

Research Article

Improved Decision-Making through a DEMATEL and Fuzzy Cognitive Maps-Based Framework

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The decision-making process is highly demanding. There has been an increasing tendency to incorporate human thinking, individual experience about a problem, and pure mathematical approaches. Here, a novel integrated approach is investigated and proposed to develop an advanced hybrid decision-support system based on the decision-making trial and evaluation laboratory (DEMATEL) and fuzzy cognitive maps (FCMs). Indeed, knowledge acquisition and elicitation may present distortions and difficulties finding a consensus and an interpretation. Thus, the proposed combined approach aims to examine in depth the potential to improve FCMs' outcomes by integrating FCM with the DEMATEL approach. The combined methodology achieves at avoiding some of the drawbacks, such as the lack of a standardized FCM theoretical model. Thus, it provides advanced comparative analysis and results in better interpretation of the decision-making process. It is highlighted that the traditional FCM approach does not allow distinguishing the whole number of defined scenarios, in contrast to the hybrid one presented here, which increases the ability of users to make correct decisions. Combining the two approaches provides new capabilities to FCMs in grouping experts' knowledge, while the DEMATEL approach contributes to refining the strength of concepts' connections.

1. Introduction and Background

Decision-making is the process of making choices by identifying a decision, collecting information, and achieving alternatives. Since their first appearance in the 1970s, decision support systems developed rapidly; initially, they performed their task essentially on mainframes, using inflexible warehouses of corporate data. In the last decade, with the entrance in the information age (e.g., development of information technologies and Industry 4.0 paradigm), companies are accumulating a huge amount of data with little knowledge, transforming the way decisions are made [1]. One can generalise by saying that the decision-making process is essentially characterized by two types of elements: organisational and technical [2]. The formers are related to

the day-to-day operation of companies, in line with corporate strategy; the latter includes a set of tools such as information systems, data repositories, formal modeling, and decision analysis. What evolves with Industry 4.0, however, is the source and nature of the information [3]. All the actors involved in the day-to-day running of the company produce data, structured and unstructured, which necessarily require standardisation mechanisms such as the adoption of PLM (product lifecycle management) systems, in the context of the integration brought about by Industry 4.0 [4]. Moreover, given the varied nature of the available information, according to [5], in order to improve the data management process and make full use of it, it is necessary to extract this knowledge from it by referring to big data analytics tools. Increasing data size also increases the

calculation and processing time: the whole process becomes quite demanding and creates the additional need to manage such data in an agile and flexible manner. In this regard, [6] suggests adopting cloud technology to manage huge sets of data and discover knowledge from them through data mining. With the support of cloud infrastructure, high levels of reliability and availability regarding data collection, management, and sharing can be obtained [7]. In addition, for a decision to be reliable, the information and knowledge on which it depends must be reliable. Thus, in their study, [8] introduced the emerging blockchain technology as a guarantee of reliability. In fact, according to [9], all the relevant information and past decisions cannot be corrupted or changed by any of the participants, unless all concerned agree to such a change. This provides reliable and unambiguous information for use in decision-making of both a structured and unstructured nature. However, the problem linked to the unstructured nature of the information still remains, since, in this case, the formulation of a quantitative model is difficult or almost impossible because of the scarcity of available data characterized by an unstructured nature. According to [10], understanding the events and factors affecting the whole problem domain is an indispensable condition for achieving decisions efficiently and adequately structuring the decision-making approach based on a wide range of related issues. For this reason, as asserted by [11], several types of problems can profit from an approach centered on people's knowledge and problem assessment and, mainly, those wherein the stakeholder's opinion is remarkable [12]. A large number of methods have been developed for the improvement of the decision-making process, focusing on the experts' opinion in many research and application fields: from economics [13, 14] to healthcare [15], from safety and security [16, 17] to manufacturing and supply chain [18–20], and so on. However, all of them highlight complexities in conflict mitigation due to the collaborative process [21].

Among the well-known decision-making techniques that can be mentioned are the analytic hierarchy process (AHP) [22], the technique for order of preference by similarity to ideal solution (TOPSIS) [23], or the most adopted Strengths, Weaknesses, Opportunities, and Threats (SWOT) matrix [24]. However, because explaining human reasoning is a very hard task using only numbers, many decision-making techniques consider the fuzzy theory application [25]. For instance, [26] provided an integrated approach based on the multiobjective mathematical programming and fuzzy analytical hierarchy process for sustainable suppliers' selection and the definition of the best order allocation. Saidi Mehrahad [27] defined a method based on the preference ranking organization method for enrichment evaluations, taking advantage of the method, flexibility, and simplicity, jointly to the evaluation of fuzzy data for preferences, weights, and scores.

Interestingly, between 1972 and 1979, the Science and Human Affairs Program of the Battelle Memorial Institute of Geneva provided the DEMATEL method to study complex and intertwined issues. Thus, DEMATEL is a practical and helpful approach to envision the composition of complex

causal relationships using diagrams or matrices [28]. Specifically, these matrices or diagrams can describe a contextual relationship among the system elements, and a numeric value characterizes the relevance strength [29]. DEMATEL allows decision-makers to identify the fundamental criteria to efficiently explain the problem and avoid evaluation overfitting [30]. For instance, [31] built a hybrid dynamic multiple criteria decision-making approach to solving problems related to the complex dynamics in the real world, combining DEMATEL with the analytic network process (ANP). Seleem et al. [32] developed an integrated model for the manufacturing organizations' support in selecting and managing appropriate initiatives using the theory of constraints, balanced scorecard, jointly to DEMATEL. Keskin [30], analogously, developed an integrated model through fuzzy DEMATEL and fuzzy C-means to increase quality in selecting and evaluating the supplier.

