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Introducing Fuzzy Cognitive Maps for developing Decision Support System for Triage at Emergency Room Admissions for the Elderly

Voula C. Georgopoulos*. Chrysostomos D. Stylios.**

*School of Health and Welfare Professions, TEI of Patras, Greece.
(Tel: 30-2610362472; e-mail: voula@teipat.gr).
**Dept. of Informatics and Communications Technology, TEI of Epirus, Artas, Greece (e-mail: Stylios@teiep.g r)

Abstract: This work presents a Fuzzy Cognitive Map Medical Decision Support System (FCM-MDSS) for supporting the triaging of elderly patients arriving in the emergency room for medical assistance while trying to minimize unnecessary admission and/or over/undertriaging. A Fuzzy Cognitive Map MDSS architecture is developed and described here based on existing medical protocols on patient triaging, along with the consultation support of emergency care nurses and physicians.

1. INTRODUCTION

Triaging involves an initial sorting of patients who arrive at the emergency room, usually called emergency department (ED), 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. Triage is a complex decision-making process, and as a result, several triage scales have been designed as decision support systems (Bullard *et al.,* 2008) to guide the triage nurse to a correct decision.

Unfortunately, in the emergency room elderly patients, as a general rule, undergo more diagnostic testing and have longer length of stays than younger patients, because of their multiple health problems and therefore, they usually use more resources. Globally, the Emergency Departments (EDs) are faced with a continuous increase in visits, partly due to their excessive use for non-urgent problems. The elderly frequently visit the ED because of their increased prevalence to chronic-degenerative diseases and susceptibility to frequent exacerbations. Since the ageing population is destined to increase further, providing quality cost-effective care of these patients with multiple, complex conditions is a very crucial problem (Salvi *et al.,* 2007; Soar *et al.,* 2007).

Elderly patients are admitted to the hospital, most of the times, unnecessarily due to the complexity of decision-making about their health conditions (since the clinical problems and needs of older patients are often substantially different from those of younger patients) and they may be accompanied by cognitive or functional deterioration. In addition to this, many older patients have multiple co-morbidities, polypharmacy and further complex social care needs. Additionally they have higher re-admission rates. Many physicians and junior doctors are not specially trained in geriatric medicine so they may have difficulty in assessing the patient's condition as being of an intermediate risk or requiring observation (Conroy & Cooper, 2004).

Besides the various clinical tests and laboratory exams run in the ED and the medical history taking, various questionnaires are used to assess patient status. For example, risk factors known to have often-adverse health outcomes are used by the Questionnaire Identification of Seniors at Risk tool to detect impaired functional status and depression at the evaluation (Samaras *et al.,* 2010). It is significant to mention that in a sample of 50 randomly selected cases ED patients 65 years or older, discrepancies were found between the medical staff and expert nurses in 20 cases, with staff nurses having undertriaged 13 patients and overtriaged 7 patients (Mccall *et al.,* 2009).

Nowadays, the new technological advances, the utilization of ICT in the hospital and all the new technology based diagnostic tests produce a huge amount of information being available to make decisions but under tight time constraints, as is the case of EDs. On the other hand, the limited number of medical professionals requires the efficient exploitation of human resources to make the right decisions and leads to the need to develop automatic decision making systems, such as in the process of triage in the emergency departments.

Generally speaking, Medical Decision Support Systems have a crucial role in complex health systems, since it is necessary to combine the human clinical experience acquired through hospital practice with widely accepted systematic analytic approaches. Such hybrid methods that combine both of them are favored by medical professionals. One such approach is the soft-computing modeling methodology of Fuzzy Cognitive Maps, which is discussed in the next section.

2. FUZZY COGNITIVE MAPS

Fuzzy Cognitive Maps with their modifications integrate aspects of fuzzy logic, neural networks, semantic networks, expert systems and they are usually supplemented by other soft and hard computing methodologies. An FCM is illustrated as a causal graphical representation consisting of

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interrelated concepts . FCMs are fuzzy signed directed graphs permitting feedback, where the weighted edge w_{ij} from causal concept C_i to affected concept C_j describes the degree by which the first concept influences the latter. FCMs are characterized as fuzzy feedback models of causality, where the weighted interconnections between concepts of the FCMs present causality between concepts by creating an interconnected network of interrelated entities, like an abstract mental model. Feedback interconnections are permitted along with if- then inferencing; that permits FCMs to model complex nonlinear dynamic systems. FCMs have the ability to include hidden nonlinear dynamics.

