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ПП "ТЕХНОЛОГІЧНИЙ ЦЕНТР"

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DEVELOPMENT OF A MODEL FOR THE RATIONAL USE OF RAW MATERIALS IN THE TECHNOLOGY OF MEAT PROCESSING ENTERPRISES

The object of the research is meat raw materials obtained from animal slaughter. The research is aimed at addressing the problem of the efficient utilization of meat raw materials under conditions of their natural variability and production uncertainty, which limits the ability to make timely and well-founded technological decisions. The research developed a mathematical model for planning the production of a diverse assortment of meat products, taking into account regional characteristics of raw materials and the production and technological potential of enterprises. The use of the model enables the formation of the consumer properties of meat products, including grade, taste, nutritional and biological value, through the rational utilization of raw materials of different origins, considering the species, breed, age, sex, and fatness of animals. The article shows that product quality should be evaluated using a comprehensive criterion integrating physicochemical, functional-technological, and structural-mechanical indicators. Particular importance is given to rheological characteristics correlating with properties of raw materials, minced systems, and finished products.

Within the research, an objective function was developed that accounts for availability and quality of raw materials for different products. Sets of enterprises, assortments, animal characteristics, and supply zones were formalized considering environmental conditions of origin areas. Production constraints were described using a compatibility matrix, emphasizing water-binding processes and preservation of intramuscular fat as key quality factors. Production variants were also formalized, considering technological constraints under conditions of production uncertainty.

The practical application of the developed model provides digital support for production management, optimizes raw material allocation, and enables product yield prediction. It also reduces production losses and meets the current requirements for the digital transformation of meat processing enterprises.

Keywords: *meat raw materials, resource efficiency, quality, technology, mathematical modeling, digitalization, meat processing enterprises.*

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1. Introduction

One of the priority directions in the development of the meat industry is the creation of high-quality products based on raw materials of various species origin, with nutritional value that meets the requirements of technical regulations and normative documentation. Modern technologies play an important role in this, in particular a global calibration model for predicting intramuscular fat and pH in red meat using hyperspectral imaging [1], and the assessment of meat microbiological quality using deep convolutional neural networks (CNNs) on embedded hardware systems [2].

One of the priority tasks of the modern meat industry is to improve the efficiency of raw material utilization and increase production intensity. Achieving this goal is possible through the implementation of innovative technologies for assessing the quality of livestock carcasses. A promising approach is the classification of beef based on its intramuscular fat content using hyperspectral imaging technology. This approach enables objective grading of raw materials and optimization of their technological utilization. Furthermore, it creates opportunities for expanding the range of meat products and improving the overall efficiency of meat processing operations [3]. This is achieved, in particular, through the development of composite products that combine different types of meat raw materials, spices and functional additives, as well as the application of modern principles and Industry 4.0 technologies in the meat industry [4], and the Internet of non-thermal food processing technologies [5].

When designing multi-component products with varying compositions, it is crucial to model characteristics and predict properties using blockchain technology within the agri-food supply chain [6] and in food safety and the traceability of livestock products [7]. Modern methods of formulation development are based on the principles of food combinatorics, utilising linear programming, experimental-statistical programming and an object-oriented approach to the application of artificial intelligence methods in meat processing [8]. This approach enables the informed selection of ingredients to achieve the desired organoleptic properties, as well as the required nutritional and energy value of the products. Therefore, predicting future production requires comprehensive information about the chemical composition and biological value of individual ingredients used in formulations. It is also important

to consider sustainability aspects and regulatory requirements related to cultured meat [9]. In addition, the specific characteristics of cultured meat production from pig muscle stem cells should be taken into account [10]. Furthermore, data on the actual values of the functional and technological properties of the main raw materials and additional ingredients are important. It is also necessary to take into account the kinetics of biochemical and colloidal processes in multi-component food systems. Analytical and empirical relationships that characterize the fundamental patterns of behavior in heterogeneous dispersed systems as physical and chemical factors vary are of significant importance.

There is growing scientific and practical interest in developing simulation and predictive models for the production processes involved in manufacturing a wide range of meat products [11]. This is achieved through the development of structured models and specialized software to support decision-making. Such approaches also play an important role in ensuring the future supply of animal protein for human consumption [12, 13]. This involves the systematic collection of representative experimental and operational data, followed by their formalization, statistical analysis and parametric identification. The development of the model involves forecasting production output and resource efficiency, as well as determining optimal operating modes for technological processes. The application of the model enables computer-assisted calculation of the enterprise's production program based on the concepts of Industry 4.0 and resource efficiency, using raw materials of varying quality and different regional origins.

However, in the analyzed scientific sources, functional and technological properties of raw materials were not considered, nor were the production constraints required for mathematical modeling of meat product assortment. In addition, issues related to adaptive production planning under conditions of production uncertainty, using modern mathematical modeling methods, remain insufficiently investigated.

The growing scientific and practical interest in developing simulation and predictive models for the technological processes of manufacturing a wide range of meat products is driven by the need for digital support in technological decision-making. Implementing this approach requires the development of structured mathematical models and specialized software. Such models and software provide optimization of meat raw material utilization, prediction of production processes, and improvement of production efficiency. This creates important prerequisites for ensuring an adequate supply of animal protein to the population.

In accordance with the requirements of the ISO 9000 series of international standards, the guiding principle of management is fact-based decision-making, which entails the mandatory and systematic use of statistical methods, model validation procedures and quantitative risk assessment.

Therefore, *the object of research* is meat raw materials obtained from animal slaughter.

The aim of this research is to develop a model for the rational use of raw materials in meat processing enterprises, accounting for the functional and technological properties of the main raw materials under conditions of production uncertainty. This will allow for the optimization of raw material allocation, the prediction of production yield, and the reduction of production losses.

