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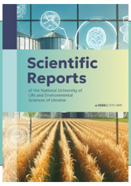

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Models for optimising the volume of material flows in the technological chain of corporate vertically integrated structures of the agricultural sector

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Abstract. The relevance of this study lies in the need to optimise supply cycles and volumes in value chains, which helps to reduce costs and increase the profitability of agricultural enterprises. The purpose of this study was to investigate and optimise the costs of initial material flows in the production subsystems of corporate vertically integrated structures of the agricultural complex under conditions of non-stationary demand. To fulfil this purpose, the study investigated the relationship between the amount of raw material stock stored in the production subsystem and the time of its consumption, based on which an extended model of the economic order quantity (EOQ) was considered, which, apart from the defined costs, also considers the costs of raw material shortages associated with the inability to fulfil deliveries and losses associated with supply failures caused by the unpredictability (stochasticity) of the order flow itself. It was found that in continuous

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production systems there is an opportunity to reduce the costs associated with failures by using an additional regular supply batch. For this, the mathematical "point-of-order" model was built based on the theory of mass service, which allows determining not only the best point to order, but also the optimal amount of the safety stock. A model for optimising the volume of material flows was proposed, which combines the model of the economic order quantity order adapted for use in product subsystems of corporate integrated structures of the agricultural complex and the "point-of-order" model, which allows calculating the minimum size of the insurance stock of raw materials using the tools of operations research. As an example, the material flow was optimised for Kivshovata Agro LLC. The findings of the study, such as the use of analytical tools and models for determining the economic order quantity and safety stock, can be used by the management of agricultural enterprises to improve the efficiency of material flow management

Keywords: production systems; economic order quantity; demand; queuing system; stock management

Introduction

One of the most pressing issues in value chain management is optimising the number of cycles and batch sizes of the initial material flow. The required annual volume of raw materials and financial resources to support the production programme is calculated based on product demand. With one delivery cycle providing an annual volume of raw materials, the production subsystem faces the problem of storing the incoming volume and increasing the costs associated with this process. In contrast, organising deliveries in smaller batches increases organisational costs. For the entire process chain to function smoothly, the required amount (volume) of raw materials or semi-finished products, i.e., stock, must be present at the inlet of the chain links at any given time.

Optimisation of material flows reduces the cost of transporting, storing, and handling raw materials and finished products. This helps to reduce overall production costs and increase the profitability of enterprises. Effective material flow management helps to reduce waste, optimise resource use, and reduce the negative impact on the environment. Modern optimisation models consider the latest technologies, which helps to increase productivity and reduce the impact of the human factor. This is especially true for large corporate structures with a complex logistics network. T. Kovtun (2020) considered the problem of forming reverse material flows and proposed a model of a reverse linkage logistics system, which should solve the problem of optimising material flows using circular economy processes and achieve maximum benefit from the implementation of circular processes. F.F. Galimulina & N.V. Barsegyan (2024), raising the problem of optimising economic systems to improve the efficiency of material flows management, proposed to apply an interdisciplinary approach that allows tools and methods from different fields of knowledge to be combined into a single methodology. A. Ghasemi *et al.* (2024) developed a methodology for radically improving the efficiency of industrial systems, which proposed the use of an optimally designed production scheduling (PS) module that can actively control the budget, timing, and volume of deliveries and which can improve the efficiency of material flow management in the supply chains of many production systems. M. Pekarcikova *et al.* (2020) developed a simulation model of production and supply of goods based on the control logic of the Kanban system to track the movement of material flows in real time and optimise delivery times.

Both Ukrainian and foreign researchers have addressed the problems of optimising material flows in agricultural production and the impact of stock management on the efficiency of corporate agrarian structures V. Matsiuk *et al*. (2023) developed an agent-based simulation model in the AnyLogic environment to improve the transport and technological system for the supply of material resources of an agricultural enterprise under conditions of partial uncertainty. O. Zagursky (2021) proposed a model of a technological system for the supply of perishable food products, which considers compatibility of technical means; technological parameters of technical systems; adaptability of technical systems to environmental conditions and technological properties of perishable food products; parameters of transport and technological cycles, etc. Among the main challenges of supply chains for perishable agricultural products, S. Osman *et al*. (2023) identified the lack of scheduling for product shelf life, lack of product characteristics that affect shelf life, difficulties in storing the product during deliveries, and difficulties in tracking and monitoring the product throughout the supply chain. Exploring the possibilities of a closed-loop economy in small farms, H. Fernandez-Mena *et al*. (2020) propose a new agent-based model, Flows in Agri-Food Networks (FAN), which simulates the optimum exchange of material flows (feed, fertiliser, food) and agricultural waste between farms and partners at different levels (food industry, fertiliser and feed suppliers, waste recyclers, etc.)

