Decision Making in External Beam Radiation Therapy based on Fuzzy Cognitive Maps

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Abstract— This work introduces the use of the soft computing technique of Fuzzy Cognitive Maps to model the decision-making process of radiation therapy and develop an advanced system to estimate the delivered dose to the target volume. During radiotherapy planning numerous factors are taking into consideration that increase the complexity of the decision-making problem. The modeling methodology of FCM has the ability to integrate and consider different, discipline and conflicting factors to determine the dose. A Fuzzy Cognitive Map Model is developed, that can handle imprecise and uncertain information and is used as the decision-making model determining the radiation dose and the complex radiation therapy system. The proposed FCM model is implemented for a practical radiotherapy treatment planning case of gynecological cancer.

Index Terms—**Decision Support, Fuzzy Cognitive Maps, Modeling, Soft Computing**

I. Introduction

Radiotherapy is the implementation of ionizing radiation to cure pathological illness by eliminating the infected cells. In the case of cancer cells, there are used photons or electrons and the major issue is the determination of radiation dosage distribution. For the determination of the treatment, it is necessary to know how this tumor will be destroyed by irradiation and how surrounding healthy tissue is likely to be adversely affected by the applied radiation. Doctors have to take into consideration many different factors that some are complementary, other similar and other conflicting. On the other hand each factor influences the selection of the dose and finally the result of the therapy with a different degree.

A large number of treatment techniques have been developed to allow optimization of the delivered dose distribution in radiation therapy, where the most important clinical requirement is their ability to deliver strongly nonuniform beams on the patient from arbitrary directions. For very complex tumours the number of beams required to eradicate the tumour without severe injury to normal tissues is quite high, to accurately make the three-dimensional dose distribution conform to the target volume. For simple target geometries fewer beams are sufficient, and in many cases with small tumours the classical uniform rectangular beams will do nicely. The calculation of radiotherapy dose involves a trade-off between computation time and accuracy [1].

The kind, nature and number of the parameters-factors that have to be taken under consideration in determining the radiation treatment bring up the fuzziness, the complexity and the uncertainty of the model. These characteristics and qualities lead to use the Soft Computing technique of Fuzzy Cognitive Maps to model the decision-making process of radiation therapy [2]. FCMs can model complex systems that involve different factors, states, variables, and events. FCMs can integrate and include in the decision-making the partial influence of controversial factors [3]. FCMs can take under consideration causal effect among factors in recalculating the value of all the causal concepts that determine the radiation dose, keeping it in a minimum level and at the same time having the best result in destroying tumor and with the minimum injuries to healthy tissues and organs at risk. This is the uppermost goal of any radiation therapy treatment [4].

II. Fuzzy Cognitive Map Model

A Fuzzy Cognitive Map can be used to assist in the decision making process of treatment planning. The radiation treatment decision-making process is a complex system and Fuzzy cognitive maps have been successfully used to model complex systems and support making decisions.

FCMs follow a method similar to the human reasoning and decision-making process; they use a symbolic representation for the description and modeling of complex systems. They utilize concepts to illustrate the different aspects of the model and behavior of the system and these concepts interact with each other showing the dynamics of the system. FCM structures are used to represent qualitative and quantitative data. A Fuzzy Cognitive Map integrates the accumulated experience and knowledge on the causal relationship between factors/characteristics/components of the system; due to the way it is constructed, i.e., using human experts that know the system and its behavior under different circumstances [5].

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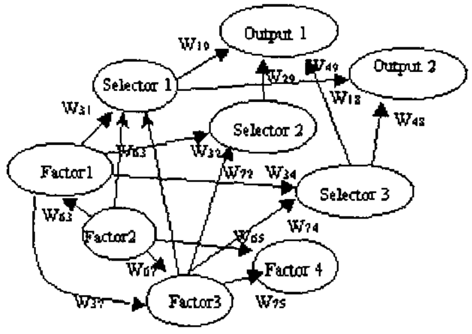

Fig.1 FCM model consisted of selectors, factors and outputs.

