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THE MODEL TO OPTIMIZE DELIVERIES OF PERISHABLE FOOD PRODUCTS IN SUPPLY CHAINS

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Вдосконалено ймовірнісно-статистичну аналітичну модель оптимізації постачань швидкопсувних продуктів харчування (ШПХ). Ефективне забезпечення задоволення попиту на ШПХ в системах ланцюгів постачань досягається через введення можливості додаткової поставки ШПХ у випадку виникнення їх дефіциту в періоді між черговими поставками. Доведено, що на оптимальну величину основної поставки, яка відповідає максимуму прибутку системи ланцюга постачань ШПХ, впливають:

- ***величина прибутку від реалізації одиниці ШПХ, який надходить за основною і додатковою поставкою;***
- ***величина збитку від утворення надлишку одиниці ШПХ;***
- ***параметри розподілу попиту за період між черговими поставками;***
- ***техніко-експлуатаційні та економічні показники, які характеризують роботу автомобілів на розвізних маршрутах.***

Проведено порівняльний аналіз умов забезпечення постачань ШПХ в системах ланцюгів постачань із використанням відомого і пропонованого вдосконаленого варіанта ймовірнісно-статистичної аналітичної моделі оптимізації постачань ШПХ. Даний аналіз показав, що двоступенева, тобто така, яка передбачає додаткову поставку, система постачань є більш економічно-доцільною за умовами роботи ланцюгів постачань ШПХ. Доведено доцільність збільшення транспортних витрат, пов'язаних з транспортним забезпеченням додаткової поставки. Саме їх збільшення спричиняє значуще збільшення прибутку системи за рахунок досягнення високого рівня задоволення попиту і скорочення збитків через утворення нереалізованих надлишків

Ключові слова: ланцюги постачань, швидкопсувні продукти, модель управління постачаннями, раціональна величина замовлення

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1. Introduction

In 2018, the Food and Agriculture Organization (FAO) of the United Nations published statistical data regarding the loss of food products [1]. According to these data, in North America and Oceania, 300 kg of food are wasted per one person annually. About two thirds are lost in production or trade, the rest is discarded by consumers. In Europe, the ratio of general waste per one person to losses in production or trade is estimated at the level of 280 to 190 kg. At the same time, for example, in the sub-Saharan African countries, it is 155 to 150 kg.

In other words, losses of food products are considered in two aspects. These are the losses that occur during production processes, starting in agriculture, and, subsequently, at different stages of processing and trade, and the losses as waste by end-customers. The first kind of losses is characteristic mainly of developing countries that have poorly developed infrastructure, low level of applied technologies, as well as small investments in food-producing and selling systems. At the same time, the second kind of losses – the losses of food products as waste by end consumers – is more inherent in economically developed countries.

In the context of recognition, at the present stage of society development, the problem of food losses as the global one, of special significance is to further improve the management processes of supplying perishable food products (PFPs). In the theory and practice, one of the main unresolved issues has been the problem of general observable presence or unmet demand that, consequently, results in that the profits are lost, or that unsold excess products are left, which is associated with losses. Studies and publications that directly address the approaches to resolving the latter of the above problems can be conceptually represented within two interrelated groups. These are those which relate to the search for effective means to slow down the processes of losing those properties of PFPs that render the latter perishable, and those that focus on the methods and models of rational management of PFP supply.

As regards the first of these groups, the techniques to slow down the loss of freshness by PFPs, which are known today and are widely used, do not in many cases make it possible to exclude the respective product from the category of perishable ones. That is, to a certain degree, one can argue about different products with the same title. A product whose production and/or storage employed additional means that prolong its shelf life may lose its initial properties. At the same time, these techniques are felt by taste and may even compromise health benefits of a given product. In contrast, a product that found the consumer without extending its shelf life artificially, that is, without the use of the above additional means, retains its taste and useful properties.

Note that there is an alternative to separating the processes of production and sale of PFPs – food products are sold at enterprises (coffee shops, confectionery, restaurants, etc.) where they are made. If the duration of a functional logistics cycle, that is a cycle to fulfill a purchase order, is longer than, or equal to, the shelf life of the product, then the above alternative simply does not exist. In other words, the place of production and the point of sale (or consumption) must coincide. In this case, duration of the functional logistics cycle depends on the duration of its components, which, in general, are variable.

When following those business models that imply the separation of PFP production and selling processes, still relevant is the above-mentioned issue of existing demand or unmet demand, or the formation of unsold products between the periods of planned deliveries. In turn, under the conditions for solving a given problem, the methodology of supply management puts forward an important task that requires further improvement of approaches to solving it, specifically the task on determining the optimal (rational) order size in the PFP supply chains.