Therewith, despite the sufficient elaboration of the subject, the issue of managing the dynamics of changes in the volume of material flows of corporate structures of the agricultural complex with a multi-nomenclature assortment in the conditions of non-stationary demand for products is still understudied in Ukrainian and foreign literature.

The purpose of this study was to investigate and optimise the costs of input material flows in the production subsystems of corporate vertically integrated structures of the agricultural complex under conditions of non-stationary demand.

To fulfil this purpose, the following objectives had to be met:

J to investigate the relationship between the amount of raw materials stored in the production subsystem and the time of their consumption;

J to determine the optimal point of order based on queuing theory;

J to optimise the material flow using the "point-of-order" model for an existing agricultural enterprise.

Materials and Methods

In studying the influence of stock management on the efficiency of corporate vertically integrated structures of the agrarian complex, the study employed general scientific methods: analysis and synthesis – in collecting research materials; systemic – when assessing the interaction of individual elements of the supply system, their impact on the functioning and overall costs of the system and optimisation of supply chain resources as a whole; process – when forming a sequence of actions and working within the supply process to minimise the cost of material flows; synergistic – when considering the dynamics and changes in the supply of vertically integrated structures of the agricultural complex in conditions of non-stationary demand, which are in a state of changing equilibrium, when small changes can lead to large effects; economic and quantitative – to assess the quality of supply processes of the enterprise under study.

To improve the accuracy of the analysis, mathematical modelling techniques were employed to assess the impact of various factors on the behaviour of inventories over time, including linear programming methods to optimise the allocation of resources in the supply chain; simulation modelling to analyse possible scenarios and determine the best stock management strategies; and discrete optimisation methods to minimise costs and maximise the efficiency of logistics operations.

To accommodate the complexity of the processes taking place in production subsystems, a multi-criteria optimisation approach was applied, which allows simultaneously considering several conflicting goals, such as cost minimisation and service level maximisation. This approach used Pareto-optimisation methods to identify the optimal points for managerial decision-making.

Specialised methods of operations research were also used, namely: queuing systems to represent the process of ordering stocks; determining the "point-of-order" to establish the relationship between the amount of raw materials stored in the production subsystem and the time of its consumption; economic order quantity (Harris–Wilson model) to determine the size and interval of delivery batches.

To verify the correctness of the results, additional modelling was performed based on real data from an agricultural enterprise, which helped to confirm the adequacy of the proposed models and methods. A multivariate analysis was performed to investigate the relationships between various elements of the logistics system, such as storage costs, lead times, and service levels.

The findings of this study were experimentally confirmed based on the operational data on the dynamics of changes in material flows for 2023 at the agricultural enterprise Kivshovata Agro LLC, which engages in agricultural production activities in the Kyiv Oblast (Ukraine).

To collect the data, the study employed the methods of questionnaires and expert interviews, which helped to obtain valuable information on the specifics of stock management at the enterprise. Data from automated enterprise management systems (ERP systems) were also used, which ensured high accuracy and reliability of the results.

To ensure the scientific reliability and validity of the results, a comprehensive approach to data collection and analysis was used. The study covered the entire production and logistics process of the agricultural enterprise, from the receipt of raw materials at the warehouse to the delivery of finished products to the consumer. A detailed analysis of the dynamics of raw material stocks was performed, the optimum ordering intervals were determined, and the impact of various factors, such as seasonality and demand fluctuations, on the efficiency of stock management was assessed. The use of statistical methods helped to assess the probabilistic characteristics of supply chain processes, which helped to conclude on the stability and reliability of the stock management system in the face of volatile demand. The use of correlation analysis helped to identify the crucial factors affecting the efficiency of stock management, which became the basis for developing recommendations for improving logistics processes.

Results and Discussion

Agricultural production is specific and has a series of features related to the biological nature of production, as biological organisms, land, and other natural resources are used as the main means of production, and therefore material flows in agro-logistics also have their specific features related to the following:

- diversification – the ability to generate 2 or more streams that differ significantly from each other in terms of their properties, promotion routes, and end users;
- seasonality – the need to store products due to seasonality;
- duality – the ability of a material flow at any stage to act as both a raw material for the next stage and a final product;
- transformation – a significant change in the material flow on the way towards the end consumer, which requires relevant changes in the storage and transportation regime;
- range – expanding the range of material flow as it moves through the supply chain, which requires increased efforts to maintain it.

