Supervisory Fuzzy Cognitive Map Structure for Triage Assessment and Decision Support in the Emergency Department

Voula C. Georgopoulos and Chrysostomos D. Stylios

Abstract Soft Computing techniques, such as Fuzzy Cognitive Maps (FCMs), can handle uncertainties in modeling complex situations using abstract inference mechanisms; they have been successfully used to select among different suggestions, to lead to a decision and to develop Medical Decision Support Systems for many medical-discipline applications. FCM models have great ability to handle complexity, uncertainty and abstract inference as is the case in the health care sector. Here is examined the case of the triage procedure in the Emergency Department (ED), where a decision supporting mechanism is quite invaluable. A Hierarchical structure is proposed within an integrated computerized health system where the Supervisor is modeled as an abstract FCM to support the triaging procedure and assessment of the health condition of people with communication difficulties such as the elderly arriving at the ED. There is also the lower level of the hierarchical structure where a FCM-ESI DSS has been developed and used to assign the Triage ESI level of every patient. Here a new methodology for designing and developing the FCM-ESI DSS is presented so to ensure the active involvement of human experts during the FCM-ESI construction procedure.

Keywords Medical decision support system · Triage assessment modeling · Soft computing · Fuzzy cognitive maps

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1 Introduction

Hospital Emergency Departments (EDs) require prompt decisions that are significantly difficult in their making as they have to deal with situations characterized by inherent complexity, intrinsic uncertainty and dynamic nature. Frequently, the Hospital Emergency departments are overcrowded by elderly patients requiring critically urgent to non-urgent medical services while they may not able to objectively describe and communicate their own health situation. Older patients (>65 years of age) account for 12–24 % of all ED attendees worldwide [25] and according to recent census data across Europe [9] and the US [29], adults over the age of 65-years-old comprise 17.7 and 13 % of the population making them one of the fastest growing segments of the population estimated to reach 25 % over the next 25 years. Given the constantly increasing age of a population this leads to increased numbers of visits of elderly patients to the ED and as a result to an increased burden on the EDs [32]. Older patients frequently have atypical clinical presentation and/or higher severity of illness, multiple comorbidities, increased frailty, a high prevalence of chronic-degenerative diseases which may include cognitive disorders, are susceptible to frequent exacerbations, all of which contribute to a higher risk of adverse outcomes [1, 26]. Taking into consideration the aging population, with its complexities, increasingly seeking services at the ED in combination with the limited resources and increased costs, this leads to the need for development of advanced decision making tools that will effectively and efficiently provide patient care in a timely fashion.

Although Emergency Departments (EDs) vary worldwide both in terms of range of services offered as well as patients arriving for care in EDs, a recent definition provides an accurate description of what goes on in EDs: “Emergency departments provide unscheduled care for a wide variety of persons for reasons that range from life-threatening conditions to problems that could be treated in a primary care setting” [22].

In all Emergency Departments, specific protocols are followed to evaluate the health condition and sort all the patients entering the ED. This procedure is called triaging and it involves an initial sorting of patients based on their health condition by rapidly identifying patients requiring immediate care due to urgent, life-threatening conditions, as well as assessing the severity of the problem so as to ensure that care is appropriate and timely [8]. According to general accepted protocols, patients are categorized to various levels of urgency [10, 28], based on their general condition as it is concluded by their appearance, their complaints about pain level along with a brief health examination which may include physiological factors when necessary. When available the patient record is also consulted. Following this procedure, the triage approach achieves minimizing of the waiting time for treatment of the most urgent patients, while those not in need of urgent treatment are placed in a waiting area.

A widely used tool for ED triage is the Emergency Severity Index (ESI). The ESI triage procedure yields rapid, reproducible, and clinically relevant stratification of patients into five groups, from level 1 (most urgent) to level 5 (least urgent). The ESI provides a method for categorizing ED patients by both acuity and resource needs [17].

Triage decisions are often made with limited objective data, ambiguous information [16] while other times that there are numerous patient factors (some subjective), physiological measurements, and medical history variables that the ED triage nurse must consolidate during the decision making process [23].