Achieving this aim requires solving the following interrelated *tasks:*

– to investigate the quality of meat raw materials and mineral composition as a basis for modeling and development of meat processing industries;
– to develop an objective function and an algorithm for implementing a mathematical model for the optimal use of raw materials;
– to substantiate the mathematical description of product assortment production with consideration of production and technological constraints;
– to perform the practical implementation of the developed mathematical model.

2. Materials and Methods

The research employed mathematical modeling, systems analysis, process formalization, and parametric modeling methods to develop a model for the rational utilization of raw materials at meat processing enterprises under conditions of variability in raw material characteristics and production constraints.

The mathematical model was developed based on a matrix representation of the relationships between raw material resources and the assortment of finished meat products. The model consists of an objective function, a system of technological constraints, and a set of decision variables describing the allocation of raw materials among product recipes. The objective function was formulated to ensure the rational utilization of available meat raw materials while simultaneously satisfying technological requirements and the quality requirements of the finished products.

The system of constraints includes production constraints related to the overall availability of raw materials, technological requirements of the production process, and the required chemical composition of meat products, including the contents of moisture, protein, fat, carbohydrates, and other components. In addition, the model incorporates constraints that account for the functional and technological properties of raw materials and the requirements for product formulation.

The model input variables include the physicochemical and functional-technological properties of meat raw materials, the morphological composition of carcasses, animal species, breed, age, sex, body condition, region of origin, and the available quantities of each type of raw material. These variables were selected because of their direct influence on the technological properties of the raw materials, the performance of production processes, and the quality characteristics of the finished meat products.

The output variables of the model comprised the optimal formulation of multicomponent meat products, the optimal allocation of raw material resources among product groups, predicted quality indicators of finished products, production yield, and indicators of production efficiency.

The model considers the production of multicomponent meat products, which formulations are developed from raw materials of different origins and with different technological characteristics. Particular attention is paid to ensuring the technological compatibility of raw material components and the compliance of the finished products with established quality requirements.

The database used for modelling consisted of information on the chemical composition, functional-technological properties, and biological value of meat raw materials obtained from scientific publications, reference sources, and experimentally determined technological characteristics. Prior to modelling, the data were verified, standardized, and transformed into a unified parametric format suitable for mathematical processing.

The model was implemented through computational calculations using matrix operations and numerical optimization procedures. The adequacy of the model was evaluated by comparing the predicted formulation parameters, production performance indicators, and available raw material resources with the technological requirements for meat products. The predicted production volumes were also assessed for consistency with the production capacity and the feasibility of product realization.

3. Results and Discussion

3.1. Investigation of meat raw material quality and mineral composition as a basis for modeling and development of meat processing industries

The concept of meat quality is universal: it should be healthy, nutritious and tasty. For example, goat meat is a product of many different production systems involving various environments, feeding regimes

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and genotypes. The physical, chemical, sensory and nutritional properties of goat meat at the time of consumption result from the cumulative influence of factors, each of which, to a greater or lesser extent, can be controlled by producers, retailers and processors. The researchers examined the genetic and physiological factors influencing goat meat production [14].

The mineral composition of meat is influenced by a range of internal and external factors. Researchers have quantified the different sources of variation in beef mineral profiles [15]. Samples of the *Longissimus thoracis* muscle (N. 182) from young bulls and heifers were analyzed using ICP-OES, covering 6 macrominerals, 5 essential microminerals, and 9 environmental trace elements. The results of mixed models showed that breed and sex had little effect on the mineral profile. The main sources of variation – such as farms, individual animals within a farm, and subgroups within an animal breed – showed marked differences in mineral profiles, thereby influencing reproducibility coefficients. Multivariate factor analysis showed that five latent factors account for 69% of the covariance among the 20 minerals. The first factor represented overall mineral quantity, while the remaining factors were linked to specific mineral groupings: Na–Fe–Cu, K–B–Pb, Fe–Mn, and Zn. Overall, the primary source of variation in mineral content depends on the complex interactions among genetics, physiological processes, farm environment, management practices, and feeding regimes. Latent factor analysis proved valuable for uncovering these relationships.

The animals were slaughtered in accordance with European Union regulations. The day after slaughter, beef samples were taken from the *Longissimus thoracis* muscle (the longest thoracic muscle) at the point where the carcass is divided into two quarters (at the level of the 5th rib), known as "pistol cuts".

Samples were taken from both sides of each carcass (a total of 182 meat samples) to investigate variations in mineral content in meat from the same anatomical location within the same animal. The meat samples were cooled, vacuum-packed, labelled and sent for analysis to the DAFNAE meat laboratory at the University of Padua (Italy). Descriptive statistics and analysis of variance for the content of essential and trace macro- and microelements in meat are presented in Table 1. The input data were obtained from the research reported in [15] and were used as the information basis for the development of the mathematical model.

The researchers determined the concentrations of K, Na, Fe, Zn, Ca, Cu and Mg in the *longissimus dorsi, semimembranosus* and diaphragm muscles. In 94 animals of slaughter weight, the mean concentrations of the elements, expressed in ppm relative to fresh weight, in the three muscles varied within the following ranges: Cu = 0.70–1.66; Fe = 18.0–38.1; Ca = 23.8–30.2; Zn = 26.8–40.5; Mg = 198–248; Na = 528–708; K = 3060–3840 [16]. The concentrations of all seven elements in the diaphragm muscle differed statistically significantly from their levels in the other two muscles. The concentrations of Cu, Fe, Zn and Mg in the *longissimus dorsi* also differed significantly from those in the *semimembranosus* muscle. The influence of sex and breed was less pronounced. In a group of 20 adult cows, an age-related pattern was observed for Fe, Ca, Zn, Mg and Na.