This specificity in the production subsystems of the full technological cycle of production in the market conditions causes (especially in crop production) the movement of certain volumes of annual financial, material, and information flows. In Figure 1, the financial flow (d_1) compensates for the cost of purchasing raw materials $M_1=k_1d_1$, where k_1 is considered as the conversion factor of the financial flow (d_1) into the material flow (M_1).

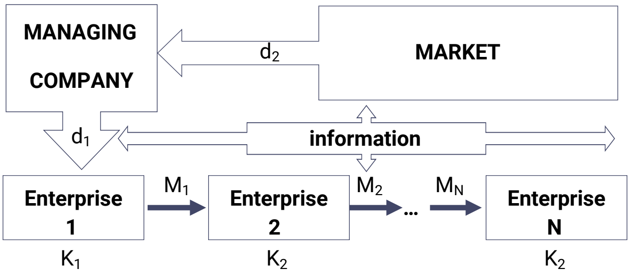

Figure 1. *General scheme of the technological chain of vertically integrated structures of the agricultural sector*

Note: d – financial; M – material; I – information flows

Source: compiled by the authors of this study based on O.M. Zagurskiy (2021)

Determining the volume of material flow (M_2) and the number of cycles (m) in the production subsystems of vertically integrated structures of the agricultural complex requires additional information (I) and the application of the stock management methodology on its basis. Therewith, the need for stocks of these structures is characterised by random processes, as the probability of receiving the required amount of raw materials at the input of the technological link at the time of the requirement is not high. And in case of a stock shortage, the production process may stop or slow down, leading to financial losses.

Accordingly, the production subsystems of vertically integrated structures of the agricultural sector need to strike a balance between the processes of raw material shortages and the processes of increasing stocks, which entails an increase in storage costs (Yablonskyi *et al.*, 2024).

Notably, the stock management methodology allows making an optimal (suboptimal) decision under certain conditions and strategic constraints (Volokha *et al.*, 2023). Therefore, the issue of optimising the output material flows in production subsystems comes down to the following issues:

J what volume (quantity) of goods should be periodically delivered to the warehouse to create the required stock (delivery lot size);

J at what time (at what minimum stock level) should the stocks be replenished ("point-of-order").

Thus, there is a need to establish a link between the quantity or volume of raw materials (Q) stored in the production subsystem and the time (t) of its consumption, i.e., the study of the following function:

$$Q = f\,(t), \tag{1}$$

where Q is the stock of one type of raw material.

The classic Harris-Wilson (Wilson, 1934; Harris, 2013) model for calculating the economic order quantity (Formula 2) relates ordering costs to stock storage costs:

$$EOQ = \sqrt{\frac{2S \times D}{H}}, \tag{2}$$

where S is the ordering cost (per year, per unit), which includes the cost of delivery, processing, and settlement of orders; D is the demand coefficient or resource requirement (number of units sold per year); H is the stock storage cost (per year, per unit), which includes the cost of storing materials or goods in a warehouse and losses due to stock-outs.

It involves the continuous consumption of raw materials, as well as their immediate receipt, which is impossible in practice (Rogovskii *et al.*, 2022). Even if a continuous production process is organised in corporate integrated structures, to maintain its rhythm, the rate of supply of raw materials (p) must exceed the rate of resource consumption (a). That is, the condition ($p > a$) must be met. Therefore, in contrast to the classical approach, when formulating the task of stock management in corporate vertically integrated structures of the agricultural sector, it is assumed that batches of raw materials will arrive evenly at the rate of delivery (*p*) rather than instantly, and within the interval (t_p), as presented in Figure 2.

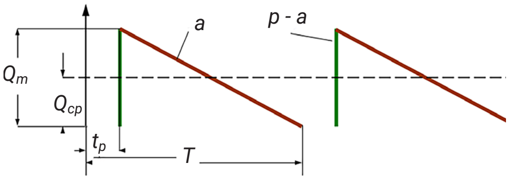

Figure 2. *Diagram of the dynamics of production stocks of corporate vertically integrated structures of the agricultural sector*

Note: *Q* is the stock of raw materials; *t* is the time of consumption; *p* is the rate of supply of raw materials; *a* is the rate of resource consumption

Source: compiled by the authors of this study based on I. Rogovskii *et al.* (2022)

In this regard, the following types of expenses arise:

1. Organisational costs associated with the processing and delivery of goods that are required for each warehousing cycle and are subject to recycling.
2. Expenses related to storage and depreciation of goods subject to deterioration, ageing, and reduction in quantity during storage.
3. Raw material shortage costs associated with the inability to deliver raw materials, which results in lost profits.