The concepts of the Fuzzy Cognitive Model stand for the main characteristics of an abstract model of any system, each concept of the FCM represents a granular entity such as state, variable, input, output, event, action, goal, trend of the 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]. This produces the initial concept value which is then is updated as it is 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 from 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 $(W_{ij} < 0)$ which 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 concept C_i expresses the degree 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:

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

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:

$$f = \frac{1}{1+e^{-\lambda x}} \tag{2}$$

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) (Georgopoulos and Stylios, 2008) which consists of two main types of concepts: diagnosis-concepts and factor-concepts. Fig.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 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.

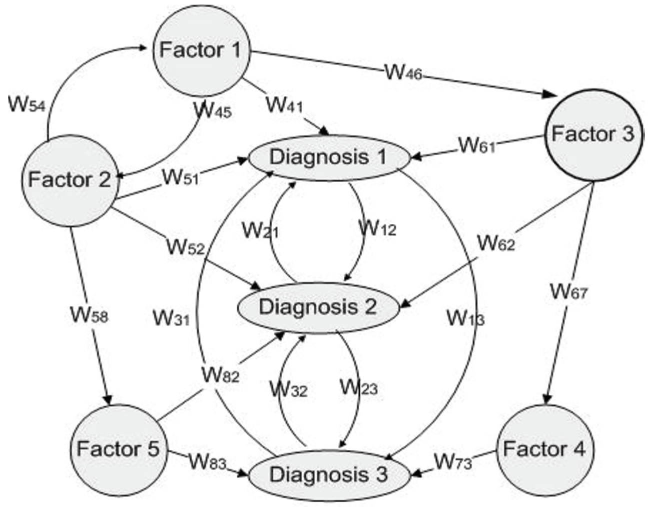

Fig. 1. A CFCM model for Medical Diagnosis.

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. EMERGENCY ROOM TRIAGING

3.1 Emergency Department Triaging Details

To ensure patient safety and provide quality services, hospitals must be certain that each patient entered to the emergency department (ED) receives the appropriate care at the right time. Triage is the initial assessment and sorting of patients in an emergency setting to ensure that patients with life-threatening conditions are quickly identified and treatment is started immediately. An experienced triage nurse evaluates the patient's condition, as well as any changes, and determines their priority for admission to the ED and their need for treatment (Barbee *et al.,* 2010). This is necessary to make patient assessments in order to properly anticipate the resources needed for each patient and recognize abnormal vital signs; thus, tools such as the ESI are "only as good as the person using them". For example, a study conducted among 305 triage ratings comparing triage nurses' ratings to retrospective ratings assigned by an expert panel of emergency department triage nurses revealed an agreement in approximately half of the cases.

Of course, the primary goal of triage is to decrease morbidity and mortality for all ED patients. However, a gap in the knowledge exists regarding the real time reasoning process of clinical decision making that occurs during ED triage.

The ESI uses the following scale based on decision points to determine its categories (Barbee *et al.,* 2010):

- *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 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.

3.2 Decision Support for ED Triage

The significance of the ED triage assessment has lead researchers to investigate and developed Decision Support Systems for ED Triage. A Web-based triage decision support tool (eTRIAGE) based on the Canadian Triage and Acuity Scale (CTAS) has been developed in Canada and is now used in a number of ED regional hospitals. Decision support, such as an electronic triage tool, can assist the medical staff performing triage by displaying the key elements for each complaint that help define the criteria for each triage level. It is expected that experienced triage staff are better able to estimate a triage level based on their initial clinical assessment than those with less experience, giving them greater confidence to override the tool if required (Zimmermann, 2001).

Wilkes and colleagues (2010) proposed a system of cognitive agents and a supervisor, dubbed the TriageBot System that would gather both logistical and medical information, as well as take diagnostic measurements, from an incoming patient for later use by the triage team. TriageBot would also give tentative, possible diagnoses to the triage nurse, along with recommendations for non-physician care.

Finally, Aronsky and colleagues (2008) have described an integrated, computerized triage application which exchanges information with other information systems, including the ED patient tracking board, the longitudinal electronic medical record, the computerized provider order entry, and the medication reconciliation application. The application includes decision support capabilities such as assessing the patients' acuity level, age-dependent alerts for vital signs, and clinical reminders.