Table 1

Descriptive statistics and analysis of variance of the content of essential and trace macro- and microelements in meat

Elements	Number of half-carcasses	Average	SD	Min.	Max.	Breed	Sex	RMSE
Macroelements, mg/kg								
Na (Sodium)	175	436	46	324	559	–	–	14
Mg (Magnesium)	178	179	13	147	205	–	–	4
P (Phosphorus)	179	1488	144	1162	1744	–	–	38
S (Sulphur)	180	1354	78	1165	1535	–	–	40
K (Potassium)	181	2821	79	2590	3021	–	$P < 0.05$	56
Ca (Calcium)	174	46	13	26	103	$P < 0.05$	–	10
Essential microelements, μg/kg								
Cr (Chromium)	94	12.5	6.4	1.6	33.7	–	–	5.7
Mn (Manganese)	174	47.6	8.1	26.7	74.6	–	–	4.3
Fe (Iron)	172	14260	2373	8481	21288	–	–	530
Cu (Copper)	174	460	60	264	618	–	–	26
Zn (Zinc)	180	39782	5395	26378	53967	–	$P < 0.05$	1968
Environmental trace elements, μg/kg								
Li (Lithium)	175	4.1	1.7	1.5	8.8	–	–	0.5
B (Boron)	173	164	105	41	505	$P < 0.01$	–	27
Al (Aluminum)	172	755	263	324	1529	–	–	158
Ti (Titanium)	177	14	5.1	4.6	28.1	–	–	3.5
Ni (Nickel)	153	20.6	11.6	6.3	59.4	–	–	11.5
Sr (Strontium)	175	47.3	20.3	17.5	132.3	–	–	13.1
Sn (Tin)	172	350	154	109	719	–	$P < 0.001$	79
Ba (Barium)	147	11.2	5.9	1.5	31.5	–	–	5.7
Pb (Lead)	127	61.9	13.4	27.3	90.1	–	$P < 0.05$	5.6

Notes: SD – standard deviation; RMSE – root mean square error of the model

As meat is one of the key sources of metals in the human body, researches of trace element content in various types of muscle tissue are particularly relevant. In this context, the effect of copper supplementation on mineral status was determined and analyzed. Samples were taken from four different muscles (diaphragm, cardiac, semitendinosus and pectoral; $n = 120$) from beef calves. The calves were fed standard commercial diets, either supplemented with Cu (15 mg Cu_2SO_4/kg dry matter) or without supplementation. Their acid digestibility was also investigated. Concentrations of non-essential elements (As, Cd, Hg, Pb and Sn) and essential elements (Co, Cr, Fe, Mn, Mo, Ni, Se and Zn) were determined using ICP-MS. Statistical evaluation involved two-way ANOVA, post hoc DHS Tukey and Spearman correlations. In general, muscles with higher activity and lower fat content exhibited greater concentrations of essential trace elements and lower levels of non-essential elements. Residues of As and Hg in muscle tissue indicate the impact of these elements on animals. However, when mineral status is adequate, the concentrations of essential trace elements in muscle are independent of the animal's mineral status and may be related to their specific muscular metabolism. Copper supplementation led to a significant reduction in As levels but caused a significant decrease in Se, which could be detrimental to the animal's health [17].

The use of raw materials from specialized feeding systems (marbled beef, pork with an increased content of oleic acid, and poultry meat produced under specialized feeding regimes) creates prerequisites for the production of premium and functional food products. It has been established that the key parameters of such raw materials are not only the mass fraction of protein and fat, but primarily the structure of fat inclusions and the fatty acid composition, which require differentiated thermal processing regimes.

It is important to develop food products with a high level of nutritional balance and to enhance daily diets, which is achieved through computer modelling of meat product recipes. In particular, the researcher examines the main phases of simulation modelling within the established classical algorithmic approach to modelling, followed by the development of computer programmes. The research analyses the stages involved in designing software for the technological process of meat product manufacturing, as well as the user interface for meat production technologists. The need to develop a mathematical model for meat product design is driven by the necessity of a formalized description of the processes and subprocesses within the technological system. Such a model integrates specialized analytical and probabilistic mathematical models of different types, combined within a unified formal framework [18].

In addition, the paper examines the main challenges and their solutions in the construction of new food processing plants. It sets out the key approaches to regulating the development of integration processes in food production, focusing on the rational distribution of regional agricultural processors and their supply of raw materials. The researchers examined the factors determining the composition of the raw material base for food enterprises, their raw material supply areas and evaluation criteria, as well as the principles governing the location of food industry enterprises. The process of optimizing the location of various types of production and business entities is a key prerequisite for the effective operation and successful development of enterprises in the sector. An algorithm has also been developed to determine the optimal location of food processing enterprises, taking into account the distribution of raw material resources across Ukraine. The research highlights the need to develop processing enterprises of various sizes – large, medium and small – which will enhance the regional economy's adaptability to market demands [19].

The raw material base of meat processing enterprises is quite diverse. It includes various types of livestock such as cattle, pigs, and small ruminants. In some regions, game animals also constitute a significant part of the meat raw materials used for processing. Meat is an important source of nutrients for humans, and its nutritional impact depends on the concentration of trace elements in different types of muscle tissues.

3.2. Development of an objective function and an algorithm for implementing a mathematical model for the optimal use of raw materials

One of the key factors in expanding the production of a new range of high-quality products, increasing productivity and enabling the rapid adaptation of production processes to new product types is the use of digitalization. The implementation of the stated tasks requires a scientifically grounded integrated approach to the rational utilization of the consumer properties of raw materials and the production and technological potential of the enterprise. This approach is based on the modeling of the elements of the model matrix. It also involves the development of an algorithm for its implementation and the formulation of an objective function. This, in turn, ensures the adoption of well-founded managerial and technological decisions.

To achieve the set objective under real production conditions, it is necessary to make efficient use of the available raw materials and supplies. In doing so, sensory characteristics are prioritized (weighting 0.35–0.48), as they are the ultimate criterion for consumers.

