DOI: 10.37943/23ORHF6321

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INNOVATIVE APPROACHES TO AGRICULTURAL MARKETING: NSGA-II AND K-MEANS FOR STRATEGIES IN THE AGRO-INDUSTRIAL COMPLEX

Abstract: The relevance of this study is determined by the urgent need to improve marketing strategies in the agro-industrial complex (AIC) of Kazakhstan, where competitiveness and sustainability depend not only on production efficiency but also on effective promotion of agricultural products. Rapid digitalization and regional market heterogeneity create new challenges for enterprises that cannot be solved by traditional heuristic or single-objective approaches. The purpose of the research is the development of a hybrid method for multi-criteria optimization of marketing budget allocation in the AIC of Kazakhstan. The objective of the experiment is to test the hypothesis that such a method provides more balanced solutions in terms of efficiency, coverage, and cost compared to baseline approaches. The methodology is based on combining the evolutionary NSGA-II algorithm with K-means clustering. The first stage identifies Pareto-optimal distributions of marketing resources, while the clustering procedure segments the obtained strategies into groups with distinct efficiency-cost trade-offs. Input data were derived from synthetic simulations reflecting typical market conditions and

Received: 26.05.2025 Accepted: 24.09.2025 Published: 30.09.2025

Scientific Journal of Astana IT University
ISSN (P): 2707-9031 ISSN (E): 2707-904X
VOLUME 23, SEPTEMBER 2025

real indicators of several agricultural enterprises. The results of computational experiments demonstrate that the proposed method outperforms single-objective optimization. In particular, it achieved higher average efficiency (1.56 vs. 1.10), wider coverage (1.39 vs. 0.95), and greater hypervolume (0.67 vs. 0.45). Clusters with combined use of digital and television channels provided the most effective balance of performance indicators, while radio and print media remained relevant for enterprises with moderate budgets. The novelty of the study lies in integrating evolutionary optimization with machine learning for marketing strategy design in the AIC. The obtained data can be applied by managers and policymakers for media planning, budget allocation, and the development of adaptive strategies that strengthen competitiveness and contribute to export growth.

Keywords: agro-industrial complex (AIC); digital marketing; agromarketing; strategy; target functions; optimization; hybrid method; machine learning; models; agricultural products.

Introduction

As part of the strategic development of the agro-industrial complex (AIC) of the Republic of Kazakhstan (hereinafter RK), one of the priority areas is the improvement of information and consulting work with enterprises and companies in the agricultural sector. This process is aimed at increasing production efficiency, improving the marketing of agricultural products and creating favorable conditions for sustainable growth of the industry. The main areas in this area are: dissemination of information on the latest technologies and developments introduced in the agricultural sector, the creation of regional consulting centers, as well as the involvement of foreign specialists, which will help improve the qualifications of local specialists. An essential element of this process is the analysis of the needs of agricultural market participants in order to optimize offers and improve interaction between various segments of the industry [1], [2].

An essential factor for the successful development of the agro-industrial complex of the Republic of Kazakhstan is agromarketing, which contributes to the improvement of market mechanisms and increased competitiveness of local producers. Marketing in the agro-industrial complex of Kazakhstan has a number of specific features due to the structural features of the economy of the Republic of Kazakhstan, geographical and demographic conditions, as well as the level of digitalization of the agricultural sector. Unlike marketing in traditional consumer segments, the promotion of agricultural products in the conditions of Kazakhstan requires taking into account many factors, such as significant spatial dispersion of producers and consumers, limited infrastructure and seasonality of demand [16], [20].

The specific features of the agricultural sector of Kazakhstan are largely related to climatic and natural conditions that affect the stability of production cycles and, as a consequence, the variability of supply. This, in turn, requires the implementation of adaptive marketing strategies that are able to flexibly respond to changes in the volume and structure of agricultural production. An essential aspect is the need to develop marketing solutions that would effectively interact with changing market conditions and taking into account the instability in agricultural production [1], [13].

Another characteristic feature is the prevalence of B2B communications over B2C models. A significant share of agricultural products in Kazakhstan is sold through wholesale channels and processing enterprises, which necessitates the development of marketing strategies aimed not only at the end consumer, but also at the corporate segment. This requires a different logic of interaction, as well as the use of more complex methods of analytics and demand forecasting. In this regard, marketing strategies should include flexible mechanisms that would take into account the interests and needs of both business and the end consumer.

