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A fuzzy graph approach analysis for COVID-19 outbreak

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ABSTRACT

Complex systems require rigorous analysis using effective method, in order to handle and interpret their information. Spectrum produced from Fourier transform infrared (FTIR) instrument is an example of a complex system, due to their overlapped bands and interactions within the spectrum. Thus, chemometrics techniques are required to further analyze the data, in particular, chemometrics fuzzy autocatalytic set (c-FACS). The c-FACS is initially used to analyze the FTIR spectra of gelatins. However, in this study, the c-FACS is generalized and implemented for analysis of Coronavirus disease 2019 (Covid-19), particularly, the pandemic outbreak in Malaysia. The daily Covid-19 cases in states in Malaysia are modeled and analyzed using c-FACS, to observe the trend and severity of the disease in Malaysia. As a result, the classification of severity of zones in Malaysia are identified. The obtained results offer descriptive insight for strategizing purposes in combating the Covid-19 outbreak in Malaysia.

Introduction

A complex system is often complicated to be analyzed and requires further analysis using various mathematical methods [1]. It involves multi structures due to inter-relation between its components. These components offer significant information that describe the behavior and dynamic of the system. Chemical data in form of signal obtained from spectroscopy is an example of a complex system. It is difficult to analyze due to its large amount variables and features [2]. Large amount of such dataset can cause overlap bands and peaks that lead to difficulties in identifying and differentiating the possible hidden patterns. Thus, a new approach for analysis of the chemical data using mathematical techniques was introduced in 1970s, which is called chemometrics [2].

Chemometrics is a data driven approach with the aid of mathematical tools, which is used in gaining deeper insight and detail interpretation of complex chemical data [3]. Chemometrics methods have been widely used in numerous applications in food and pharmaceutical related industries [4]. Food authentication analyses usually combine chemical techniques such as Fourier transform infrared (FTIR) spectroscopy (see Fig. 1(a)) with chemometrics method called principal component analysis (PCA), especially in identification of gelatin sources, due to large similarity of their protein structure [5,6].

Recently, Hassan et al. [7] introduced a new chemometrics technique by means of fuzzy graph, namely chemometrics fuzzy autocatalytic set (c-FACS) for analysis of gelatin sources. The effectiveness of the technique was proven when published data of food products were analyzed, and it has the capability and can be enhanced for other applications [7].

The Coronavirus disease 2019 (Covid-19) is one of the most devastating pandemics that has claimed over million lives worldwide [8]. Various actions and strategies have been adopted by countries around the world to mitigate the outbreak, such as city lockdown, travel restriction and movement control [9]. Nevertheless, the effectiveness of mitigation strategies taken can be determined or assessed with the aid of mathematical modelling methods [10]. Numerous researchers have been racing in their efforts to seek for solutions and ways to control the spreading of the virus, by developing predictive models and analyzing the trend of cases [11–16]. In particular, a number of researchers...
introduced and applied a mathematical model for infectious disease, namely susceptible – exposed – infectious – recovered (SEIR) model, which consists of framework of differential equations, to describe the dynamic and trend of Covid-19 cases and predict their peaks [11,12]. Tan and Chen [11] applied the SEIR model on data obtained from Hubei, Italy and United States, while Lin et al. [12] applied it on data obtained from Wuhan. Their models showed that the actual measured cases in the respective countries match well with their estimated results. In addition, Verma et al. [13] and Poonia and Azad [14] applied statistical techniques using time-series and autoregressive integrated moving average (ARIMA) models to forecast the trend of infected cases in India. On the other hand, Girardi et al. [15] and Rath et al. [16] applied regression model for cases in Italy and India, respectively. These researchers have come up with mathematical models that can determine the dynamic and trend of Covid-19 cases using differential equations and statistical approaches. In this study, dataset of Covid-19 cases in Malaysia is analyzed using fuzzy graph approach, to classify the trend and severity of the Covid-19 cases in Malaysia.

Fig. 1. (a) FTIR spectra of gelatin (b) Reported new cases of Covid-19 in Malaysia from 10th March to 10th April.