To implement this model, the symbols J, I, P and Z have been introduced to denote, respectively, the set of enterprises, the product range, animal characteristics and the raw material supply zone. Let P_1, P_2, ..., P_k, P_l, P_n, ($P_s \subset P$, $s = 1, 2, ..., k, l, n$) denote subsets defined according to the breed, age, sex and body condition of the animals. If there are m ($m < n$) animals of the predominant breed among $P = \{P_1, ..., P_n\}$, then it is assumed that $P^1 = \{P_1, ..., P_m\}$, $P^2 = \{P_{m+1}, ..., P_k\}$ and so on. Let z_1 be an ecologically clean zone, z_2 a zone containing large industrial enterprises, z_3 a zone of partial pollution, and z_4 an ecologically hazardous zone subject to chemical, radioactive or other forms of pollution. Thus, $z = \{1, 4\}$. In what follows, the superscript "1" will be used to denote a fixed element from any set. The structural elements of the model matrix are presented in Table 2.

Table 2

Structural elements of the model matrix

Model elements	Description of technological specifications
$i(z^1, P_s)$	the set of product assortment for which the raw material supply zone z^1 is used, originating from the subset P_s ($s = 1, 2, ..., k, l, n$)
$V(i^1, j^1, z^1, P^1)$	the maximum technologically feasible production volume of the i^1-th product assortment from the z^1 supply zone, using the P^1 subset of animals, produced by the j^1-th enterprise
$G(i^1, P^1, j^1)$	the minimum required production volume of the i^1th assortment of products from the P^1 subset of animals at the j^1-th enterprise
$P(i^1, P^1)$	production task for the i^1-th assortment of products from the P^1 subset of animals at the processing enterprise
$Q(j^1)$	production capacity of the j^1-th enterprise
$C(i^1, P^1, j^1)$	the average selling price of the marketable products of the i^1-th assortment from the P^1 subset of animals produced at the j^1-th enterprise
$\varphi(i^1, z^1, P^1, j^1)$	the utilization coefficient of the technologically available resource of the z^1-th supply zone of the P^1 subset of animals to produce the i^1-th assortment of products at the j^1-th enterprise
(i^1, P^1, j^1)	the production volume of the i^1-th assortment of products from the P^1 subset of animals that can be produced at the j^1-th enterprise

To implement the proposed model, an algorithm for its execution has been developed and is shown in Fig. 1.

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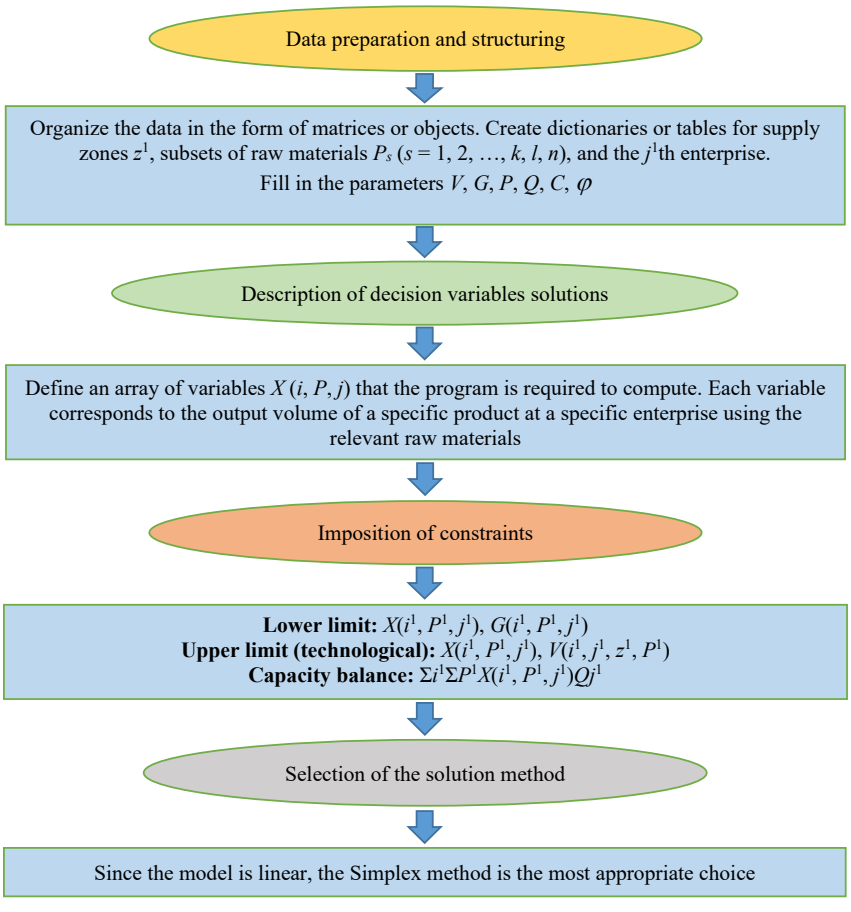

Fig. 1. Algorithm for the implementation of the model

This approach ensures the scalability, adaptability, and versatility of the model. It enables its integration into digital decision support systems for meat processing enterprises. The proposed model can also be used to optimize the production of a wide range of meat products without the need to develop separate models for each type of raw material.

3.3. Mathematical description of product assortment production with consideration of production and technological constraints

The objective function of the model is to maximize the value of marketable products obtained from the processing of animal raw materials (1). This is achieved through the rational utilization of their product properties of animal origin [15–17]. It also considers the production and technological capabilities of the processing enterprise [19]

$$\sum_{i\in j}\sum_{s=1}^{n}\sum_{j\in J}\omega\left(i,P_s,j\right)\subset\left(i,P_s,j\right)\rightarrow\max. \quad (1)$$

Production constraints:

1. The total production volume of all product assortments at the j^1-th enterprise must not exceed its processing capacity

$$\sum_{i\in j}\sum_{s=1}^{n}\omega\left(i,P_s,j\right)\leq Q_{j1}. \quad (2)$$

2. The total production volume of the i^1-th product assortment from the P^1 subset of animals across the entire association must satisfy the overall demand for it

$$\sum_{i\in j}^{n}\omega\left(i^1,P^1,j\right)\geq R\left(i^1,P^1\right), \quad (3)$$

where R – the production volume of the enterprise's product assortment, t.