A Fuzzy Cognitive Map stores the existence knowledge on the behavior of the system on the structure and kind of nodes and their weighted interconnections between nodes. Each node-concept represents one of the key-factors of the modeled system and is characterized by its value A_i. Between concepts there is cause and effect relationship that is illustrated in the FCM graph with the weighted arc W_{ij} from one concept towards another. The value of W_{ij} indicates the degree that concept C_i influences concept C_j. The sign of W_{ij} indicates whether the relationship between concepts C_i and C_j is direct or inverse. The direction of causality indicates whether concept C_i causes concept C_j, or vice versa. These three parameters have to be considered when a weight W_{ij} is assigned to an interconnection. During the development of FCM fuzzy values are assigned to the weight for each interconnection that are transformed using a defuzzification method in numerical weights.

Every concept of Fuzzy Cognitive Map takes a value that represents the quantity of the representing input, output, state and variable; for which this concept stands for. The value of a concept is influenced by the interconnected concepts. The value A_i for each concept C_i is calculated by the equation:

$$A_i^{t+1} = f\Big(\sum_{\substack{j=1 \\ j\neq i}}^{n} A_j^t W_{ji}\Big) \qquad (1)$$

Namely A_i^{t+1} is value of concept C_i at step t+1, A_j^t is the value of concept C_j at step t, and W_{ji} is the weight of the arc from concept C_j towards concept C_i and f is a threshold function.

A generic FCM model for the radiotherapy decision-making model is consisted of 3 kinds of concepts. There are the **Factors-concepts** that are taking into consideration in determining the value of **Selector-concepts. Selectors-concepts** influence the **output-concepts** that determine the final decision. The FCM model has the capability to represent all the factors and selectors and the existing relationships among factors and among selectors; because factors are dependable and there is an influence of one factor to the others; and the same happens with the selectors. Moreover, factors influence the degree of selectors and the value of each selector can subsequently influence the degree of the output concept. In fact, when a doctor makes decision on the radiation therapy he determines the selectors concepts their values, and the output concepts taking into consideration all the related factors. Figure 1 illustrates the FCM decision-making model.

The FCM is developed using a fuzzy logic based methodology [6]. Experts are asked to describe relationships among concepts using IF-THEN rules to justify the cause and effect relationship among concepts and infer a linguistic weight for each interconnection. The inference of the rule is a linguistic value describing the causal relationship between the two concepts. Every expert suggests for each interconnection a linguistic weight and so the group of expert a set of linguistic weights of each interconnection that are integrated and then defuzzified using the Center of Area (CoA) method that produce a numerical weight for each interconnection [7].

III. Factors in Radiotherapy Treatment Planning

When treating complex tumors a variety of factors are taken into consideration in order to optimize the treatment plan.

These may include:

1. The depth where the tumor is located from skin surface.
2. The shape (geometrical / irregular) and size of the tumor.
3. The location of the tumor in part of the body or head and/or size of cross section treated.
4. The local invasive capacity of the tumor and its potential spread to the regional lymph nodes.
5. The type of tissue with the tumor, as well as the type of tissue that surrounds the tumor. The presence of inhomogeneities within the irradiated volume such as bone, muscle, lung, fat and air.
6. The dose distribution within the target volume should be reasonably uniform (within ± 5%).
7. The 90% isodose curve should surround completely the treatment volume.
8. The tumor position regarding the center of the contour cross section.
9. The existence of radiation-sensitive organs within the irradiated volume, such as: eyes, bladder, salivary glands, etc that should not receive doses.
10. Damage to the healthy tissue outside the treatment volume (maximum dose ≤ 110% of prescribed dose).
11. Patient thickness and contour shape in treatment area.
12. The number of radiation fields and the daily dosage on the tumor based on the biological damage of the healthy subcutaneous tissue. When treating with multiple fields, the question arises whether one should treat one field per day or all fields per day.
13. Cost of equipment, shielding, and of usage space.

14. The length of time required administering the treatment - it is difficult to keep a patient immobilized for a long period of time. The length of procedure preparation time (both for patient and staff).
15. Amount of scattered radiation accepted by the patient.
16. Almost perfect matching of beam with target volume.
17. Degree of difficulty in repeatability (flexibility) of setup of the patient and treatment geometry.

On the other hand, in order to achieve a good distribution of the radiation on the tumor, as well as to protect the healthy tissues the following should be taken into consideration:

1. Selection of appropriate size of the radiation field.
2. Increase of entry points of the beam.
3. Selection of appropriate beam directions.
4. Selection of weight of each field..
5. Selection of appropriate quality, energy and type.
6. Modification of field with cerrobend blocks or multileaf collimators and/or wedge filters.
7. Processing the outline of the patient with addition of compensating filter or bolus in place of missing tissue.
8. SSD (Source to Skin Distance).
9. Use of isocentric rotation or stationary beam therapy.
10. Patient immobilization.
11. Use conformal (3D) or conventional (2D) radiotherapy.