Figure 3 shows an approximate graph of the cost function as a function of the quantity of stocks C = f(q) for corporate vertically integrated structures of the agricultural sector. Figure 3 shows that the process of stock management for corporate vertically integrated structures of the agricultural sector is based on assumptions analogous to the Harris-Wilson model and differs in that if the stock in the warehouse approaches zero, deliveries will be started and continued until one batch is available. Therewith, the supply of raw materials to the technological process, i.e., its shipment, will not be interrupted. Thus, the presented classification of the costs of the process under study can be defined by the following formula (3):

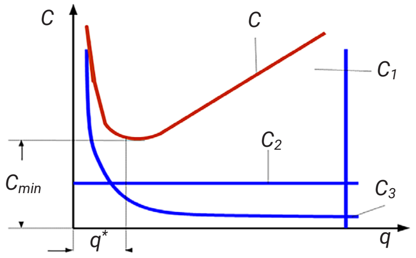

Figure 3. *Diagram of changes in costs of corporate vertically integrated structures of the agricultural sector*

Note: C – the costs; C_1 – the total stock storage costs; C_2 – the cost of goods; C_3 – the total organisational costs; C_{min} – the minimum costs

Source: compiled by the authors of this study

$$\mathrm{C} = \mathrm{C}_1 + \mathrm{C}_2 + \mathrm{C}_3 = h\frac{Q_m}{2} + C_a + S\frac{a}{q}, \qquad (3)$$

where $\mathrm{C}_1 = h\frac{Q_m}{2}$ is the total stock storage costs; $\mathrm{C}_2 = \mathrm{C}_a$ is the cost of goods; $\mathrm{C}_3 = S\frac{a}{q}$ is the total organisational costs.

The modified Harris-Wilson formula for finding the optimal lot size for delivery (Q*), which corresponds to the volume of the original material flow, will have the following form:

$$Q^* = \sqrt{\frac{2pSa}{h(h-a)}}. \qquad (4)$$

However, the Harris-Wilson stock management model and its modifications are deterministic and do not accommodate the stochastic nature of the flow of requirements (requests) in a vertically integrated production system (Rogovskii *et al.*, 2021). To accommodate stochastic processes in stock management in the production chain (especially in the sales unit), it is proposed to use the mathematical model of the "point-of-order" based on the theory of mass service (Nobil *et al.*, 2016; Balestra *et al.*, 2021; Utama *et al.*, 2022).

According to this model, for any queuing system, the stock ordering process can be represented by two functions:

1. Number of applications received by the system by time t: *x(t)*.

2. Number of applications that have left the system by t: *y(t)*.

The above functions are characterised by a jump (an increase by one at the moments of arrival and departure of orders). Graphically, the functions x(t) and y(t) are presented in Figure 4:

- lines representing functions are stepped;
- the upper bound is x(t);
- the lower bound is y(t).
- the difference z(t) = x(t) – y(t) at any time t is the number of orders in the system. If z(t) = 0, there are no orders in the system.

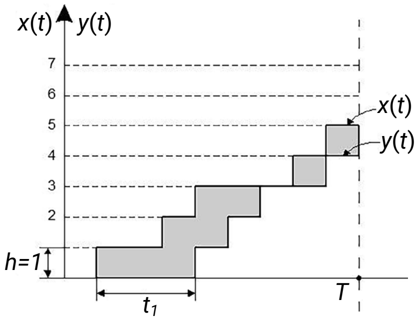

Figure 4. *Graphical representation of the functions x(t) and y(t)*

Note: *x*(*t*) is the number of orders that entered the system by time *t*; *y*(*t*) is the number of orders that have left the system by time *t* – orders in the system at a given time

Source: compiled by the authors of this study based on S. Minkevičius *et al*. (2021)

To apply the queuing theory in solving this problem, the study investigated the flows of requirements that differ in their internal structure and performed their quantitative description. The simplest flows are characterised by the following properties: ordinariness; stationarity; and absence of after-effects.