Moreover, [33] defined a hybrid framework referring to fuzzy AHP with fuzzy Delphi and fuzzy DEMATEL to overcome the weaknesses related to supplier selection. Unequivocally, the framework allows designing a methodology to achieve the performance scores of three PLC suppliers, taking into consideration 11 attributes. Tadić et al. [34] combined fuzzy ANP, fuzzy VIKOR, and fuzzy DEMATEL methods to select and analyze the concept related to Belgrade's city logistics to improve the city organization with more relevance. Some years later, still the hesitant fuzzy VIKOR was combined with the hesitant fuzzy DEMATEL by [35] to investigate the relationships among the customer requirements and determine their relevance weights to prioritize the engineering characteristics; this issue is also analyzed by [36].

Even [37] realized a DEMATEL-based approach for investigating barriers to the green supply chain in Canada. The barriers considered were investigated using causality and prominence relations to help decision-makers in providing successful practices. However, [38] pointed out that DEMATEL, in spite of the advantages listed above, is insufficient to provide a good decision-making tool when the information available is obtained from experts whose knowledge may be limited or incomplete. The same can be said when the information becomes innumerable as it would require complex mechanisms for its interpretation.

Some years after the introduction of DEMATEL, the fuzzy cognitive maps (FCMs) were proposed by [39] to model the causal relationship among concepts and evaluate inference patterns.

Indeed, causal reasoning in decision-making is important, since it is inherent to the human reasoning process [40], and thus, easily comprehensible, as well as based on cause-effect relations between components of the system being modeled. Pure mathematical modeling systems that are based on regression analysis rely on correlation, which does not confirm causation. Also, data-driven decision-making systems can be designed even without system-specific knowledge, since they use pattern recognition and statistical techniques [41]. Causal-based and model-driven systems such as FCMs and Bayesian belief networks (BBNs) are based on visual graphs consisting of nodes (variables) and

directional links between nodes that represent cause-and-effect relationships between the variables. The research findings show that in comparison to BBNs, FCMs are more suitable for use as a front-end modeling tool to elicit expert knowledge, since the causal model is simpler, more intuitive, and user-friendly, making easier their composition and decomposition [42, 43].

More, in particular, FCMs are a tool for knowledge and inference depiction, an essential step for any intelligent system. Remarkably, they offer a far more flexible and potent framework for human reasoning and knowledge representation [44]. In addition, always related to the application of FCMs for the decision-making process, many studies can be mentioned in many fields, from industrial plants to healthcare, mainly concerning risk assessment for complex systems [45, 46]. For example, [47] used FCM to explore and evaluate the importance of human factors affecting human reliability in the industrial sector. A hybrid model has been proposed by [48], based on competitive FCM for medical decision support systems introducing genetic algorithms. In addition, [49] developed an FCM tool for identifying the most critical injury causes in a refinery plant and addressing the economic efforts to reduce them, and then, [50] developed a decision-support system for the criticality ranking of the plant equipment. Poczeta et al. [51] presented how to optimize FCMs operation for better decision-making and prediction. Al-subhi et al. [52] proposed an extension of FCMs, the neutrosophic cognitive map, that was successfully applied to model multistage sequential decision-making problems.

Also focusing on the healthcare field, FCMs have been applied to assess the risks. Amirkhani et al. [53] have modeled with the help of the FCMs various aspects in the medical field. Smith [54] proposed a prototype for the IT risks evaluation in healthcare. Furthermore, [55] used FCMs to evaluate cancer thermography, finding in them a valuable tool to diminish medical errors. Bevilacqua et al. [56] referred to a similar approach to evaluating drug administration risk in an Italian hospital.

By analyzing the literature review, it is possible to assert that DEMATEL and FCM techniques are characterized by several similarities, as given in Table 1. At the same time, they also have differences demonstrating the complementarity of the two approaches.

Due to the many similarities and complementarity of DEMATEL with FCMs, as given in Table 1, the two modeling methods are chosen here for decision-making. For example, in 2014, fuzzy cognitive maps, DEMATEL, and ANP have been combined by [57] to realize an analytical hybrid multiple criteria-decision making (MCDM) model for a private primary school selection problem to help parents in the primary school selection problem.

In particular, the possibility of improving FCMs outcomes using the DEMATEL approach wants to be evaluated since

- (i) Knowledge can present distortions once transferred among persons [58]
- (ii) Extreme difficulty can be encountered in finding a consensus [59]

- (iii) The traditional FCM approach does not allow to distinguish the entire number of defined scenarios for decision-making [60]

As [61] asserted, the lack of a standardized FCM theoretical model pinpoints the problem of comparative analysis in problem-solving. Axelrod [62] presented similar conclusions, stressing that the lack of formal methods for the construction of cognitive maps affects the results' reliability and the interpretability of problem situation analysis [63]. How the results' reliability and interpretability are also due to the oversized FCM models were also studied. Generally, human reasoning is characterized either by oversimplification or by overcomplicated mental processes. Indeed, as [64] asserted, the critical dependence on experts' knowledge is an important deficiency in managing FCMs in control processes, since the FCM output must describe the real system output as closely as possible. Therefore, researchers have developed several learning algorithms to reach this purpose [65]. Lee et al. [66] developed an FCM-based holistic method to solve the semantic ambiguity problems due to different FCMs, thus ensuring semantic enhancement and interoperability through effective collaboration. In addition, [67] highlighted the inability of the FCM to model the uncertainty introduced by people's hesitation in a complex system and how this can affect the reliability of the entire decision-making process. Therefore, they refer to the dual hesitant fuzzy sets (DHFSS) theory to consider the degree of membership and nonmembership to model uncertainty and epistemic uncertainty.

For all of these reasons, the proposed study investigates in a comparative approach and analyses the features of DEMATEL and FCM methodologies and how they could be used jointly, in a complementary way, as described in Section 2. Section 3 describes the case study used to underline pros and cons in their combined use, while in Section 4, the relative outcomes are discussed. Last, Section 5 focuses on the further analysis and improvement needed to model a hybrid decision-making support system.