Fig. 2. (a) FACS of FTIR spectra (b) Some possible travel routes among states and federal territories of Malaysia.
The fuzzy graph approach of c-FACS for complex system is introduced and applied for identification of signature and pattern of multiple systems. Initially, the c-FACS method was first introduced in [7], for authentication of gelatin sources. It was introduced as an advanced form of the ordinary FACS [7]. The ordinary FACS is a merging of two concepts, namely, fuzzy graph [17] and autocatalytic set [18]. Fuzzy graph is a concept that combines the idea of graph and fuzzy set. Numerous researchers have studied the properties and different types of fuzzy graphs. Poulik and Ghourali [19,20] studied the concept and properties of bipolar fuzzy graphs, and Poulik et al. [21] discussed interval-valued fuzzy graph (IVFG) and its applications. Ahmad et al. [22] studied the concept of fuzzy graph in combination with ACS to form FACS. Later, Ashaari et al. [23] used the FACS to model pressurized water reactor (PWR) system. Bakar et al. [24] then studied the transformation of the ordinary FACS into its coordinated form in Euclidean space. However, in this paper, the c-FACS is further studied and applied on the recent outbreak of Covid-19 in Malaysia (see Fig. 1(b)). This is possible due to the fact that the outbreak is a complex phenomenon, similar to the FTIR system in [7]. Thus both systems can be represented as FACS graph (see Fig. 2).

The large and complex dataset of Covid-19 cases from multiple states in Malaysia are modeled and analyzed using the c-FACS to identify their signatures of trend of new cases. The structure of FACS is described in the following section.

**Fuzzy autocatalytic set (FACS)**

Graph theory is an important area of mathematics and it has been used extensively in various fields of science and network analysis [25]. According to Chartrand and Zhang [26], a graph, \( G = (V, E) \) consists of set of vertices, \( V = \{v_1, v_2, v_3, v_4, \ldots, v_{n-1}, v_n\} \) and set of edges, \( E = \{e_1, e_2, e_3, e_4, \ldots, e_{n-1}, e_n\} \). The advancement on graph theory has led to the development of several new concepts such as fuzzy graph [17] and FACS [22]. The FACS was introduced by Ahmad et al. [22] as a merger concept of fuzzy graph [17] and autocatalytic set (ACS) [18]. The formal definition of FACS is given as follows:

**Definition 1.** [22] *Fuzzy Autocatalytic Set (FACS)* is a sub graph each of whose nodes has at least one incoming link with membership value \( \mu(e_i) \in (0, 1) \), \( \forall e_i \in E \).

The adjacency matrix of the FACS is a square matrix, \( A = [a_{ij}] \), such that the entries are the membership values from 0 to 1. The dynamicity of the graph is determined via FACS graph dynamic procedure [22]. The procedure involves computation of the Perron Frobenius eigenvalues and eigenvectors of the matrix. The smallest value of Perron Frobenius eigenvector (PFE) is identified and its element is removed from the system. A schematic portrayal of the removal process is shown in Fig. 3.

The graph dynamic procedure removes the insignificant elements until \( 2 \times 2 \) matrix is obtained. In addition, further properties on FACS graph was studied in [24] to transform the graph into coordinated FACS. Ahmad et al. [27] guarantees that any FACS graph with fuzzy vertices and edges can be induced to coordinated FACS graph. Some properties on coordinated FACS have been elaborated in [24,27]. The coordinated FACS involves several procedures such as construction of Laplacian matrix, to obtain \( x \) and \( y \) coordinates that are presented in Euclidean space. The construction of the Laplacian matrix for FACS is described as follows:

**Definition 2.** [24] Suppose \( P^* \) is the transition matrix for fuzzy graph of FACS. Let \( 1 \) denotes the all \( 1 \) s vector such that \( P^* 1 = 1 \). If the graph is strongly connected and aperiodic, then based on Perron Frobenius Theorem, there exist a unique (row) vector, \( \Phi \) for which \( \Phi P^* = \Phi \) with \( \Phi(v) > 0 \) for all \( v \) and \( \sum \Phi(v) = 1 \) which is called Perron vector of \( P^* \). Let \( \Phi \) be the diagonal matrix with \( \Phi(v, v) = \phi(v) \), then the combinatorial directed Laplacian of FACS is defined as:

\[
L = \Phi - \frac{1}{2}(\Phi P^* + (P^*)^t \Phi)
\]

where \((P^*)^t \) denotes the transpose of \( P^* \). The \( x \)-coordinates of the FACS nodes are obtained by finding the Fiedler vector of the combinatorial directed Laplacian matrix. The \( x \)-coordinates are obtained using conjugate gradient method to solve for \( Lx = b \), in which \( b \) is the balance of \( i^\text{th} \) node such that \( b_i = \sum_{j=1}^n b_j = -\sum_{j=1}^n (1-H_j) \). The \( x \)-coordinates of the FACS nodes are then assigned in the Euclidean space.