In spite of its widespread use, it is significant to mention that, for older patients, it may present difficulty in accurate categorization by medical personnel not experienced in geriatrics. Also, communication as well as cognitive deficits may present a problem limiting the patient's ability to participate or cooperate during the initial triage process to identify chief complaints, symptoms and history [20]. This may result in potential under-triage or over-triage. In under-triage a patient is assigned a triage code level that is lower than their actual level of urgency based on objective clinical and physiological measures. Under-triage is defined as the underestimation of the severity of an illness or injury, resulting in a patient receiving lower levels of treatment (and/or with lower priority) than required. This decision has the potential to result in a prolonged waiting time to medical intervention for the patient and risks an adverse outcome [7, 30]. Of course, perfect triage is not possible in all cases and triage algorithms are usually designed with an under-triage rate of 5 % as an acceptable error rate trade-off in order to minimizing over-triage [5]. In a study of a sample of 50 randomly selected cases of ED admissions patients 65 years or older, discrepancies were found between the medical staff and expert nurses in 20 cases: where staff nurses had under-triaged 13 patients and over-triaged 7 patients [21]. According to another study [19] of 519 patients over 65, it was found that under-triage occurred in 117 cases, i.e. 22.5 % of the cases. In yet a third study of 4,534 geriatric trauma patients undergoing triage in an ED within a 10 year period, it was found that 15.1 % were under-triaged [24]. Therefore, there is a general consensus that under-triaging is not a result of ESI being a poor tool (quite the opposite actually), but rather the possible overlooking of high-risk situations and not appropriately considering vital signs.

Another difficulty arises from the fact that in various studies conducted of agreement between nurses in rating of triage levels to be only fair to moderate [18] even when conducted within the same hospital with the same group of patient case scenarios [6].

It is generally accepted that all patients arriving at the ED are not of equal severity and complexity requiring those that do not have a severe/and or life threatening condition to wait to receive medical care. These patients are triaged at levels 3–5 and do not normally receive immediate care even though those triaged as level 3 are treated with higher priority over those with levels 4 and 5, etc. When there are several patients waiting with the same ESI level, there are no clear differentiators to establish a prioritization [2]. Normally, after triage patients are prioritized within their level on a first-come-first served basis. For the elderly population where the complexity of problems is increased, a long wait may cause deterioration of their condition. This combined with under-triaging can lead to adverse effects for these particular patients. Therefore, the problem at hand is two-fold, on one hand to be able to provide decision support in order to minimize, as much as possible, under-triaging and on the other hand it is important that patients are also prioritized after the triage classification within their classification category and not be tended to only on a first-come first-served basis.

Emergency departments are not only extremely complex because of the patient assessment and treatment protocols that are in place, but also due to the high level of automation and instrumentation, huge amounts of information, and interdisciplinary coordination that is necessary. Thus, the complex triage decision can be modeled using soft computing modeling techniques such as Fuzzy Cognitive Maps discussed in the next section.

In this work, a two-level Decision Support System is proposed to perform two complementary decisions: automatically assist in the triage classification as well as to suggest and update the priority for patients within their initial classification range.

2 Fuzzy Cognitive Maps

The soft computing technique of Fuzzy Cognitive Maps has been derived through the synergistic combination and integration of aspects of fuzzy logic, neural networks, semantic networks, expert systems and knowledge based systems. FCMs have been supplemented with other soft and hard computing methodologies in order to create advanced Decision Support Systems.

An FCM is illustrated as a causal graph representation consisting of interrelated weighted concepts. FCMs are fuzzy signed directed graphs permitting feedback, where the weighted edge w_{ij} from concept C_i to affected concept C_j describes the degree of causality by which the first concept influences the latter. It is mentioned that FCMs permit feedback and so they are characterized as fuzzy feedback models of causality, where the weighted interconnections between concepts of the FCMs stand for the influence between concepts and so they create an interconnected network of interrelated entities, similar to the abstract mental model than humans creates in their minds to model a complex situation and to infer decisions and suggestions. Feedback interconnections are permitted along with if- then inferencing; this is the main strength of the FCM to model any complex nonlinear dynamic system. Thus, FCMs have the ability to include hidden nonlinear dynamics.

