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OPTIMIZATION OF SUPPLY CHAINS USING FUZZY COGNITIVE MAPS

ПОШУК НАПРЯМІВ ОПТИМІЗАЦІЇ В ЛАНЦЮГАХ ПОСТАЧАННЯ ЗА ДОПОМОГОЮ НЕЧІТКИХ КОГНІТИВНИХ КАРТ

A method of building Fuzzy Cognitive Maps for mathematical modelling of supply processes is proposed to optimize the operation of supply chains, in particular by detailing the dynamic characteristics of the component parts of supply chains. The considered method reveals the influence of stochastic factors on the supply system state and provides information for the decision-maker about the most priority directions for implementing optimization changes.

The proposed method expands the possibilities for optimization methods, including the use of multi-criteria optimization in combined methods of system analysis and expert evaluations.

The analysis methods with Fuzzy Cognitive Maps ensure the simplicity of building a system model, ease of interpretation, and clarity of cause-and-effect relationships in processes, which allows for reducing the level of requirements for the analytic user.

***Keywords**: Supply Chain, Fuzzy Cognitive Maps, transitive closure.*

У статті були проаналізовані фундаментальні математичні методи побудови нечітких когнітивних карт. Запропоновано метод побудови нечітких когнітивних карт для математичного моделювання процесів постачання з метою оптимізації роботи ланцюгів постачання. Складна проблема моделювання та управління системами досліджується за рахунок деталізації динамічних характеристик її складових частин ланцюгів постачання з використанням методів системного аналізу. Нечіткі когнітивні карти використовують, у тому числі, в випадках, коли неможливо повністю виконати завдання, спираючись лише на досвід людини.

Розглянутий метод вимагає використання вагових коефіцієнтів, що характеризують взаємну залежність факторів впливу на стан системи. Для побудови точної моделі складної системи пропонується використовувати досвід групи експертів та кореляційний аналіз накопичених даних. Експерти визначають кількість і вид концептів, з яких складається структура нечіткої когнітивної карти та взаємозв'язки між її концептами (факторами впливу) та перетворюють ці знання у зважений граф, що імітує систему, яка досліджується.

Розглянутий інструмент дозволяє виявляти силу впливу стохастичних факторів на стан системи постачання та надає інформацію для особи, яка приймає рішення, о найбільш пріоритетних напрямках для впровадження оптимізаційних змін. Використання запропонованого методу розширює можливості для оптимізаційних методів, в тому числі дозволяє використовувати багатокритеріальну оптимізацію в поєднанні з методами системного аналізу, експертних оцінок, нейронних та семантичних мереж.

Методи аналізу з використанням нечітких когнітивних карт забезпечують простоту побудови моделі системи, легкість інтерпретації, наочність причино-наслідкових зв'язків у процесах, що дозволяє знизити рівень вимог до користувача-аналітика. Перевагою методу є простота масштабування.

Корисність запропонованого методу доведена наведеним прикладом розв'язання задачі побудови нечіткої когнітивної карти та інтерпретації отриманих результатів.

Ключові слова: *ланцюг постачання, нечіткі когнітивні карти, транзитивне замикання.*

Problem's Formulation

The functioning of supply chains is related to the management of uncertainty in the processes and components of the supply system. The multifactorial character and interconnectedness of processes, low-quality forecasts, delay in receiving information, variability of the environment, conflicts of interests of the parties involved, changing customer needs, and many other things make managing the supply system extremely difficult.

An effective supply system can be designed only with a complete and thorough understanding of the dynamic characteristics of its constituent parts. Identifying the degree of significance and influence of factors on the system allows one to focus on the most important aspects and save resources. Modelling of a dynamic system can provide organizations with reduced response time to customer requests, lower operating costs, increased process flexibility, reduced inventory levels, etc. System dynamics is a powerful tool for studying the influence of factors on the efficiency of the supply chain and the development of its operation policy [1]. However, using a powerful tool requires a lot of resources, which are usually only available for big organizations.