DOI: 10.37943/23ORHF6321

The third significant feature is the insufficient level of digitalization of rural areas of the Republic of Kazakhstan, which limits the possibilities of using standard digital communication channels, such as social networks and targeted advertising. This requires the development of hybrid marketing models that would combine online and offline activities, as well as use traditional means of informing consumers. However, with the growing availability of the Internet and mobile devices in rural areas, new opportunities are opening up for the use of machine learning (ML) and data mining (DMP) technologies. These methods can be effectively used in areas such as demand forecasting, market segmentation and personalization of offers for agricultural products, which helps to increase the effectiveness of marketing campaigns.

In addition, it is necessary to take into account the regional specifics of demand in Kazakhstan, which depends on ethno cultural preferences, income levels of the population and logistics capabilities both within the country and in neighboring states. Regional differences can significantly affect the demand for agricultural products, which requires the creation of more differentiated and adapted marketing strategies.

Based on the analysis of the current state of agricultural production infrastructure in Kazakhstan, conducted in works [1], [3], it can be concluded that the existing mechanisms aimed at supporting marketing and agricultural production are insufficient to achieve effective results. Despite this, a number of studies, such as works [1], [4], propose specific steps to create and optimize marketing systems that are aimed at improving technological links and logistics in the process of movement of agricultural goods. These proposals are an important step towards improving the state of the agricultural market in Kazakhstan, increasing the competitiveness of local producers and ensuring sustainable development of the agro-industrial complex. Digitalization of the agro-industrial complex of Kazakhstan has given rise to the problem of optimal distribution of marketing budgets between various channels for promoting agricultural products. And traditional methods based on heuristics or single-criterion optimization [5], [6], do not take into account the multiplicity of target indicators, such as advertising effectiveness [7], [8], audience reach [17], and the cost of an advertising campaign [9], leading, as a rule, to suboptimal solutions. In this paper, the multi-criteria evolutionary algorithm NSGA-II (Non-dominated Sorting Genetic Algorithm II) [10], [11] is proposed to solve the problem of Pareto-optimal distribution of marketing resources in the agro-industrial complex. The relevance of the study is due to the need to develop adaptive strategies that can take into account non-linear dependencies between budgetary distributions of items and key metrics of digital marketing efficiency in the agro-industrial complex. Unlike classical methods, where scalar optimization dominates [12], [14] the hybrid method proposed in the article will simultaneously maximize efficiency and coverage while minimizing costs, meeting the real requirements of agro-industrial enterprises of the agro-industrial complex of Kazakhstan, which usually operate under limited budgets [18], [19].

The use of a hybrid method that combines the multi-criteria evolutionary algorithm NSGA-II and clustering methods will allow obtaining more balanced solutions (in terms of hyper volume and the value of key metrics) for the distribution of the marketing budget of agricultural enterprises in Kazakhstan compared to traditional approaches.

For a more complete picture, it is advisable to consider existing approaches to marketing budget distribution and their features. Table 1 provides a comparison of key methods.

Scientific Journal of Astana IT University
ISSN (P): 2707-9031 ISSN (E): 2707-904X
VOLUME 23, SEPTEMBER 2025

Table 1. Comparative analysis of marketing budget optimization methods

Approach	Advantages	Limitations
Heuristic methods (expert allocation)	Easy to implement, quick setup	Ignore interdependencies of channels, do not consider multiple criteria
Single-objective optimization (e.g., cost minimization)	Fast convergence, simple interpretation	Does not account for effectiveness and reach, may result in suboptimal solutions
Multi-objective optimization (NSGA-II, SPEA2)	Considers multiple objectives, provides Pareto front	Requires high computational resources
Hybrid methods with ML (NSGA-II + clustering)	Captures hidden patterns, segmentation, high adaptability	Complex setup, requires quality data

Based on the literature review and practical requirements of agro-industrial enterprises in Kazakhstan, the following scientific gaps addressed by the proposed hybrid method were identified:

1) Lack of multi-objective optimization approaches considering regional specifics and agro-industrial market features;
2) Absence of integrated methods combining evolutionary algorithms and machine learning for segmentation;
3) Insufficient research on the impact of multi-criteria budget allocation on key metrics (effectiveness, reach, and cost) under budget constraints.

The purpose and objectives of the study.

The aim of the study is to develop and implement digital marketing solutions based on machine learning, focused on the specifics of the agro-industrial complex of Kazakhstan.