2. Complementarity and Combination of DEMATEL and FCMs

2.1. The Need for Expanding FCM Methodology. As described in the introduction section, several methods have been developed for the decision-making process improvement, focusing on experts' opinion, but underlining how the transferred knowledge can be affected by biases [58], and concurrently, extreme difficulties can occur in obtaining a consensus [59] or in the results' interpretation [68]. Even though FCMs have been proposed as a unique methodology able to aggregate a significant amount of knowledge and beliefs [11, 69], the lack of a standardized FCM theoretical model pinpoints the problem of comparative analysis in problem-solving [61, 62]. Many applications solve this problem by developing learning algorithms or analogous but de facto, modifying, or even neglecting the experts' contribution. Indeed, referring to [70], experts can introduce realism for dynamic planning and modeling, improving the system's performance. This means that every developed

TABLE 1: Compared aspects of DEMATEL and FCM approaches.

	DEMATEL	FCM
Similarities		Cause-effect relationships Graph visualization Factor prioritization Based on matrices Structural modeling approach
Differences	No threshold function for the algorithm convergence Only nonnegative judgments matrix No parameters to be set for the output readability	A threshold function for the algorithm convergence is mandatory Negative and nonnegative judgments matrix Few parameters to be set for the output readability

decision-making approach must seriously consider human expertise, but concurrently, it must avoid ambiguous results analysis for an effective decision-making procedure.

It is concluded that the proposed approach aims at showing how the combination of the traditional FCM approach with another experts-based decision-making tool allows to solve or reduce the questioned problem.

Moreover, given the analogy between DEMATEL and FCM, it is possible to adopt the same assumption for this research. Presume that m experts are involved in solving a complex problem described considering n main concepts. The grades assigned by all the experts (for example, adopting a 5-point Likert scale: 0, no influence; 1, very low influence; 2, low influence; 3, high influence; 4, very high influence) produce an $n \times n$ matrix X^k , with $1k \leq m$. Consequently, X^1, X^2, \dots, X^m are the resultant matrices for each expert, and each element of X^k (denoted with x_{ij}^k) assumes an integer value. The elements on the main diagonal of each X^k have a null value to neglect the effects of each concept with itself.

2.2. The DEMATEL Methodology. Zhu et al. [71] provided an in-depth description of the DEMATEL procedure. First, using the X^k matrices, a collective scores matrix A can be calculated using (1) as their average influence.

$$a_{ij} = \frac{1}{m} \sum_{k=1}^m x_{ij}^k. \quad (1)$$

Thus, by normalizing the average influence matrix A through (2) and (3), the direct influence matrix D can be determined.

$$D = sA, \quad (2)$$

$$s = \min \left[\frac{1}{\max_{1 \leq i \leq n} \sum_{j=1}^n a_{ij}}, \frac{1}{\max_{1 \leq j \leq n} \sum_{i=1}^n a_{ij}} \right]. \quad (3)$$

Once the direct influence matrix is defined, the total influence matrix T can be calculated according to the following equation [72].

$$T = D + D^2 + D^3 + \dots + D^\infty \\ = \sum_{i=1}^{\infty} D^i = D(I - D)^{-1}. \quad (4)$$

A threshold or benchmark value is chosen to ignore the concepts with negligible effects from the total influence

matrix T . Therefore, a value lower than the threshold can be omitted from T to obtain the inner dependency matrix [37].

The influence-relations map can be provided by considering the values of $d + r$ and $d - r$, referring to the following equations. It is possible to realize a visible structural model to figure out the complex causal connections in the set of all identified concepts.

$$r_i = \sum_{j=1}^n t_{ij}, \quad (i = 1, 2, \dots, n), \quad (5)$$

$$d_i = \sum_{i=1}^n t_{ij}, \quad (j = 1, 2, \dots, n). \quad (6)$$

In particular, the term $r_i + d_i$ represents the influences' strength by and on the i^{th} concept, measuring its relevance. Analogously, $r_i - d_i$, called relation, allows the concepts classification in a "cause" and "affected" unit: if $d_i - r_i$ has a nonnegative value, the i^{th} concept affects the other concepts more than those belonging to the cause group influencing it. Conversely, a negative value defines the i^{th} concept as belonging to the affected group [31].

2.3. FCM Approach. Kosko's elementary FCM approach [39], named in this study with "traditional approach," has been extensively expanded and applied by [73, 74] in the decision-making process to assign fuzzy weights to every FCM relationship. The expert or decision-maker is asked to express the degree of belief in terms of the strength of all the causal relationships for a particular organisational environment. Thus, the relationship weights can be personalized by each organization and industry sector. As shown in Figure 1, the first step of the map realization has been carried out by an experts' panel who were asked to give a numerical r_{ij} (the significance of the relation between concept i^{th} and j^{th}) to the R matrix where columns and rows identify the concepts. The expert panel session seeks to limit errors due to subjectivity. Once the experts agree on each interconnection, the proposed linguistic values are aggregated through the SUM method [75] for an overall linguistic weight evaluation. The defuzzification method of the centre of gravity allows changing to a numerical weight r_{ij} [76]. The so obtained r_{ij} describes the effect of concept C_i on C_j , varying in the range (1; 1). Specifically, if $r_{ij} = 0$, there is no causality; if $r_{ij} > 0$ can be identified as a relationship between the involved concepts