**Chemometrics fuzzy autocatalytic set (c-FACS)**

An advance form of FACS was studied by Hassan et al. [7], particularly for facilitating the analysis of chemical data or chemometrics analysis. The fuzzy graph-based chemometrics method, namely c-FACS was introduced and applied to analyze sources of gelatins [7]. The spectra of the gelatins were obtained using Fourier transform infrared (FTIR) spectroscopy, and then c-FACS was applied to further distinguish the gelatins. The c-FACS comprises of several procedures to identify dominant signature of samples and to determine the sample’s pattern in coordinated space. An algorithm for the c-FACS method, which combines the FACS graph dynamic and coordinated FACS procedures was developed and described in [7]. The algorithm was specifically developed in order to facilitate the gelatin analysis, due to the large similarity found in their FTIR spectra. The technique was applied to bovine, porcine and fish gelatins for halal authentication purposes in [7]. The early stages of the c-FACS involve the development of fuzzy graph model of the system and followed by the construction of its matrix. The FACS graph of FTIR system is shown in Fig. 2(a).

The set of vertices \( V = \{v_1, v_2, v_3, v_4, \ldots, v_{n-1}, v_n\} \) represents the wavenumbers’ locations of the gelatin molecules during the emission of light while the set of edges \( E = \{e_1, e_2, e_3, e_4, \ldots, e_{n-1}, e_n\} \) represents the light that passes through the molecules and travels during the FTIR analysis [7]. Absorption of light by the molecules are described as the membership values of the graph. The FACS graph is then transformed into matrix in which its entries are the membership values. The construction of the matrix for FTIR is described in the following Definition.
3. Definition 3. [7] A square matrix $A = [a_{ij}]$ is called an FTIR matrix where $a_{ij} = \mu(v_{ij})$ is the membership value of the absorbance readings, $Q_i$, that is defined as follows:

$$
\mu(v_{ij}) = \begin{cases} 
0 & \text{if } Q_i < 0 \\
1 & \text{if } \max(Q_i) \text{ for } i = 1, 2, 3, \ldots, n \\
\frac{Q_i}{\max(Q_i)} & \text{others}
\end{cases}
$$

Such that the dimension of the matrix $A$ is defined as:

$$
A = \begin{bmatrix} [a_{ij}] & [a_{ij}]_{k+p} \end{bmatrix}
$$

if $n = k^2$ for some $k \in \mathbb{N}$

$$
A = \begin{bmatrix} [\mu(v_1)] & [\mu(v_2)] & \cdots \\
\cdots & \cdots & \cdots \\
\cdots & \cdots & \cdots \\
[\mu(v_{n-1})] & [\mu(v_1)]_{k} & \cdots
\end{bmatrix}
$$

and whenever $n \neq k^2$, then

$$
A = \begin{bmatrix} [\mu(v_1)] & [\mu(v_2)] & \cdots & \cdots \\
\cdots & \cdots & \cdots & \cdots \\
\cdots & \cdots & \cdots & \cdots \\
[\mu(v_{n-1})] & [\mu(v_1)]_{k} & \cdots & \cdots
\end{bmatrix}_{k+p}
$$

The c-FACS algorithm for solving the FTIR systems was described in [7]. However, an updated and brief description of the c-FACS algorithm for solving any general complex system that can be represented as FACS is summarized as follows.

Algorithm 1

1. Input the preferred and selected variables from a given system.
2. Build the FACS graph $G_r(V, E)$ such that the set of its vertices, $V = \{v_1, v_2, v_3, \ldots, v_n\}$ represents the variables, and the set of its edges, $E = \{e_1, e_2, e_3, e_4, \ldots, e_{n-1}, e_n\}$ represents the relationships between the variables.
3. Find the membership values for the vertices and edges of the graph.
4. Construct square matrix, $A = [a_{ij}]$, where the entries, $a_{ij} = \mu(v_{ij})$ are the membership values such that the dimension of the matrix $A$ is defined as:

$$
A = \begin{bmatrix} [a_{ij}] & [a_{ij}]_{k+p} \end{bmatrix}
$$

if $n = k^2$ for some $k \in \mathbb{N}$

$$
A = \begin{bmatrix} [\mu(v_1)] & [\mu(v_2)] & \cdots & \cdots \\
\cdots & \cdots & \cdots & \cdots \\
\cdots & \cdots & \cdots & \cdots \\
[\mu(v_{n-1})] & [\mu(v_1)]_{k} & \cdots & \cdots
\end{bmatrix}_{k+p}
$$