3. The production volume of the i^1-th product assortment from the P^1 subset of animals at the j^1-th enterprise must not exceed the consumers' transportation capacities $T(i^1, P^1, j^1)$, in terms of warehouse storage periods

$$V\left(i^1,P^1,j^1\right)\leq T\left(i^1,P^1,j^1\right), \quad (4)$$

where V – the potential production output of the enterprise, t/shift; T – the consumers' transport and storage capacity, t.

When selecting raw materials, the compatibility matrix plays a key role, with the focus shifting from how to bind water to how to preserve intramuscular fat. The compatibility matrix is shown in Table 3.

Technological constraints:

1. The maximum technologically feasible production volume of the i^1-th assortment of products from the P^1 subset of animals must correspond to the raw material base from which the j^1-th enterprise sources it

$$\omega\left(i^1,P^1,j^1\right)\leq V\left(i^1,j^1,z^1,P^1\right). \quad (5)$$

2. The total output of products and items at the j^1-th enterprise from the P^1 subset of animals, using raw materials from unfavorable zones (z_3, z_4), must not exceed the permissible limit established by the state standard

$$\sum_{i\in j\left(z_3,z_4,P^1\right)}^{n}\omega\left(i^1,P^1,j^1\right)\leq R\left(i^1,P^1,j^1\right). \quad (6)$$

3. The production of premium-grade products and delicacies (assigned indices i = 2 and i = 3, respectively) from the z_1 raw material zone, subset of animals s = 3, at the j^1-th enterprise must satisfy the following condition

$$\omega\left(2,3,j^1\right)+\varphi\omega\left(3,3,j^1\right)\le 1, V\left(3,j^1,3,2\right), \quad (7)$$

where $\varphi\left(3,z^1,3,j^1\right)=\frac{V\left(3,j^1,3,2\right)}{V\left(2,j^1,3,2\right)}$.

4. The average selling price of products and items produced at the j^1-th enterprise from the P^1 subset of animals, using raw materials from supply zones z_3 and z_4, must satisfy the following condition

$$C\left(i^1,P^1,j^1,z_3,z_4\right)<<C\left(i^1,P^1,j^1,z_1,z_2\right). \quad (8)$$

The structure of model (1)–(8) may vary depending on specific production conditions within meat processing. A distinctive feature of this model is the technological balance of options both for individual enterprises and for the cluster, considering the rational and full utilization of raw materials and the production and technological capabilities of each enterprise within the association.

The mathematical description of specific technologies is complicated by operation under conditions of various types of production uncertainty. In this regard, it is advisable to apply modeling methods capable of identifying hidden patterns in large data sets and ensuring the adaptability of the model, considering the methodology of technological processes (Table 4).

Technology is determined by the variable properties of raw materials, the stochastic nature of technological factors, measurement errors, and incomplete information about the production objective functions.

The specified parameters of the final product are defined by certain minimum (min) and maximum (max) values of its characteristics and/or the quantities of ingredients used. It is proposed to take the following constraints into account when solving the task.

For the overall chemical composition (moisture, protein, fat, and carbohydrate content)

$$F_{\min i}\le j\sum E_{j,i}\cdot X_j=E_{\max i};\ \text{for } i=1,\ 2,\ 3,\ 4. \quad (9)$$

For the content of essential amino acids

$$A_{\min}k\le j\sum A_{j,k}\cdot X_j\le A_{\max}k;\ \text{for } k=1,2,\ldots,8\ (\text{or } 10). \quad (10)$$

For the content of fatty acids

$$L_{\min\nu}\le j\sum L_{j,\nu}\cdot X_j\le L_{\max\nu};\ \text{for } \nu=1,\ 2,\ \ldots,\ V. \quad (11)$$

For the content of essential microelements

$$\mu E_{\min\mu}\le j\sum \mu E_j,\ \mu\cdot X_j\le \mu E_{\max\mu};\ \text{for } \mu=1,2,\ldots,\ M. \quad (12)$$

For the mass of the ingredient used

$$X_{\min j}\le j\sum X_j\le X_{\max j};\ \text{for } j=1,2,\ldots,\ N, \quad (13)$$

where $E_{\min i}$ and $E_{\max i}$ – the minimum and maximum allowable contents of the i-th chemical element in the final product, including environmental microelements; $E_{j,i}$ – the actual content of the i-th chemical element in the j-th ingredient; $A_{\min k}$ and $A_{\max k}$ – the minimum and maximum allowable contents of essential amino acids.

The concept of this research is not to develop a model for a specific enterprise or a particular type of meat raw material, but rather to create a universal mathematical model for supporting technological decision-making. Therefore, the model parameters describe the patterns of variation in the properties of meat raw materials under the influence of factors such as animal species, age, sex, body condition, carcass morphological composition, and region of origin. Production data from an individual enterprise may be used only for model adaptation or validation. However, such data cannot encompass the full range of raw material characteristics and production scenarios for which the proposed model is intended.

These parameters reflect the natural variability of meat raw materials of different biological origins and technological conditions, which is a characteristic feature of modern meat processing. The proposed mathematical model has been specifically developed to operate under such conditions of uncertainty. Based on a comprehensive assessment of raw material properties, technological constraints, and production criteria, the model determines the most rational utilization pathways for the raw materials available at the enterprise. This ensures the optimal allocation of raw materials among different product categories to maximize economic efficiency, improve raw material utilization efficiency, and ensure the consistent quality of finished products.

3.4. Practical implementation of the mathematical model

Considering the diversity of slaughter animals and the wide range of meat products, incorporating all possible combinations into a single mathematical model is practically impossible. This would lead to the formulation of a mathematical system containing an extremely large number of equations and constraints, making its solution computationally prohibitive or practically infeasible. For this reason, a universal parametric model is proposed that can be adapted to specific production conditions through the specification of the corresponding input parameters.