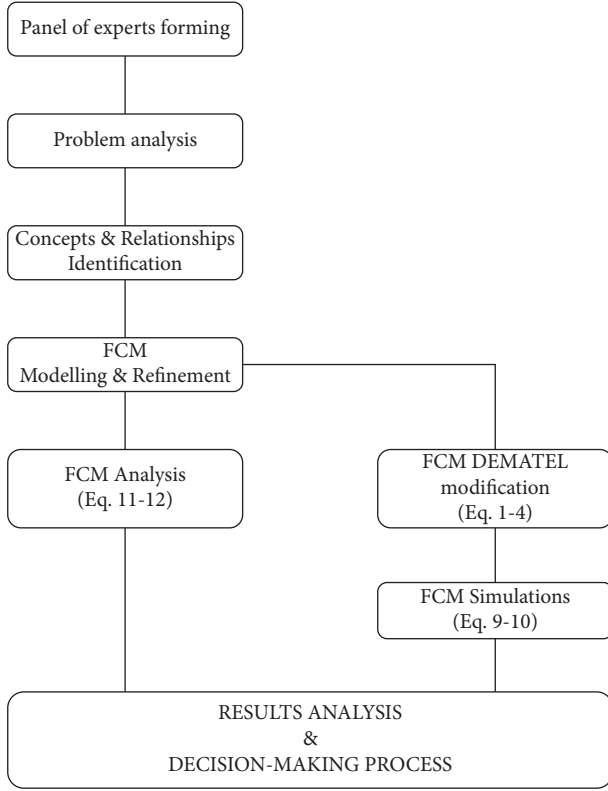


FIGURE 1: The proposed FCM modeling and analysis approach.

and if C_j increases, then C_i increases (or C_j decreases as C_i decreases); at the same time, if $r_{ij} < 0$, there is a causal decrease or negative causality. This means that if C_j decreases, C_i increases (and or C_j increases as C_i decreases). The final adjacency matrix is

$$R = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & r_{ij} & \vdots \\ r_{n1} & \cdots & r_{nm} \end{bmatrix}. \quad (7)$$

Moreover, a state vector $[C_1 \dots C_n]$ describes the values of the current concepts (specifically, C_i represents the i^{th} concept). If $C_i = 0$, the concept is not active; if $C_i \neq 0$, it is active [77]. Bertolini[47] stated that equation (8) describes the time evolution of the map. A maximum iterations number can impose the stop condition or if between two successive iterations, there is a slight variation of the $[C_1 \dots C_n]_{\text{NEW}}$ and $[C_1 \dots C_n]_{\text{OLD}}$.

$$[C_1 \dots C_n]_{\text{NEW}} = [C_1 \dots C_n]_{\text{OLD}} \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & r_{ij} & \vdots \\ r_{n1} & \cdots & r_{nm} \end{bmatrix}. \quad (8)$$

Thus, simulate the cognitive map (CM) dynamics and analyze all CM paths. If A_i is the instantaneous value of concept C_i , its time evolution can be calculated by computing the impact of the related concepts C_j on the concept C_i , according to

$$A_i^{k+1} = f \left(A_i^k + \sum_{\substack{j=1 \\ j \neq i}}^n A_j^k r_{ij} \right), \quad (9)$$

where A_i^{k+1} is the value of concept C_i at the instant $k+1$, A_i^k is the value of concept C_j at simulation step k , and $f()$ is a threshold function for the algorithm convergence [78], since it is used to force the concept value to range into a normalized range [56, 79].

Generally, four activation functions can be used: hyperbolic tangent function, sigmoid function, step function, and threshold linear function.

Regardless of the lack of standard rules to choose activation functions, [78] thoroughly described the activation function's advantages and disadvantages, highlighting how they can modify FCM analysis. Decision-makers' predilections can decide the choice of a specific function. In the proposed study, the hyperbolic tangent function has been used, since it can tackle concepts varying in $[-1, 1]$ interval, according to [80]. The normalization range is reached with λ close to 0.6 for the following equation.

$$f(A_i^k) = \frac{e^{\lambda A_i^k} - e^{-\lambda A_i^k}}{e^{\lambda A_i^k} + e^{-\lambda A_i^k}}. \quad (10)$$

The indirect and total causal effect evaluation is relevant in FCM analysis [81]. The indirect effect I_k of C_i concept on C_j concept is described by

$$I_k(C_i, C_j) = \min\{r(C_p, C_{p+1})\}. \quad (11)$$

I_k is defined as the minimum value of the r_{ij} weight and a particular path starting from concepts i^{th} and ending in j^{th} . The total causal effect $T(C_i, C_j)$, expressed in (12), is subsequently evaluated as the maximum of all the indirect effects starting from C_i and ending in the concept C_j :

$$T(C_i, C_j) = \max\{I_k(C_p, C_{p+1})\}. \quad (12)$$

$I_k(C_i, C_j)$ and $TE(C_i, C_j)$ must be interpreted according to the fuzzy mathematics theory and $e(C_p, C_{p+1})$ with the relationship weight expressed using fuzzy numbers. As explained by [39], $I_k(C_i, C_j)$ and $TE(C_i, C_j)$ are identified with t -norm (triangular-norm) operator t and t -conorm s . For instance, the connections between concepts C_1 and C_5 are

$$\begin{aligned} I_1(C_1, C_5) &= \min\{e_{13}, e_{35}\} \\ &= \min\{\text{much}, \text{lot}\} = \text{much}, \\ I_2(C_1, C_5) &= \text{some}, \\ I_3(C_1, C_5) &= \text{some}. \end{aligned} \quad (13)$$

The presence of three paths connecting the nodes C_1 and C_5 implies that the concept C_1 can affect the final node (C_5) in different ways. Thus, with the TE calculus, the maximum effect of C_1 on C_5 can be evaluated:

$$\begin{aligned}
 TE(C_1, C_5) &= \max\{I_1(C_1, C_5), I_2(C_1, C_5), I_3(C_1, C_5)\} \\
 &= \max\{\text{much}, \text{some}, \text{some}\} = \text{much}.
 \end{aligned}
 \tag{14}$$

This means that concept C1 affects “much” concept C5.

In the same way, if a more complex evaluation scale is necessary, considering a symmetric scale with negative connections (i.e., ranging from very low to very high), it could be possible to identify situations in which some IEs manifest positive effects, while in other situations, they can manifest negative effects: “an indeterminate effect.” If $I_1(C_1, C_5) = \text{very low}$ and $I_2(C_1, C_5) = \text{very high}$, both of the connections have a high impact on the concept C5. But they have different behaviors on the final concept: the first relationship negatively impacts them. In contrast, the second one has positive effects, so it is impossible to evaluate just one of them. Still, the analyzer must distinguish all the possible situations according to the analysis point of view.