2. Literature review and problem statement

Existing food products classifications do not offer a generally defined definition of PFPs. Thus, the studies conducted in the USSR [2] specified that perishable goods were those food products whose shelf life was up to 2–3 days; work [3] suggested a term even less than a day. The means that are used at present to prolong an expiry date are associated with the transition of appropriate products to another category. Thus, the current work considers that perishable food products are those foods whose shelf life before selling and, accordingly, storage, does not exceed three days.

The methods and models to determine the optimal delivery size, widely known in the methodology of supply management, such as the model of economic order quantity, as well as its modifications (extensions), provide for a practically acceptable result for a wide range of products.

Based on modern ideas about the theory and practice of PFP supply optimization, the latter should be considered in the context of supply chains management, taking into consideration the alignment of economic requirements of enterprises that are engaged in supply chains [4].

The possibility of discrepancy between the economic positions of participants in supply chains in terms of determining an optimal delivery batch is addressed by authors of work [5] who analyze the issues of harmonization of incentives in supply chains. They propose solving this task by implementing an approach that can be regarded as a classic inductive in the context of systems construction. At the same time, they ignore the situation, related to the actual conditions for business operations, of power imbalance, particularly economic, among a supply chain's participants, for example, predetermined by the type of a market; whether it is the buyers' market or the market of sellers [6]. In this case, the "degree" of influence exerted by some enterprises, for example, chain supermarkets, can be significantly larger than that from others – for instance, small shops within walking distance.

Study [7] examines methodological approaches to supply chains management, including determining an optimum batch size. However, the cited research is theoretical, it was not tested in practice and has limitations for delivery optimization in the PFP supply chains.

Paper [8] addresses the restructuring of supply chains in PFPs markets, specifically meat and meat products. The authors proposed a procedure to build supply chains, which makes it possible to rationalize schemes of product movement, reduce the duration of a complete logistics cycle and minimize logistic costs. However, the cited study has not paid enough attention to the task on determining an optimum batch size. In addition, the food products whose supply is considered fail to meet the criteria for a shelf life of PFPs adopted in the current work.

It should be noted that in a series of papers, in particular [9, 10], which report research into PFP supply management, the authors actually focus on the issues related to supplying perishable cargoes. It has been proven that such goods require special storage and transportation regimes, but they are not exactly the PFPs.

Conditions for PFP supply management require the use of a probabilistic-statistical modeling method. This particularly concerns the influence exerted by many random factors on the demand for PFPs in the predefined short period of time between planned deliveries.

The issue of existing demand or unmet demand, or the formation of excess unsold products, when managing PFP supplies, has been comprehensively enough, even given the later studies, described in work [11] by a corresponding probabilistic-statistical analytical model using supply of bread as an example. In this case, the reported mathematical model is limited to the economic position of a trade enterprise and does not take into consideration a potentially competitive nature of relations between the latter and the enterprise-manufacturer. Under conditions of imbalance in power, the model's parameters [11], which may be subject to discussion by supply chain participants, would be accepted, first of all, in the interest of the source of power, which, as can be expected, would seek to maximize its own profit. Accordingly, the other party would also strive for maximization, but under the conditions of accepting the parameters at the level that correspond to the interests of the source of power. It is obvious that the optimum batch size would be, in a general case, different in terms of the position of each participant of the supply chain.

Adhering to the assumption about a power balance in a competitive environment, the "production-trade" link in a PFP supply chain can be considered as a system, thereby building an appropriate model, based on wide-system notions about the latter's parameters. Subsequently, taking into consideration the profitability requirements of industry markets at which a manufacturer and a seller operate, as well as the level of risk accepted, the profit earned in the system can be rationally redistributed by the involved participants of the supply chain among themselves. This requires building the relationship between manufacturers and those who sell the product, in accordance with the principles of partnership, which in turn implies a different degree of integration. Conditions for selecting a partnership type are presented in the partnership establishment model [12].

The target level of meeting demand for a certain type of PFP depends on the group to which the latter belongs based on the ABC analysis. One can expect that relative to a group A PFP, selected either based on sales or profit volume or based on the conditions for a compatible analysis for these indicators, one has to set the high target level for meeting demand. In addition, important in terms of requirements to the level of demand satisfaction is also the fact to which group a certain kind of PFP belongs to according to the results from FMR analysis. The high request frequency, that is the attribution of the PFP to group F, even for cases of non-belonging to group A according to the ABC analysis, can be a condition for establishing a high target level of demand satisfaction. The availability of group F PFPs on sale should help sell other goods.