An ordinary request flow is one where more than one request will be received in the system in a short period of time (Δ*t*) with probability *R* > *1*(Δ*t*), which is quite small compared to the fact that only one request will be received in the same period of time, as expressed by the following:

$$R > 1(\Delta t) << R1(\Delta t). \qquad (5)$$

A flow is called stationary if the probability of occurrence of some requirements (*k*) in a time interval (Δ*t*) depends on the length of the interval and does not depend on the location of the interval on the time axis, i.e., in a stationary flow of requirements, the probability characteristics are not subject to changes on the time scale. The average number of claims, expressed as (*λ*), received per unit of time and characterising the intensity or density of the flow. In a stationary flow, the intensity value (*λ*) will be the same at any interval (Δ*t*).

If the number of demands entering the system in a non-overlapping time slot does not depend on the number of demands in another time slot, then such a flow is characterised by no consequences. The Poisson's law is used to describe the simplest requirement flow with a certain parameter (*λ*):

$$R_{k(t)} = \frac{(\lambda t)^k}{k} e^{-\lambda t}, \qquad (7)$$

where: $R_{k(t)}$ is the probability that reflects the process of receipt of (*k*) claims at an arbitrary time interval with duration (*t*).

Then, according to Poisson's law, the probability of no claims at a time interval (*t*) after one of the claims enters the system will be as follows:

$$R_0(t) = e^{-\lambda t}. \qquad (8)$$

However, the given probability corresponds to the probability that the value (*t*) will be no more than a random variable *T*. Then:

$$R_0(T \geqslant t) = e^{-\lambda t}, \qquad (9)$$

Accordingly:

$$F(T) = 1 - e^{-\lambda}{}_{t}, \qquad (10)$$

where: F(*T*) is a function that distributes a random variable *T*.

The distribution for a random variable *T* will be carried out with density as follows:

$$f(t) = \lambda_e^{-\lambda t}. \tag{11}$$

Thus, for the simplest flow, the time interval between any two neighbouring demands will be distributed according to the exponential law and using the parameter (*λ*). In addition, the simplest flow is characterised by a higher probability of short intervals between events than long ones. Approximately 63% of the time intervals between events in the system are characterised by a length that is less than the average and equal to (*1/λ*).

Furthermore, the Harris-Wilson model does not consider the losses associated with failures during order processing due to the unpredictability of the order flow itself (stochasticity). In practice, it may happen that an order is received at a time when the current batch has already been exhausted and the next delivery has not yet taken place. To account for such losses, it is proposed to introduce a cost coefficient (*g*), the value of which is determined by the probability of failure when servicing an incoming request (*R*), and determines the probability of failure and the amount of costs associated with this process for the Harris-Wilson model of production supply.

Accordingly, there is a probability, expressed as *Ri(t)*, that at the time of the next arrival of a batch of goods, there is a stock of units of goods in the amount from 0 to Q_m. Moreover, the probability of a decrease in the current batch ($Q_m - i$) of units of goods corresponds to or is equal to the probability *Ri(t)*. The probability of reducing the current batch $RQ_m - i(t)$ is determined by Poisson's law, and the probability of no failure during maintenance is as follows:

$$R_{00}(t) = \sum_{i=1}^{Q_m} R_i(t), \tag{12}$$

or

$$R_{00}(t) = \sum_{i=1}^{Q_m} R_{Q_{m-i}}(t). \tag{13}$$

Consequently, the probability of a failure to service the order will be as follows:

$$R_f(t) = 1 - \sum_{i=1}^{Q_m} R_{Q_{m-i}}(t), \tag{14}$$

and the amount of costs incurred in case of a failure is determined by the following expression:

$$I_f(t) = g[1 - \sum_{i=1}^{Q_m} R_{Q_{m-i}}(t)]. \tag{15}$$

If one replaces the following variables with $j = q^* - i$, one gets that when $i = 1$, the value of (j) is equal to $Q_m - 1$, and when (i) is equal to Q_m, the value of (j) is 0. Then, changing the bounds of the sum in places, the resulting expression is brought to a standard form as follows:

$$I_f(t) = g[1 - \sum_{j=1}^{Q_m - 1} R_j(t)]. \tag{16}$$

The parameters of the Harris-Wilson model for production conditions are substituted into the formula. Poisson's formula for *Rj(t)*, where the parameter λ is the annual demand intensity expressed as a, which characterises the intensity of the flow of applications on average during the year. And the time interval for considering the probabilistic characteristics of the stock management system is the interval between the receipt of batches of goods, expressed as $Q_{m/a}$. Thus, for the process described, the Poisson's formula will take the following form:

$$R_j(t) = \frac{\left(a\frac{Q_m}{a}\right)^j}{j!}\ exp\left(-a\,\frac{Q_m}{a}\right). \tag{17}$$

Substituting the formula for I_f (t) instead of Rj(t) in expression (17), one obtains the following:

$$I_f = g[1 - \sum_{j=0}^{Q_m - 1} \times \frac{\left(a\frac{Q_m}{a}\right)^j}{j!}\ exp\left(-a\,\frac{Q_m}{a}\right)], \tag{18}$$

where Q_m is the maximum volume of stocks; a is the intensity of the annual flow of applications; $Q_{m/a}$ is the time interval during which one delivery batch is consumed, year.