2.4. DEMATEL and FCM Comparison. By comparing the mentioned methods, it is possible to underline that obtaining the finishing relationships matrix is quite comparable. Both derive the final matrix after experts have evaluated the more relevant concepts and their relationships.

Significantly, this connection has been investigated by [82], demonstrating that FCMs are a simplification of the DEMATEL approach if the threshold function $f()$ in (9) is the linear one to equal their convergence behaviors. Additionally, considering the previously mentioned condition, FCMs can manage the dynamic criteria status and overcome the limitation of the DEMATEL method adopting nonlinear dynamics. In contrast, many authors analyzed the chance to merge both approaches [83]. An efficient decision-making tool is provided to support leanness extent evaluation through DEMATEL to ascertain the impact of every leanness factor on others and FCM to identify several scenarios. These two methods are used differently in the decision-making process, and only in the final step, the relative results can be analyzed jointly. The literature review underscored the lack of the combined application of these two approaches. Possibly, this could be referred to as one of the main fundamentals of DEMATEL aspects. In fact, it is limited to a non-negative assessments matrix, while FCMs also consider negative values. However, the matrix convergence is also ensured for a negative if its values range in $(-1, 1)$. The condition is verified for the FCM, since each evaluation mark varies in this range.

2.5. Combining DEMATEL and FCM. Under the discussed mathematical similarities and practical approaches, Figure 1 shows the proposed hybrid modeling application combining DEMATEL and FCM.

The proposed approach is the result of further development with respect to [84] which has been proposed to use a combined approach.

Beginning from the experts panel forming, each component has to be involved matching the criteria of competence and area. The panel of experts must describe all of the main aspects of the questioned problems.

The analysis aims at defining and classifying the internal and external aspects connected to the problem, as discussed in the problem analysis step. The analyzed system’s requirements, regulations, and adequacy criteria must be clear, since they are considered “boundary conditions.”

Using their experience and literature, experts are asked to express their opinions on the factors relating to the problem identified and the paired relations of concepts in the concepts and relationships identification step.

In the FCM modelling and refinement step, the different experts’ experience produces different FCMs in terms of identified concepts and relationship and direction of the connection. They are analyzed to define a collective knowledge model helpful in analyzing the problem.

Therefore, the collective FCM can be analyzed to identify the most significant concept involved in the system, analyzing the hidden patterns and indirect/total effects. Then, to avoid the results understanding problem obtained during FCM simulation, the collective FCM has been revised, taking into account the DEMATEL procedure in the FCM DEMATEL modification step. In particular, the collective FCM becomes the collective scores matrix A (equation (1)), i.e., the starting point of the DEMATEL approach.

Finally, the results analysis can help managers adopt the proper corrective action or improve the proposed problem.

3. The Case Study

The examined case study analysis of clinical risk in drug administration was initially investigated by [56]. It is, in brief, used to show the efficacy of what has been proposed in [84]. Indeed, reducing the clinical risk reduces the likelihood of errors (prevention) or recovering and mitigating their effects (protection).

To continue the study with the simulation step for ranking and correcting critical situations, according to [61] and their assertion about the difficulty in defining concepts, so that the semantic and mathematical meaning is clear, the authors needed to modify the designed FCM for simulative purposes.

A new experts panel has been formed: two nurses, two physicians, and one pharmacist giving their own assessment on the involved relations referring to a fuzzy Likert scale with ten items, according to [85], to carry out and refine the collaborative relationships matrix for the considered problem.

The panel identified the main concepts connected to the clinical risk in drug administration and classified them into “Immediate Causes” and “Subordinate Causes.” The first set causes immediate consequences on the system, while the second one remains dormant until a triggering event makes them manifest their potential and “Root Causes” or causes generating a reaction.

4. Results and Discussion

Concerning the previous analysis [56], a new panel of experts reduced by 40% the list of main concepts (from 30 to 17 concepts) due to the unfeasibility to give them a

TABLE 2: The FCM referred to the clinical risk due to the drug administration through the traditional approach.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17
Prescription errors	C1	0.00	0.53	0.66	0.69	0.51	0.00	0.00	0.00	0.96	0.00	0.00	0.00	0.00	0.00	0.00	0.49
Transcription errors	C2	0.23	0.00	0.71	0.55	0.60	0.00	0.00	0.00	0.28	0.00	0.24	0.00	0.00	0.00	0.00	0.87
Interpretation errors	C3	0.38	0.97	0.00	0.41	0.05	0.00	0.00	0.00	0.84	0.00	0.13	0.00	0.00	0.00	0.00	0.68
Preparation errors	C4	0.58	0.99	0.60	0.00	0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50
Drug management errors	C5	0.00	0.00	0.00	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.86
Experience	C6	-0.88	-0.52	-0.75	-0.12	-0.39	0.00	0.57	0.28	0.00	-0.46	-0.74	0.00	0.00	0.00	-0.75	0.00
Therapy knowledge	C7	-0.16	-0.65	-0.67	-0.20	0.00	0.00	0.00	0.00	0.00	-0.69	-0.17	0.00	0.00	0.00	0.00	0.00
Pathology knowledge	C8	-0.55	-0.15	-0.10	-0.14	0.00	0.00	0.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Patient information	C9	-0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.57	0.00	-0.46	0.00	0.00	0.00
Mistaken procedures	C10	0.60	0.25	0.14	0.73	0.88	0.00	0.00	0.00	0.00	0.20	0.31	0.00	0.00	0.00	0.00	0.00
Lack of procedures	C11	0.89	0.14	0.65	0.12	0.35	0.00	0.00	0.00	0.56	0.00	0.04	0.45	0.80	0.00	0.00	0.00
Patient identification	C12	0.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.46	0.00	0.00	0.00
Work-related stress	C13	0.26	0.10	0.65	0.40	0.29	0.00	0.00	0.00	0.36	0.00	0.70	0.00	0.08	0.00	0.00	0.00
Binds occurrence	C14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.63	0.00	0.00	0.00	0.00
External staff use	C15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.65	0.00	0.00	0.48	0.82	0.00	0.00	0.00
Clinical documentation quality	C16	0.22	0.50	0.72	0.11	0.26	0.00	0.00	0.00	-0.10	0.52	0.00	0.05	0.00	0.11	0.00	0.00
Clinical risk	C17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

