

Application of fuzzy cognitive map-based TRIZ inventive principles for sustainable sediment management in dam reservoirs

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Abstract

The present paper contributes to the development and discussion on fuzzy cognitive map (FCM)-based theory for inventive problem solving (TRIZ) for sustainable sediment management in reservoirs. FCM combines aspects of fuzzy logic, neural networks, semantic networks, expert systems, and nonlinear dynamical systems. TRIZ is a constructive methodology that includes practically reproducible models and methods that allow the development of new inventions as well as the teaching of the process, the models, and the methods of creating inventions. A proposed approach in this paper is an improvement methodology that is designed to bring about rapid improvements/changes to processes by defining and implementing the changes that can be quickly identified and easily implemented, thereby reducing the cost and time to bring about improvement and change in reservoirs. Results of this study provide a road map for how to introduce FCM and TRIZ into local sustainable sediment management with consideration of technical and executive requirements, economic factors, social welfare, and environmental impacts.

Key words: fuzzy cognitive map, sediment management, theory for inventive problem solving (TRIZ)

INTRODUCTION

The reduced rate of dam construction throughout the world combined with storage loss due to reservoir sedimentation currently results in more storage being lost annually than is added. This problem is further exacerbated by population growth, which results in a sharply declining storage volume per capita. Climate change will further adversely impact the performance of reservoirs (Nikolaos *et al.* 2017).

Consideration of technical and executive requirements, economic factors, social welfare, and environmental impacts should be the used combination of alternatives to extend the useful life of reservoirs. Based on the literature and existence experiences, a list of alternatives for sediment management in dam reservoirs can be categorized as follows (Khakzad & Elfimov 2014a). (1) Reducing sediment inflows: watershed management, upstream check structures, reservoir bypass, off-channel storage. (2) Managing sediments within the reservoir: operating rules, tactical dredging. (3) Evacuation of sediments from the reservoir: flushing, sluicing, density current venting, mechanical removal. (4) Replacing lost storage: increased dam height, construction of a new dam. (5) Decommissioning. The cost and applicability of each strategy will vary from one site to another and study of sites will create appreciation of the complexity of sediment problems and the way in which they can be controlled (Khakzad & Elfimov 2014b, 2015).

In light of the potential problems described above, there is a clear need for a strategy that can combine traditional scientific knowledge with public local context, thereby reducing uncertainty and

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providing for a diversified and adaptable knowledge base (Gray *et al.* 2014). To assist in the development of a sediment management plan based on both public participation and expert knowledge, we propose the use of fuzzy cognitive maps (FCMs) as a semi-quantitative model tool that provides a structured, simple, and inexpensive way to model overall fluvial systems through a soft evaluation of the relationship between different concepts and factors interpreted by stakeholders. In environmental sciences, cognitive mapping techniques have been used mainly in environmental conflict management (Ozesmi & Ozesmi 2004; Papageorgiou & Kontogianni 2012; Gutiérrez *et al.* 2017; Malek 2017; Paolisso & Trombley 2017).

In addition, to help the engineer effectively solve contradiction problems occurring in the system, the theory for inventive problem solving (TRIZ) method was invented. Altshuller (1984), an inventor, introduced a contradiction table and 40 inventive principles including 88 sub-principles that have been extended by an additional 72 sub-principles extracted from TRIZ standard solutions, by analyzing over 400,000 patents. This enhanced version of 40 inventive principles with 160 sub-principles is used in the presented research. D'Anna & Cascini (2011) proposed the sustainability map, based on two key items of TRIZ: the existence of evolution trends and the system operator to identify scenarios to achieve sustainability. Practically, all these TRIZ tools can be used for solving different tasks and problems of eco-innovation. Because of the capability of solving conflict problems, implementing TRIZ for eco-innovative design tasks have been proposed in the literature, establishing a link between eco-efficiency and the inventive principles and the contradiction matrix (Chen & Liu 2003; Chang & Chen 2004; Justel *et al.* 2006; Vidal *et al.* 2015).

In the present study, the general methodology applied to the development of a major process improvement for sediment management in dam reservoir is based on FCM-based TRIZ inventive principles. Experimental designs were applied to the execution of process characterization studies evaluating the impact of operating parameters on process performance parameters. Data from process characterization experiments were used to define the proven acceptable range and classification of operating parameters.

