Application of multi-criteria decision-making models in dairy product storage processes

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Abstract: This paper investigates the application of multi-criteria decision-making (MCDM) models in dairy product storage processes. The study considers key decision criteria, including temperature, relative humidity, CO_2 concentration, energy consumption, and product quality and safety. The Analytic Hierarchy Process (AHP) is employed to determine the relative importance (weights) of the decision criteria based on pairwise comparisons, while the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method is applied to rank alternative storage strategies by measuring their distances from ideal and anti-ideal solutions. In addition, fuzzy logic is used to address uncertainty and variability in storage conditions under real operational environments. The results demonstrate that the integrated application of AHP, TOPSIS, and fuzzy logic enables the selection of an optimal storage strategy that ensures product quality preservation, improves energy efficiency, and maintains microbiological safety. The proposed approach provides a scientifically grounded and practical decision-support framework for optimizing dairy product storage systems.

Keywords: dairy products, multi-criteria decision making, AHP method, TOPSIS method, fuzzy logic, storage strategies, energy efficiency, product quality and safety

Introduction. Dairy products are among the strategic products that play an important role in ensuring public health and strengthening food safety in the food industry. The quality indicators and shelf life of these products largely depend on the technological conditions provided during their storage processes and are determined by factors such as temperature, relative humidity, gas environment and microbiological activity. Deviation of these parameters from optimal limits during storage leads to a rapid deterioration in product quality, a shortened shelf life and increased economic losses.

In practice, storage process management is often carried out on the basis of one or two parameters, which does not give the expected result in real conditions with complex and interrelated factors. Therefore, the need for flexible and intelligent decision-making approaches that take into account several criteria at the same time in the management of dairy product storage processes is growing. The introduction of multi-criteria decision-making models allows reducing uncertainties in storage processes, ensuring a balance between technological parameters, and simultaneously optimizing product quality and economic efficiency. Especially in conditions of constant variability of parameters in storage processes and their lack of clear boundaries, decision-making models based on multi-criteria and fuzzy logic provide higher accuracy and stability compared to traditional control methods. In this regard, the study of the mechanisms of action of multi-criteria decision-making models in dairy product storage processes, assessing their practical effectiveness and integration into modern digital control systems is an urgent scientific and practical problem.

Multi-criteria decision-making models and their analysis

Decision-making in the storage process of dairy products is considered a multi-criteria problem. In this, criteria such as temperature, relative humidity, CO2 concentration, energy consumption and product quality are simultaneously taken into account. The following models are widely used to make decisions based on these criteria: AHP (Analytical Hierarchy Process), *TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) and non-rigorous logic approaches[1,2]*.

1. Criteria table.

Table 1

Criteria	Symbol	Impact	Optimal Range
Temperature	T	Affects product shelf life and quality	2-4 °C (milk)
Relative Humidity	R	Influences drying or condensation processes	85-90 %
CO_2 Concentration	C	Affects microorganism activity	0.03-0.05 %
Energy Consumption	E	Economic efficiency	Minimum, ≤ kWh/m³
Product Quality	Q	Quality and safety	Maximum (1-point scale)

In the process of decision-making for dairy product storage, it is necessary to consider multiple criteria simultaneously. Temperature is the primary parameter determining the shelf life and quality of products; deviation from the optimal range leads to a rapid deterioration in quality. Relative humidity affects drying or condensation processes and plays a crucial role in maintaining microbiological stability. CO_2 concentration makes it possible to regulate microorganism activity; excessively high concentrations increase the risk of product spoilage. Energy consumption determines the economic efficiency of the storage process and ensures rational use of resources. Finally, product quality and safety are directly related to consumer health and therefore represent the highest-priority criteria in any decision-making process. At the same time, these criteria are interrelated, and their comprehensive optimization is achieved through multi-criteria decision-making models.

2. Formulas of the AHP model.

The AHP model plays an important role in determining the importance of decision criteria and arranging them in a hierarchical order. The AHP methodology developed by [2-4] serves to determine the weight of each criterion through pairwise comparisons and compatibility indices. Pairwise comparison matrix:

$$A = [a_{ij}], \quad a_{ij} = \frac{i}{j}, \quad i, j = 1, 2, \dots, n$$

Consistency Index, CI:

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

Consistency Ratio, CR:

$$CR = \frac{CI}{RI}, \quad CR < 0.1$$

The problem of optimal decision-making in the storage of dairy products is complex and multi-criteria, where each parameter has its own role and importance. In this context, the TOPSIS model allows us to evaluate decision options by the distance to ideal and anti-ideal solutions. The formulas of this model were presented by [1,5] and are expressed as follows:

1. Normalizatsiya qilingan qaror matritsasi:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}$$

2. Normalization with weights:

$$v_{ij} = w_j \cdot r_{ij}$$

3. Ideal (A^+) and anti-ideal (A^-) solution:

$$A^+ = \{\max v_{ij}\}, \quad A = \{\min v_{ij}\}$$

4. The distance of each alternative:

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2}, \quad S_i = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j\right)^2}$$

Multi-criteria decision-making models can be practically applied in the storage process of dairy products as follows. As an example, three storage strategies (A, B, C) were analyzed for the same type of dairy product based on 5 criteria - temperature (T), relative humidity (RH), CO2 concentration (C), energy consumption (E) and product quality (Q). In the first stage, the importance of each criterion is determined using the AHP model[7]. The following weights were obtained through pairwise comparisons and the fit index:

Table 1. Weights derived based on the AHP model for decision-making criteria. The weight (wj) of each criterion in the adval is derived using the AHP model..