mathematical meaning. The significance of the “Motivation” concept is unquestionable, but its mathematical formalization can be considered complex. Likewise, “Hurry,” “Workload,” and “Fatigue,” representing the causes concerning work quality, cannot be easily quantified. Nevertheless, all of them can be clustered, considering their effects, in the unique “Stress” concept because, i.e., workload and fatigue are causes of work-related stress [86]. Then, studying the research approach in Figure 1, this section explores the improvement introduced by the DEMATEL equations into the FCM theory.

Table 2 provides the collective FCM realized considering the experts’ FCMs on the discussed problem. Table 3 provides the collective FCM, once equations (2)–(4) have been used.

By comparing Tables 2 and 3, it is possible to identify five new relationships and the lack of 19 initial ones. The relationships among concepts increase their complexity, assuming more relevance than others, allowing algorithm convergence.

The comparison underlines one of the most relevant aspects, not judged directly by the experts. Four out of five added relationships refer to the concept C15 (“external staff

use”). The experts negatively evaluate the presence of external staff because they do not know the internal system. Thus, seeking help from external personnel increases the probability of committing “mistaken procedures,” producing “binds occurrence,” and subsequently, increasing the level of “work-related stress.” Subsequent to the application of equations from 1 to 4, what has been revealed is the influence of the “external staff use” concept on those concepts identified as “unsafe acts” with direct effects on the patient: “Prescription errors,” “Interpretation errors,” “Preparation errors,” and “Drug management errors,” despite their low relationship strength (about 0.11, weak strength). Considering those vanished, it is possible to mention, for example, the relationship of the concepts “Transcription errors” (C2) and “Interpretation errors” (C3) with “Patient identification” (C12). This means that the effects of “Transcription errors” and “Interpretation errors” on the “Patient identification” during the system evaluation are so scarce that they do not influence the system convergence.

By analyzing the relationships of the concepts, highlighting is possible as the concepts’ centrality does not change considerably concerning the approach used, and

TABLE 3: The FCM referred to the clinical risk due to the drug administration through the revised approach.

		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17
Prescription errors	C1	0.00	0.24	0.23	0.27	0.23	0.00	0.00	0.00	0.00	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.26
Transcription errors	C2	0.12	0.00	0.21	0.19	0.20	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.30
Interpretation errors	C3	0.17	0.30	0.00	0.20	0.13	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.28
Preparation errors	C4	0.18	0.30	0.21	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25
Drug management errors	C5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20
Experience	C6	-0.35	-0.31	-0.35	-0.22	-0.27	0.00	0.13	0.00	0.00	-0.32	-0.16	0.00	0.00	0.00	-0.16	0.00	-0.22
Therapy knowledge	C7	-0.12	-0.24	-0.23	-0.15	-0.11	0.00	0.00	0.00	0.00	-0.23	0.00	0.00	0.00	0.00	0.00	0.00	-0.13
Pathology knowledge	C8	-0.15	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Patient information	C9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.12	0.00	-0.11	0.00	0.00	0.00
Mistaken procedures	C10	0.19	0.15	0.11	0.23	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14
Lack of procedures	C11	0.28	0.16	0.25	0.16	0.20	0.00	0.00	0.00	0.00	0.24	0.00	0.00	0.12	0.18	0.00	0.00	0.15
Patient identification	C12	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Work-related stress	C13	0.13	0.00	0.20	0.16	0.13	0.00	0.00	0.00	0.00	0.15	0.00	0.17	0.00	0.00	0.00	0.00	0.10
Binds occurrence	C14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00
External staff use	C15	0.11	0.00	0.11	0.10	0.12	0.00	0.00	0.00	0.00	0.22	0.00	0.00	0.14	0.22	0.00	0.00	0.00
Clinical documentation quality	C16	0.12	0.20	0.22	0.12	0.14	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.12
Clinical risk	C17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

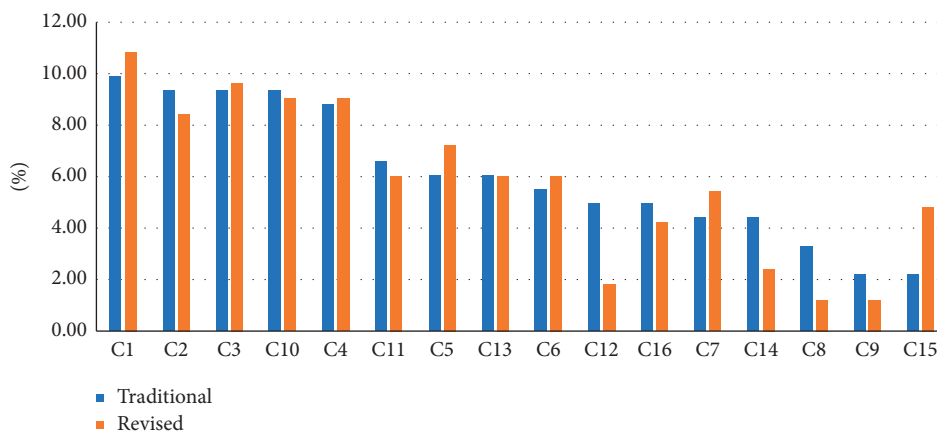


FIGURE 2: Comparison of the traditional and revised FCM approaches in terms of centrality.

Figure 2 shows this consideration. Indeed, it is shown that the percentage of influencing and influenced concepts (by each other) does not change. The unique variations are connected to the concepts that have shown a relationship change in the previous analysis. Thus, the experts' analysis of

these changes could be an essential step in the FCM refinement phase.