Analysis of recent research and publications

Ensuring the functioning of supply chains is related to implementing practical management tasks using fuzzy-set methods, which limits the possibility of using traditional system analysis tools. The management of organizations strives to use tools that allow eliminating the human factor in decision-making in the face of uncertainty or incomplete information. Standard planning methods and adjustments based on monitoring results do not allow for obtaining the results expected by interested parties, which is due to the emergency criteria for decision-making and the non-transitivity of the closed system of the processes functioning. However, the use of multi-criteria models requires the implementation of hybrid control systems, which combine human experience and the logic of mathematical models. Management in such models takes place at two levels: in the state space — system supervision using mathematical logic, and at the level of criteria — decision-making by a person [2] using a set of system state indicators that belong to a certain set [3] of probable (acceptable) states.

One of the modern methods of system modelling is the method based on the building Fuzzy Cognitive Maps of processes [4—6]. The advantage of using fuzzy cognitive maps is the ease of building and interpretation, the visibility of cause-and-effect relationships in processes, and the impact rate of various factors on the overall state of the system.

The use of Fuzzy Cognitive Maps demonstrated the reliability of this method for decision-making by autonomous agents — computer systems that assess the situation, make decisions, and perform a certain action [7]. Fuzzy Cognitive Maps are intended for modelling and analysis in decision-making and control systems [8—10], game theory [11], multi-agent technologies [12], the development of geographic information systems [13], and electrical networks [14], for modelling economic and demographic problems [15].

The technology of using cognitive maps is in constant search for the possibility of improvement to solve heuristic and analytical problems that arise during the study of ill-structured problems and complex systems.

Formulation of the study purpose

The purpose of the paper is to propose a tool for identifying the most priority directions for implementing changes in order to optimize the operation of supply chains; develop analysis methods for defining the influence of uncertainty factors on the supply system that can forecast the system's future state, ensure the ease of interpretation of the obtained results by users without additional requirements for the level of their competencies, and maintain the reliability and accuracy of the analysis using mathematical modelling.

Presenting main material

The process of building a cognitive map can be described in the form of the following sequence of steps:

- defining a set of variables that potentially have an impact on the system;
- determining key performance indicators of the system, controlled and investigated by the decision-maker;
- analysing the cause-and-effect relationships between variables and indicators of system functioning efficiency;
- determining the weighting factors;
- building a cognitive map and dynamic model;
- conducting the stability analysis of the built model;
- modelling training based on accumulated data.

A set of variables $x_i \in X$ in the supply system is defined by analysing the path of the product along the supply chain from the manufacturer (x_0 — outflow in the graph $G(X,E)$) to the final consumer (x_n — stock in the graph $G(X,E)$). In this case, the analysis aims at building a graph (map) depicting all factors (variables) that affect the possibility of carrying out the supply process within the agreed performance indicators.

The influence of each factor is determined by a weighting factor ω_{ij}. The study of the cause-and-effect relationship (the path in the graph $G(X,E)$) is of greatest interest, it is characterized by the maximum cumulative impact rate $\sum \omega_{ij}$. To simplify the interpretation of the study results, it is recommended to group them by the range of influence (tabl. 1).

Table 1. The range of the value of the weighting factor

Range of values ω_{ij}	Comment
0,0	No impact
$(0{,}0;0{,}2] \vee [-0{,}2;0{,}0)$	Very little (VL) impact
$(0{,}2;0{,}4] \vee [-0{,}4;0{,}2)$	Little (L) impact
$(0{,}4;0{,}6] \vee [-0{,}6;0{,}4)$	Medium (M) impact
$(0{,}6;0{,}8] \vee [-0{,}8;0{,}6)$	Strong (S) impact
$(0{,}8;1{,}0] \vee [-1{,}0;0{,}8)$	Very strong (VS) impact

The person making a decision is interested in the value of the output variable x_j or variables characterizing the state of the supply system, and is determined by the formula:

$$x_j = g\sum_{i=1}^{n}(x_i \cdot \omega_{ij}),\ i = \overline{1,n}, j = \overline{1,n},\ x_i, x_j \in \mathbb{R}^+, \quad (1)$$

where x_i — the value of the input variable; g — the normalization coefficient (a sigmoid function is used for the calculation $f(g) = \frac{1}{1+e^{-\lambda x}}, \lambda > 0$).