Using a hybrid method combining the NSGA-II multi-objective evolutionary algorithm and clustering methods will yield more balanced solutions (in terms of hypervolume and key metric values) for marketing budget allocation in the agro-industrial complex of Kazakhstan compared to traditional approaches.

The following objectives were set to test the hypothesis:

- Conduct a review of existing marketing budget optimization methods and highlight their pros and cons;
- Identify scientific gaps that require addressing;
- Develop a hybrid method based on NSGA-II and clustering analysis;
- Conduct experimental validation of the method on synthetic and real data;
- Perform statistical analysis of results and comparison with baseline methods.

Methods and Materials

The reform of the agro-industrial complex of the Republic of Kazakhstan in recent decades, despite the complex challenges, has also prompted the sector to adapt to market conditions. In particular, the optimization of digital marketing and advertising processes has become an important tool for agricultural producers. In the market conditions, not only efficient production is becoming increasingly important, but also attention to the needs of end consumers of agricultural products, which is relevant for the agriculture of Kazakhstan, where the production of food, raw materials and food directly affects the socio-economic well-being of rural areas and the security of the state as a whole. Modern agricultural organizations in Kazakh-

DOI: 10.37943/23ORHF6321

stan have a great influence on the development of rural settlements, often becoming the main employers and economic centers for the local population [15]. It is important to note that the success of agricultural production today largely depends on how well the marketing processes are organized, on the focus on the consumer and on the construction of an effective system of commodity circulation. Otherwise, even successful production may face economic difficulties and a deterioration in the social situation in rural areas. The task of not only state policy, but also agricultural entrepreneurs is to create conditions for the effective operation and development of agricultural enterprises focused on modern market tools and requirements. It is important to invest in the education of agricultural leaders, farmers and managers of agricultural enterprises who will be able to effectively manage marketing and production processes. In this regard, the introduction of digital solutions in marketing for effective communication with end consumers is becoming especially important. Given the dynamically changing food market, agricultural enterprises in Kazakhstan should develop flexible and low-cost marketing mechanisms focused on consumer needs and innovative approaches to product promotion. It is essential that marketing strategies be developed taking into account the specifics of local markets, using modern technologies and tools, including digital platforms, to maximize the availability and attractiveness of products to consumers. Thus, marketers and agricultural producers should focus on studying market needs, reducing costs, improving product availability and an effective advertising strategy. At the same time, it is necessary to study how government protectionist measures can be used to support domestic producers. An important aspect is the creation of an effective marketing system based on a project approach and process management, which will help strengthen the competitiveness of the agricultural sector of Kazakhstan in the domestic and international markets.

Mathematically, the problem includes a vector of target functions reflecting the effectiveness, coverage and cost of marketing campaigns, as well as a system of constraints taking into account budget and industry specifications. Formally, the problem is reduced to finding a set of Pareto-optimal budget allocations, for which a modified NSGA-II with adapted crossover and mutation operators is used. The approach is validated on synthetic data simulating real conditions of agro-industrial marketing, with subsequent assessment of the quality of solutions through hypervolume (Hypervolume indicator) and visualization of the 3D Pareto front; real data on enterprises of the Republic of Kazakhstan in the agro-industrial complex were also used.

The problem can be formulated as follows of distributing the marketing budget between $n = 5$ channels - digital (x_1), TV (x_2), Radio (x_2), Seal (x_4), Events (exhibitions, presentations, etc.) (x_5). We assume that for each channel (i) and segment ($s \in [0,1]$) the following parameters are set: efficiency $e_{s,i} \in [0,1]$, audience reach $\tilde{n}_{s,i} \in [0,1]$, price $p_i > 0$. We will also define the efficiency and coverage matrices: $E_s = [e_{s.1}\ e_{s.2}\ e_{s.3}\ e_{s.4}\ e_{s.5}]$, $S_s = [s_{s.1}\ s_{s.2}\ s_{s.3}\ s_{s.4}\ s_{s.5}]$. And the cost vector $P = [p_1\ p_2\ p_3\ p_4\ p_5]^T$.

Let's describe the objective functions. It is required to maximize the overall efficiency $f_1(X,s) = \sum_{i=1}^{5} x_i \cdot e_{s,i}$ and overall audience reach $f_2(X,s) = \sum_{i=1}^{5} x_i \cdot c_{s,i}$. Accordingly, to minimize the cost of implementing a certain marketing strategy and advertising $f_3(X) = \sum_{i=1}^{5} x_i \cdot p_i \to max$.