In the Fuzzy Cognitive Model the key elements are concepts that stand for the main characteristics of an abstract mental model for any complex system. Each concept of the FCM model represents a granular entity representing a state, variable, input, output, event, action, goal, and/or trend of the real system that is modeled as an FCM. The value of every concept C_i is A_i and it results from the transformation of the fuzzy real value of the system's variable, for which this concept stands for, in the interval [0,1]. So the initial concept values are produced, which then are updated as they are computed through the interaction of the interconnected concepts with the corresponding weight. Generally, between two concepts there are three possible types of causal relationships that express the type of influence of one concept to the other. The weight of the arc between concept C_i and concept C_j could be positive $(W_{ij} > 0)$ which means that an increase in the value of concept C_i leads to the increase of the value of concept C_j, and a decrease in the value of concept C_i leads to the decrease of the value of concept C_j. When there is negative causality $(W_{ij} < 0)$, this means that an increase in the value of concept C_i leads to the decrease of the value of concept C_j and vice versa. Finally, there can be no causality $(W_{ij} = 0)$.

The value A_i of every concept C_i expresses a fuzzy value of its corresponding physical value. FCMs are used to model the behavior of systems; during the simulation step, the value A_i of a concept C_i is calculated by computing the influence of the interconnected concepts C_j's on the specific concept C_i following the calculation rule:

$$A_i^{(k+1)} = f(A_i^{(k)} + \sum_{\substack{j \neq i \\ j=1}}^{N} A_j^{(k)} \cdot w_{ji}) \quad (1)$$

where $A_i^{(k+1)}$ is the value of concept C_i at simulation step $k+1$, $A_j^{(k)}$ is the value of concept C_j at simulation step k, w_{ji} is the weight of the interconnection from concept C_j to concept C_i and f is the sigmoid threshold function:

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

where $\lambda > 0$ is a parameter that determines its steepness. In this approach, the value $\lambda = 1$ has been used. This function is selected since the values A_i of the concepts must lie in the interval [0,1].

Fuzzy Cognitive Maps have been used to develop Medical Decision Support Systems (MDSS). A specific type for Medical Diagnosis is the Competitive Fuzzy Cognitive Map (CFCM) [11, 12, 15] which consists of two main types of concepts: diagnosis-concepts and factor-concepts. Figure 1 illustrates an example CFCM model that is used to perform medical diagnosis. Here, the concepts of the FCM and the causal relations among them that influence concepts and determine the value of diagnosis concepts indicating the final diagnosis are illustrated.

In the CFCM model each diagnosis concept represents a single diagnosis, which means that these concepts must be mutually exclusive because the main intention is to always infer only one diagnosis. This is the case of most medical applications, where, according to symptoms, medical professionals conclude to only one diagnosis and then decide accordingly concerning the treatment. Actually, this comes from the medical axiom: "every patient has only one disease" but may represent many symptoms related to different diseases but all are results of the primitive disease. The general diagnosis procedure is a complex process that has to take

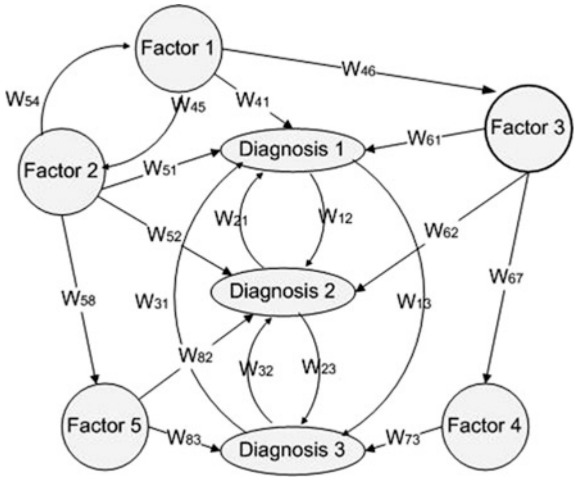

Fig. 1 A CFCM model for medical diagnosis

under investigation a variety of interrelated factors, symptoms and functions. In accomplishing any diagnosis process, some of these factors are complementary, others are similar and even others are conflicting.