At the same time, when supplying PFPs in the volume optimal for the profit criterion, according to the model considered in [11], there may be a relatively low level of demand satisfaction for PFPs. A prerequisite for this, in particular, is the presence of a significant difference between the magnitude of the lost benefit due to the deficit of PFPs and the losses from the formation of their surplus per unit product "in favor of" the latter under conditions of a significant variation in demand.

In practice, there are situations when certain varieties of PFPs cannot be delivered to end consumers at all through distribution channels involving retail trade, since the latter refuses to work with these PFPs. In addition, not all aspects of the spent benefit from the deficit of PFPs can be assessed in monetary terms. The above requires the improvement of the considered model, in terms of identification of alternative and/or complementary variants of configurations of PFP supply chains concerning the supply management of the latter, with subsequent clarification of the mathematical notation of appropriate modifications. These variants must make it possible to effectively ensure a high level of demand satisfaction.

To optimize deliveries in supply chains, study [13] proposes an inventory management model, which treats demand to be dependent on the price, the degree of freshness, and the availability of the product on sale (stock). The issue of accumulation of unsold products is proposed to be resolved based on the justification of a discount system, which is established depending on the time remaining until the expiry date.

The short shelf life of PFPs predetermines specific requirements for reliability, in particular, timeliness, in maintaining transportation, which is partially considered in papers [14, 15]. This, as well as the identification of PFP supply chains configurations, which can be implemented based on the improvement of transportation services, requires the separation of transportation factors in the considered model. That would make it possible to assess the impact of the latter on the optimum batch size of PFPs and, consequently, improve efficiency in the management of processes and transportation systems in the PFP supply chains.

According to study [16], the policies and inventory management strategies can significantly improve operation of supply chain systems. At the same time, the authors proved the lack of effective mathematical modeling regarding the specified problem. The scientific literature in this field, according to researchers, is in the decline phase.

Based on the foregoing, there are reasons to believe that modern ideas about the theory and practice of delivery management in the PFP supply chains require improvement and further development based on the application of probabilistic-statistical modeling methods.

The scientific gap is identified exactly in the aspect of optimization – in terms of effectively enabling the high level of demand satisfaction – PFPs deliveries taking into consideration the alignment of economic positions by production and trade enterprises as participants in the PFP supply chains. In this case, there is a need to distinguish, based on the objective function, transportation factors, to be followed by the assessment of the nature of their impact on the optimum batch size of PFPs.

3. The aim and objectives of the study

The aim of this study is to improve the probabilistic-statistical analytical model for optimizing PFP deliveries in supply chains under the conditions for effectively meeting the existing demand for PFPs.

To accomplish the aim, the following tasks have been set:

– to consider a possibility to additionally supply PFPs in case of shortage of the latter in the period between planned deliveries in the supply chain systems;

– to conduct a comparative analysis of conditions for ensuring the supply of PFPs in the supply chain systems employing a known and the proposed improved variant of the probabilistic-statistical analytical model of PFP supplies optimization.

4. Defining a direction for improving the model of PFP delivery optimization in the supply chain systems

Let the periodicity of PFP supply to a trade enterprise be established based on the maximum shelf life of the latter according to a relevant schedule. Demand for PFPs over the established period between planned deliveries is a random magnitude X. Density of the distribution of the random magnitude of demand for PFPs over the established period between planned deliveries is $f(x)$. For the case $X>g_r$, where g_r is the size of delivery to a trade enterprise, the latter incurs losses due to unmet demand, and if $X<g_r$, then there are losses due to the accumulation of unsold products.

According to work [11], the profit of a trade enterprise earned at purchasing PFPs in the amount of g_r units can be represented as one consisting of the following terms:

– the expected revenue from selling PFPs:

$$P_r \int_0^{g_r} x f(x)\,\mathrm{d}x, \tag{1}$$

– the expected loss – as an opportunity cost – due to unmet demand caused by a defect (out of stock) of PFP:

$$U_r\int_{\mathrm{g_r}}^{\infty}(x-\mathrm{g_r})f(x)\mathrm{d}x, \tag{2}$$

– the expected loss, which, incidentally, can actually happen to be a profit, from the accumulation of excess PFPs whose shelf life exceeded the set one:

$$\mathrm{C_r}\int_{0}^{\mathrm{g_r}}(\mathrm{g_r}-x)f(x)\mathrm{d}x, \tag{3}$$

where P_r is a profit, provided for a trade enterprise by each unit of a sold PFP (as the difference between the selling price and the cost of purchase from the manufacturer and sale); U_r is the loss (lost profit) for a trade enterprise, incurred under conditions of shortage, per each unit of PFP, which was lacking.