Research using empirical results from a clinical trial of an emergency DSS with a decision model based on expert knowledge has shown (Hine *et al.,* 2009) that there are differences in how clinician groups of the same specialty, but different level of expertise, elicit necessary emergency DSS input variables and use these variables in their clinical decisions.

4. FUZZY COGNITIVE MAPS DEVELOPMENT

Since the ESI instrument categorizes ED patients into 5 mutually exclusive categories, the type of Fuzzy Cognitive Map that will be used here is the Competitive Fuzzy Cognitive Map (CFCM) where the possible decision outcomes are mutually exclusive and compete with each other (Georgopoulos and Stylios, 2005; 2008).

The proposed approach here is not only based on human experts, but, also, it introduces the usage of existent widely accepted procedures and bibliographic data, demonstrating a hybrid methodology. It is proposed to use the experience and human reasoning procedure, in order to determine the importance of every factor and, therefore, its degree of influence on the corresponding assignment. Usually every individual, in order to conclude to a decision, doesn't take into consideration all the possible factors but focuses on the most important factors, a procedure that is dependent on the specific conditions; that means that the same expert, in another case, may select another set of essential factors.

In order to generalize the procedure and produce a generic decision making model, the following approach is introduced. First, the possible factors that may influence a decision are determined based on bibliographic and generally accepted methodologies, then specific cases are presented to a group of experts asking them to select the most important factors for each case and reach to a decision. Thus, for every case, every expert usually selects 3-5 factors, based on which he concludes to a decision/ diagnosis. So for every factor / concept, we introduce its ***importance weight***, which will be used then to determine its influence to the final decision:

iw = (times of considering this factor)/(total number of cases). (3)

Moreover, we introduce a complementary second weight, the "influence to specific decision" ***specific weight-*** sw, 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 the 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 "strong influence", "medium influence", "weak influence", etc.

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 lingustic weight with the defuzzification method of Center Of Gravity (COG), is transformed to a numerical weight sw, 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:

$$w_{ji} = \text{sgn}(sw)\left(l_1 * iw + l_2 * |sw|\right) \quad (4)$$

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.

4.1 Developing FCM model for the 5-level ESI Triage System

The proposed approach here is implemented for the case of constructing a decision making model for the 5-level Emergency Severity Index (ESI) triage system (Wuerz *et al.,* 2000; Tanabe, *et al.,* 2004). The ESI describes the main factors and based on them provides a standardized algorithm for the triage process using a systematic approach and utilizes both intuitive and analytical approaches to clinical decision making.

Based on the literature and a study of 18 triage nurses (Garbez *et al.,* 2010), a series of factor concepts were concluded to be part of the Competitive Fuzzy Cognitive Map decision support for ESI (CFCM-ESI) for triage. Twenty-two (22) factors are selected that represent the potential concepts of the Fuzzy Cognitive Map decision model, but they do not all have the same importance in order to infer an assignment on the severity of the patient based on the 5- level triage system. In the research of Garbez and colleagues (2010), only ESI level 2 or level 3 were studied, where triage nurses were asked to select 3 to 4 factors that they rated as important in their clinical decision making process as they assigned an acuity level for each individual patient. Examples of these are shown in Table I as well as the corresponding ***iw*** values (the times of considering this factor)/(total number of patient cases, i.e. 334), which will be included as factor concepts of the CFCM-ESI.

Table I. The ***importance weight*** iw for Factor Concepts

Physical meaning	iw = (times of considering this factor)/ total number of cases.
Patient chief complaint	0.67=224/334
Vital signs	0.4=136/334
Medical history	0.35=120/334
Other factor	0.32=110/334
Expected number of resources	0.31=106/334
Patient age	0.16=54/334
Required timely intervention	0.15=53/334
Additional symptoms other than chief complaint	0.14=49/334
Severe pain or distress	0.12=42/334
Patient referred to ED from outside	0.08=29/334
Behavioral or psychiatric issue	0.07=25/334
No additional symptoms to chief complaint	0.05=18/334
Absence of medical history	0.05=18/334
Patient medications	0.05=17/334
Hospital or ED discharge<3 days	0.04=15/334
Patient immune-compromised	0.04=14/334
Alcohol or illicit drug use	0.03=13/334