Three critical scenarios have been defined mathematically in the simulation phase, imposing the value 1 for those concepts having negative effects on the system and 0 for

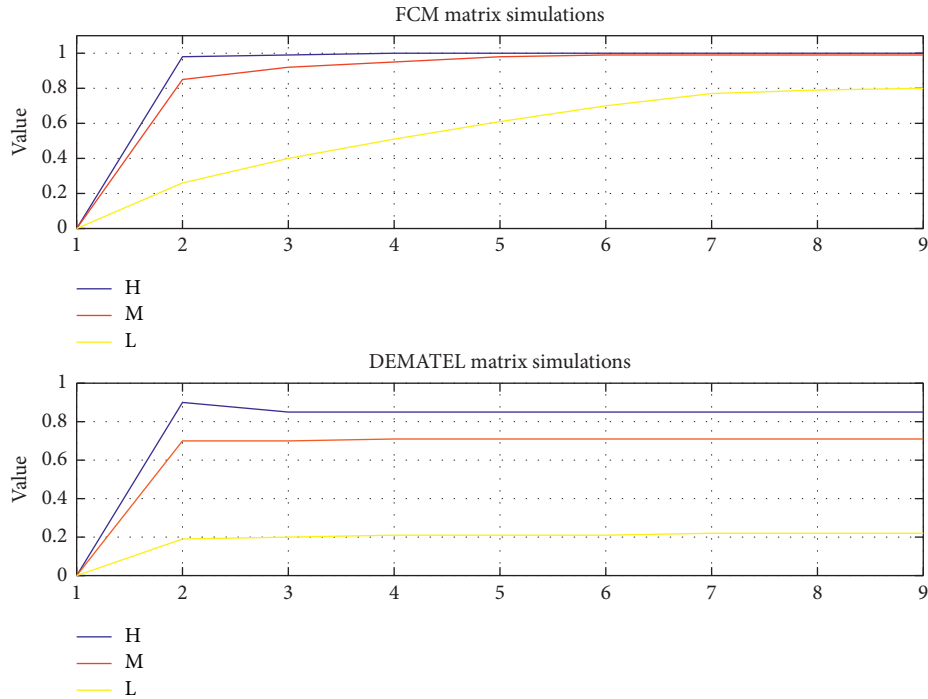


FIGURE 3: Comparison of different scenarios outcomes using the traditional and revised approach.

TABLE 4: The array to be considered as the input for calculating the criticality value.

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17
H	—	M	—	—	VL	VL	VL	VL	—	M	VL	VH	VH	—	VL	—

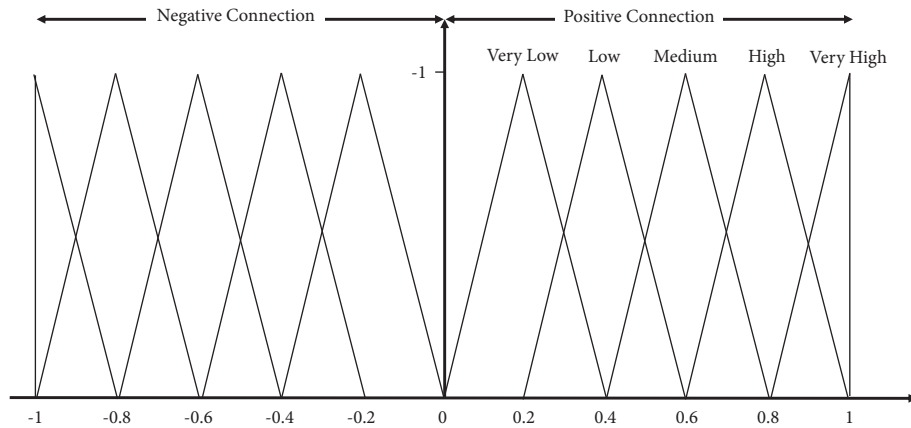


FIGURE 4: The adopted membership function for the fuzzy weights' definition.

those with positive effects to realize an extremely critical scenario. Then, the opposite represents a low critical scenario. The value of 0.5 has been given to all concepts to realize a medium-critical scenario (Figure 3).

This scenario highlights that the system outcomes, considering the same inputs but using different approaches, are not easily distinguishable. This is the validation of the problem mentioned in the introduction section. Indeed, the

traditional FCM does not distinguish all the defined scenarios because the convergence value is always the same. Besides, the algorithm convergence time is variable according to specific cases. Contrariwise, the hybrid FCM allows distinguishing the different scenarios to make correct decisions.

Moreover, to test other discrepancies between both maps and understand the efficacy of the revised approach, several

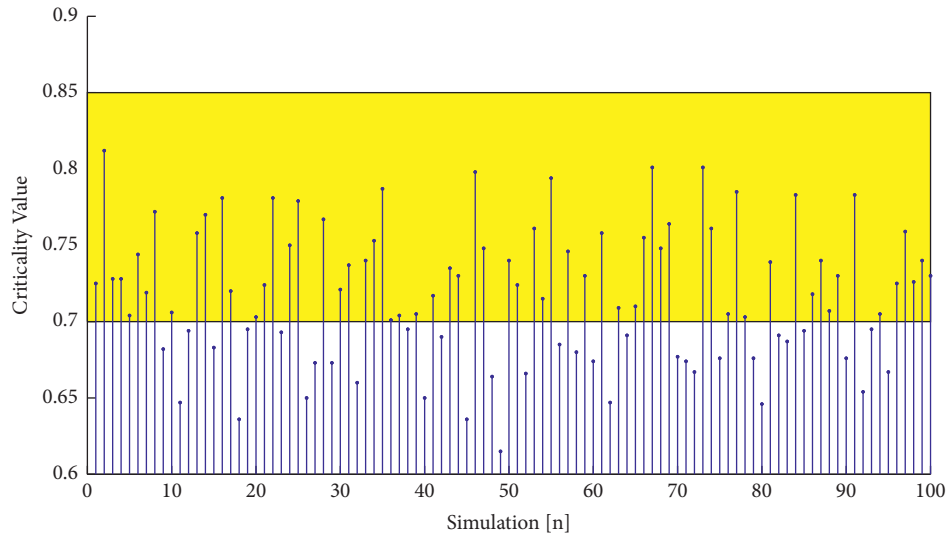


FIGURE 5: Criticality values for the considered scenario obtained by the revised FCM approach.