Table 3

Compatibility matrix for special raw materials

Type of feeding	Characteristics of the raw materials	Effect on water-binding capacity and texture	Practical solution (Model *W*)
Grain-fed (beef)	High marbling, labile fat	Fat melts easily at low temperatures	Sous-vide or low-temperature cooking methods
Oil-fed/grass-fed (pork)	Increased omega-3 and omega-6 content	Susceptibility to rapid oxidation	Use of natural antioxidants (rosemary extract)
Finisher feed (poultry)	Increased tissue density	Stable structure, high water-binding capacity	Production of whole-muscle delicacies

Table 4

The adaptability of the model, taking into account the methodology of technological processes

Condition of raw materials	Priority product	Technological model	Final objective
High fat content (>30%)	Second-grade sausages, pâtés	Emulsification model with fat replacers	Retention of structure during heating
High collagen content	Aspics (meat jelly), headcheese, and liver sausages	Pre-hydration and grinding model	High profitability of by-products
Frozen raw materials (defrosted)	Semi-finished products (dumplings, cutlets)	Moisture recovery model based on cryomassage	Compensation for juice losses

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In practice, the model can be applied to a specific enterprise by considering its typical raw material base, characterized by a defined animal species and standard breeding and production conditions. In addition, the model considers transport constraints, raw material supply conditions, and the subsequent utilization of raw materials to produce the planned assortment of meat products.

To demonstrate the applicability of the proposed mathematical model, its practical implementation was carried out using a hypothetical meat processing enterprise as a case study. For this purpose, five production scenarios differing in production output volumes were developed. Based on the proposed mathematical relationships, the objective function was calculated, and compliance with the production and technological constraints was verified.

The maximum technologically feasible production volume $V(i^1, j^1, z^1, P^1)$ of the i^1-th product category, manufactured by the j^1-th enterprise from the P^1-th subset of animals supplied from the z^1-th supply region, shall not exceed the transport and storage capacity of consumers $T(i^1, P^1, j^1)$ within the permissible storage period (4).

The production volume of a particular product type shall not exceed the quantity that consumers are able to purchase within the permissible storage period. For example:

– product category i^1 – beef half-carcasses;
– subset of animals P^1 – cattle;
– supply region z^1 – supply region No. 1 (Stryi District, Lviv Region, Ukraine);
– enterprise j^1 – meat processing enterprise No. 1 (Lviv, Ukraine).

Five demand scenarios were considered for a meat processing enterprise with a processing capacity of 100 t/shift of livestock meat (Table 5).

Based on Table 5, it is possible to determine:

– production dynamics under different scenarios;
– changes in the product assortment structure;
– the limit of achieving maximum production capacity;
– the transition from half-carcass sales to value-added deep processing.

Since Equation (1) defines the objective function of the optimization problem, a system of weighting coefficients for the production and technological value of each product type was introduced (14). This approach is consistent with economic and mathematical modelling principles and allows obtaining specific quantitative results

$$F = \omega_j^1 Q_j^1, \quad (14)$$

where F – the objective function; ω_j^1 – the weighting coefficient of the i-th product type; Qj^1 – production capacity of the j^1-th enterprise.

The model assumes that the production and technological significance coefficients of individual product types correspond to the values given in Table 6.

Table 6

Weighting coefficients of the production and technological significance of meat products

Product Type	Notation	Weighting coefficient
Beef half-carcasse	ω_1^1	1.00
Pork half-carcasses	ω_2^1	0.95
Lamb half-carcasses	ω_3^1	1.20
Meat cuts	ω_4^1	1.10
Sausage products	ω_5^1	1.60
Other products	ω_6^1	0.80

The results of calculating the objective function values for different scenarios are presented in Table 7.

Table 7

Calculation of the objective function values

Scenarios	Objective function value (F)
Scenario 1 – low demand	66.8
Scenario 2 – moderate	83.9
Scenario 3 – baseline	101.0
Scenario 4 – increased	110.7
Scenario 5 – maximum	109.3

The results presented in Table 7 demonstrate that the maximum value of the objective function is achieved under Scenario 4, although Scenarios 4 and 5 both correspond to full production capacity utilization (100%). This can be explained by the substantially higher share of sausage products in Scenario 4 (14 t compared to 11 t), which have the highest production and technological significance (weight coefficient of 1.6). Despite the identical total production output, the product mix in Scenario 4 provides an objective function value that is 1.4 points (approximately 1.3%) higher than that of Scenario 5, indicating greater overall production efficiency.

In the subsequent stage of the research, the arbitrary weighting coefficients were replaced with coefficients calculated from three objective, real-world criteria that characterize the production and technological properties of meat products

$$\omega_j = \alpha K_i^1 + \beta D_i^1 + \gamma M_i^1, \quad (15)$$

where K_i^1 – value-added coefficient of product i; D_i^1 – market demand coefficient of product i; M_i^1 – technological complexity or processing efficiency coefficient of product i; $\alpha + \beta + \gamma = 1$.

This approach enables the development of a scientifically grounded integrated indicator of production and technological capabilities, rather than relying on arbitrary weighting coefficients.

Table 8 presents the calculated production volume of the i_1-th product category from the P_1 subset of animals, determined using Equation (3). For illustrative purposes, assume that the subset corresponds to beef, the product category to beef half-carcasses, and the forecasted demand $R(i^1, P^1)$ is 25 t.