In the Competitive Fuzzy Cognitive Map model, the factor-concepts can be considered as inputs into the MDSS from patient data, observed symptoms, patient records, experimental and laboratory tests etc., which can be dynamically updated based on the system interaction, whereas the decision-concepts are considered as outputs where their estimated values outline the possible diagnosis for the patient.

3 ESI Triage System

When a patient first arrives in the Emergency Department, the first stop is triage where a trained and experienced registered nurse typically prioritizes each patient's condition into one of five general categories. This is done according to the Emergency Severity Index (ESI) which was designed for use in ED triage by the US Department of Health and Human Services. The ESI is a five-level categorization algorithm that prioritizes patients into five groups from 1 (most urgent) to 5 (least urgent) on the basis of severity and the number of resources that the patient may need to receive proper care [31].

In particular, the ESI uses the following scale based on decision points to determine its categories [3, 17]:

- ESI category 1-Emergent: patient intubated, without pulse or respiration, or unresponsive i.e. the patient requires immediate life-saving intervention so as to prevent loss of life, limb, or eyesight,
- ESI category 2-Urgent: patient is in a high-risk situation, or confused, lethargic or disoriented, or in severe pain, or danger zone of vital signs.

- ESI category 3-Acute: patient is in need of many resources to be taken care of. These may include, for example, Laboratory Tests, ECG, X-rays, CT-MRI-ultrasound-angiography, IV fluids, specialty consultation, complex procedures etc.
- ESI category 4-Routine: patient is in need of one resource.
- ESI category 5-Non urgent: patient is in need of no resources.

In comparison with other previously used triage severity scales along the dimensions of ease of implementation, ease of use, and in predicting resource demand, users reported that the ESI is much better or at least better [27]. Triage is a dynamic decision-making process and so continuous reassessment of relative factors and evolving information is necessary to ensure that whoever requires the most immediate receives it. It requires a continuously monitoring and keeping track of patients waiting to be seen and a prompt assessment of each new patient who arrives at the triage area. Therefore, due to the dynamic, complex and uncertain nature of the overall triage process in addition to the difficulty in differentiating severity levels, decision support methods are needed to help the triage nurse to be efficient in prioritizing patients with the same acuity classification [2, 23]. Therefore a Hierarchical Decision Support System for ESI Triage based on Fuzzy Cognitive Maps is developed in the next section: the first layer is a FCM-ESI Triage Model and the second layer is a supervisor assisting in patient prioritizing for those patient categorized as ESI 3–5.

4 First Layer Fuzzy Cognitive Map Model for ESI Triage System

In an ED triage system each patient is assigned one of the 5 ESI levels and therefore, the Fuzzy Cognitive Map ESI has to include 5 Decision Concepts (DC), each one corresponding to an ESI level: DC1-ESI Level 1, DC2-ESI Level 2, DC3-ESI Level 3, DC4-ESI Level 4, DC5-ESI Level 5.

The FCM development procedure is based on human experts who must define the main factor concepts that influence the triaging procedure and thus, they have to be represented in the FCM-ESI DSS. The well-known procedure of FCM construction is followed, where there is a group of experts whose knowledge and experience is exploited to design the FCM-ESI DSS and so they are asked to select the main factors based on which they usually conclude to an ESI triage level. Every expert replies with a set of factors that based on his experience are essential to conclude to a triaging decision, this is a blind procedure and no expert knows what the others have suggested. Then, based on the frequency with which each factor was chosen by the group of experts as a whole, the importance weight (*iw*) between a factor concept and a decision concept is determined. It is obvious that the greater the the number of experts the more objective an FCM-ESI DSS will be constructed.