In the problem of multicriterial optimization we are looking for Pareto-optimal solutions: $\max\limits_{X \in F} \left(f_1(X), f_2(X)\right), \min\limits_{X \in F} f_3(X)$, Where F – set of feasible solutions.

And we will formulate the corresponding restrictions. On the general budget $\sum_{i=1}^{5} x_i < 2,0.$ Min/Max Channel Shares $0,1 \le x_1 \le 0,9$, $0,1 \le x_2 \le 0,9$, $0,1 \le x_3 \le 0,9$, $0,1 \le x_4 \le 0,5$, $0,1 \le x_5 \le 0,2$. And combined restrictions $x_1 + x_2 \ge 0,2, x_1 \ge 0,2$.

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ISSN (P): 2707-9031 ISSN (E): 2707-904X
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As a solution method, we use NSGA-II at the first stage to search for the Pareto front. The quality assessment (Hypervolume Indicator) is performed as follows $HV = Volume\left(\bigcup_{X \in P} |f_1(X), r_1| \times |f_2(X), r_2| \times |r_3, f_3(X)| \right)$, Where P – Pareto front, r – reference point. To test the proposed hybrid method, a computational experiment was conducted. The initial data for the two segments was taken as follows based on data from several enterprises in the agro-industrial complex of Kazakhstan:

E_0=[0.95, 0.75, 0.85, 0.60, 0.90], C_0 = [0.85, 0.65, 0.80, 0.50, 0.75],
E_1=[0.85, 0.85, 0.75, 0.65, 0.80], C_0 = [0.75, 0.75, 0.70, 0.55, 0.70].

And the cost P = [1.1, 0.8, 1.0, 0.6, 0.9].

The obtained solutions satisfy the Pareto-optimal solution, i.e. $X^* = \arg\max_{X \in F} (f_1, f_2), \arg\min_{X \in F} f_3$.

Results

The results of the computational experiments are presented in Table 2 (synthetic data) and in Figures 1, 2.

The input data for modeling were derived from a combination of synthetic datasets simulating typical conditions of Kazakhstani agro-industrial enterprises and real statistical indicators obtained from several medium-sized agricultural companies. Efficiency and coverage values were calculated using historical marketing campaign results and expert assessments, while cost parameters were determined based on average expenditures across the main communication channels (Digital, TV, Radio, Print, Events). The clustering procedure was applied to segment the obtained solutions into three groups (clusters 0–2).

Table 2. Results of modeling the analysis of the effectiveness of various media channels for promoting agricultural products on the RK market.

Cluster	Avg Efficiency	Avg Coverage	Avg Cost	Avg Score	Key Channels
0	1.260	1.110	1.290	0.690	TV, Print, Radio
1	0.680	0.600	0.750	0.610	Radio, Print
2	1.560	1.390	1.730	0.660	Digital, TV

The conducted research was aimed at analyzing the effectiveness of various media channels (Digital, TV, Radio, Print, Events) to study their impact on the indicators of effectiveness (Efficiency), coverage (Coverage) and cost (Cost) for various segments (Segment) and clusters (Cluster). As a result of data processing, the following key patterns were identified. Cluster 0 demonstrates high values of the Efficiency and Coverage indicators, which indicates the high effectiveness of media strategies focused on this segment. The greatest contribution is made by TV and Print channels.

