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IFAC PapersOnLine 54-13 (2021) 305–310

Why Modelling the COVID-19 pandemic using Fuzzy Cognitive Maps (FCM)?

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Abstract: The coronavirus disease known today as COVID-19, has created tremendous chaos around the world, affecting people's lives and causing a large number of deaths. The WHO has accepted COVID-19 as a pandemic leading to a global health emergency. Global collaboration is sought in numerous quarters. Research efforts have been intensified all around the humankind. Most studies for COVID-19 are done based on statistical models which depend solely on correlation factors. The factor of causality has not been considered appropriately. The approach of Fuzzy Cognitive Maps (FCM) that is considering the causality factors is proposed, to investigate the whole spectrum of COVID-19. An FCM COVID-19 model is proposed having 10 symptoms-concepts. Early theoretical simulation studies using an FCM COVID-19 model and real data from the local hospital, have been conducted. Simulations with real patient data give excellent results. Future research directions are provided.

Keywords: COVID-19, pandemic, modelling, fuzzy cognitive maps, simulation, correlation, causality.

1. INTRODUCTION

The coronavirus disease known today as COVID-19, has created tremendous chaos around the world, affecting people's lives and causing a large number of deaths. The deadly coronavirus continues to spread across the globe, and mathematical models can be used to show suspected, recovered, and deceased coronavirus patients, as well as how many people have been tested. Throughout the natural and artificial world, one observes phenomena of great complexity. Yet research in physics, to some extent health and other fields has shown that the basic components of many systems are quite simple. It is now a crucial problem for many areas of science, especially health, to elucidate the mathematical mechanisms by which large numbers of such simple components, acting together, can produce behavior of the great complexity observed. Therefore, today's health systems have become more and more complex and dynamic. Modelling and controlling complex health systems are a very difficult and challenging task. Such a complex health system are the coronavirus diseases like the COVID-19 pandemic. As a result, "complex systems theory" cuts across the boundaries between conventional scientific disciplines. It makes use of ideas, methods and examples from many different fields.

The main purpose of this paper is to raise an interesting question: why should and/or could the COVID-19 pandemic be modelled by Fuzzy Cognitive Maps? Will it be useful and profitable in fighting this tragic disease? It is hoped YES. In late 2019 a virus apparently closely related to SARS coronavirus emerged in Wuhan, China. The rapid spread of the epidemic worldwide has aroused serious concerns in the international community. The virus, later named severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). Today everybody is referred to it as COVID-19 and it has spread to almost countries around the world. From mild, self-limiting respiratory tract illness to severe progressive pneumonia, multiorgan failure, and death (Chen 2020), (Wang 2020).

With the progress of the pandemic and rising number of the confirmed cases and patients who experience severe respiratory failure and cardiovascular complications, there are solid reasons to be tremendously concerned about the consequences of this viral infection (Guoet 2020). Determining appropriate approaches to reach solutions for the COVID-19 related problems have received a great deal of attention. From the outbreak of the COVID-19 pandemic, many scientists but primarily physicians look upon different scientific areas searching for promising approaches to investigate all aspects of COVID-19. We have just started this difficult health journey. The generation of a large volume of data, known as Big Data World (BDW) is a fact that complicates even further the problem in finding solutions on the process of fighting the pandemic. However, this BDW of COVID-19 provided a chance to health physicians and scientists to search solutions based on theories of Artificial Intelligence (AI). (Jamshidi et al. 2020). Methods that use correlation as the basis for hypothesis tests for causality, including the Granger causality test and convergent cross mapping have been used extensively in the past (Granger 1969). However, the results are not satisfactory since it uses statistical methods. This brings up the serious problem of confusing statistical correlation and causal relationship between variables and especially in the case of medical problems. Correlation does not imply causation; even though the research question at hand involves causality. A mathematical model that provides information on the causality of a dynamic complex system is the Fuzzy Cognitive Map

10.1016/j.ifacol.2021.10.464

(FCM) (Kosko 1986) (Groumpos 2010). Thus, FCM is proposed in this study for the first time to model the COVID-19 without using statistical models or probability density function.