Accordingly, the expected profit from the sale of PFPs in the amount of g_r from the position of a trade enterprise can be recorded in the form:

$$p_r(g_r)=P_r\int_{0}^{g_r}xf(x)\mathrm{d}x-U_r\int_{g_r}^{\infty}(x-g_r)f(x)\mathrm{d}x-$$
$$-C_r\int_{0}^{g_r}(g_r-x)f(x)\mathrm{d}x\rightarrow\max. \tag{4}$$

Note that similarly to expression (4) and, accordingly, its components – expressions (1) to (3), it is possible to record the expected profit of the manufacturer from the sale of PFPs in the amount of g_p units to a trade enterprise:

$$p_p(g_p)=P_p\int_{0}^{g_p}xf(x)\mathrm{d}x-U_p\int_{g_p}^{\infty}(x-g_p)f(x)\mathrm{d}x-$$
$$-C_p\int_{0}^{g_p}(g_p-x)f(x)\mathrm{d}x\rightarrow\max, \tag{5}$$

where P_p is the profit provided for a production enterprise by each unit of a sold PFP (as the difference between the selling price for a trade enterprise, or the purchase price for the latter, and the cost of production); U_p is the loss (lost benefit) of a production enterprise, incurred under conditions of shortage, per each unit of PFP, which was lacking.

As regards the loss arising under conditions of excess products at production and trade enterprises, C_p and C_r, respectively, it can be considered in the context of different variants of provisions in contracts for supply between production and trade. The basic approaches to estimating the losses specified, in terms of application acope, are given in work [17].

Note that the losses from the accumulation of excess products, in fact, might be a profit.

It is obvious that in a general case we shall obtain negative values for the objective function parameters in terms of profit from the position of a trade enterprise and from the position of a manufacturer. That is, the batch size of PFP delivery, which is optimal by the profit criterion for a manufacturing enterprise, g_{popt}, is not equal to optimal for the criterion of profit from the order size for a trade enterprise, g_{ropt}.

Solving the problem of inconsistency between g_{popt} and g_{ropt} can be considered in the plane of the two variants of approaches to the formation of systems – classical inductive and systemic. As one knows, construction of the system in line with the classical approach happens via a combination of system components that are developed separately. At the same time, in contrast to the classical one, the systematic approach implies a consistent transition from total to partial, when a global goal is the basis, achieving which is the focus of system operation.

Conditions for implementing a systematic approach to the considered problem, according to expressions (4) and (5), can be represented in the following form:

$$p_s(g_s)=P_s\int_{0}^{g_s}xf(x)\mathrm{d}x-U_s\int_{g_s}^{\infty}(x-g_s)f(x)\mathrm{d}x-$$
$$-C_s\int_{0}^{g_s}(g_s-x)f(x)\mathrm{d}x\rightarrow\max, \tag{6}$$

where P_s is a profit provided by each unit of a sold PFPs for the “production-trade” system, which is regarded as the difference between the selling price in trade to the end consumer and the cost of production and selling of a PFPs unit in the system “production-trade”; U_s is the loss (lost benefit), which arises in the system “production-trade” under conditions of shortage per each unit of PFPs, which was lacking; C_s are the costs in the “production-trade” system, associated with the accumulation of an unsold PFP in the system “production-trade”, which are regarded as production and sale costs, possibly at a discount, and/or recycling (disposal) of the unsold PFP unit.

The relevant logistical costs within the system can be considered, depending on the problem statement, both included in the production, sales or processing, costs, and separately, which, accordingly, requires the adjustment of expression (6).

Analysis of the function of total systemic profit, expression (6), indicates that determining a batch size g_s is the optimization problem. Therefore, it is necessary to find g_{sopt}, which maximizes function $p_s(\mathrm{g_s})$. From equation

$$\frac{\partial p_s(g_s)}{\partial g_s}=0,$$

we determine the optimum batch size for a certain PFP in the link “production-trade”. In order to ensure that g_{sopt} matches a maximum of function $p_s(g_s)$, it is necessary to check the sign of a second derivative, that is

$$\frac{\partial^2 p_s(g_s)}{\partial g_s^2}<0.$$

It is possible to align positions of production and trade enterprises and motivate them to deliver a batch in the amount that corresponds to the maximum profit magnitude within a supply chain system, rather than its individual participants, through the rational distribution among the latter of losses due to the accumulation of unsold products. It is obvious that the mechanism for executing a delivery in the amount that maximizes the systemic profit of a supply chain requires the implementation of partnership relations.