The functioning of supply chains involves the iterative execution of processes. Therefore, there is a probability of signal-level accumulation at certain links (processes). Thus, equation (1) will have the form:

$$x_j(t) = g\left[\sum_{i=1}^{n}(x_i \cdot \omega_{ij}) + x_j(t-1)\right], i = \overline{1,n}, j = \overline{1,n},\ x_i, x_j \in \mathbb{R}^+, \quad (2)$$

Let us suppose that the residual level of the signal passing to the next iteration is $x_j(t-1) \cong 0$. Thus, a Fuzzy Cognitive Map should be built only considering certainty of the variables of the current cycle, and the unification is performed using the *S*-norm [2, 16]. The value of the output variable of the current iteration x_j can be determined using the equation:

$$x_j = S_{i=1}^{n}(x_i \cdot T \cdot \omega_{ij}), i = \overline{1,n}, j = \overline{1,n},\ x_i, x_j \in \mathbb{R}^+, \quad (3)$$

where T — operation T-norm [2, 16].

Let us consider a path in graph $\mu_e = (x_1, x_n) = (e_1, e_2, \dots, e_l)$, where $e_l \in E$ — a curve in graph $G(X,E)$ incident to the vertices x_{n-1} and x_n. Thus, there is a reachable set $D(x_0) = \cup_{x_i \in X} D(x_i)$ vertices of graph $G(X,E)$, which represents a certain impact factor on the system (variable) and requires the study of the maximum cumulative influence ω_{ij}. So, the influence ω_{ij} of the variable x_n on the variable in the path μ_e between $x_0 \xrightarrow{\sum e} x_n$ is determined by the equation:

$$\omega_{0n} = S_{i=1}^{n}(T_{l\in L}(\omega_{\mu,\mu+1})), i = \overline{1,n}, j = \overline{1,n}, \quad (4)$$

where $T_{l\in L}$ — the *min*() or $\prod_{i=1}^{l} e_i$ operation is used as the T-norm operation, as an *S*-norm operation, the *max*() operation.

Let *W* be a fuzzy matrix of weights of mutual influence of variables (factors) $x_i \in X$ on each other. Then the operation of transitive closure of the matrix *W* is used to determine the mediated effect:

$$\widehat{W} = W^1 \cup W^2 \cup \ldots \cup W^k \cup \ldots 0 \text{ , } k = 2,3,\ldots \quad (5)$$

where the ratio W^k is defined recursively:

$$W^1 = W;\ W^k = W^{k-1} \circ R, k = 2,3,\ldots \quad (6)$$

Since $\omega_{ij} = [-1;1]$ (see Tabl. 1), the matrix *W* contains positive-negative fuzzy relations. For further analysis, it is advisable to convert the matrix *W* into a matrix of positive relations *R*. The following algorithm is used for the conversion [2]:

if $\omega_{ij} \geq 0$:

$r_{2i-1,2j-1} = \omega_{ij}$

$r_{2i,2j} = \omega_i$

elif $\omega_{ij} < 0$:

$r_{2i-1,2j-1} = -\omega_{ij}$

$r_{2i,2j} = -\omega_{ij}$

else:

$r_{2i-1,2j-1} = 0$

$r_{2i,2j} = 0$

Consequently:

$$\hat{R} = R^1 \cup R^2 \cup \ldots \cup R^k \cup \ldots 0 \text{ , } k = 2,3,\ldots \quad (7)$$

To determine the dynamics of the influence of variables on the overall state of the system and the mutual influence of variables on each other, we will write down the results of the transformation into a double matrix *A*, consisting of positive-negative pairs of elements $(a_{ij}, \bar{a}_{ij})$, which is determined using S-norm.

$$A = \left\|(a_{ij}, \bar{a}_{ij})\right\| , \quad (8)$$

where,

$$a_{ij} = S\{r_{2i-1,2j-1}, r_{2i,2j}\},\ r_{ij} \in R,$$

$$\bar{a}_{ij} = S\{r_{2i-1,2j},\ _{2i,2j-1}\},\ r_{ij} \in R.$$

Values of pairs of elements $(a_{ij}, \bar{a}_{ij})$ are used to calculate the main information indicators that provide information for decision-making about factors that affect both positively and negatively the state of the supply system. The following can be identified among the main indicators:

– a measure of trust and a function of the impact level of factors on each other:

$$c_{ij} = \frac{|a_{ij}+\bar{a}_{ij}|}{|a_{ij}|+|\bar{a}_{ij}|}; \quad (9)$$

– a function of mutual influence of factors on each other:

$$d_{ij} = 1 - c_{ij}; \quad (10)$$

– assumption that the supply chains are characterized by the presence of mutual influence of factors, both in direct sequence and in reverse:

$$\overleftrightarrow{c}_{ij} = \overleftrightarrow{c}_{ji} = \frac{|(a_{ij}+a_{ji})+(\bar{a}_{ij}+\bar{a}_{ji})|}{|(a_{ij}+a_{ji})|+|(\bar{a}_{ij}+\bar{a}_{ji})|}; \quad (11)$$

– the function of mutual influence of factors on each other in a direct sequence and reverse:

$$\overleftrightarrow{d}_{ij} = 1 - \overleftrightarrow{c}_{ij} = 1 - \overleftrightarrow{c}_{ji}; \quad (12)$$

– the influence of factor x_i on x_j:

$$p_{ij} = sign(a_{ij} + \bar{a}_{ij}) \cdot max(|a_{ij}|, |\bar{a}_{ij}|), \forall a_{ij} \neq -\bar{a}_{ij}; \quad (13)$$

– mutual positive influence of factors x_i on x_j:

$$\overleftrightarrow{p}_{ij} = \overleftrightarrow{p}_{ji} = (a_{ij} S a_{ji}); \quad (14)$$

– mutual negative influence of factors x_i on x_j:

$$\overleftrightarrow{n}_{ij} = \overleftrightarrow{n}_{ji} = -\left|\bar{a}_{ij}\right|S\left|\bar{a}_{ji}\right|. \tag{15}$$

Since system modelling is carried out with the aim of determining the factors that have the greatest influence on the system state, it is important to decompose the influence of each factor. Thus, it is necessary to determine the following indicators:

– confidence measure and function of the impact rate of factor x_i on the system:

$$\vec{c}_i = \frac{1}{n}\sum_{j=1}^{n} c_{ij}; \tag{16}$$

– confidence measure and a function of the impact rate of the system on the factor:

$$\overleftarrow{c}_j = \frac{1}{n}\sum_{i=1}^{n} c_{ij}; \tag{17}$$

– impact rate of the factor   on:

$$\overrightarrow{D}_i = \frac{1}{n}\sum_{j=1}^{n} d_{ij}; \tag{18}$$

– impact rate of system on:

$$\overleftarrow{D}_j = \frac{1}{n}\sum_{i=1}^{n} d_{ij}. \tag{19}$$

It is possible to determine the following indicators as indicators of the overall state of the system:

– mutual consonance of   and the system:

$$I_c = \left(\vec{c}_i S \overleftarrow{c}_j\right); \tag{20}$$

– mutual dissonance of   and the system:

$$I_d = \left(\overrightarrow{D}_i S \overleftarrow{D}\right). \tag{21}$$

Example: let the matrix W determine the impact rate of factors on the system state.

$$W = \begin{vmatrix} 0 & 0.8 & 0 & 0.6 & -0.2 \\ -0.2 & 0 & 0.6 & 0 & 0 \\ 0 & -0.1 & 0 & 0 & 0 \\ -0.2 & 0 & 0.3 & 0 & 0 \\ 0.4 & 0 & 0 & 0 & 0 \end{vmatrix}.$$

Let us perform the operation of transitive closure of the matrix W:

$$\widehat{W} = \begin{vmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \end{vmatrix}.$$

Let us build a matrix of positive connections $\hat{R}$:

$$\hat{R} = \begin{vmatrix} 0 & 0 & 0.8 & 0 & 0 & 0 & 0.6 & 0 & 0 & 0.2 \\ 0 & 0 & 0 & 0.8 & 0 & 0 & 0 & 0.6 & 0.2 & 0 \\ 0 & 0.2 & 0 & 0 & 0.6 & 0 & 0 & 0 & 0 & 0 \\ 0.2 & 0 & 0 & 0 & 0 & 0.6 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.2 & 0 & 0 & 0.3 & 0 & 0 & 0 & 0 & 0 \\ 0.2 & 0 & 0 & 0 & 0 & 0.3 & 0 & 0 & 0 & 0 \\ 0.4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}.$$