and whenever $n \neq k^2$, then

5. Compute the eigenvalue and eigenvectors of the matrix to identify for Perron Frobenius eigenvectors (PFE).
6. Identify the lowest PFE and remove its corresponding elements. Update the matrix to obtain the dominant matrix with $2 \times 2$ dimension.
7. Display the dominant output matrix and its corresponding dominant variables.
8. Compute the Laplacian matrix of the FACS graph as described in Eq. (1).
9. Identify the $x$-coordinates of the FACS by finding the Fiedler vector of the Laplacian matrix.
10. Determine the $y$-coordinates of the FACS by solving $L y = b$, using conjugate gradient method, such that $b_1 = \sum_{j=1}^{n} \mu_{ij} y_1 - \sum_{j=1}^{n} \mu_{ij} y_j$.
11. Plot the coordinates of the system to observe its pattern.
12. Repeat step 1 to 11 to analyze another system and to compare their patterns.
The c-FACS algorithm is used to represent a system in a form of graph and determine the system’s significant feature and pattern. Multiple systems can be analyzed using the algorithm for comparison and pattern classification.

A software, namely, Multisystem Dynamic Identification of Gelatin Sources, is developed to help the user evaluate the dynamicity and pattern of gelatin sources. It has received copyright © 2020 Universiti Teknologi Malaysia - All Right Reserved. It is used to identify the significant features and patterns of gelatin sources via the c-FACS algorithm. In addition, the software algorithm has also successfully analyzed food products such as meat and coffee [7]. Thus, the efficiency and capability of the algorithm have been verified. The software is also applicable in analyzing complex systems and large dataset. In this study, the c-FACS is performed using the software to analyze the Covid-19 outbreak in Malaysia. The implementation of the method is discussed in the next section.

Implementation and discussion

The first positive case of Coronavirus disease 2019 (Covid-19) in Malaysia was detected on 25th January 2020, in Johor, Malaysia [28]. It was an imported case from Wuhan, China whereby the patient had a travel history to Singapore. Since then, the disease has been spreading and the government has taken several actions to overcome the pandemic [28]. Nevertheless, constructive studies and analyses, especially on the severity and trend of the cases are crucial in order to predict and arrange proper strategies for combating the pandemic. In this study, the dataset of Covid-19 cases in Malaysia, which is obtained from Ministry of Health (MOH) Malaysia [29], is analyzed using the c-FACS.

The c-FACS is implemented on dataset of reported new cases between states in Malaysia from 28th March to 5th April 2020. The period is selected due to the irregularity of its trend and highly erratic dataset (see Fig. 1(b)). Some possible travel routes and networks between states and federal territories of Malaysia are illustrated in Fig. 2(b). The networks in Fig. 2(b) can be considered as an ACS if one views it as a graph, whereby each state has an incoming route. The 16 vertices of the graph represent the 13 states of Malaysia and 3 federal territories. The edges are links that connect them. The fuzzy value of the vertex are represented by the daily cases reported in its respective state. The graph is analyzed using c-FACS to observe their clusters in coordinated FACS with respect to their daily cases from 28th March to 5th April 2020. The regions in Malaysia are categorized into 4 groups. Group 1, which is in the north region of Malaysia, consists of Perlis, Kedah, Pulau Pinang and Perak whereas Group 2 contains Selangor, Negeri Sembilan, Melaka and Johor. Group 3 includes Pahang, Terengganu, Kelantan and Sabah, and finally, Group 4 is made up of Sarawak, WP Kuala Lumpur, WP Labuan and WP Putrajaya. Fig. 4 is the output of c-FACS for the classified groups.