2. ISSUES OF THE HEALTH SYSTEMS

Major challenges face today's health care system for which health professionals have to be prepared. The health care system can hardly be called a system as is defined by academicians and scientists. Rather it is a bewildering array of a large number of subsystems and in highly decentralized sectors. It is true that the number of hospitals and of the physicians has been growing steadily the last 40-50 years. The science of complex dynamical systems is a multidisciplinary field aiming at understanding the complex real world that surrounds us (Levin 2003), (Morton 1971). A good number of Clinical Decision Support Systems (CDSS) have also been developed the last 30-35 years based on different methodologies. They can be found on many references (Berner 2007), (National Academy of Medicine 2018). No one can deny that most of them served to a certain extent many of the medical problems. The majority of them are based on statistical approaches. Indeed, all mathematical models used in confronting the recent pandemic of COVID19 also are using statistical models. However, all medical problems are non-linear and statistical models are based on the assumption that variables have linear correlation between them. It is an undeniable fact that all medical problems are dynamic and non-linear. At present, many discussions are held regarding the decision mechanisms relating the inputs and the desired outputs of medical systems using non-statistical methods. A new approach, the Fuzzy Cognitive Map (FCM) methodology (Kosko 1986) and (Groumpos 2010), has been proposed as not a statistical method to study and analyze such systems. Fuzzy Cognitive Maps (FCMs) constitute a simple computational and graphical methodology to represent complex problems.

3. THE COVID-19 PANDEMIC

In late 2019 a virus apparently closely related to SARS coronavirus emerged in Wuhan, China. The rapid spread of the epidemic worldwide has aroused serious concerns in the international community. The virus, later named severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). Today everybody is referred to it as COVID-19. By early 2020, it had spread throughout regions of China and had reached many countries around the world. (Alon 2020), (Chen2020), (Wang 2020) and (WHO 2020). Most probably been carried by travelers from affected regions. In March 11 of 2020, the World Health Organization (WHO), after many hesitations, declared the outbreak a pandemic. The placing of entire cities and/or countries in 'lockdown' directly affects urban economies on a multi-lateral level, including from social and economic standpoints. This is being emphasized as the outbreak gains ground in most countries of the world, leading towards a global health emergency, and as global collaboration is sought in numerous quarters. Recent events have shown us (again) how rapidly a new disease can take root and spread. Such events are accompanied by an explosion of clinical and epidemiological information and research. Reported illnesses have ranged from mild symptoms to severe illness and death for confirmed coronavirus disease 2019 (COVID-19) cases. The virus is mainly transmitted via respiratory droplets and contact, and the population is generally susceptible. The basic productive number (R0) at the beginning of the epidemic was 2.2, with an average incubation period of 5.2 days. Elderly human beings with underlying diseases and affected by COVID-19 had a higher mortality rate. Younger ages and especially children are not easily affected by the disease. For some reason's males are more susceptible to the disease. Since the pandemic has caught the whole world by surprise, no one was ready to deal with it. Studies have been conducted and research articles are either on SARS and MERS (de Wit E 2016). Since the pandemic outbreak numerous studies have been conducted and reported with most of them available on the open literature, (Science News 2020), (The Lancet Digital Health 2021). The current source of the disease is mainly patients infected with COVID-19. So far, all studies of COVID-19 (as well as for SARS-COV-2) are based on statistical methods and/or precise models using either static equations or ordinary differential equations. However, all of them have a number of drawbacks. In addition, all medical problems are non-linear and statistical models are based on the assumption that variables are simply correlated. All medical problems are dynamic and non-linear. Moreover, physicians are requested to handle information of different nature, e.g. patient's history, clinical diagnostic tests, medical images, personal health problems and demographic characteristics. The interpretation of these results involves ambiguity, fuzziness and uncertainty, which plays a critical role for the decision-making to a wide and diverse set of medical problems. The COVID-19 pandemic has all these characteristics. Although these approaches provide us with answers that are needed and used to study the medical problems, there are still not sufficient and adequate to provide us with acceptable and convincing solutions. Therefore, new advanced scientific approaches and new mathematical models are urgently needed. This paper provides a different mathematical approach based on fuzzy logic and theories of Fuzzy Cognitive Maps (FCM) in tackling COVID-19 issues.