However, based on bibliographic data and in order to develop an integrated advanced FCM-ESI, some additional Factor Concepts mostly related to the other 3 ESI levels, but not exclusively, are included:

- Life or organ-threatening condition, ***iw***=.45 based on prevalence statistics of emergency room triaging of elderly (Platts-Mills *et al.*, 2010) in conjunction with the fact that this is a very significant determining factor for ESI level 1.
- Limb threatening state ***iw***=0.40, based on prevalence statistics of limb loss in the general population (NLLIC, 2008) and elderly visits to the emergency room in conjunction with the fact that this is a very significant determining factor for ESI level 1.
- Weakness, ***iw***=0.20 (Nicket *et al.*, 2009)
- No recent change mental state, ***iw***=0.75 (Wilber, 2006)
- Patient can walk or sit for prolonged periods ***iw***=0.12, based on non-urgent presentations (Australian Institute of Health and Welfare, 2010)

The ***importance weight, iw,*** values for these factors were calculated on incidence % of arrivals in an ED and refers to patients over 65 years of age.

It is concluded that the CFCM-ESI will consist of these 22 Factor Concepts in total; based on them a possible triage Decision will be assigned, and more accurately, each patient is assigned one of the 5 ESI levels, thus the Fuzzy Cognitive Map will include 5 Decision Concepts (DC) each one for every ESI level:

Table II. Decision Concepts

Decision concept (DC)	Physical meaning
DC1	ESI Level 1 (ESI1)
DC2	ESI Level 2 (ESI2)
DC3	ESI Level 3 (ESI3)
DC4	ESI Level 4 (ESI4)
DC5	ESI Level 5 (ESI5)

After determining the concepts of the Fuzzy Cognitive Map, the most important issue is the assignment of the influence between concepts, which is the second step on FCM development (Stylios and Groumpos, 2004). The FCM development procedure is very important so that this model is used for decision making and diagnosis. Here, we use the methodology proposed in the previous section in order to assign weight values between the Factor Concepts (FC) and the Decision Concepts (DC).

This developing methodology is mainly based on the data used and provided at the study of Garbez and colleagues (2010), where 334 cases of patients were examined and 18 experts assigned them to ESI levels.

According to this methodology, the first stage is the assignment of the ***importance weight***, at every concept using the equation (3) and depicted in Table I.

Then the ***specific weight, sw***, representing the influence from a Factor Concept FC to a Decision Concept DC must be determined following the approach presented in the previous section. Subsequently equation (4) is applied in order to calculate the weight from Factor Concept to Decision Concepts. Here, for this case, in order to calculate the overall weight from FCs to DCs, a simplified version of equation (4) is used along with the normalization to 1, where $l_1 = 1$ and $l_2 = 0.5$.

$$w_{ji} = \text{sgn}(sw)\left(1 * iw + 0.5 * |sw|\right) \quad (5)$$

The overall weight after the normalization to 1, is then fuzzified and the weights from FCs to DCs are depicted in Table III. These are used to produce the Fuzzy Cognitive Map illustrated in Figure 2.

At this stage of the research we only assign weights from Factor Concepts to Decision Concepts, but the FCM capabilities permit us to introduce weights among the Factor Concept themselves, that create a more accurate but too complex model; this is part of on-going research.

Table III. Specific weights sw from FCs to DCs of the CFCM-ESI

FC#	Name of concept	ESI1	ESI2	ESI3	ESI4	ESI5
FC1	Life threatening	VVS	0	0	0	0
FC2	Limb threatening	VVS	0	0	0	0
FC3	Patient chief complaint	0	MS	MS	0	0
FC4	Vital signs	0	M	MW	0	0
FC5	Medical history	0	MW	MW	0	0
FC6	Other factor	0	MW	MW	0	0
FC7	Expected number of resources	0	W	MW	-W	-M
FC8	Patient age	0	W	VW	0	0
FC9	Required timely intervention	0	W	VW	-W	-M
FC10	Weakness	0	VS	S	VV W	0
FC11	Additional symptoms other than chief complaint	0	W	VW	0	0
FC12	Severe pain or distress	0	VW	VW	0	0
FC13	Patient referred to ED from outside	0	VV W	VW	0	0
FC14	Behavioral or psychiatric issue	0	VV W	VVW	0	0
FC15	No additional symptoms to chief complaint	0	VV W	VVW	M	MS
FC16	Absence of medical history	0	VV W	VVW	0	0
FC17	Patient medications	0	VV W	VVW	0	0
FC18	Hospital or ED discharge 3days	M	VV W	VVW	0	0
FC19	Patient immunocompromi sed	M	VV W	VVW	0	0
FC20	Alcohol or illicit drug use	0	VV W	VVW	0	0
FC21	No recent change mental state	0	0	0	M	M
FC22	Patient can walk or sit	0	0	W	VS	VVS