There are 23 factor concepts (FC1-FC23) that have been identified for the FCM-ESI DSS. The importance weights *iw* for the first 22 have been detailed reported in [13, 14] and are mentioned in Table 1. Factor FC23 is a pre-existing communication/cognitive deficit which affects the patient's ability to explain and/or identify the chief complaint. This is an important factor to be assessed because studies have shown that unrecognized cognitive deficits are present in 30–40 % of older emergency department patients [4]. This is due the fact that these patients usually do well in basic communication functions making it not obviously detectable. Therefore, detecting cognitive dysfunction is important because it may affect the ESI level at which they are characterized as well as their thereafter waiting priority.

Moreover, the experts are asked to evaluate the triage stage of specific cases and based on their assessment we infer additional information, which leads to a complementary second weight, the "influence to specific decision" specific weight- *sw*,

Table 1 Factors of the FCM-ESI

Factor concept	Factor	Importance weight (***iw***)
FC1	Life threatening	0.45
FC2	Limb threatening	0.40
FC3	Patient chief complaint	0.67
FC4	Vital signs	0.4
FC5	Medical history	0.35
FC6	Other factor	0.32
FC7	Expected # of resources	0.31
FC8	Patient age	0.16
FC9	Required timely intervention	0.15
FC10	Weakness	0.20
FC11	Additional symptoms other than chief complaint	0.14
FC12	Severe pain or distress	0.12
FC13	Patient referred to ED from outside	0.08
FC14	Behavioral or psychiatric issue	0.07
FC15	No additional symptoms to chief complaint	0.05
FC16	Absence of medical history	0.05
FC17	Patient medications	0.05
FC18	Hospital or ED discharge <3 days	0.04
FC19	Patient immune-compromised	0.04
FC20	Alcohol or illicit drug use	0.03
FC21	No recent change mental state	0.75
FC22	Patient can walk or sit	0.12
FC23	Pre-existing communication/cognitive deficits	0.10

which represents how much the specific factor leads towards a specific decision/ diagnosis. The procedure to calculate the *sw* is the following: every expert who considers one factor as important and takes it into consideration, is asked to present the degree with which this specific factor leads the expert to select one decision. Every expert describes the degree of influence of one factor towards one decision using a linguistic variable, such as "very strong influence *vsi*", "strong influence, *si*", "medium influence, *mi*", "weak influence *wi*", "very weak influence *vwi*", as it is depicted in Fig. 2.

Thus, every expert describes the specific weight *sw* of each interconnection with a fuzzy linguistic variable from the above mentioned set, which stands for the relationship between the two concepts and determines the grade of causality between the two concepts. Then, all the proposed linguistic weights for one interconnection suggested by experts, are aggregated using the SUM method and an overall linguistic weight is produced. The overall linguistic weight with the defuzzification method of Center Of Gravity (COG), is transformed to a numerical weight belonging to the interval [−1, 1].

Then, the overall weight describing the influence from one factor concept towards a decision concept is calculated using the form:

$$w_{ji} = \mathrm{sgn}(sw)(l_1 * iw + l_2 * |sw|) \quad (3)$$

where the two parameters l_1, l_2 are introduced to represent the participation of the *importance weight iw* and the *specific weight sw*, on the overall weight describing the influence of every factor concept towards the decision/diagnosis concept. It is mentioned that the value of w_{ji} has to be normalized in the interval [−1, 1], where the weight takes values.

The current FCM-ESI DSS model has extended the previous developed one [14] to include interactions between the various factor concepts since the decision is complex and there are always cause-effect relationships between factors contributing to the triage decision. These are as follows:

- Vital signs (FC4) and Patient chief complaint (FC3); Vital signs (FC4) and Patient immuno-compromised (FC19)—for example patients that are experiencing fever and are on chemotherapy.