4. BASICS OF FUZZY COGNITIVE MAPS (FCM)

Fuzzy Cognitive Maps came as a combination of methods of fuzzy logic and neural networks. FCMs were first, introduced by (Kosko1986), in order to represent the causal relationship between concepts and analyze inference patterns. They take advantage of the knowledge and the experience of experts, offering them an alternative way of addressing the problems, yet in the same way a human mind does. This is achieved by using a conceptual procedure, which can include ambiguous of fuzzy descriptions (Groumpos 2010). Late in 1999s and early in 2000s, Fuzzy Cognitive Maps were employed for the first time to describe and solve medical problems by the research team been supervised by the author of this paper (Papageorgiou 2011), (Anninou 2017).

The FCM theories embody the accumulated knowledge and experience from experts who know how the medical system behaves in different circumstances. This is one of the strongest points of the FCM approach that rely mainly on the experience of the experts. This knowledge is extracted using linguistic variables which then are transformed to numeric values using a defuzzification method. In other words, they recommend a modeling process consisting of an array of interconnected and interdependent nodes Ci (variables), as well as the relationships between them W (weights). Concepts take values in the interval [0,1] and weights belong in the interval [-1,1]. Figure 1 shows a representative diagram of an FCM.

The full procedure of the development of a FCM is provided in (Groumpos 2010). During the simulation the value of each concept is calculated using the following rule:

$$A_i(k+1) = f\left(k_2 A_i(k) + k_1 \sum_{j=1, j\neq i}^{N} A_j(k) W_{ji}\right) \quad (1)$$

where N is the number of concepts, Ai(k + 1) is the value of the concept Ci at the iteration step k+1, Aj(k) is the value of the concept Cj at the iteration step k, Wji is the weight of interconnection from concept Cj to concept Ci. The constant “k1” expresses the influence of all the other interconnected concepts on the configuration of the new value of the concept Ai and “k2” represents the proportion of the contribution of the previous value of the concept in computing the new value. Their values usually are set equal to 1, unless the experts of a particular dynamic system can determine these influences and contributions to the behavior of the system. This could be an interest future research topic for certain medical problems, such as COVID-19. Meanwhile function f, is the sigmoid function:

$$f(x) = \frac{1}{1+e^{-\lambda x}} \quad (2)$$

Where λ>0 determines the steepness of function f. The FCM’s concepts are given some initial values which are then changed depending on the weights Wij and the way the concepts affect each other. The calculations stop when a steady state is achieved, the concepts’ values become stable.

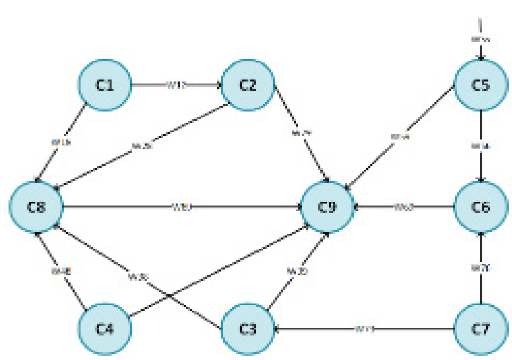

Figure 1: A simple Fuzzy Cognitive Map (FCM)

5. MODELLING COVID-19 WITH FCM METHODOLOGIES

The COVID-19 pandemic has sparked an unprecedented wave of research, data sharing and open science as the scientific world seeks to understand the disease, track its spread and analyze the SARS virus that causes COVID-19 or called more medically correct, SARS-CoV-2. Existing Medical Decision Support Systems (MDSS) methods are complex, difficult and insufficient to address the new emerged pandemic.