Treatment planning refers to procedures and decisions preceding the radiation treatment that are consisted of both physical and clinical procedures. The treatment planning process comprises several methods for treatment preparation and simulation towards achieving a reproducible and optimal treatment plan for the patient. Irrespective of the temporal order, these events include:

- Patient fixation, immobilization and reference point selection.
- Dose prescriptions for target volumes and the tolerance level of organ at risk volumes.
- Dose distribution calculation
- Treatment simulation
- Selection and optimization of
  - -radiation modality and treatment technique
  - -the number of beam portals
  - -the directions of incidence of the beams
  - -beam collimation
  - -beam intensity profiles
  - -fractionation schedule

The dose calculation system should also be capable of utilizing all the technical capabilities of existing treatment units, and have reliable routines for optimizing the most important treatment parameters [8]. The calculation of the physical dose distribution, which means the prediction of response in radiation therapy, mainly utilize the following data: beam energy, basic beam data, field sizes, distances, arrangement of beams, and patient data, including body size and shape, location of structures of interest and inhomogeneity distributions. But it is clear that we are far from having the necessary data for predicting biological response as a function of the physical and temporal variables.

What is "best", of course, still depends on the clinical judgment of the radiation oncologist, who must define tolerance dose levels and organ volumes, which are permitted to exceed these levels, as well as target, overdose and underdose levels and their corresponding volumes. These parameters are generally used for prescribing and performing the treatment and for reporting the treatment results with regard to tumor and normal tissue effects or the general quality of life of the patient after radiation therapy [9][10].

IV. Development of FCM for Modelling Radiotherapy Treatment Planning

All the factors that are taken into consideration to determine the characteristics and other values of the radiotherapy system have described and analyzed in the previous section. These factors and characteristics consist the concepts of the Fuzzy Cognitive Map that models the decision-making procedure of the radiotherapy treatment.

The Fuzzy Cognitive Map model for the radiotherapy treatment system is consisted of is 33 concepts, which are divided into 3 categories: **factor-concepts, selector-concepts** and **output-concepts**. Factor-concepts represent inputs given or measured that take their values from the real system with sensors and their measurements. The values of the selector-concepts are influenced and determined by the value of the factor-concepts with the corresponding causal weight. On the other hand, the values of the output concepts are influenced and determined by the value of the factor-concepts and the selector-concepts with the corresponding causal weight. The decision making process is the determination of the values of the output nodes.

Values of concepts are described using linguistic variables depending on the particular concept, such as high, medium and small that are transformed in numerical values using a defuzzification method. On the other hand, some concepts may represent continuous values and in this case their value is calculated as the percentage of the real value. Another case is when concepts represent events and discrete situations, in this case there is a threshold (0.5) that determines which event is activated. All the values of concepts in the FCM belong to the interval [0,1]. The Fuzzy Cognitive Map consists of the following concepts:

Concept 1: Depth of tumor. This concept can be scaled in five fuzzy values.

Concept 2: Size of tumor. This concept can be scaled in seven fuzzy values.

Concept 3: Shape of tumor. This concept represents the degree of irregularities scaled in three fuzzy values.

Concept 4: Location of tumor - size of cross section.

Concept 5: Regional metastasis of tumor. This concept can be scaled in five fuzzy values.

Concept 6: Type of tissue(s) included in irradiated volume – inhomogeneities. This concept represents the degree of inhomogeneity scaled in 4 fuzzy values.

Concept 7: Dose uniformity within target volume. The most important concept taking desired almost fixed value.

Concept 8: 90% isodose surrounding treatment volume. The most important concept taking desired almost fixed value

Concept 9: Skin sparing. This concept can be scaled in five fuzzy values.

Concept 10: Patient thickness. This concept can be scaled in five fuzzy values.

Concept 11: Patient contour. This concept can be scaled in five fuzzy values.

Concept 12: Scattered radiation received by patient. This concept can be scaled in five fuzzy values.

Concept 13: Time required for treatment procedure or planning. This concept can be scaled in five fuzzy values.

Concept 14: Cost of equipment, shielding and space. This concept can be scaled in five fuzzy values.

