes that claimed 24 lives. A study by the World Weather Attribution group found that human-induced climate change made such storms 40% more likely and increased rainfall intensity by 9% compared to pre-industrial times. (Borenstein, 2025)

In 2022, Pakistan experienced unprecedented monsoon rains and glacial melt, resulting in floods that submerged a third of the country, displaced over 7.9 million people, and caused approximately $40 billion in damages. The floods were labelled the worst in the country's history and were linked to climate change. (World Weather Attribution, 2022)

Conversely, crises can hinder efforts to combat climate change and exacerbate its effects. In regions like the Central African Republic and Mali, ongoing conflicts have disrupted environmental governance and conservation efforts, leading to deforestation and land degradation, which in turn exacerbate climate change.

Displacement caused by crises can also strain urban infrastructure and increase carbon footprints. Displaced populations often migrate to urban areas, resulting in unplanned settlements with inadequate infrastructure, which in turn increases emissions and vulnerability to climate impacts.

The increasing frequency and severity of climate-induced disasters strain economic systems and infrastructure. For instance, in Australia, climate change poses significant risks to critical infrastructure, including transportation and energy networks. Floods have disrupted supply chains, and heatwaves have strained energy systems, leading to power outages and economic losses (The Conversation, 2023)

The connection between climate change and crises is both reciprocal and cumulative. Climate change acts as a threat multiplier, exacerbating pre-existing vulnerabilities and initiating fresh crises. Similarly, crises can obstruct efforts related to climate mitigation and adaptation, perpetuating a cycle of challenges. Tackling this relationship demands comprehensive strategies that factor in both climate resilience and crisis management, emphasizing the importance of global collaboration and sustainable development.

6.1. DIFFERENTIAL EQUATIONS IN CLIMATE CHANGE

Climate change, as many other areas of our surroundings, is a very complex dynamic process. Climate models incorporate the atmosphere, the ocean, land, and ice. With an atmosphere climate model (3) we just show an example of a very complex system of differential equations without any further explanation because it is above the scope of this article (MacKenzie, 2007). One should be deep into the climate notions and factors that influence one another and deep into vector functions in mathematics to be able to understand this model. However, we can just say that this model represents how the atmosphere moves heat, air, and moisture around the planet to simulate weather and long-term climate. The function whose solution is sought by this model, the function u, describes the wind — the speed and direction that air is flowing through the atmosphere. The idea with this model is just to show how tangled and complicated things can be. The differential equations and some accompanying equations and explanations are:

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} + 2\Omega \times \vec{u} = -\frac{1}{\rho} \nabla p + g\hat{k} + \bar{F} + \tau(\vec{u})$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0$$

$$p = \rho R T; \qquad \rho = f(T, q)$$

$$\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T = SW \updownarrow + LW \updownarrow + SH + LH + \tau(T) \qquad (3)$$

$$SW = f(clouds, aerosols, \dots)$$

$$LW = f(T, q, CO_2, GHG, \dots)$$

$$\partial q + \vec{u} \cdot \nabla q = Evap - Condensation + \tau(q)$$

7. CONCLUSION

In crisis situations, whether it is a pandemic, economic collapse, or climate emergency, decision-makers must act based not just on current conditions, but on how things are likely to evolve. This is exactly where differential equations become essential tools. They allow us to predict the future based on how things are changing now, test scenarios and policies before applying them in the real world and much more. By modelling the rate of change, not just the state/quantity itself, differential equations provide a way to estimate the long-term consequences of short-term actions.

Differential equations and other mathematical models do not predict the future perfectly since they are a simplified representation of a part of our reality. Misusing or misinterpreting models can also lead to unwanted crisis situations. Nevertheless, in today’s world, mathematical models are an unavoidable tool for handling and solving many crisis situations.

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