METHOD

Fuzzy cognitive maps

An FCM has the topology of a fuzzy signed directed graph and dynamics similar to feedback non-linear neural networks, as is illustrated in Figure 1 (Kosko 1986, 1992; Papageorgiou *et al.* 2010). The fuzzy causal relationship between two concepts C_j and C_i is described with the weight R_{ji} ,

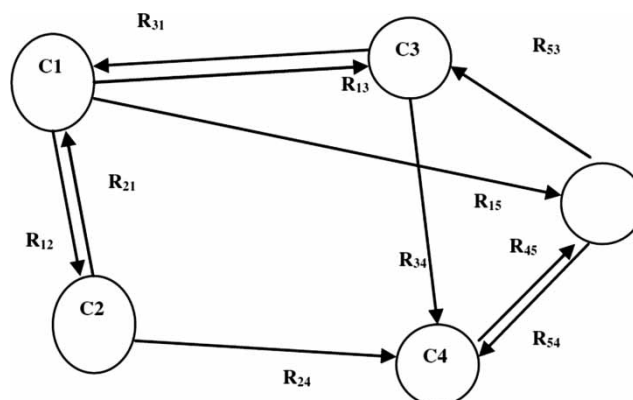


Figure 1 | Conceptual representation of fuzzy cognitive map.

taking a value in the range -1 to 1 . There are three possible types of causal relationships between concepts:

- $R_{ji} > 0$ which indicates positive causality between concepts C_j and C_i . That is, an increase (decrease) in the value of C_j leads to an increase (decrease) in the value of C_i .
- $R_{ji} < 0$ which indicates negative causality between concepts C_j and C_i . That is, an increase (decrease) in the value of C_j leads to a decrease (increase) in the value of C_i .
- $R_{ji} = 0$ which indicates no relationship between C_j and C_i .

The simulation and inference process of the FCM is based on a mathematical formulation described in Equation (1). Through the following calculation rule, the values of concepts are calculated at every simulation step k iteratively:

$$A_i^{k+1} = f \left[A_i^{(k)} + \sum_{\substack{j=1 \\ j \neq i}}^N A_j^{(k)} \cdot R_{ji} \right] \quad (1)$$

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 , R_{ji} is the weight of the interconnection from concept C_j to concept C_i , and f is a sigmoid threshold function:

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

where $\lambda > 0$ is a parameter that determines its steepness. In our approach, the value $\lambda = 1$ has been used. This function is selected since the values A_i lie within $[0, 1]$. The values A_i of concepts C_i are initially fuzzy and arise from the transformation of the real values of the corresponding variables to each one concept. Also, the values for the weights of the interconnections R_{ji} among concepts are fuzzy. These fuzzy values are converted into numerical values after the defuzzification process of fuzzy logic and are used in the FCM simulation process. The value A_i of the concept C_i expresses the degree of its corresponding physical value. At each simulation step, the value A_i of a concept C_i is calculated by computing the influence of other concepts C_j 's on the specific concept C_i following the corresponding mathematical formulation.

The theory for inventive problem solving

The simplest TRIZ algorithm is shown in Figure 2. General comments regarding the scheme are as follows (Cong & Tong 2008; Collan 2018; Orloff 2018).

Stage TREND

Resolution of any problem starts with an analysis of the initial situation or, if you will, with diagnosing the problem. The analysis naturally involves determination of 'what,' 'where,' and 'when' occurs in the system so that the quality of outcomes produced by such a system and, accordingly, the efficiency of its operation and makeup, become suspect answers to these questions and must produce a sufficiently accurate and concise description of the initial problem situation.