By simplifying expression (18), the final formula is obtained:

$$I_f = g[1-\sum_{j=0}^{Q_m-1} \times \frac{(Q_m)^j}{j!}\, exp(-Q_m)]. \quad (19)$$

Notably, in continuous production systems, it is possible to reduce the costs associated with I_f failures by using an additional regular supply batch (Zagurskiy *et al.*, 2024) in the time interval Δt. A graphical description of the process is presented in Figure 5.

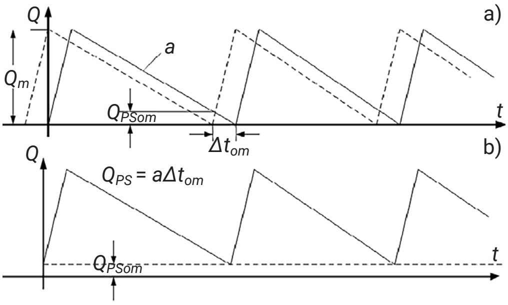

Figure 5. *Supply shift by* Δt_{om}

Note: a – the delivery with failures in the time interval Δt; b – the delivery with the use of an additional regular batch

Source: compiled by the authors of this study

The application of this adjustment requires a change in expressions (18) and (19):

$$I_f = g[1-\sum_{j=0}^{Q_m-1}\frac{\left(a\left(\frac{Q_m}{a}-\Delta t\right)\right)^j}{j!}\, exp\left(-a\left(\frac{Q_m}{a}-\Delta t\right)\right)], \quad (20)$$

or

$$I_f = g[1-\sum_{j=0}^{Q_m-1}\frac{(Q_m-a\Delta t)^j}{j!}\, exp\big(-(Q_m-a\Delta t)\big)]. \quad (21)$$

An analysis of Figure 5 shows that such a change in supply is equivalent to a process of increasing the shelf life by (1 + Δ*t*). Accordingly, the storage costs will be as follows:

$$I_x = h * \frac{Q_m}{2*(1+\Delta t)}, \quad (22)$$

while the total costs will be equal.

$$I = I_x + I_f. \quad (23)$$

Thus, with the optimum precautionary supply interval Δt_{op}, the total costs are minimal:

$$min(I) = g\left[1-\sum_{j=0}^{Q_m-1}\frac{(Q_m-a\Delta t_{on})^j}{j!}\, exp(-(Q_m-a\Delta t_{on}))\right] + h\frac{Q_m}{2}(1+\Delta t_{on}), \quad (24)$$

and the optimum ordering point (optimum safety stock volume) Q_{PSt}, which is defined as follows:

$$Q_{PSt} = a\Delta_{top}. \quad (25)$$

Table 1 and Figure 6 show an example of considering the dependences that reflect the dynamic result of all the functions of the stock storage unit of the integrated agricultural supply chain for the operating agricultural enterprise of Ukraine Kivshovata Agro LLC.

Table 1. *Results of material flow optimisation using the "point-of-order" model for Kivshovata Agro LLC*

Intensity of application flow per year, I	Stock storage costs, h	Maximum stock level, Qm	Interval of validity of one delivery batch, Δt	Storage costs, Ix	Failure costs, If	Total costs, I
20	6	150	1	900	0.0000000	900.0
20	6	150	2	1350	0.0000000	1350.0
20	6	150	3	1800	0.0000000	1800.0

Table 1. *Continued*

Intensity of application flow per year, *l*	Stock storage costs, h	Maximum stock level, Qm	Interval of validity of one delivery batch, Δt	Storage costs, Ix	Failure costs, If	Total costs, I
20	6	150	4	2250	0.0000000	2250.0
20	6	150	5	2700	0.01897892	2700.0
20	6	150	6	3150	0.00000003	3150.0
20	6	150	7	3600	0.0000000	3600.0
20	6	150	8	4050	0.0000453	4050.0
20	6	150	9	4500	22026.460	26526.5
20	6	150	10	4950	38026.460	42976.5