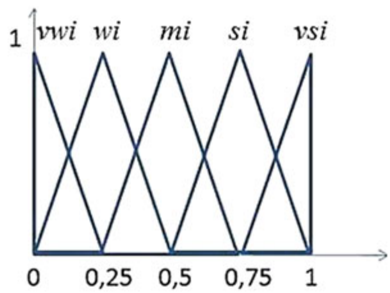

Fig. 2 The positive fuzzy linguistic weights

- Over the counter medications (F15) and chief complaint (FC3)—patients using over the counter pain medication may have a decrease in their pain level and as a result the severity indicated concerning their chief complaint may be decreased
- Over the counter medications (F15) and vital signs (FC4)—over the counter medications may change vital signs, e.g. reduced fever, increased blood pressure etc.
- Pre-existing communication/cognitive deficits (FC23) and Chief Complaint (FC3)—there is increased inaccuracy of the description of the chief complaint with the existence of communication/cognitive deficits.
- Pre-existing communication/cognitive deficits (FC23) and Medical History (FC5)—the reliability of medical history can be compromised by communication/cognitive deficits of the patient.
- Pre-existing communication/cognitive deficits (FC23) and Severe Pain or Distress (FC12)—there may be on one hand inability to judge severity of pain and

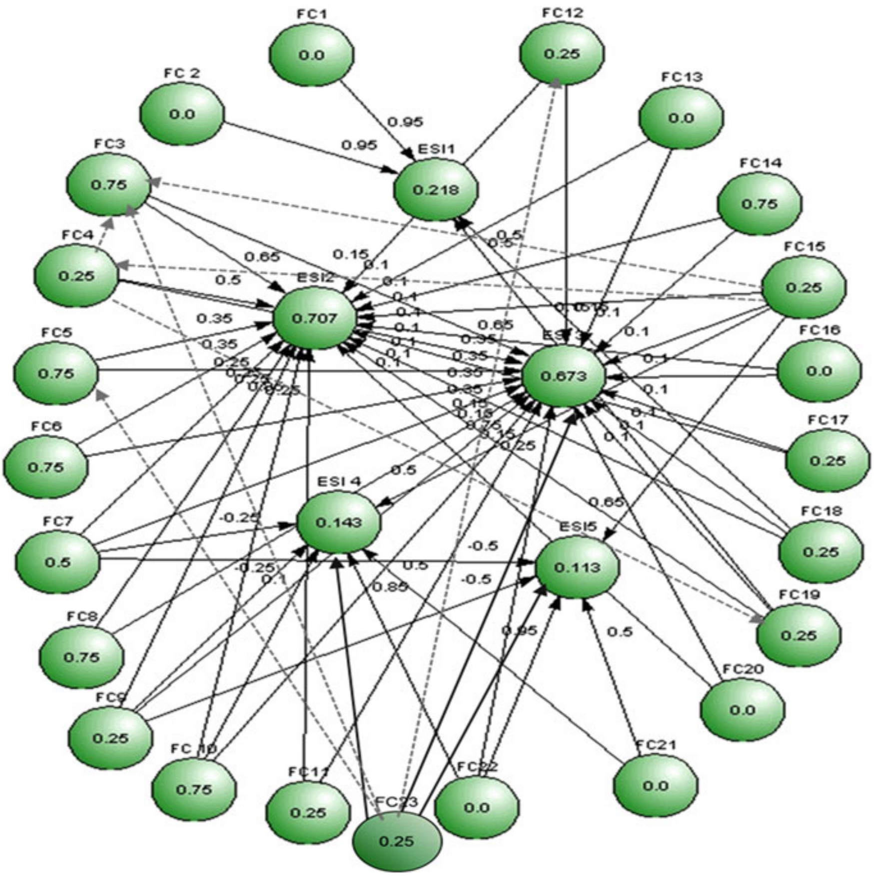

Fig. 3 23 factor FCM-ESI including factor interactions

on the other hand increased distress may be related to unfamiliar environmental change and not to actual medical condition.

Experts were asked to identify the possible interactions among Factor Concepts. At first, every expert is asked to determine the pair of concepts that are coupled. Thus, a set of possible paired factors concepts is created and then all the experts are asked to suggest the degree (using a linguistic weight) of coupling/influencing among the previously identified pairs of factor concepts. A set of five fuzzy linguistic values are used: "very strong", "strong", "medium", "weak", and "very weak".

The complete FCM-ESI is illustrated in Fig. 3 where the 5 central nodes are the decision nodes (ESI levels). The decision node with the maximum value is the level at which a patient is triaged.