To determine the level of demand satisfaction for g_{sopt}, PFP, which is achieved at the established optimum batch size, one can use a coefficient of demand satisfaction, calculated from expression of the following form:

$$K_{dem}\left(g_{s_{opt}}\right)=\frac{\int_0^{g_{s_{opt}}}xf(x)\mathrm{d}x}{m_x\int_0^{g_{s_{opt}}}f(x)\mathrm{d}x}. \tag{7}$$

Introducing the target value for a demand satisfaction coefficient, equation (6), is acceptable under the conditions of complexity of the proper assessment of lost benefit in a supply chain system (in monetary terms) due to the shortage of PFPs. Namely, group *F* – based on FMR analysis, and *A* – based on ABC analysis. Under conditions of separating a transportation component – represented by two terms, specifically, dependent and non-dependent on the batch size (dispatching), it is possible, according to expression (6), to represent the expected systemic profit from PFP sale in the following form:

$$\left(P_s^{'}-a_{s_1}\right)\int\limits_0^{g_s} xf\left(x\right)\mathrm{d}x-b_{s_1}, \tag{8}$$

where $P_s^{'}$ is the profit provided by each PFP unit (as the difference between the sale price to the end consumer and the costs of production and sale of PFP unit excluding transportation costs); a_{s1}, b_{s1} are the linear dependence coefficients that determine transportation costs when delivering PFP in the amount g_s.

Similarly, when separating a transportation component and under conditions for the accumulation of unsold PFPs, the corresponding component, in line with expression (6), can be represented as follows:

$$(C_s^{'}+a_{s_3})\int\limits_0^{g_s}\left(g_s-x\right)f\left(x\right)\mathrm{d}x+b_{s_3}\int\limits_0^{g_s}f\left(x\right)\mathrm{d}x, \tag{9}$$

where $C_s^{'}$ are the costs associated with the accumulation of unsold PFPs (as the cost of production, sale and/or recycling, excluding transportation costs); a_{S3}, b_{S3} are the linear dependence coefficients, which determines transportation costs when returning the unsold PFPs in the amount g_s-x to the production enterprise.

Taking into consideration expressions (8) and (9), the model of PFP supply management, in the form of equation (6), when separating a transportation component while delivering PFPs to a trade enterprise and possible return as a remainder, can be represented as follows:

$$\begin{aligned}&p_s\left(g_s\right)=\left(P_s^{'}-a_{s_1}\right)\int\limits_0^{g_s}xf\left(x\right)\mathrm{d}x-b_{s_1}-\\&U_s\int\limits_{g_s}^{\infty}\left(x-g_s\right)f\left(x\right)\mathrm{d}x-\left(C_s^{'}+a_{s_3}\right)\int\limits_0^{g_s}\left(g_s-x\right)f\left(x\right)\mathrm{d}x-\\&-b_{s_3}\int\limits_0^{g_s}f\left(x\right)\mathrm{d}x\rightarrow\max(10)c.\end{aligned}$$

As mentioned above, there is a potential problem related to a relatively low value for PFP demand satisfaction, which can be achieved at an optimum batch size. This necessitates the identification of variants for supply chain configurations as the business models that make it possible to ensure a high level of PFP demand satisfaction.

Paper [18], based on actual practices, as well as on analysis of scientific works, gives variants for the specified business models. In particular, the authors separate the variant of an operational response of the system to the event of PFP shortage at a trade enterprise in the period between planned deliveries.

In a given case, let the demand for PFPs over the set period between planned deliveries be a random magnitude *X* with a distribution density *f*(*x*). One can also assume that after a certain time there is a possibility to predict, with a sufficient degree of accuracy, the need for an additional delivery, as well as its magnitude. If it turns out that the total demand projected, $X>g_s$, where g_s is the size of the main delivery, then an order is placed for additional delivery in the amount $X–g_s$. Under conditions of excess delivery, that is, $X<g_s$, there are losses of magnitude C_s per unit of an unsold PFP.