Concept 15: Almost perfect match of beam to target volume. This concept can be scaled in three fuzzy values.

Concept 16: Edge Effect. Value of this concept can be scaled in three fuzzy values.

Concept 17: Tumour position regarding center of contour cross section. It can be scaled in three fuzzy values.

Concept 18: Irradiation of one side of skin surface.

Selector 1: Type of radiation. This concept represents three discrete values.

Selector 2: Quality of radiation. This concept represents the quality of radiation, so it takes continuous values.

Selector 3: Size of radiation field(s). The size of radiation field is categorized into five fuzzy categories.

Selector 4 : Single or multiple field combinations. This concept represents two discrete conditions.

Selector 5: Beam direction(s)

Selector 6: Weight of each radiation field. It represents the percentage of each field.

Selector 7: Stationary versus rotation - isocentric - beam therapy. This concept represents two discrete conditions.

Selector 8: SSD (used in non isocentric techniques).

Selector 9: Wedge filters. This concept takes fuzzy values representing the degree of the applied filters.

Selector 10: Compensating filter or bolus. This concept represents two discrete conditions.

Selector 11: Patient immobilization. This concept represents discrete conditions.

Selector 12: 2D versus conformal (3D) radiotherapy. This concept represents two discrete conditions.

Output-concept 1 (OUT1): Dose given to the target volume in acceptable limits. It can be scaled in three fuzzy values.

Output-concept 2 (OUT2): Damage to healthy tissue in irradiated volume. It can be scaled in three fuzzy values.

Output-concept 3 (OUT3): Radiation sensitive organs within irradiated volume. It is scaled in 3 fuzzy values.

Concepts C_1 to C_{18} are the factor-concepts, concepts S_1 to S_{12} are the selector-concepts and the OUT1-3 are the output concepts. The values of the selector-concepts will determine, for example, what type and/or energy of radiation is chosen, whether there are multiple or single fields, if wedge filters are used, etc. The values of the output concepts will determine if the amount of dose given to the target volume and to surrounding healthy tissues and to organs at risk is acceptable (according to the doctors and the protocols for the treatment).

In this phase of the research, we use published research work as "experts" in order to retrieve the main factors (radiotherapy parameters) and the relationships among them. Using the previous described methodology for development of FCMs [8], an ensemble of fuzzy rules is used to describe every relationship. The fuzzy rules for each interconnection are evaluated in parallel using fuzzy reasoning and the inferred fuzzy weight are combined and deffuzified and the result is a crisp value representing the weight of each interconnection. This methodology is applied for every interconnection of the FCM, and so the weights among factor-concepts and selector-concepts, selector and output concepts, and output-output concepts, are calculated and gathered in Tables I, II III respectively.

As an example, experts describe the influence from selector-concept S_3 to output-concept OUT_1 representing the amount of dose to target volume using a set of fuzzy rules from which it is inferred that there is positive influence:

IF a small change occurs in value of selector-concept S_3 ***THEN*** a large change in value of concept OUT1 is caused. This means that if a small change occurs in the size of radiation field, which used for the specific case of treatment therapy then a change in the value of dose to the target volume happens, increasing the amount of dose. So, the influence of S_3 to OUT_1 is positively strong. This transformed in weight 0.72 (Table I).

Analogous is an influence among the factor-concept C_2 towards the selector-concept S_3 representing the size of radiation field, using the set of fuzzy rules from which it is inferred that there is positive high influence:

IF a small change occurs in value of factor-concept C_2 ***THEN*** a large change in value of concept S_3 is caused. This means that the size of the tumour influences the size of radiation field. For larger size of target volume, the size of radiation field increases. The influence of C_2 to S_3 is positively strong. This transformed in weight 0.8 (Table I).

Also, there is a positively very strong influence among the factor-concept C_1 towards the output-concept OUT_2, meaning that if the depth of tumour is great, the delivered dose to normal tissues is larger. This influence is positively very strong, transformed in weight 0.88.

The existence of causal relationships from selector-concepts towards the factor-concepts creates cycles of causality. For example there is a causal relationship from selector-concept S_2 towards factor-concept C_{15}. It relates the quality of radiation with the perfect match of beam to the target volume. When the quality of radiation is low, the match of beam to the target volume decreases, which means less perfect match than the accepted value, this transformed in weight 0,6. Analogous is the influence from selector-concept S_2 towards the factor-concept C_{13}. When the quality of radiation is high, it causes the almost perfect match of beam to the target volume, which means that the concept C_{13} is increased.