The FCM-ESI for every patient takes the concept factor values from measurements, laboratory test and examination and these values are transformed in the interval [0,1] where concepts take values and then the values of Decision Concepts are calculated, so that to infer the ESI level.

5 Supervisor System for Priority Between Equally Triaged Patients for ESI Levels 3–5

An important issue after initial triage for patients with ESI levels 3–5 in an overcrowded ED is the priority with which patients receive care. Patients within a given triage level may end up being seen by a physician on a first come—first served basis. However, unfortunately, severity may change over time. For example, in some cases injuries and illnesses that need medical and nursing intervention are time sensitive. The longer the wait, the more damage may occur because of changes for example such in oxygen, blood, electrolytes (potassium, sodium, etc.), sugar, etc. Failure to prioritize triaged patients appropriately may result in very sick patients at risk for deterioration while waiting. Since this is also difficult and critical decision for the personnel in the ED, a supervisory level has been added on the FCM-ESI DSS model, where the outcome reflects changes in priority for patients within the same ESI level.

In order to develop the supervisor priority FCM-ESI Decision Support Systems, the most essential factor concepts are selected that may influence the patient status. The supervisor priority FCM-ESI consists of the concepts (Fig. 4):

- Change in vital signs (FC4).
- Patient report of worsening symptoms.
- Change in mental state (FC21).
- Change in patient can walk or sit (FC22).
- Triage ESI level.
- Time in waiting area.
- New symptoms.