Table 9 presents the calculated production volume of the i^1-th product

Table 5

Production scenarios for different types of meat products at a meat processing enterprise

Scenarios	Product type							
	Beef half-carcasses, t	Pork half-carcasses, t	Lamb half-carcasses, t	Meat cuts, t	Sausage products, t	Other products, t	Total production volume, t	Capacity utilization, %
Scenario 1 – low demand	18	16	7	12	6	3	62	62
Scenario 2 – moderate	22	18	8	16	9	4	77	77
Scenario 3 – baseline	26	20	9	20	12	5	92	92
Scenario 4 – increased	28	22	10	22	14	4	100	100
Scenario 5 – maximum	30	24	10	23	11	2	100	100

category from the P^1 subset of animals at the j^1-th enterprise, determined using Equation (4). This production volume must not exceed the consumers' transportation capacity $T(i^1, P^1, j^1)$, as constrained by warehouse storage life. For example, $T(i^1, P^1, j^1) = 95$ t.

Table 8

Calculation of production volumes under different scenarios

Scenarios	Production volume, t	Forecasted demand, t	Condition satisfied
Scenario 1 – low demand	18	25	No
Scenario 2 – moderate	22	25	No
Scenario 3 – baseline	26	25	Yes
Scenario 4 – increased	28	25	Yes
Scenario 5 – maximum	30	25	Yes

Table 9

Calculation of production volumes under different scenarios considering consumers' transportation capacity

Scenarios	Production volume, t	Transportation capacity, t	Condition satisfied
Scenario 1 – low demand	62	95	62 < 95 Yes
Scenario 2 – moderate	77	95	77 < 95 Yes
Scenario 3 – baseline	92	95	92 < 95 Yes
Scenario 4 – increased	100	95	100 > 95 No
Scenario 5 – maximum	100	95	100 > 95 No

Therefore, under Scenarios 4 and 5, the constraint defined by Equation (4) is not satisfied. In this case, achieving maximum production capacity requires measures to increase consumers' transportation capacity while ensuring that the products can be transported and stored within their allowable warehouse storage periods.

The obtained results confirmed the applicability of the proposed model for evaluating the feasibility of production decisions and selecting the optimal operating scenario for the enterprise. According to the calculation results, Scenarios 1–3 were characterized by sufficient production and transport-logistics resource reserves. In Scenarios 4 and 5, the total production volume reaches the maximum production capacity of the enterprise (100 t). Given the transport capacity constraint of 95 t, Scenarios 4 and 5 do not satisfy constraint (4), since the actual production volume exceeds the available transport capacity by 5 t, or 5.3%. This indicates that, despite the availability of sufficient production capacity, the transport and logistics factor becomes the limiting element of the production system. Thus, the obtained results confirm that the proposed model not only enables the identification of feasible production scenarios but also allows the timely detection of limiting factors affecting the enterprise's operation.

3.5. Discussion

The modeling results demonstrate that the proposed mathematical model is sufficiently sensitive to variations in production and technological parameters. It provides a reliable basis for informed managerial decision-making in selecting the optimal production scenario. The proposed model can be used as a decision support tool for production planning in meat processing enterprises under conditions of uncertainty regarding market demand, raw material availability, and logistics resources.

The model enables the assessment of the production and technological capabilities of a meat processing enterprise under different production scenarios. As production volume increases from 62 to 100 t, production capacity utilization rises proportionally from 62% to 100%. These results confirm the validity of the developed model and its compliance with the specified production constraints. At low demand levels (62–77 t), the enterprise operates with a substantial reserve of production capacity. Therefore, the selection of the optimal product assortment is determined primarily by economic criteria and the efficiency of raw material utilization. When demand reaches 92 t, the enterprise approaches full resource utilization. Any further increase in production requires improvements in logistics capabilities or the expansion of transport infrastructure. When the production capacity reaches 100 t, the transport system becomes the primary limiting factor. The model automatically rejects such solutions as infeasible, confirming its ability to generate production plans that comply with all specified technological constraints.

A distinctive feature of the obtained results is the development of a mathematical model that, unlike existing approaches, provides an integrated consideration of meat raw material characteristics, production capacity, product assortment structure, forecasted demand, and transport and logistics constraints in the formation of the enterprise's production program. The proposed model enables the automated identification of feasible production scenarios and the timely detection of limiting factors affecting the production system. In addition, it provides an assessment of production reserves and improves the validity of managerial decision-making under conditions of production uncertainty.

Mathematical modeling plays a vital role in understanding and optimizing various aspects of the food industry. Scientists have provided an overview of the applications of mathematical modeling and equations in the food industry [20]. They explore various sectors of the food industry where mathematical models are successfully applied, highlighting their advantages and challenges. Moreover, the importance of mathematical modeling for improving food safety, quality, and efficiency is discussed. This research serves as a valuable resource for scientists, engineers, and professionals working in the food industry.

Unlike other industries, where virtualization and mathematical modeling have already become standard practices, their potential in the meat processing industry has not yet been fully utilized. That is why research is focused on the implementation of virtualization and mathematical modeling approaches in the food industry [21]. The need for their application is justified, the fundamentals of mathematical modeling are presented, and various approaches are considered, along with solution methods, required initial and boundary conditions, and thermophysical properties. It also critically analyzes the complexity of existing models, computational costs, and their implementation procedures.

Thus, mathematical models for resource management in meat processing production ensure improved efficiency of planning and product output optimization through the integration of demand forecasting, analysis of available raw materials, inventory levels, and human resource allocation. For formalizing the problem, it is appropriate to use mixed-integer linear programming combined with stochastic modeling. This approach allows for an adequate description of multi-variant flows of raw materials and products. It also enables optimization of grinding processes. In addition, it supports the optimization of heat and mass transfer in information environments.

A review of current global trends in the development of the meat industry demonstrates the continuous expansion of meat raw material sources, increasing variability in supply chains, and considerable diversity in the technological properties of raw materials. Under such conditions, there is a growing need for digital decision support tools. To address this need, a mathematical model has been developed to generate optimal recommendations for the utilization of available meat raw materials based on their characteristics and the production requirements of the meat processing enterprise.