Table 2

Criterion	Weight (w_i)
Temperature (T)	0.35
Relative Humidity (RH)	0.20
CO_2 Concentration (C)	0.15
Energy Consumption (E)	0.10
Product Quality (Q)	0.20

These weights are calculated by experts or specialists based on a pairwise comparison matrix to determine the relative importance of the criteria. The weights obtained as a result of pairwise comparisons according to the AHP method are included in the table (Saaty, 1980). For example, a weight of 0.35 for temperature indicates that it is one of the most important criteria in decision making[8].

In the next step, the distances of each strategy to the ideal and anti-ideal solution are calculated using the TOPSIS model. The results are presented in the following table:

Evaluation of storage strategies using the TOPSIS model.

Table 3

Strategiya	S^+	S^-	Qaror ko'rsatkichi C_i
A	0.084	0.276	0.767
B	0.112	0.248	0.689
C	0.150	0.220	0.595

As can be seen from the table, strategy A is the most optimal, since its decision indicator is Ci=0.767 with the highest value.

In the table S^+, S^- and decision indicators C_i The values were calculated using the TOPSIS model. The calculation process is as follows:

The criterion values for each strategy are normalized to a range of 0-1. For example, if the temperature is 4°C for strategy A, it is normalized to a value of 0.90.

The weights (w_j) obtained using the AHP model take into account the importance of the criteria[10].

Using the TOPSIS formulas, ideal (x^+) and anti-ideal (x^-) solutions are determined based on the strategy and criteria:

$$S_i^+ = \sqrt{\sum_{j=1}^{n} w_j \left(x_{ij} - x_j^+\right)^2}, \quad S_i = \sqrt{\sum_{j=1}^{n} w_j \left(x_{ij} - x_j\right)^2}$$

The decision indicator is:

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-}$$

A fuzzy logic approach was also applied, taking into account the uncertainty of the parameters. Linguistic ratings (“low”, “optimal”, “high”) were assigned to the temperature, humidity and CO2 parameters based on fuzzy sets, and the final storage conditions were determined through defuzzification. The result recommended the use of strategy A, which is consistent with the TOPSIS result and maintains product quality even in real conditions[3].

The data obtained as a result of practical application show that each multi-criteria decision-making model has its own advantages and limitations. The TOPSIS model evaluates options based on the distance to the ideal and anti-ideal solution, which allows for quick and accurate decision-making. As an example, the calculated decision indicators for strategies A, B and C are shown in Table Ci, which shows that strategy A has the highest value and provides optimal storage conditions. However, the TOPSIS model does not take into account the interdependencies between criteria and the uncertainty of parameters, which slightly reduces the accuracy in real conditions.

The AHP model is useful in determining the importance of criteria, organizing the decision-making process in a systematic and hierarchical manner. The weights obtained through pairwise comparisons reflect the relative importance of criteria and serve as a basis for evaluating decision options. However, the AHP model is more complicated in that the calculations become more complex as the number of criteria increases, and subjective assessments can significantly affect the result.

The fuzzy logic approach increases the accuracy of the decision-making process by linguistically evaluating variable parameters such as temperature, humidity, and CO2. Fuzzy sets and defuzzification processes allow maintaining product quality even when parameters are variable in real conditions. This approach serves as a means of reinforcing the results of TOPSIS and AHP, since it takes into account the uncertainty and natural variability of the parameters[3].

The following conclusions are drawn as a result of the analysis:

1. Determination of the optimal strategy - Strategy A was found to be the most optimal based on the TOPSIS model.

2. Evaluation of the weight of the criteria - the AHP model made it possible to clearly determine the importance of the criteria in the decision-making process.

3. Consideration of uncertainties - the fuzzy logic approach provided stable decision-making under conditions of variable parameters.

4. The advantage of combining models - the combination of TOPSIS, AHP, and fuzzy logic helps to simultaneously optimize quality, safety, and economic efficiency in the storage of dairy products.

In real conditions, it is also necessary to monitor criteria such as energy consumption and CO2 concentration, as they directly affect economic efficiency and product safety. The results show that the practical application of multi-criteria decision-making models creates an intelligent, stable and optimal management system in the storage process of dairy products.

Conclusion

This study has shown that multi-criteria decision-making models - TOPSIS, AHP and fuzzy logic - are effective and important tools in the storage process of dairy products. The results of practical analysis found strategy A to be the most optimal, which maximizes the shelf life and quality of the product, reduces energy consumption and maintains the CO_2 concentration in the optimal range. The TOPSIS model allows for quick and accurate decision-making by evaluating options based on the distance to the ideal and anti-ideal solution, while the AHP model stabilizes the decision-making process by systematically determining the relative importance of the criteria. The fuzzy logic approach provides stable and reliable decision-making in real conditions, taking into account the variability and uncertainty of the parameters.

The combination of models allows for the simultaneous optimization of quality, safety and cost-effectiveness, taking into account each criterion in its place, reducing energy consumption, controlling CO_2 concentration and ensuring microbiological stability. At the same time, when multi-criteria decision-making approaches are integrated with digital twin and artificial intelligence technologies, the dairy storage system becomes more automated, intelligent and economically efficient.

The study also showed that these approaches are recognized as an integral part of a scientifically sound, sustainable and innovative management system and have scientific and practical value in optimizing the dairy storage process.

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