The pandemic COVID-19 is an acute resolved disease, but it can also be deadly, with a not easily determined case fatality rate. Severe disease onset might result in death due to massive alveolar damage and progressive respiratory failure or due to other chronic diseases of the patient that are been further deteriorating from COVID-19. First, the early and automatic diagnosis of COVID-19 would be extremely beneficial to the patient and his/her relatives. It will also be beneficial to any state and private health system. In addition, it would be beneficial for countries for timely referral of the patient to quarantine, rapid incubation of serious cases in specialized hospitals, and monitoring of the spread of the disease. Although the diagnosis has become a relatively fast process, the financial issues arising from the cost of diagnostic tests concern both states and patients, especially in countries with private health systems, or restricted access health systems due to prohibitive prices.

The symptoms reported have been growing since the first detection of VOVID-19. These symptoms may appear 3-14 days after exposure. In order to develop an FCM model following the methodology been outlined in section 4 the first step is to determine the number and the kind of concepts Ci that constitute the Fuzzy Cognitive Map (FCM). Talking to MD doctors of the Patras University hospital and other relevant data by official organizations, the following ten (10) concepts have been selected, see Table 1.

Table 1: Concepts of COVID-19

Concepts and Symptom description
C1: Fever-body temperature
C2: Cough
C3: Shortness of breath-breathing problems
C4: Headache
C5: Persistent pain or pressure in the chest
C6: Bluish lips or face
C7: Feeling weak
C8: heart rate
C9: hemodynamic instability
C10: outcome of test: positive or negative

The next steps are:

- Each expert defines the relationship between the concepts: 1) as “positive” or “negative” or “zero”
- degree of influence using a linguistic variable, such as “very low”, “low”, “medium”, “high”, “very high”.
- The FCM schematic diagram is developed similar to figure 1 (due to space limitation the figure is not shown)
- The table of weights Wij is determined (same for the Wij)
- Run simulations with equations 1 and 2 and report obtained results.

This must be further developed to an algorithm. All concepts are contributing to the value of concept C10 and is similar to figure 1. The output concept C10, is referred to as positive if the patient is sick with the COVID-19 and negative if the patient does not have COVID-19. Of course, when running the simulations, the positive and negative interpretations will be defined by thresholds been determined by the physicians.

6. SIMULATIONS AND DISUSSION OF RESULTS

Using the Fuzzy Cognitive Map (FCM) methodologies a number of simulations were conducted. An example given here using the following basic assumption for the COVID-19 for running simulation studies based on real data of more than 200 patients.

NP: Not present=0.0, VL: Very low=0.1, L: Low =0.3, M: Medium=0.5, H: High=0.7, VH: Very High=0.9

6. 1 CASE WITH REAL DATA

Using above values for the 9 concepts for 80 medical data and in consultation with the physicians, an FCM COVID-19, is developed similar to figure 1. Then using fuzzification and defuzzification methods, the weight matrix Wij needed for equation 1 for the FCM COVID-19 model is developed. Each of the weight matrix Wij a 10x10 matrix is determined. Using FCM theories simulations were conducted for all 50 patients. Out of the 80 cases (real data), 4 patients-cases were selected for conducting more extensive simulations, using the FCM methodologies. Table 2 provides the linguistic variables for the 9 concepts for the COVID-19 disease. Simulation results are given in figure 2.

Table 2: Linguistic variables for the concepts of COVID-19

Concepts	Case 1	Case 2	Case 3	Case 4
C1: Fever-body	VH	VH	VH	VH
C2: Cough	VH	H	M	L
C3: Shortness of breathing	VH	H	M	M
C4: Headache	VH	H	VH	VH
C5: Persistent pain in the chest	VH	H	M	L
C6: Bluish lips or face	NP	L	NP	NP
C7: Feeling weak	M	NP	M	VL
C8: heart rate	M	NP	M	VL
C9:hemodynamic instability	VH	VH	M	NP