Source: compiled by the authors of this study

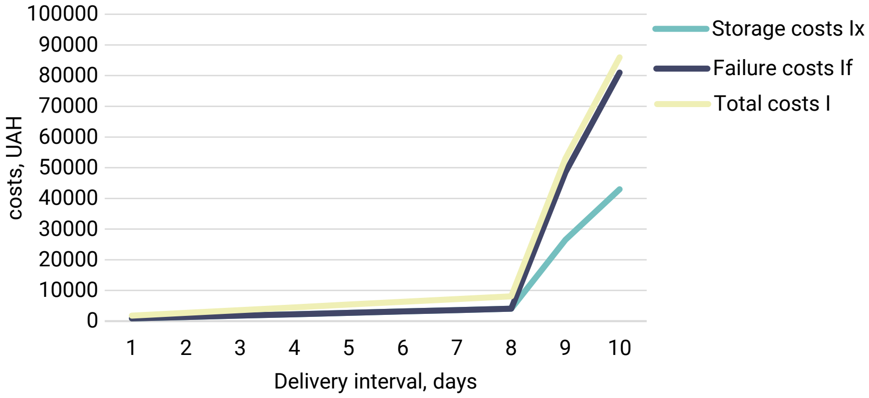

Figure 6. *Schedule for determining the optimum interval for the advance delivery ofthe next batch* (Δt_{op})

Source: compiled by the authors of this study

As Figure 6 shows, the minimum value of the total cost is maintained up to Δt_{op} = 8, when the delivery interval of one delivery batch reaches eight days, while increasing the delivery interval of batches to nine or ten substantially increases the total cost of supply.

Comparing the obtained approaches and results with other comparable studies, all of them, like the present study, are devoted to building effective stock management models and investigating the relationship between the amount of stock stored at the enterprise and the time of its consumption. Thus, H. Starushenko (2022) proposed a digital model for calculating the economic order quantity developed based on the Harris-Wilson EOQ stock management model. The researcher used the minimisation of total expected costs of the enterprise as the optimisation criteria, while organisational and storage costs were used as constraints, and did not consider the possible shortage of stocks. The present study, apart from the above costs, also considered the costs of raw material shortages associated with the inability to supply raw materials, which results in lost profits.

T. Nestorenko *et al.* (2020) conducted a thorough investigation of stock management models with uncertain demand (variations of the Harris formula based on the Markov equation and the Wilson formula developed to minimise expected replenishment costs and stock-outs). Their model considers fluctuations in demand, lead time, and price, among other criteria. Therewith, the model does not accommodate the possibility of potential supply failures. In the present study, for vertically integrated production systems, the possibility of failures is allowed, and therefore during the servicing of orders, the losses associated with failures caused by the unpredictability (stochasticity) of the order flow itself are also considered, and therefore the possibility of reducing the costs associated with failures by means of an additional regular supply batch is calculated.

To ensure supply sustainability, S. Zeng *et al*. (2019) presented a modified version of the Wilson model that considers consumer demand trends and provides flexibility in re-ordering time, which allows determining the economic order quantities and intervals between them. In contrast to S. Zeng *et al*. (2019), the current study proposes to use a mathematical model of the "point-of-order" based on the theory of queuing to account for stochastic processes in stock management in the supply chain of a vertically integrated agricultural production system, which allows determining not only the optimum point of order but also the optimum amount of safety stock.

C. Çalışkan (2021) proposed an extended classical Harris-Wilson model for stock management and compound interest accounting, which, according to the researcher, is an intuitive closed-form equation for the economic order quantity, but, like previous studies, it also does not consider possible stock-outs and losses associated with supply failures.

Notably, some modern researchers consider the problem of stock optimisation from the standpoint of sustainable economic development and, apart from economic components, include environmental and social components in stock management models. Thus, N. Liao & Q. Deng (2018) propose an environmental sustainability model (EES-EOQ), which uses benefit-cost ratios to indirectly control production to overcome the limitations of the classical EOQ model. To this end, the researchers derive three optimum strategies: (I) minimise stock costs, (II) maximise the overall environmental benefit in a dedicated recovery model, and (III) coordinate forward logistics and reverse logistics to achieve environmental optimisation in a combined recovery model. Using stochastic analysis, they mathematically prove the existence and uniqueness of the optimum ratio in each strategy. S. Turki *et al*. (2020) also propose an EOQ model that considers the costs of waste disposal. A. Jokar & S.-M. Hosseini-Motlagh (2020) and S. Pattnaik *et al*. (2021), defining the stock management policy of companies in the face of demand volatility, included corporate social responsibility issues in models for determining optimum stock quantities in supply chains. Therewith, this model is more in line with the development of optimum restoration strategies to mitigate environmental problems caused by excessive carbon emissions and is suitable for restoration enterprises.