TABLE I
The weights of the interconnections among Factors and Selectors

Factors/ Selectors	S1	S2	S3	S4	S5	S 6	S7	S8	S9	S10	S11	S12
F1	0,78	0,8	0,6	0,62	0,4	0,42	0,58	0,6	0,7	0	0,2	0
F2	0,75	0,75	0,7	0,6	0,2	0,53	0,55	0,52	0,5	0	0,6	0,5
F3	0,42	0,4	0,6	0,63	0,4	0	0,38	0	0,41	0	0	0,7
F4	0,68	0,38	0,36	0,6	0,37	0,52	0,4	0,6	0,54	0,52	0,8	0
F5	0,45	0,78	0,8	0,6	0,72	0,6	0	0,45	0	0	0	0
F6	0,75	0,75	0,32	0,58	0,5	0,55	0,47	0,5	0	0	0	0,6
F7	0,62	0,62	0,6	0,7	0,65	0,6	0,2	0,74	0,7	0,7	0,5	0,4
F8	0,58	0,65	0,68	0,72	0,6	0,72	0	0,6	0,6	0,75	0	0,4
F9	0,52	0,75	0,65	0,67	0,72	0,74	0,45	0,55	0,55	0,6	0	0,6
F10	0,35	0,6	0,5	0,6	0,6	0,6	0,2	0,5	0,5	0	0,5	0
F11	0,22	0,5	0	0	0,6	0,58	0,72	0,3	0,58	0	0,68	0,6
F12	0,61	0,72	0,75	0,6	0,58	0,55	0,22	0,6	0,52	0,6	0	0
F13	0,33	0	0	0,52	0	0	0	0	0	0	0,5	0
F14	0,6	0,6	0	0	0	0	0	0	0	0,5	0	0,6
F15	0,5	0,5	0,7	0,65	0,65	0,7	0,4	0,2	0,5	0	0,6	0,72
F16	0	0	0	0,75	0	0,5	0	0	0	0	0	0
F17	0	0	0	0	0,58	0	0,7	0	0	0	0	0
F18	0	0	0	0	0	0	0	0	0,64	0	0	0

Besides the interrelationships between factor-concepts and selector-concepts, selector-concepts and output-concepts, and factor-concepts with output-concepts, there are also some relationships among the factors, selectors and output-concepts themselves. As an example there is a relationship between concept S_4 and concept S_6 in both ways, when concept S_4 has a value that stands for single field or multiple fields, this determines the value of concept S_6, which is the value of weight of each radiation field. Also there are causal relationships, in both ways, among the output-concepts OUT_2 and OUT_3 towards the OUT_1.

V. Implementation of FCM in a Complex Radiotherapy Planning Process.

The aim of radiation therapy is to maximize the delivered dose to the tumor-target volume and minimize the delivered dose to normal tissues and organs at risk. In practice, the healthy tissues and sensitive organs receive an amount of radiation, which must be minimum, in order to not evoke further implications to the patient. The radiation oncologist determines the tolerance levels of each tissue and organ, and the amount of acceptable dose for radiation therapy for each specific case.

The treatment planning case of gynecological cancer therapy is examined and the corresponding Fuzzy Cognitive Map model is developed. The values of concepts correspond to the physical measurement of their physical magnitude. It is apparent that an interface is needed, which will transform the physical measures of the system to their representative values in the FCM mode and vice versa.

Each concept has a value, which ranges in the interval [0,1] and is obtained after thresholding the real value of the concept. Initial measurements of the real system have transformed to concept values and the initial vector is formed:

A=[0.6 0.5 0.55 0.6 0.4 0.5 0.75 0.82 0.5 0.5 0.45 0.55 0.5 0.5 0.75 0.5 0.56 0.52 0.7 0.72 0.75 0.7 0.48 0.52 0.5 0.45 0.52 0.5 0.6 0.85 0.6 0.35 0.4].

Applying the methodology for determining the weights of the interconnection of FCM, that was analyzed in the previous section, the following Tables I, II and III are produced, representing the weights of interconnection between factor-concepts and selector-concepts, selector and output concepts, output-output concepts, for desired values of treatment planning. Each connection between concepts has a weight, which ranges between [-1,1].