After the execution of the algorithm of the proposed model, the following data will be obtained:

1. *Optimal production plan*: a detailed schedule defining the exact output volume of each type of product for each enterprise, considering specific raw material supply zones.

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2. *Analysis of problem issues*: identification of resources or production capacities that are in shortage. Using dual estimates, it is possible to determine how much the total profit will increase if the amount of a specific resource is increased by one unit.

3. *Efficiency of resource utilization*: an assessment of enterprise utilization $Q(j^1)$ and the balance between planned targets $P(i^1, P^1)$ and actual technological capabilities $V(i^1, j^1, z^1, P^1)$.

Practical significance of the research results:

– it has been demonstrated that mathematical modeling is a key tool for optimal design and provides a methodological foundation for modeling the rational use of raw materials. The systematic implementation of the developed model opens significant potential for improving process efficiency and introducing innovations in the meat processing industry;

– real-time data obtained on the utilization of various types of meat raw materials during technological processes forms an analytical basis for modeling their optimal use in production. Thus, an effective tool is obtained for improving resource efficiency and the ecological and economic performance of meat processing enterprises;

– the obtained results indicate the expediency of using digitalization to create prerequisites for modeling the optimal use of raw materials through the coordination of information flows in the supply chain of raw materials from different regions, which have their own specific characteristics. The application of the developed model is AI-oriented for data analytics and provides a basis for modeling the optimal use of resources and increasing the economic efficiency of production. Thus, the integration of digital technologies and AI creates conditions for the development of optimization models for the rational use of meat raw materials.

Research limitations: development of computer software based on the proposed model for specific enterprises or meat industry clusters, considering their technological features, available raw material resources, and planned product assortment, including delicacy and functional products. In the proposed version of the model, transportation costs, the raw material base and corresponding animal supply zones for processing, as well as the location of product consumers, are not taken into account in order to simplify the model. However, this can be implemented with a certain complication of the model. The proposed model is designed for strategic and tactical production planning in meat processing enterprises. Its application at the operational level requires the integration of production scheduling and dispatching modules, together with ERP and MES systems.

Prospects for further research: it is important to specify the raw material base of a particular meat processing enterprise. It is advisable to develop a model of its raw material supply, as well as indicators of raw materials obtained from slaughter animals in the region, including feeding, species, sex, breed, logistical characteristics, and supply stability, among others. The scope of analysis should be expanded through a comprehensive study of the factors that determine the quality and safety of meat raw materials. In further research, it is also appropriate to investigate the economic efficiency of using different types of local raw materials in meat product manufacturing. Furthermore, the model should consider the prediction of final product quality depending on the parameters of the raw materials used.

The implementation of a systematic approach to raw material traceability "from farm to finished product" is particularly important. It will make it possible to substantiate optimal technological solutions for a specific enterprise and increase the competitiveness of its products. Such an integrated approach will contribute to the development of a scientifically grounded model for managing meat raw material quality at the regional level.

4. Conclusions

1. The research proves that the mineral composition and quality of meat raw materials are determined by a complex interaction of genetic, physiological, environmental, and technological factors. The variability of macro- and microelement content across different muscles and production systems highlights the necessity of standardized analytical approaches for reliable assessment. Overall, these findings provide a scientific basis for the development of predictive models and optimization tools for meat processing technologies.

2. An objective function of the model has been developed, which takes into account the analysis of available raw materials for the production of various types of products with different characteristics. The model formalizes sets of enterprises, product assortment, livestock characteristics, and raw material supply zones: J, I, P, Z. Subsets $P_1, P_2, ..., P_k, P_l, P_n$, ($P_s \subset P$, $s = 1, 2, ..., k, l, n$) are introduced to formalize a complex of factors, including breed characteristics, age, sex, and degree of fatness of animals, as well as the environmental conditions of their origin zones. These zones are classified as follows: z_1 – ecologically clean, z_2 – industrially burdened, z_3 – partially polluted, and z_4 – environmentally hazardous. The developed matrix elements and implementation algorithm provide a basis for optimizing production planning and improving resource allocation efficiency.

3. Production and technological constraints for the output of product assortments based on the raw material compatibility matrix have been mathematically described, with particular attention paid to water-binding processes and the preservation of intramuscular fat as key quality factors. Product output options have been formalized considering technological constraints under conditions of production uncertainty. It has been shown that the applied modeling methods make it possible to identify hidden patterns in large data sets and ensure the adaptability of the model in accordance with the requirements of technological processes.

4. Based on the practical implementation of the mathematical model, the production and technological capabilities of a meat processing enterprise were evaluated under five production scenarios. It was established that, under Scenarios 1–3, with total production volumes of 62, 77, and 92 t, respectively, the enterprise's transport and logistics capacity is sufficient to ensure the timely delivery of products to consumers. However, when production volume increases to 100 t while the transport capacity is limited to 95 t, the model identifies a violation of the specified constraint, indicating that the enterprise's logistics capacity is exceeded by 5 t (5.3%). Consequently, Scenarios 4 and 5 are classified as infeasible under the given operating conditions. The practical implementation of the model demonstrated its suitability as a decision support tool for production planning in meat processing enterprises operating under conditions of fluctuating demand, limited resources, and production uncertainty.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, including financial, personal, authorship, or any other, that could affect the research, and its results presented in this paper.

Financing

The research was performed without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating this work.

Authors' contributions

Ihor Oshchypok: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review and editing; ***Halyna Kushniruk***: Conceptualization, Formal analysis, Writing – original draft, Writing – review and editing, Supervision; ***Igor Pandyak***: Methodology, Investigation, Writing – review and editing; ***Volodymyr Khudoba***: Investigation, Visualization, Writing – review and editing; ***Svitlana Maykova***: Methodology, Formal analysis, Writing – original draft, Writing – review and editing.

All authors have read and agreed to the published version of the article and are jointly responsible for the reliability, accuracy, and integrity of the data and research results presented in the article.

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