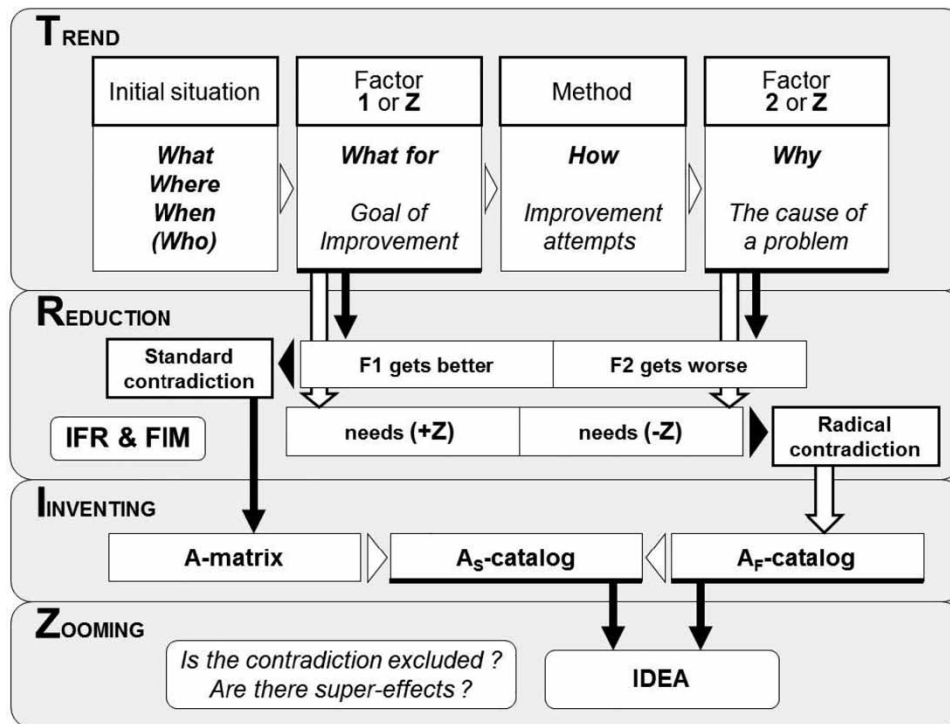


Figure 2 | TRIZ for pass through standard contradiction.

Stage REDUCING

Be that as it may, the concentrated answer to the question ‘what for’ – as posed at the Stage Trend – is formulated in the form of the ‘Ideal Final Result’ (IFR). This IFR substantially shapes the trend, i.e., the purpose and pattern, of the future system transformation.

Stage INVENTING

At this stage, the generation of ideas is supported with transformation models borrowed from catalogs created in TRIZ. In Modern TRIZ, this stage is also called ‘transformation.’

Stage ZOOMING

The use of the metaphorical name ‘zooming’ is determined by the nature of the main verification procedures, namely, that they must verify the ideas at several levels of examination. To do this, we must ‘zoom up’ and assess the quality of the solution, say, at the level of the entire system. Then, we might want to take an even broader look at the level encompassing the interests of the user for whom the artifact (system) was created in the first place.

RESULTS AND DISCUSSION

Schematic representation of a step-by-step FCM generation process is shown in [Figure 3](#). The context of the interview is explained to the interviewee. In the next step, the interviewee is asked to write down a list of factors that he or she thinks is important in relation to the central question. After the factor list is finished the interviewee is asked to start with the drawing of the map. After all the causal connections including their directions are stated, the strength of the connections is determined.

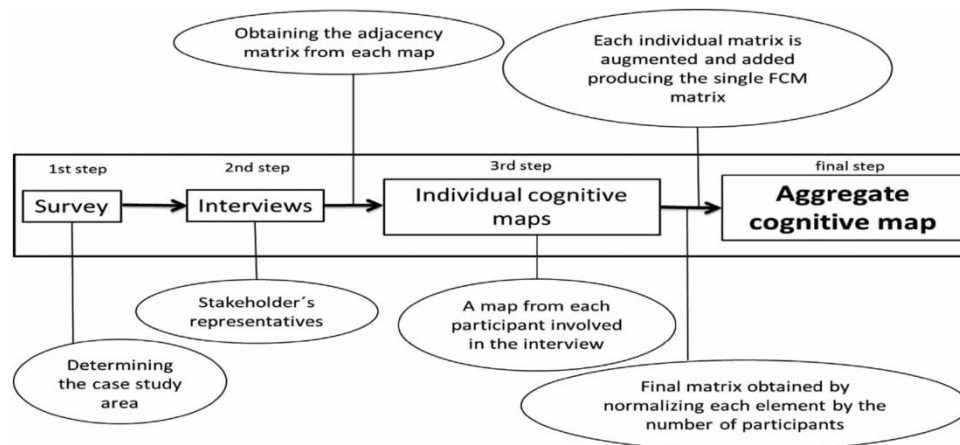


Figure 3 | Schematic representation of a step-by-step FCM generation process.

In most cases the interviewees were asked to choose numerical values right away, e.g., 0.1 for a very weak relation, 1 for a very strong connection.

For sustainable sediment management, the 12 individual maps built by stakeholders and decision-makers represented the raw data to develop the FCM. After the interview sessions, all maps were coded into adjacency-matrices and then analyzed and visualized with FCMapper (Table 1 and Figure 4). When no causal relationship was given in the individual map, zero was used. The connection values between two specific variables were summed and averaged over the total number of individual maps. Figure 4 visualizes the group map, where circles symbolize concepts of the system and lines reflect causal relationships between concepts. The size reflects the centrality of the variable within the system. The most central variables were construction and operation time, economic costs, and economic benefits.