TABLE II
The weights representing relationships among selectors and OUTs

Selectors	OUT1	OUT2	OUT3
S1	0,72	-0,65	-0,64
S2	0,62	-0,67	-0,58
S3	0,5	-0,64	-0,68
S4	0,55	-0,45	-0,4
S5	0,43	-0,58	-0,55
S6	0,48	-0,4	-0,42
S7	0,25	-0,2	-0,2
S8	0,35	-0,38	-0,3
S9	0,52	-0,63	-0,57
S10	0,45	-0,6	-0,6
S11	0,7	-0,52	-0,5
S12	0,82	-0,8	-0,75

TABLE III
The weights of the interconnections among OUT concepts.

OUTPUTS	OUT1	OUT2	OUT3
OUT1	0	-0,4	-0,3
OUT2	-0,28	0	0
OUT3	-0,22	0	0

For the constructed FCM, the initial values were assigned to the concepts and the simulation of the FCM starts. Equation (1) is used to calculate the new values of concepts after each step of the FCM. Figure 2 presents the values of concepts for eight simulation steps. FCM reaches an equilibrium region and if new values for one or more concepts change externally, then after a limited number of steps, FCM will reach again the equilibrium region.

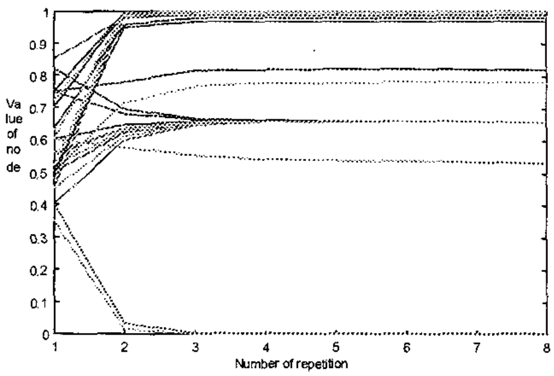

Fig. 2. Variation of values of 33 concepts for the FCM model of the treatment planning process, after 8 simulation steps.

For this simulation example, the values of output-concepts at the equilibrium region are: for OUT_1 0.9986, for OUT_2 0.0021 and for OUT_3 0.0033.

The values of output-concepts OUT_2, OUT_3 have to be very low, less than 0.005, because in reality there is a small percent of ionizing radiation which influences the healthy tissues and the organs at risk. The values of OUT_1 have to be near to 1, (greater than 0.98) because we want to have the best result, irradiating the tumour-target volume, the optimum therapy.

The simulation results give accepted values for the treatment planning because values of output-concepts OUT_2, OUT_3 are very low and very high value of OUT_1 within the suggested limits. This means that the suggested Fuzzy Cognitive Map model optimise the radiation treatment. This happens because experts have suggested all values of FCM model and they are optimal for the case of gynaecological cancer, resulting in the optimisation of radiotherapy procedure.

So, the aim and intent of the radiation treatment is to eradicate adequately the tumor without severe injury to surrounding normal tissues and sensitive organs and to accurately make the tree-dimensional dose distribution conform to the target volume. This aim is accomplished using the proposed model, that take under consideration all the necessary factors and selectors that affect the treatment procedure planning system and determine the optimum values of concepts.

VI. Conclusions

The radiotherapy treatment planning systems is a complex system for which is extremely difficult to develop a precise mathematical model. Thus, it is more useful to develop an abstract model using a FCM showing the causal relationships between states-concepts. This symbolic representation and model is easily adaptable and relies on human expert experience and knowledge.

Our research work is focusing on utilizing FCMs as a model for decision support during treatment planning. The characteristics of FCMs and the fact that are based on human experience make them suitable for application in this decision-making problem. FCMs were chosen as the design methodology because they can easily interpret and show the relationships between different concepts and, it is relatively easy to add or remove concepts, whenever necessary. An FCM has been implemented for a radiotherapy planning process problem that makes apparent the qualities and characteristics of the method. It has been observed how simply the FCM describes a system's behavior and its flexibility in any change of the system.

All the factors that determine the decision procedure were presented and examined that emerge the need for an advanced modeling approach that can take under consideration every kind of factor either complementary or controversial. Finally a Fuzzy Cognitive Map model was developed that creates a sophisticated decision support system for the radiotherapy procedure and the simulation results give acceptable-optimum amount of delivered dose to the target volume and normal tissues.

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