Let us write the results of the transformation into a double matrix A:

$$A = \begin{vmatrix} 0.14 & -0.36 & 0.80 & -0.35 & 0.66 & -0.28 & 0.60 & -0.216 & 0.07 & -0.20 \\ 0.08 & -0.20 & 0.08 & -0.22 & 0.60 & -0.17 & 0.05 & -0.12 & 0.04 & -0.02 \\ 0.02 & -0.01 & 0.02 & -0.10 & 0.02 & -0.06 & 0.01 & -0.01 & 0.00 & -0.01 \\ 0.08 & -0.20 & 0.08 & -0.19 & 0.30 & -0.15 & 0.05 & -0.12 & 0.04 & -0.02 \\ 0.40 & -0.14 & 0.32 & -0.14 & 0.26 & -0.11 & 0.24 & -0.09 & 0.03 & -0.08 \end{vmatrix}.$$

A summary table of the assessment of impact factors has been built using matrix A (tabl. 2).

Table 2. Summary table of impact factor assessment

Impact factor	Consonance of the impact of x_i on the system	Consonance of system impact on x_i	Dissonance of the impact of x_i on the system	Dissonance of the system's impact on x_i	p_i impact x_i on the system	p_i impact of the system on x_i
x_1	0.434	0.432	0.566	0.568	0.300	-0.068
x_2	0.447	0.456	0.553	0.544	0.020	0.122
x_3	0.485	0.455	0.515	0.545	-0.026	0.353
x_4	0.414	0.439	0.586	0.561	-0.034	0.122
x_5	0.441	0.439	0.559	0.561	0.229	-0.041

As shown in Tabl. 2, the impact factor x_3 has a significant positive influence on the system (0.353), compared to other factors; the system, in turn, has a significant influence on the factor x_1, the value of 0.3. The consonance of the influence of factors x_i on the system and the consonance of the influence of the system on factors x_i have close values, which indicates that the system is strengthened by the influence of factors x_i.

Let use calculate the indicators of the overall state of the system. The mutual consonance of x_i and the system is determined by the consonance matrix I_c and the dissonance matrix I_d:

$$I_c = \begin{vmatrix} 0.432 & 0.408 & 0.408 & 0.471 & 0.471 \\ 0.408 & 0.447 & 0.639 & 0.421 & 0.408 \\ 0.408 & 0.639 & 0.563 & 0.408 & 0.408 \\ 0.471 & 0.421 & 0.408 & 0.439 & 0.471 \\ 0.471 & 0.408 & 0.408 & 0.471 & 0.471 \end{vmatrix}, I_d = \begin{vmatrix} 0.568 & 0.614 & 0.592 & 0.561 & 0.529 \\ 0.614 & 0.553 & 0.438 & 0.592 & 0.614 \\ 0.592 & 0.438 & 0.438 & 0.667 & 0.592 \\ 0.561 & 0.592 & 0.667 & 0.561 & 0.561 \\ 0.529 & 0.614 & 0.592 & 0.561 & 0.529 \end{vmatrix}.$$

Analysing the I_c matrix, it is possible to conclude that the factor $x_{32} = x_{23} = 0{,}639$ has the greatest influence, and other factors have almost equal values. The matrix I_d shows almost equal values for all factors, but the factors $x_{43} = x_{34} = 0{,}667$ have a slight advantage.

Conclusions

The proposed method of building Fuzzy Cognitive Maps provides an opportunity to analyse and determine the most critical factors that have both a positive and a negative impact on the system state. The proposed method allows one to focus on factors that can increase the effectiveness of the supply system and do not require significant resources.

The developed method has several limitations, for example, the quality of determining the weighting coefficients for each factor in stochastic processes. However, this limitation can be eliminated by analysing accumulated data, such as correlation analysis, or using expert assessments combined with system analysis tools.

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