Given the above, and taking into consideration expressions (6) and (10), a given variant of deliveries can be described in the following form:

$$\begin{aligned}&\mathrm{p}_s\left(g_s\right)=\left(\mathrm{P}_s^{'}-\ a_{\mathrm{s}_1}\right)\int\limits_0^{g_s}xf\left(x\right)\mathrm{d}x-b_{s_1}+\\&+\left(P_s^{''}-a_{s_2}\right)\int\limits_{g_s}^{\infty}\left(x-g_s\right)f\left(x\right)\mathrm{d}x-b_{s_2}\left(1-\int\limits_0^{g_s}f\left(x\right)\mathrm{d}x\right)-\\&-\left(C_s^{'}+a_{s_3}\right)\int\limits_0^{g_s}\left(g_s-x\right)f\left(x\right)\mathrm{d}x-b_{s_3}\int\limits_0^{g_s}f\left(x\right)\mathrm{d}x\rightarrow\max,\end{aligned} \tag{11}$$

where $P_s^{''}$ is the profit provided by each PFP unit from an additional supply, which is supposed to be carried out in the event of shortage; a_{s2}, b_{s2} are the linear dependence coefficients, which determines transportation costs when executing additional PFP delivery under conditions of operative response to the occurrence of shortage in the volume of $x–g_s$.

To determine coefficients a_{s1}, b_{s1}, a_{s2}, b_{s2}, a_{s3}, b_{s3}, dependent on the technical-operational and economic indicators of vehicle operation along multi-drop routes along which, in many cases, the delivery of PFPs is executed, it is proposed to use the data reported in paper [19].

That is, transportation costs, dependent on the batch size (dispatching), can be recorded in the following form:

$$S\left(g_s\right)=ag_s+b, \tag{12}$$

$$\begin{aligned}&a=\frac{1}{q\gamma_p\left(1+k_c\right)}\times\\&\times\left[\frac{C_{km}}{\delta}\left(2\overline{l}_i-\overline{l}_{(i-1)-i}\right)+\left(\frac{C_{km}\overline{l}_i}{T_H\delta}+C_{\mathrm{const}}\right)\left(t_{l.unl}+t_3\right)\right],\bigcap_{i=1}^{n}X_i\end{aligned}$$

$$b=\frac{C_{km}}{\delta}\left(\overline{l}_{\mathrm{(i-1)-i+}\frac{l_H}{T_{ser}}}t_3\right)+C_{const}t_3,$$

where q is the rated automobile load capacity; γ_p is the utilization factor of automobile carrying capacity; k_c is a coefficient that takes into consideration the amount of accompanying collection; δ is a coefficient that takes into consideration the share of time spent on zero mileage,

$$\delta=\frac{T_{ser}-t_{\mathrm{H}}}{T_{ser}};$$

T_{ser} is the period when an automobile is in service; t_z is the time spent on zero mileage; C_{km} are the costs per 1 km of mileage; C_{const} are the constant expenses per 1 hour of operation; l_H is zero mileage; $\overline{l_i}$ is the average distance of cargo delivery; $\overline{l}_{(i-1)-i}$ is the average distance of automobile mileage between adjacent points of delivery (transportation) of cargoes; $t_{l.unl.}$ is the automobile idling at loading and unloading per a single trip without taking into consideration additional time for arrivals to intermediate points of delivery (dispatching) of cargoes; t_{en} is extra time for each entry to intermediate points of delivery (dispatching) of cargoes.

Separating a transportation component makes it possible to consider the system "production-trade" as the system "production-transportation-trade".

5. Analysis of conditions for applying the model of PFP delivery optimization in supply chains systems

Fig. 1 shows the dependence of profit in the supply chain system, $p_s(g_s)$ equation (6), and a demand satisfaction coefficient, equation (7), $K_{sat}(g_s)$ on batch size g_s In this case, in equation (6), the transportation component was separated in accordance with expression (12).

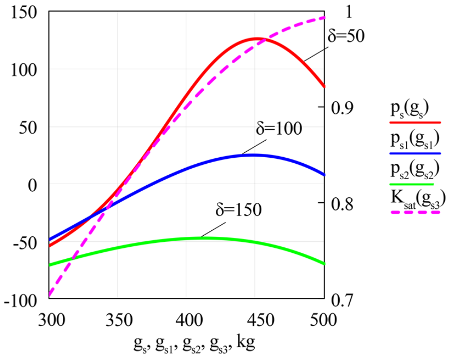

Fig. 1. Dependence of systemic profit (——) and demand satisfaction coefficient (- - -) on batch size at different values of the average quadratic deviation in demand

In other words, equation (6) was refined as follows:

$$P_s(g_s)=\left(P_s^{'}-a_{s_1}\right)\int_0^{g} x\,f(x)\mathrm{d}x-b_{s_1}-$$

$$-U_s\int_{g_s}^{\infty}(x-g_s)f(x)\mathrm{d}x-C_s\int_0^{g_s}(g_s-x)f(x)\mathrm{d}x. \qquad (13)$$