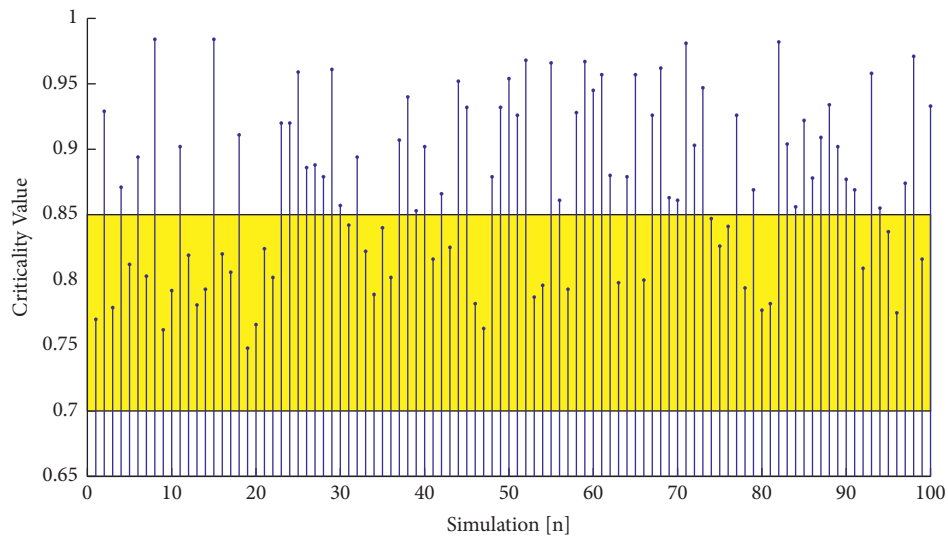


FIGURE 6: Criticality values for the considered scenario obtained by the traditional FCM approach.

critical situations have been provided with the experts' help, considering the concepts involved and giving a final value concerning the scenario's criticality.

For example, an identified scenario with a high criticality mark has referred to an actual event that happened to one of the experts.

"At about 3.00 am, an unknown patient with extreme difficulties in speaking arrived at the emergency department of the hospital at a very critical moment, since a terrible car crash had occurred on the highway, and many injured people had arrived at the same time. A young internist (who had started his activity only three weeks before) was delegated to help the patient. Due to misunderstanding what the patient was communicating, the internist misinterpreted the patient's symptoms and diagnosed a nonspecific upper airway respiratory infection. As a result, according to the guidelines, an oral antihistamine and nasal decongestant and

a counter cough suppressant were prescribed. No antibiotics were prescribed to the patient. The patient improved slightly over the next couple of days but after 10 days returned with overall worsening of systems and with an additional symptom, specifically, a very high fever."

Table 4 provides the array identifying the scenario described, according to the Likert scale developed by the experts (Figure 4).

Because the mean value of each fuzzy label has been used to compute the numerical value of the simulation array, a set of one hundred arrays has been tested to evaluate the result. Figure 5 shows the criticality value of the revised FCM approach for the scenario explained, where the yellow area identifies the expected values for the specific example. Analyzing the available data, experts defined the criticality value as medium high according to the real situation. Consequently, the black points in the yellow area represent

the whole simulation responding to reality. Results are characterised by an accuracy equal to 65% by referring to the hybrid approach DEMATEL-FCM.

Conversely, Figure 6 shows the results of the traditional FCM, underlining an overestimation of the scenario. Good results are only 38% of the identified set.

By analyzing Figure 5, the experts agreed on the suitability of the outcome obtained with the DEMATEL matrix to simulate the system, since the standard FCM outputs do not highlight different situations.

5. Conclusion

This study presents an increasing interest in the human factor for the decision-making process, which raises attention to understanding human reasoning and the individual perception of a problem. However, knowledge transfer among persons can present distortions and difficulty in finding a consensus and interpreting the results. FCMs have been demonstrated as the best tool for grouping experts' knowledge, but the lack of a standardized FCM theoretical model pinpoints the problem of comparative analysis in problem-solving. Using FCMs learning algorithms, researchers have developed several methods. However, even if these approaches bring good results considering the system control, they show deficiencies if reference is made to the experts' opinion, which is sometimes neglected.

In terms of novelty, this study examines in depth the possibility of improving FCMs' outcomes by using the DEMATEL approach, and results highlight how the traditional FCM approach does not allow distinguishing the whole number of defined scenarios, in contrast to the hybrid one allowing users to make correct decisions. The combined use of these two approaches integrates the capability of FCMs in grouping experts' knowledge and DEMATEL's, aiming to refine the strength of concepts' connections. The experts' opinion is the core of the approach, and it is fundamental in each activity of the hybrid method. In light of the advantages of combining the two techniques, work is already underway to evaluate the methodology for an industrial case. Specifically, the approach defined and discussed in this study will be integrated with the decision-making environment in question, taking into account the technological innovations introduced by Industry 4.0, which are present in the field.

The considerations made by [84] have been consolidated by analyzing in depth the mathematical theory beyond both methods, and at the same time, their explanatory example has been structured and analyzed extensively considering a new panel of experts. Thus, the proposed approach, obtained by introducing specific DEMATEL considerations and equations, shows its great opportunities in reducing the results' interpretation problem, which is typical of the FCM theory. This allows decision-makers to distinguish and analyze the system outcomes more meaningfully, so that it is possible to discriminate, with no doubt, different situations without changing the FCM procedure radically.

Data Availability

The numerical matrix used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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