The weights of Table III are based on membership functions:

- VVS positive very very strong (high end of the *pvs* membership function)
- VS positive very strong (*pvs* membership function)
- S positive strong (*ps* membership function)
- MS positive medium strong (high end of the *pm* membership function)
- M positive medium (*pm* membership function)
- - M negative medium (*nm* membership function)
- MW positive medium weak (low end of the *pm* membership function)
- W positive weak (*pw* membership function)
- -W negative weak (*nw* membership function)
- VW positive very weak (*pvw* membership function)
- VVW positive very weak (low end of the *pvw* membership function)

6. CONCLUSIONS

Here, the soft computing methodology of Fuzzy Cognitive Maps (FCMs) is applied for the first time to develop a Decision Support System (DSS) for the ESI Triage, a significant procedure during patient admission to the ED. The main focus of this application is on older patients who are admitted quite frequently at the ED suffering from chronic problems, presenting many complementary and/or controversial symptoms and often not presenting a high level communication ability that increases the complexity of any assessment and decision about their health condition, the emergency and the required treatment.

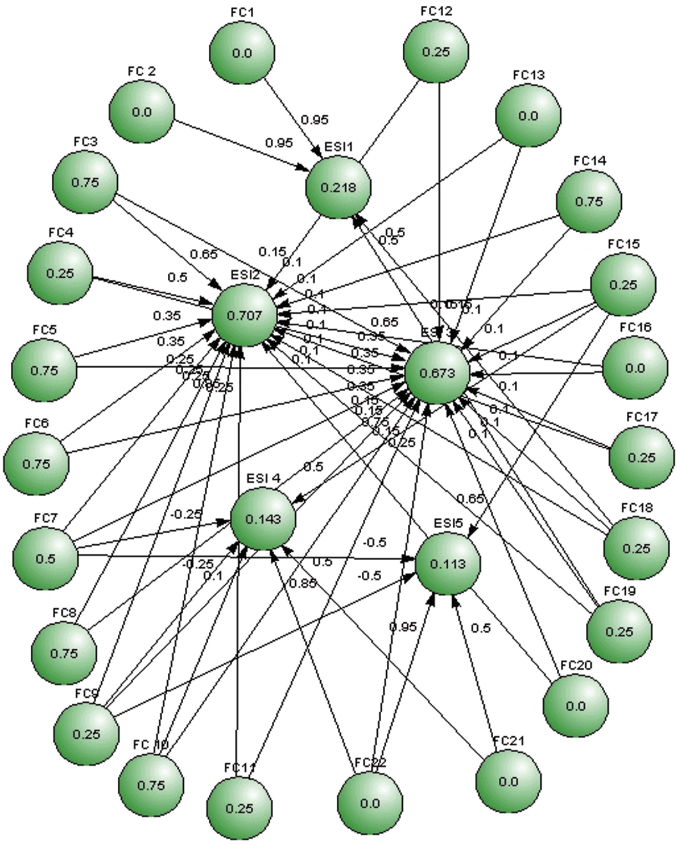

Fig. 2. The CFCM-ESI for the first case.

FCMs have been successfully used to develop Medical DSSs and here the general framework of Competitive FCMs is used. In addition to this, here a novel development methodology for FCM is applied that combines the knowledge and experience of human experts along with information and bibliographic data, in order to create a more efficient CFCM-MDSS. The clinical decision support system based on CFCM for the 5-level ESI triage scale was developed and presented in detail: it considers 22 factors and concludes to one of the 5 ESI triage levels. It is considered that the CFCM is an efficient modeling method for the complex decision-making process of triage, and it will be developed into an advanced CFCM-ESI system for the ED. This advanced CFCM-ESI, following the development methodology presented here, will take into consideration more factors, as well as interaction between factors, in order to create a generic integrated MDSS. This CFCM-ESI will be tested and its accuracy will be compared with the rating of experienced triage nurse and the rates of undertriage and overtriage will be analyzed.

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