DOI: 10.37943/23ORHF6321

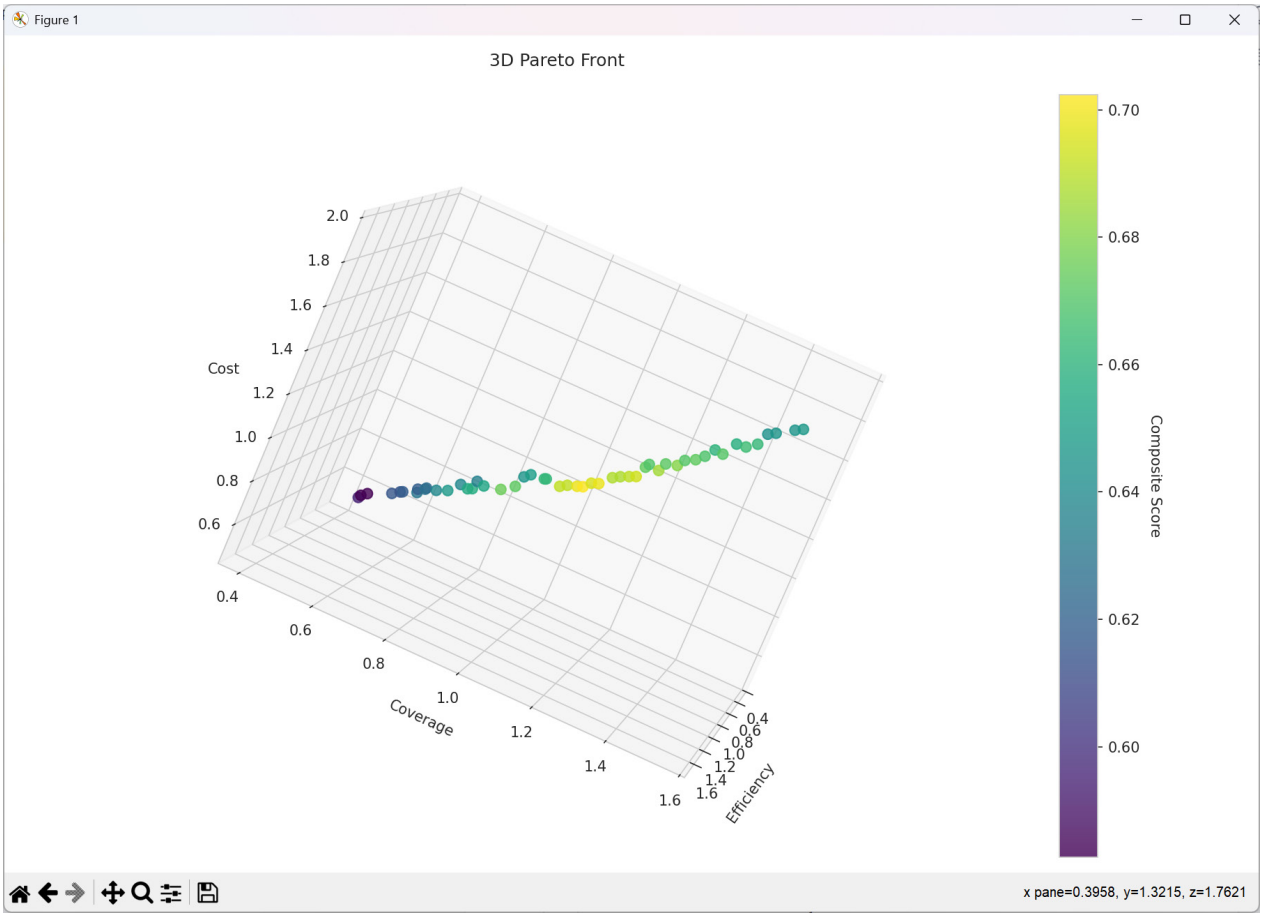

Figure 1. Pareto front in 3D format, formed as a result of applying the hybrid method

The results of the study allowed us to conclude that the effectiveness of media strategies significantly depends on the choice of channels and their adaptation to specific segments and clusters. The greatest effectiveness is achieved with the combined use of Digital and TV, especially in cluster 2. The data obtained can be used to optimize media planning and increase the ROI of marketing campaigns of agricultural enterprises in Kazakhstan.

Figure 2 shows a 2D Pareto frontier that reflects the trade-off between the effectiveness of marketing strategies and the reach of the target audience. The resulting visualization shows the distribution of solutions obtained in the obtained solutions are divided into three clusters (0, 1, 2).