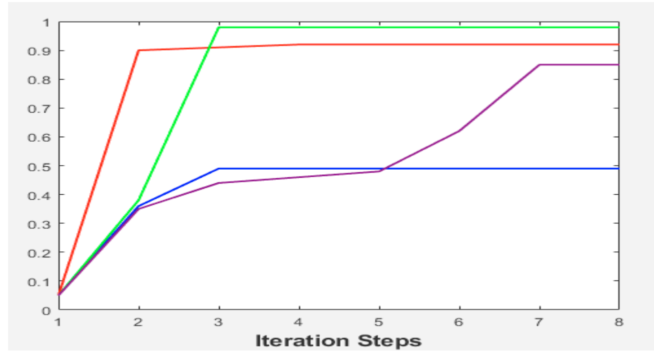

Figure 2: Simulation results concept C10, using real data for the COVID-19 FCM model

6.2 DISCUSION OF RESULTS

Simulations were conducted using the classical FCM model, equations 1 and 2 and the FCM software tools been used by the research team of LAR, Univ. of Patras. The simulation results of figure 2 confirm the validity of the FCM methodology that provides satisfactory results for modelling COVID-19 with the FCM approach. This study is based on real data from the local Patras University Hospital and simulations for all 80 patients. In this paper using the same values for the linguistic variables, table 2 provides us the necessary information to conduct simulations for the four cases (out of the 80-total data set). The iteration steps were chosen to be one full day (24 hours). If we want this can be changed and become an iteration step of one hour. This provides us with the capability to attend the health progress of a patient on a continuous basis. Different colors have been used for the outcome of concept C10. The threshold for the outcome concept C10 was set in consultation with the physicians to be 0.5. Below or slightly above it the patient was free of COVID-19, while above 0.7 a patient would be with COVID-19. From figure 2, the red, green and purple lines are for a patient having COVID-19 while the blue line is for a patient without COVID-19. Analyzing the results of figure 2 a number of useful remarks can be made. Please note that the blue line starts with a jump lower to 0.4 after the first day and rises for the next two days to a value around 0.5 and remains constant. For case 1 the C10 output, red line, rises with a steep slope and in less than a day reaches a value close to 1 (0.92). This result is considered as a positive result and thus the patient (case 1) is affected with COVID-19. The second case, green line the C10 output concept starts with a steep rise between the first and second day and then in the third day it reaches almost the value of 1 (0.98). Finally, case three (3), the third patient with COVID-19, the purple line follows the blue and the green line till the second day, then slows down between the third and the fifth days and it is below the non-COVID-19 threshold of 0.5. However, after the fifth day, it starts rising again passing the threshold point of 0.5 to reach the value of 0.85 after the seventh (7) day, thus making patient case 3, a positive case to COVID-19. These results have attracted the interest of the physicians asking more information for the FCM approach and methodologies. For this particular study of the four case-patients we were 100% in agreement with the medical outputs.

Simulations were run for 80 real cases with data from hospitals and the results been obtained using the FCM methodologies were 94% in agreement with the final medical outcome of the COVID-19's positive results. The missing cases were the cases where the FCM COVID-19 was giving a positive result, the patient had COVID-19. However, the actual medical results were showing this not to be the case. These are very encouraging results.

7. FUTURE RESEARCH

The world is witnessing a fast-growing body of research on COVID-19. International organizations, governments, scientific journals and funding agencies have been calling on researchers to join forces to tackle the pandemic crisis. Early bibliometric evidence suggests a continued existence of cross-border, interdisciplinary, cross-sectoral and multilateral collaboration between researchers of universities, research centers and other research bodies. Despite the early enthusiasm on this aspect lately a global competition and rivalry has emerged. The global race for a COVID-19 vaccine is a telling example of the influence of competition and how scientific research and the intrinsic pursuit of knowledge is tangled with individual interests, institutional benefits, commercial values, public good and (geo)political factors. This unreasonable competition will not benefit the world and especially the developing and poor countries. The research challenges and critical topics of COVID-19 are wide open.