Three clusters are identified, namely, Zones 1, 2, and 3. Zone 1 is called Under Control zone. The states in Group 1, which consist of Perlis, Kedah, Pulau Pinang, and Perak are scattered in this zone. These four states have low reported cases of Covid-19 during the period. Zone 2 in the Medium zone consists of states from Group 3, namely, Pahang, Terengganu, Kelantan, and Sabah. These states recorded increasing number of cases starting from 31st March 2020 [29]. Although Zone 2 is dominated by states in Group 3, however, there are a couple of instances in which members of Group 2 and 4 appeared in the zone too. Thus,
there is high possibility for the Group 3 states to move into Zone 3. Zone 3 is the Danger zone. This zone is dominated by the states in Group 2 and 4, namely Selangor, Negeri Sembilan, Melaka, Johor, WP Kuala Lumpur, WP Putrajaya, Sarawak and WP Labuan. Hence, the government has to pay attention to these high-risk states in Zone 3, and also the states in Zone 2 as they are close adjacent to Zone 3. The states with respect to their classified zones are depicted in Fig. 5 (a). The resultant classified zones by c-FACS concur to and almost the same as identified zones published by Ministry of Health (MOH) Malaysia 4 days later on 10th April 2020 (see Fig. 5(b)).

In addition, Jasin, which is a district in Melaka and WP Putrajaya were announced in the red zone on 6th April by Ministry of Health (MOH) Malaysia (see Fig. 6), as predicted by c-FACS with respect to the data up to 5th April, as shown in Fig. 4 and Fig. 5(a) previously.

Furthermore, few districts in Groups 2 and 4 states, namely, Sepang and Hulu Selangor in Selangor, Jasin and Melaka Tengah in Melaka and Rembau and Seremban in Negeri Sembilan were announced as red zones on 10th April 2020 by Ministry of Health (MOH) Malaysia (see Fig. 7). The report published by MOH on the 10th April verifies the c-FACS results as illustrated in Fig. 4 and Fig. 5(a) earlier.

Thus, the c-FACS was able to identify and categorize the severity zones in Malaysia with respect to Covid-19 outbreak. This analysis is useful for the purpose of strategizing, particularly in monitoring the high risk states, in order to stop the virus from spreading. The classification of zones by c-FACS concurred with the published reports released by the Ministry of Health (MOH) Malaysia.

In addition, the c-FACS is also implemented on dataset from 6th April 2020 to 2nd May 2020, to observe the trend following the previous analysis. The result of coordinated FACS for the period is illustrated in Fig. 8.

The pattern of the nodes in Fig. 8 show significant changes from previous pattern in Fig. 4, whereby the zones are now aligned. The alignment of zones (see Fig. 9) indicate that the mitigation strategies taken by the government of Malaysia are in the right track and the pattern and trend of cases in the respective zones have changed following the actions of the government. Serious preventive actions are being taken, particularly in the states in group 2, 4 and 3, thus resulted into the scattered patterns in Zone 2 and only few remain in Zone 3, while Zone 1 is considered as low risk zone and only adequate actions are required. Thus, the results showed that the Covid-19 cases can be controlled if proper and effective actions are taken at targeted zones.

### Advantages of c-FACS

The advantages of this work, particularly, the implementation of c-FACS method in Covid-19 outbreak data, are listed as follow:

- The c-FACS provides a new and simple approach in analyzing complex dataset, such as Covid-19 dataset.
- The c-FACS can classify samples of dataset and able to describe their characteristics and behavior.
- The c-FACS is a fast yet effective method that has been tested and verified in analysis involving food samples.
- The c-FACS requires no preprocessing of the dataset that is usually time consuming.
- The dynamic and trend of Covid-19 cases in Malaysia can be studied as a whole.
- This work is useful for identification of pattern of Covid-19 cases and the severity of zones, that is very important for mitigation purposes in combatting the diseases.
- The c-FACS can be implemented in any region or country that can provide the dataset.

### Conclusion

Complex problem or dataset requires suitable and effective method to describe its features and properties. Graph technique is often used in dealing with complex and network problems, due to its capability in visualizing a system in a form of points and lines. In this paper, a fuzzy graph approach using c-FACS method was successfully introduced and implemented in modeling the outbreak of Covid-19 in Malaysia. The Covid-19 has affected millions of people worldwide and has major impact on our lifestyle and economy. In this study, the c-FACS method modelled the dataset of Covid-19 cases in Malaysia in a form of fuzzy graph, to study the dynamic and trend of cases. The trend and pattern of...
cases were identified which resulted into the classification of severity of zones in Malaysia. The states in Malaysia were successfully categorized into three zones, namely Under Control, Medium and Danger. The resultant classification of zones by c-FACS are similar to the one published by Ministry of Health (MOH) Malaysia few days later. Thus, the results obtained using c-FACS offer descriptive insight and trend that are useful for strategizing actions in combating the pandemic in Malaysia. The capability of c-FACS in identifying the pattern and classification with respect to Covid-19 dataset is proven and its possibilities for other applications are endless.

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**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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