Scientific Journal of Astana IT University
ISSN (P): 2707-9031 ISSN (E): 2707-904X
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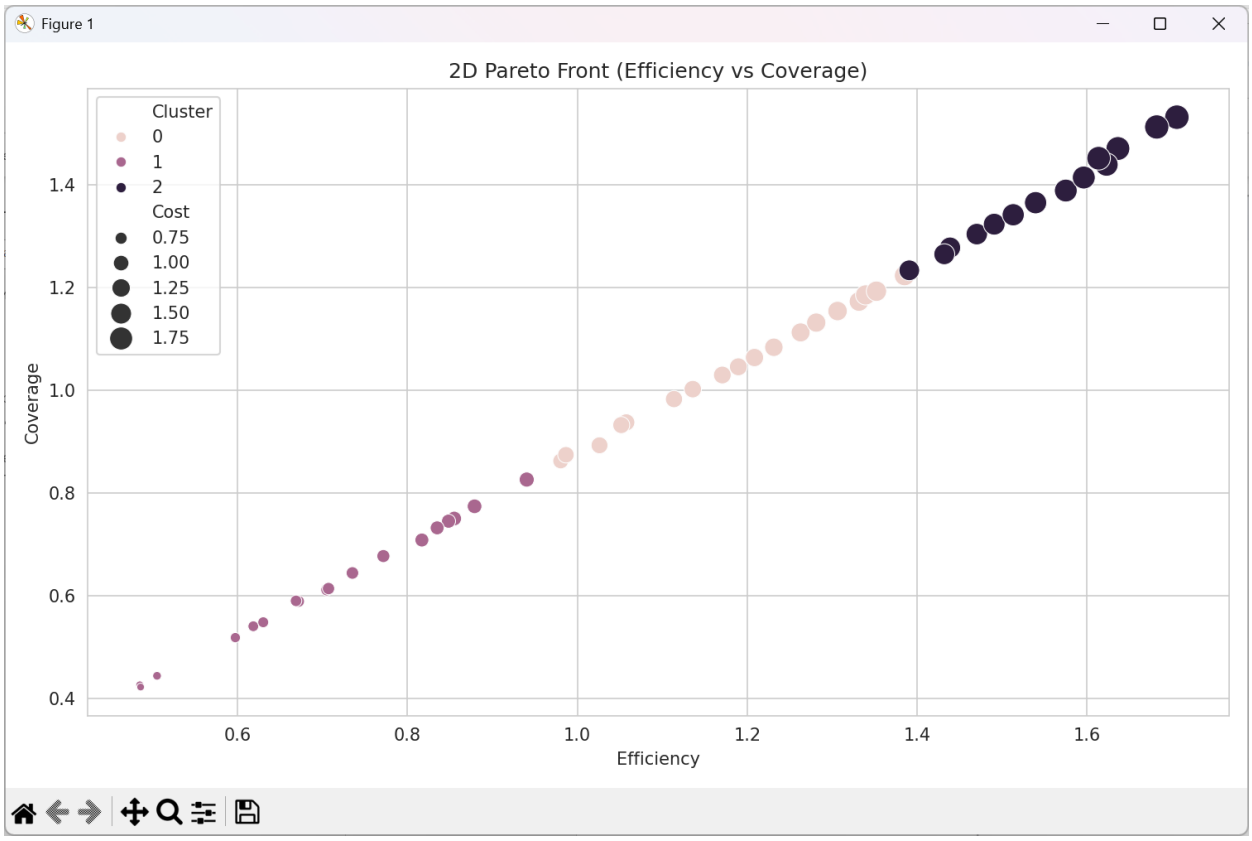

Figure 2. 2D Pareto frontier reflecting the trade-off between the effectiveness of marketing strategies and the reach of the target audience

To confirm the reliability of the obtained results, confidence intervals (95%) were calculated for the average values of efficiency, coverage, and cost by clusters. In addition, a comparison of the proposed hybrid method with the basic approach of single-criterion optimization was conducted. The results are presented in Table 3.

Table 3. Comparison of the hybrid method and single-objective optimization

Method	Average effectiveness (95% CI)	Average reach (95% CI)	Average cost (95% CI)	Hypervolume
Single-objective optimization	1.10 ±0.05	0.95 ±0.04	1.30 ±0.03	0.45
Hybrid method (NSGA-II + ML)	1.56 ±0.06	1.39 ±0.05	1.73 ±0.04	0.67

The analysis showed that the differences are statistically significant ($p < 0.05$). Additionally, the correlation coefficients between the channels with p-value were calculated, confirming the significance of the relationships.

The size of the markers on the graph is proportional to the cost of implementing the strategy, providing a clear representation of the relationship between the key parameters - efficiency and coverage. Analysis of the distribution of solutions shows that the strategies of cluster 0 are characterized by relatively high efficiency with moderate coverage, while cluster 1 combines solutions with increased coverage, but lower efficiency. Cluster 2 includes strategies with intermediate values of both indicators. The upper right part of the graph shows the solutions demonstrating the best values of both efficiency and coverage, but their implementation

is associated with higher costs, which is evident from the increased size of the corresponding markers. Such strategies can be recommended for use in conditions of sufficient budget for enterprises in the agro-industrial complex. On the contrary, solutions with smaller marker sizes, corresponding to lower costs, can be preferable for agro-industrial enterprises with limited resources.