Calculations were carried out for the conditions of bread delivery from the bakery at PAT "Kyivkhlib" (Ukraine) to a retail network in the city of Kyiv. Indicators are given in USD at the currency exchange rate of UAH 25.30 as of September 9, 2019, established by the National Bank of Ukraine [20]; they accept the following initial values: $q\gamma_p=$ $=2.17$ t, $k_c=0.26$, $C_{km}=0.59$ USD/km, $\delta=0.98$, $\bar{l}_i=30$ km, $\bar{l}_{(i-1)-i}=12$ km, $l_H=6$ km, $T_{ser}=12$ hours, $C_{\text{const}}=9.49$ USD/hour, $t_{l.unl.}=1.2$ hours, $t_z=0.3$ hours, $P_s^{`}=0.77$ USD/kg, $U_s=$ $=0.48$ USD/kg, $C_s=1.98$ USD/kg. The coefficients a_{s1} and b_{s1}, based on the given source data, equaled 0.014 USD/km and USD 10.22, respectively.

Our analysis of demand distribution in the period between planned deliveries at the trade enterprise, whose operation underlies the dependence shown in Fig. 1, has confirmed the hypothesis about its normal nature. We tested consistency between empirical and theoretical data based on the χ^2 criterion. The mathematical expectation of demand in the period between planned deliveries $m_x=400$ kg, the average quadratic deviation in demand in the period between planned deliveries is 100 kg. That is, under conditions of grouping classification objects based on the variation factor value ($K_{var}=25$ %), the examined kind of PFP can be categorized, according to *XYZ* analysis, into category *Y*.

As one can see, the optimum batch size, $g_{s\,opt}$, at the above source data is 448 kg; in this case, the system earns a profit, $P_s(g_s)$, at the level of USD 24.66. The demand satisfaction coefficient, $K_{sat}(g_s)$, is 86 %.

Analysis of the dependence of profit in the supply chain system, $P_s(g_s)$, equation (13), on batch size, g_s, under conditions that δ_x decreases to 50 kg, that is $K_{var}=12.5$ %, allows us to refer a given product to category *X* based on *XYZ* analysis. This indicates the presence of a clearly pronounced optimum at a relatively smaller scattering of demand. In this case, $g_{s\,opt}=450$ kg, and $P_s(g_s)=125.81$ USD.

At the same time, under conditions $\delta_x=150$ kg, that is $K_{var}=37.5$ %, – category *Z* based on *XYZ* analysis, $g_{s\,opt}$ equals 413 kg, $P_s(g_s)=-47.54$ USD.

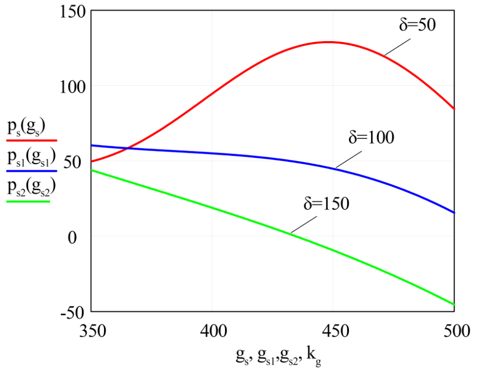

Fig. 2. Dependence of systemic profit on size of the main delivery at different values of the average quadratic deviation in demand

Fig. 2 shown the dependence of profit in a supply chain system, $P_s(g_s)$, equation (11), on batch size g_s under the same values for σ_x in the previous example, that is 50; 100; 150 kg. At the same time, during calculations, a transportation component in the accumulation of unsold products was not separated, as implied by expression (11). That is, the calculations were conducted according to the improved model of PFP delivery optimization in line with expression (11), represented as follows:

$$\mathrm{p}_s(g_s)=\left(\mathrm{P}_s^{'}-a_{s_1}\right)\int_0^{g_s} xf(x)\mathrm{d}x-b_{s_1}+$$

$$+\left(P_s^{''}-a_{s_2}\right)\int_{g_s}^{\infty}(x-g_s)f(x)\mathrm{d}x-$$

$$b_{s_2}\left(1-\int_0^{g_s}f(x)\mathrm{d}x\right)-C_s\int_0^{g_s}(g_s-x)f(x)\mathrm{d}x. \qquad (14)$$

This improved model of PFP delivery optimization implies that under conditions of shortage between planned deliveries an additional delivery can be executed. In this case, we assume the capability to fully meet the demand, which, accordingly, eliminates the need to consider the dependence $K_{sat}(g_s)$. Within the proposed model, g_s can be considered as the main, planned, delivery.