After preparing the FCM and evaluating the interrelation between factors' effects on sustainable sediment management, the definition of scenarios built on the policy objectives identified by stakeholders with the help of TRIZ which is designed to show how changes to processes can be quickly improved and change the quality of sediment management in a dam reservoir. Parameter to improve, undesired results (conflict), and principles for three scenarios with the help of stakeholders based on the TRIZ method with 40 inventive principles and 160 sub-principles are shown in Table 2. Scenarios describe events and situations that could happen in the future real-world. A scenario can be defined as a hypothetical set of plausible and logical events, built to concentrate on causal processes and decision events. Scenario-based analysis is considered as a conjectural forecasting technique usually associated with future research.

Results of changes of the interrelation between factors based on each scenario with the help of FCM for sustainable sediment management are presented in Tables 3 and 4. In general terms, an FCM is able to predict the outcome by letting the relevant issues interact with one another. These predictions can be used for finding out whether a decision made by someone is consistent with the entire collection of stated causal assertions.

A comparison of the interrelation between factors based on each scenario indicates that three alternatives were ranked as high. Sediment flushing near the dam can effectively deal with the deposition of the turbidity current sediment that is arriving at the dam. This would only be effective in flushing sediment from the wedge area in close proximity to the dam. An operational procedure is required for flushing that involves the passage of flows at various intervals to control downstream sediment concentrations and to allow water clearance time, both of which are required to address the present downstream fisheries operations.

Table 1 | Adjacency matrix of FCM for sustainable sediment management

Sustainable sediment management	Construction and operation time	Economic benefits	Economic costs	The complexity in the implementation process	Quality of recreational use	Awareness	Effects on water users	Attitude towards Standards	Effects on water quality	Resettlement	Stock of valuable fish	Water level
Construction and operation time	0.00	-0.20	0.60	0.00	0.00	0.00	-0.20	0.00	-0.20	0.00	0.00	0.00
Economic benefits	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.10	0.00	0.00
Economic costs	-0.60	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.35	0.00	0.00	0.50
The complexity in the implementation process	0.00	0.20	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20
Quality of recreational use	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.10	0.00	0.00
Awareness	0.25	0.00	-0.10	0.00	0.00	0.00	0.10	0.20	0.00	0.00	0.00	0.00
Effects on water users	0.00	0.20	0.00	0.00	0.10	0.00	0.00	0.00	0.00	-0.20	0.00	0.00
Attitude towards Standards	0.60	0.00	-0.10	0.00	0.00	0.20	0.10	0.00	0.20	0.00	0.00	0.00
Effects on water quality	0.00	0.25	0.00	0.00	0.10	0.00	0.00	0.00	0.00	-0.20	0.20	0.00
Resettlement	0.00	-0.25	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Stock of valuable fish	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.10	0.00	0.00
Water level	0.00	0.50	0.25	0.00	0.00	0.00	0.10	0.00	0.10	-0.10	0.10	0.00

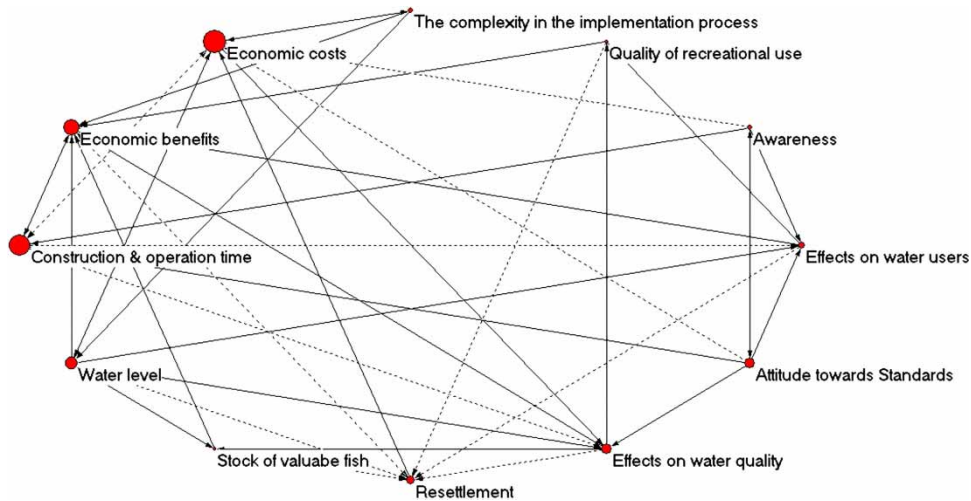


Figure 4 | Results of FCM model for sustainable sediment management.