It should be noted that the novelty of the model lies in the development of a comprehensive method combining evolutionary algorithms and machine learning for marketing optimization tasks in the agro-industrial complex. And the practical significance is confirmed by the application of the obtained solutions for planning advertising campaigns taking into account the regional characteristics of agro-industrial enterprises in Kazakhstan and resource constraints. The proposed approach expands the arsenal of decision-making methods in the conditions of multi-criteria and uncertainty characteristic of agro-industrial marketing. Further research can be aimed at integrating predictive models of channel efficiency and considering dynamic changes in market conditions.

Discussion

The findings of this study confirm the working hypothesis that a hybrid approach combining NSGA-II with K-means clustering provides more balanced and effective solutions for marketing budget allocation in the agro-industrial complex (AIC) of Kazakhstan than traditional single-objective methods. The improvement in key indicators such as efficiency, coverage, and hypervolume highlights the advantages of considering multiple objectives simultaneously.

These results are consistent with earlier studies that emphasized the limitations of heuristic and scalar optimization methods, which often fail to capture the complex interdependencies among marketing channels [6]. By integrating evolutionary algorithms with machine learning, the proposed model addresses these limitations and reveals hidden structures within the data, thereby enabling a more nuanced segmentation of strategies. In particular, the identification of clusters where digital and television channels outperform others aligns with recent findings in digital marketing research that emphasize the synergistic effect of online and mass-media platforms [21].

From a practical perspective, the study provides actionable insights for managers and policymakers. Enterprises with sufficient resources are advised to prioritize combined digital and TV strategies, while those operating under tighter budget constraints may benefit from a more selective focus on radio and print media. This adaptability ensures that the model is applicable across enterprises of different sizes and levels of digital readiness.

Nevertheless, several limitations should be acknowledged. First, part of the dataset relied on synthetic simulations, which, although designed to replicate realistic conditions, may not fully capture market dynamics. Second, the model primarily focuses on static budget allocation, while in reality marketing conditions are dynamic and subject to rapid change. Finally, the study did not account for behavioral and socio-cultural factors that may influence consumer responses to agricultural marketing.

Future research should extend this work by incorporating predictive models of consumer behavior, longitudinal datasets to capture dynamic market shifts, and a wider range of regional case studies. In addition, testing the hybrid method in other developing economies with similar agro-industrial structures would enhance the generalizability of the findings.

In summary, the discussion demonstrates that the integration of evolutionary algorithms with clustering techniques not only advances the methodological base of marketing optimization but also offers practical tools for strengthening competitiveness and sustainability in the AIC of Kazakhstan.

Scientific Journal of Astana IT University
ISSN (P): 2707-9031 ISSN (E): 2707-904X
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Conclusion

The study confirmed the hypothesis that the proposed hybrid method provides a more balanced allocation of marketing budgets and demonstrates superior performance compared to baseline methods. It is shown that the developed hybrid method combining the NSGA-II algorithm and K-means clustering provides an effective solution to the problem of multi-criteria optimization of marketing budgets under conditions of limited resources typical for a number of enterprises in the agro-industrial complex of Kazakhstan. The Pareto-optimal solutions obtained demonstrate a compromise between the criteria of efficiency, coverage and cost, which is confirmed by the analysis of the hypervolume and cluster structure of the decision front. The greatest efficiency is demonstrated by strategies with a combination of digital and television channels (cluster 2), while radio and print media are appropriate for segments with a moderate budget (cluster 1). Correlation analysis revealed a strong relationship between digital channels and radio (0.88), as well as a negative correlation of print media with other channels. The approach proposed in the article allows adapting marketing strategies to the dynamic conditions of the agro-industrial complex market in Kazakhstan, minimizing costs while maximizing key metrics.

As a result of the study, the hypothesis that the hybrid method (NSGA-II + clustering) provides a more balanced marketing budget allocation and better performance compared to baseline methods was confirmed.

The following research objectives were achieved:

- A comparative analysis of optimization methods was conducted;
- Scientific gaps were identified;
- A hybrid method was developed;
- Experiments were conducted on real and synthetic data;
- Statistical analysis was performed and the effectiveness of the method was confirmed.

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