Conditions for the operative response to the shortage of PFPs imply changes in transportation when additional delivery is executed. Thus, $t_{1.unl.}$ would increase to 2.4 h, and $l_{(i\text{-}1)\text{-}I}$ – to 18 km. Based on the constancy of other indicators, which define the coefficients for a cargo delivery along a multi-drop route, equation (12), a_{S2}=0.017 USD/km, b_{S2}=13.83 USD. At $P_s^{''} = P_s^{'} = 0.77$ USD/kg, C_S=1.98 USD/km, we obtain:

$g_{s\,opt}$=350 kg, $P_s(g_s)$=60.31 USD, at σ_x=100 kg;
$g_{s\,opt}$=398 kg, $P_s(g_s)$=128.82 USD, at σ_x=50 kg;
$g_{s\,opt}$=350 kg, $P_s(g_s)$=43.30 USD, at σ_x=150 kg.

Application of the model implies the possibility of introducing a quick response to the occurrence of shortage in the period between planned deliveries. Based on an example of the model application, one can state an increase in the supply chain profits by approximately 2.5–3 times. The magnitude of profit depends on magnitude σ_x and, accordingly, the category to which PFP can be attributed based on *XYZ* analysis.

When constructing functions $P_s(g_s)$, according to expressions (13) and (14), as well as while determining optimum values for $g_{s\,opt}$, that is, those that maximize these functions, we applied the software package Mathcad Prime.exe [21].

6. Discussion of results of improving the model of PFP delivery optimization in supply chains systems

Conditions for application of the known “classic” optimization model of PFP delivery (6) confirm the presence of a relatively low degree of demand satisfaction for PFPs. A prerequisite for this, as follows from expression (6), is the existence of a significant difference between the magnitude of the lost benefit due to the shortage of PFPs and the losses from the accumulation of unsold products per a product unit in favor of the latter under conditions of significant variation in demand. In turn, this indicates the presence of a “niche” in the market of a given kind of PFP – in the form of demand, which cannot be effectively satisfied using the existing business model, particularly in terms of ensuring deliveries.

It is proposed to introduce a possibility of operational response to the shortage of PFPs in the period between planned deliveries. Under these circumstances, there is a task on determining the optimal size of the main planned delivery. Solving a given task necessitated the improvement of the analytical probabilistic-statistical model used in the current work in the aspect of separating benefits, which can be ensured by eliminating PFPs shortage through operational response to its occurrence, and transportation costs in performing the latter.

In this case, full satisfaction of demand for PFPs is implied in the predefined periods between planned deliveries. Similarly to the conditions for determining g_{Sopt} from expression (6), it is possible to define the optimum batch size from expression (11), which, given the current problem statement, is interpreted as the main one, unlike the next, additional delivery, if the need in the latter arises. The ratio between the optimum batch size for main delivery and the mathematical expectation of demand over the interval of time between planned deliveries can define the expediency of introducing a two-stage delivery on schedule with a possibility to adjust the size of one of the deliveries – as additional.

Under the condition of an example given in the current work, the optimization of PFP deliveries in the supply chain systems according to the model, which implies the possibility of additional delivery in the event of shortage, could increase the profit within a system of supply links by 1.5 times and strongly depends on the category to which a given PFP can be attributed to, based on *XYZ* analysis.

Further research should address the justification of transportation capacity of vehicle fleets to ensure operational response to the occurrence of PFP shortage considering the conditions for achieving the predefined level of transportation service quality.

7. Conclusions

1. We have considered a possibility of additional PFP delivery in case of shortage of the latter in the period between planned flows in the supply chains systems. This improvement is valid when separating the benefits, which can be ensured by eliminating PFPs shortage through the introduction of possibilities for additional delivery of PFPs in case of shortage of the latter in the period between planned deliveries, and transportation costs to perform the latter. The proposed model proves that the optimum batch size of the main delivery, which corresponds to a maximum profit within the system of PFP deliveries, depends not only on the magnitudes of profit from the sale of a PFP unit. It also depends on losses from the accumulation of excess PFP unit, on parameters for the distribution of demand over the period between planned deliveries, as well as on technical-operational and economic indicators that characterize the operation of automobiles along multi-drop routes.

2. We have performed a comparative analysis of conditions for ensuring PFP deliveries within chain systems using a known “classic” and the proposed improved variant of the probabilistic-statistical analytical model of PFP deliveries optimization. This analysis has revealed that a two-stage delivery system, that is the one that implies a possibility of additional delivery, is more economically feasible compared to a single-step one. The feasibility of increasing transportation costs related to the transportation of additional delivery has been substantiated and justified. It is their increase that causes a significant increase in the system’s profits via achieving a high level of demand satisfaction and reducing losses due to the accumulation of unsold products.

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