Table 2 | Scenario planning based on TRIZ for sustainable sediment management

	Parameter to improve	Undesired results (conflict)	Principles	Available management alternative
Scenario 1	Harmful side effects	Waste of substance	10 Preliminary action 34 Recycling	Dam raising
Scenario 2	Amount of substance	Harmful side effects	3 Local quality 39 Inert environment	Dredging near the dam
Scenario 3	Harmful side effects	Complexity of device	19 Periodic action 1 Segmentation	Flushing

Table 3 | Comparison between different scenarios

Concepts	No changes (Scenario 1)	Scenario 1	Scenario 2	Scenario 3	Results - no changes (Scenario 1)	Results - Scenario 1	Results - Scenario 2	Results - Scenario 3
Construction and operation time	1			0.65	0.55350	0.55852	0.55392	0.65000
Economic benefits	1				0.63507	0.66489	0.64688	0.62315
Economic costs	1				0.65216	0.66510	0.65421	0.66576
The complexity in the implementation process	1	0.6			0.53256	0.60000	0.53266	0.53324
Quality of recreational use	1		0.6		0.52708	0.52937	0.60000	0.52373
Awareness	1	0.6			0.52629	0.60000	0.52629	0.52629
Effects on water users	1	0.6		0.45	0.51380	0.60000	0.51486	0.45000
Attitude towards Standards	1				0.52629	0.52996	0.52629	0.52629
Effects on water quality	1		0.65	0.5	0.57040	0.57617	0.65000	0.50000
Resettlement	1				0.38982	0.38001	0.38284	0.39663
Stock of valuable fish	1				0.54357	0.54865	0.54860	0.54012
Water level	1	0.8	0.65		0.60649	0.80000	0.65000	0.60815

Dam raising produces the highest present value of net benefits and directly addresses the loss of storage volume. Based on temperature and oxygen profiles taken in reservoirs, it appears that the reservoir does not stratify, and oxygen levels are relatively high throughout the water column. Resettlement of these communities will require that livelihoods of the residents are maintained, and undue hardship is minimized.

Table 4 | Positive and negative changes for different scenarios

Positive changes	Strength (pos)	Negative changes	Strength (neg)
Scenario 1			
Construction and operation time	2	Resettlement	2
Economic benefits	1		
Economic costs	1		
Quality of recreational use	2		
Attitude towards Standards	2		
Effects on water quality	2		
Stock of valuable fish	2		
Scenario 2			
Construction and operation time	3	Resettlement	2
Economic benefits	1		
Economic costs	2		
The complexity in the implementation process	3		
Effects on water users	2		
Stock of valuable fish	2		
Scenario 3			
Economic costs	1	Economic benefits	1
The complexity in the implementation process	3	Quality of recreational use	2
Resettlement	2	Stock of valuable fish	2
Water level	2		

Dredging is very sensitive to the cost of dredging and produces present values of net benefits, which range from a small positive value to negative. Dredging operations often result in increased suspended sediment in the water column. The extent of increased suspended sediment in the water column is highly dependent on the type of dredger used with a clam-type dredge most likely to increase suspended sediment and an airlift dredger or suction dredge less likely to significantly increase suspended sediment.

SUMMARY AND CONCLUSIONS

In this study, FCM and TRIZ were used successfully for identification and prioritization of effective factors on sustainable sediment management in dam reservoirs and to evaluate the derived prediction model. Our proposal goes beyond the eco-rules definition or the prioritization of eco-friendly guidelines with traditional techniques used in technological forecasting. FCMs assess TRIZ evolution trends for eco-design innovation, allowing prioritizing and further decision-making based on scenario analysis. This study is based on technical and executive requirements, economic factors, social welfare and environmental impacts and their respective categories. The FCM algorithm was invoked for building and evaluating a cognitive map, and TRIZ algorithm was employed for scenario building. Based on results, flushing, dredging near the dam option and the dam raising alternative, were ranked at a high level for different scenarios. Results and application of the proposed framework to rank sediment management alternatives showed that this method provides a powerful tool for the selection of the optimum response scenario against the identified risks and can be an important instrument for change in the quality of sediment management.

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First received 3 March 2019; accepted in revised form 26 June 2019. Available online 31 July 2019