There are many questions related to this pandemic that need to be taken into consideration. What causes a coronavirus infection? Do humans first get a coronavirus from contact with animals? Do health officials comprehend and understand the COVID-19 pandemic? Which patients require an Intensive Care Unit (I.C.U.)? Which of today's drugs are most effective? What might be the long-term effects of the disease for the people that recover from the disease and especially those who had severe symptoms and/or had the need of an I.C.U.? What might be the long-term effects of different vaccines? Do we have mathematical models that can address the many aspects of the pandemic and/or follow the patient for 24 hours a day? On a broader sense questions such how is spread throughout the populations? What are the consequences of all restricted measures imposed by governments on the economic and social life of the societies? On the financial markets?

Therefore, future research directions are many when solutions are searched for all or some of the above questions. This paper is focusing on questions related to the questions if the today's mathematical models are adequate and sufficient to find solutions to this medical problem. In particular it raises the need to pay more attention on the causality parameters and factors that are associated with all aspects of COVID-19. The use of FCMs which is the only mathematical approach that takes into consideration the causality factor when addressing medical problems and thus also COVID-19 seem to be an open field for future research efforts. This paper clearly demonstrates the FCM's usefulness in studying COVID-19. The proposed COVID-19 FCM model provides a good start for further studies. For example, to develop new models for studying the pandemic taking into consideration all related factors. FCM models can be used to track the patients progress in 24 hours and also to predict long term effects of the disease. In addition, the new Advanced FCM (AFCM) been proposed by (Mpelogianni and Groumpos 2018) seem very promising to be applied tackling problems of COVID-19. Both the Classical FCM and the AFCM approaches depend heavily on experts' knowledge and assistance. The process of experts' assistance plays a very important and crucial role in creating the Fuzzy Cognitive Maps according the steps been described above in section 5, Gubanov et al. (2014). The physician experts determine the number and weight of each concept depending the individual case. Another challenging future research direction is the new trend of cognitive modelling and specifically the creating of cognitive semantics that cannot be formalized and has to be taken into account by the indirect way (the inverse problem-solving method on topological space, quantum and relativistic semantics (Raikov 2021). The book by Raikov (2021) is bringing into the pharetra of methods the Artificial Intelligence (AI) in tackling COVID-19 problems with a good degree of success (Nguyen 2020), (Tayarani 2021).

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8. CONCLUSIONS AND FINAL REMARKS

The COVID-19 pandemic remains one of the most significant crises in modern times (Alon, 2020). It is a global pandemic affecting all regions of the world, but more severe North America and Europe especially on the early times of the pandemic. Today many regions of the world continue to experience the tragic effects of the pandemic. COVID-19 is reshaping the world, including the scientific world. What we were familiar with as 'normal' is fading away and will need to be rewritten. Innovation and futuristic thinking are needed to derive useful medical solutions and better policies to address the COVID-19 pandemic challenges. This study gives strong evidence that the FCM theories are probably the only ones that explore the causality between the variables of medical problem in a sound mathematical and scientific foundation. In addition, the FCM is also the only one that has recursive equations and new concepts can be added and/or concepts that are not pertinent to the research study can be removed without having to start the problem from the beginning. In this research study the COVID-19 is reviewed with today's existing knowledge. The Fuzzy Cognitive Maps (FCM) approach is briefly presented. A COVID-19 FCM model was developed using 10 symptoms-concepts. An algorithm is proposed to investigate the problem of determining if a candidate patient is affected or not with the COVID-19 virus. The excellent results been obtained using real data from clinical studies and having satisfying very much medical doctors have powered this author to dare to address the pandemic COVID-19 with FCM theories. The difference between correlation (statistical) and causality is recognized. Medical problems affecting humans and the involvement heavily of human intervention makes the problem of causality more acute. Solutions cannot rely on classical methods. The FCM methods seems to be an appropriate and very useful method in battling COVID-19. A new state space Advanced Fuzzy Cognitive Map (AFCM) methodology is proposed. A big and challenging future research directions are provided with useful guiding recommendations. The references provided are the more recent ones and very useful.

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