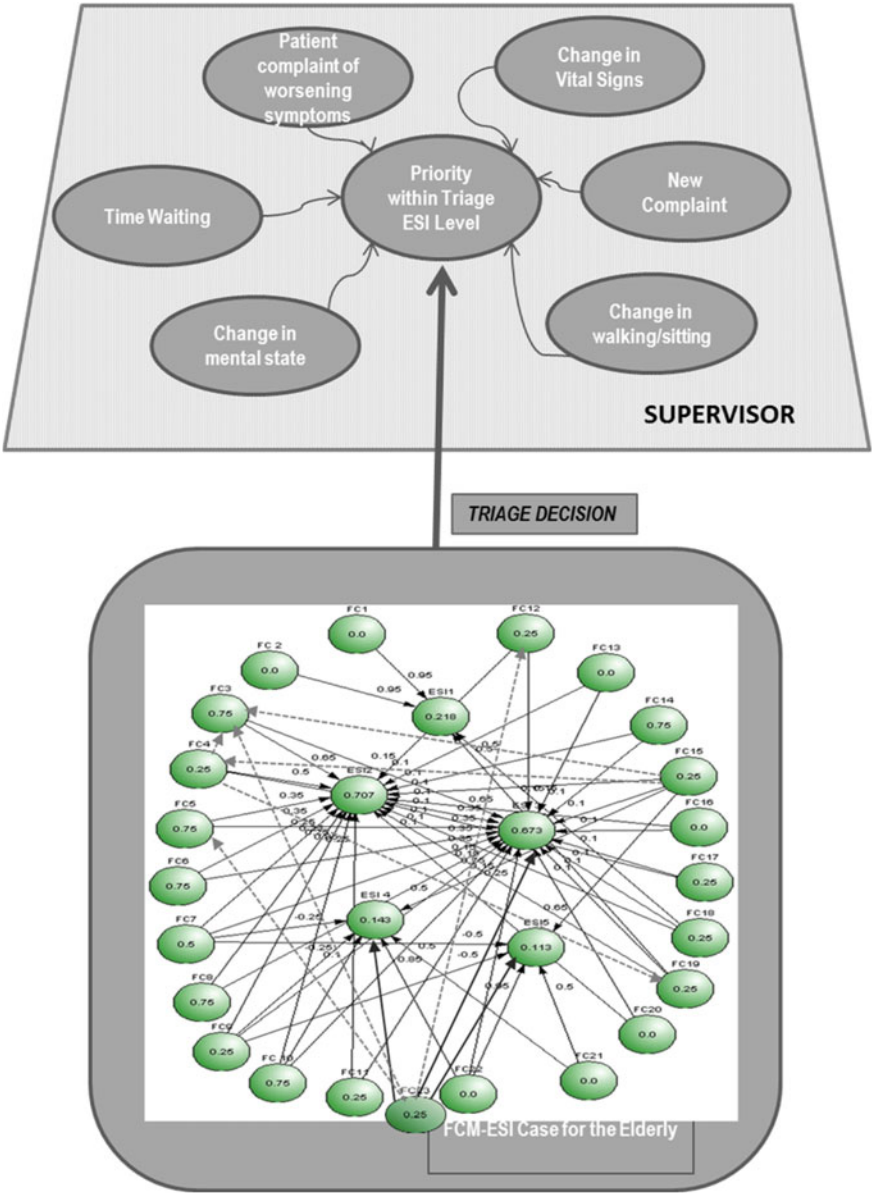

Fig. 4 Supervisory fuzzy cognitive map structure for triage assessment and decision support in the emergency department

Therefore, for each patient where a particular ESI Decision Concept had the maximum value (i.e. the ESI Level with which the patient was characterized) this decision node interacts dynamically with other FC nodes as new information is provided over time and is checked every half hour.

This leads to prioritizing of the patients that have equal or almost equal ESI status in order to avoid adverse events after triage due to long wait in overcrowding. Thus, the supervisor priority FCM-ESI is called to prioritize among patients with the same ESI level.

6 Case Example

A 72-year-old woman presented to a busy emergency department (ED). During triage she told the triage nurse that she experienced face and tongue swelling in the last 2 days. The vital signs at triage, including respiratory rate and oxygen saturation, were normal (BP 125/70 mm Hg, HR 72 beats/min, RR 12 breaths/min, and Body Temperature 36.5 °C). No previous history indicated this condition, the patient had not taken medications, was not in any pain, and there were no problems with the patient's mental state. Also the patient was able to sit and walk. Using the information collected at triage, both a triage nurse and the FCM-ESI resulted in ESI-Level 3.

The patient sat in the waiting room for more than 2 h after which she was placed in a room in the ED. After an additional hour a physician evaluated her. In the meantime, her tongue and throat had swollen substantially, and she was having difficulty breathing. She was diagnosed with angioedema and required emergency intubation, a potentially dangerous and high-risk procedure accompanied by aggressive treatment with intravenous epinephrine.

On the other hand, if the supervisor priority FCM-ESI DSS had been used, due to the change in state after 1.5 h when the patient was experiencing substantial swelling and difficulty breathing, the triage the patient priority would be increased to Very-Very High and thus, the patient would receive immediate care without the need for intubation.

7 Summary

This paper is an extension of previous work [13, 14] and it presents an integrated methodology for developing a hierarchical Decision Support System for ESI Triage. Usually at the Emergency Department (ED) of hospitals medical staff has to cope with many patients, asking for urgent treatment and so they have to assess their health condition under significant time constrains. The case of elderly patients has great importance as they usually are admitted quite frequently at the ED suffering from chronic problems, their health condition is characterized by complementarity and/or controversy and usually with a lack of interaction and low level communication ability. Thus, triaging of elderly people is characterized by high complexity and it makes the assessment and decision about the health condition a difficult task.

For such cases, Soft Computing methodologies are rather suitable and so Fuzzy Cognitive Maps (FCMs) are proposed here to model and develop a Supervisory Decision Support Systems for the ESI Triage during patient admission at the Emergency Department (ED) of hospitals. Generally, FCMs have been successfully applied to develop Medical Decision Support Systems for many discipline fields.

Here, there is further expansion of a recently proposed methodology to develop FCMs exploiting and combining knowledge and experience of human experts along with information and bibliographic data. Moreover, a hierarchical two level structure is introduced consisting of a FCM at each level. In the lower level a FCM-ESI system categorizes patients according to the 5 levels of the ESI. Then in the supervisor layer there is a prioritization of patients within ESI levels 3–5 which is continuously updated, as new information is received, in order to assist in preventing adverse outcomes while waiting.

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