Conclusions

Determination of the volume of the required material flow and the number of cycles in the production subsystems of vertically integrated structures of the agricultural complex requires the application of the stock management methodology. The frequent need for stocks of these structures is characterised by random processes, as the probability of receiving the required amount of raw materials at the input of the technological link at the time of the requirement is not high. Moreover, in case of a stock shortage, the production process may stop or slow down, leading to financial losses. Therefore, the production subsystems of vertically integrated structures of the agricultural sector need to strike a balance between the processes of raw material shortages and the processes of increasing stocks, which entails an increase in storage costs.

It was found that optimisation of material flows is a critical aspect of ensuring uninterrupted operation and reducing the cost of transporting, storing, and handling raw materials and finished products. This helps to reduce overall production costs and increase the overall profitability of subsystems of vertically integrated structures in the agricultural sector. The integration of classic stock management models such as the economic order quantity and point-of-order models allows for more accurate calculations and reduced costs.

Optimisation of material flows reduces the cost of transporting, storing, and handling raw materials and finished products. This helps to reduce overall production costs and increase the overall profitability of subsystems of vertically integrated structures in the agricultural sector.

A model of optimisation of volumes of material flows in subsystems of corporate integrated structures of the agrarian complex was proposed, which combines two classical models: the model of economic order quantity adapted for use in product subsystems of corporate integrated structures of the agrarian complex and the "point-of-order" model, which allows calculating the minimum size of the insurance stock of raw materials using the tools of operations research.

For example, the material flow was optimised for the operating agricultural enterprise Kivshovata Agro LLC. The above calculations showed that the total costs stay at a minimum value up to $\Delta t_{op} = 8$, when the delivery interval of one batch of supplies does not exceed eight days; an increase in the interval by even a day or two substantially increases the total cost of supplies.

Prospects for further research are related to improving the models of stock management of agricultural enterprises, considering current trends in sustainable economic development.

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Conflict of Interest

None.

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Моделі оптимізації обсягів матеріальних потоків у технологічному ланцюзі корпоративних вертикально-інтегрованих структур аграрного комплексу

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Анотація. Актуальність дослідження полягає в необхідності оптимізації циклів та обсягів поставок у ланцюгах створення доданої вартості, що сприяє зниженню витрат і підвищенню рентабельності аграрних підприємств. Метою статті було дослідження та оптимізація витрат вихідних матеріальних потоків у виробничих підсистемах корпоративних вертикально-інтегрованих структур аграрного комплексу в умовах нестаціонарного попиту. Для досягнення поставленої мети в роботі досліджено зв'язок між обсягом запасу сировини, що зберігається у складі виробничої підсистеми і часом його споживання на основі якого розглянуто розширену модель оптимального розміру замовлення EOQ, у якій окрім визначених витрат враховуються ще й витрати дефіциту сировини, пов’язані із неможливістю виконання постачання і втрати пов'язані з відмовами у постачаннях обумовленими непередбачуваністю (стохастичністю) самого потоку заявок. Визначено, що у безперервних виробничих системах існує можливість зменшення витрат, пов'язаних із відмовами за допомогою додаткової чергової партії постачання. Для цього на засадах теорії масового обслуговування побудовано математичну модель «точка замовлення», що дає можливість визначити не тільки оптимальну точку замовлення, а й оптимальний обсяг страхового запасу. Запропоновано модель оптимізації обсягів матеріальних потоків, що поєднує модель оптимального розміру замовлення EOQ адаптовану до використання в продуктових підсистем корпоративних інтегрованих структур аграрного комплексу та модель «точка замовлення», що дозволяє розраховувати мінімальні розміри страхового запасу сировини з використанням інструментів дослідження операцій. Для прикладу проведено оптимізацію матеріального потоку для ТОВ «Ківшовата Агро». Результати дослідження, такі як застосування аналітичних інструментів і моделей визначення оптимального розміру замовлення та страхового запасу можуть бути використані менеджментом аграрних підприємствами для підвищення ефективності управління матеріальними потоками

Ключові слова: виробничі системи; оптимальний розмір замовлення; попит; система масового обслуговування; управління запасами