Digital algorithms for supply chain automation of mechanical engineering production

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Abstract. The modern concept of the developing engineering production is based on a digital interaction. At the same time, management of all related processes is possible due to a digital shadow at each stage of work. This primarily related to supply, marketing and operational units within the enterprise. The solution of the automation problems of the industrial production, matching to the priorities of the Industry 4.0 program is ought to begin with the organization of the inter-machine interaction M2M. This article presents the results of a study devoted to a search for optimal algorithms for managing the flow of goods and cargoes of the engineering production in modern supply chain management concepts such as 3PL logistics, pick-by-line, cross-docking, as well as ensuring the implementation of managerial decision-making systems based on outrunning economic indicators.

1. Introduction

The concept of digital supply chain management is widely used in leading industries around the world. It is based on software products [1] using inter-machine interaction algorithms. The result of the work of such systems is the intellectual support [2] of management, up to the mode of fully automated decision making. Market uncertainty is the environment in which a commercial activity occurs. Such indicators as demand volume, supply stability can be set only by average values depending on the situation in the economy [3]. They are affected by the unevenness of traffic flows, logistics, seasonal dependencies. Today, the world has created and has unified the technical base for inter-machine information exchange. First of all, it is the development of a global computer network and alternative access channels through a 4G mobile network and reliable scalable communication systems via 5G digital cellular networks [4]. Systems of machine-readable codes are based on barcode, QR code, RFID tag, NFC communication and other information tools available for recognition by artificial intelligence sensors that have also been widely introduced. It should be noted that although real-time means of information interaction are already available, the objectives of optimizing the physical flows
of goods [5] and goods are still fragmented. Among the well-known forwarding solutions, such as the Warehouse Management System as part of CRM, ERP supply chain management of SAP software products, EWM, the innovative 3PL (Third Logistic Outsourcing) [6] complex stands out. In this concept, manufacturers and consumers are spared from a number of problems associated with the transportation, storage, freight forwarding. 3PL providers solve these problems, and business entities concentrate their efforts on their core competencies. The work of the 3PL operator [7] is to ensure the physical movement of inventory and their processing at distribution centers. The cost-effective organization of such interaction requires the prognostic planning for an extended time horizon. The main problem of the study lies in the scientific substantiation of the order of processing inventory and commodity flows in an optimal way.

The solution to this problem [8] should be carried out in conjunction with the development of the 3PL structure, based on mathematical algorithms for its calculation. The solution to the problem of digital algorithms [9] for supply chain automation of mechanical engineering production must be carried out on the basis of world experience in organizing network logistics. It is convenient to present the supply chain in the form of a directed graph, in the nodes of which are the corresponding units. Between them there are information and material flows of inventory and commodity. The optimal solution to the structure of 3PL activities today is considered to be the participation of distribution centers (DC) in the nodes of such a network except for manufacturers and consumers. The role of such DC nodes [10] is to smooth the flows, as well as to reduce the volume of their own warehouses and, thus, reduce the costs of consumers. This reflects the impact of the JIT management concept. First of all, the advantage is given to wholesale supply companies due to the minimization of emergent stocks and costly SW (store warehouse). At the same time, the volume of enterprises' funds, frozen in warehouses decreases [11,12]. In addition, the presence of reverse logistics in JIT technology provides mutual benefits to manufacturers. In addition, DC uses advanced cross-docking, pick-by-line technologies. The main criteria of economic efficiency [13,14] is the maximum profit of 3PL operator. At the same time, the costs of DC volume are minimized, and a balance [15] must be maintained between possible costs (for example, demurrage and detention factors or contractual penalties for short delivery or late shipment).

2. Statement of the research problem

It is required to develop a mathematical description of the process of movement of flows of inventory and commodity. The initial information is the probability distribution function of volumes and directions of their movement. Next, it is necessary to form an economically optimal control, while the input data comes from digital interaction systems using machine-readable encodings containing information about the name, destination and deadlines. Based on the calculations, one have to develop a methodology for designing the volumes of distribution centers.

3. Research method

The formalisms for describing the movement of inventory items are applied. At the same time, real market conditions, primarily uncertainty factors [16,17], are taken into account. To compose the equations, stochastic modeling methods are used. The optimal solutions were found by minimizing the total cost. The balance of costs for logistics and delivery delays are determined. The maximum profit from logistics activities [18] is determined. The numerical methods of the mathematical theory of optimal processes, calculations on a PC are applied.

4. The main formalisms

In modern logistics, a digital footprint remains at every stage of inventory and commodity movement. We will use optimization algorithms [19] as the basis of computer programs. We apply stochastic modeling methods. Let us denote: the inventory and commodity assortment are equal to \( n \). Streams have probability density \( \lambda_i \), where \( i = 1, 2, \ldots, n \). Then the sum of the \( n \) flows at the time of arrival \( T_1, T_2, \ldots \) has a distribution [20] density:
\[ g_{(n)}(t) = (-1)^n \prod_{i=1}^{n} \lambda_i \sum_{j=1}^{\infty} \prod_{\ell=1}^{n} (\lambda_j - \lambda_\ell) \quad (t > 0). \]

The distribution function is:
\[ G_{(n)}(t) = \int_0^t g_{(n)}(\tau) d\tau = (-1)^n \prod_{i=1}^{n} \lambda_i \sum_{j=1}^{\infty} \lambda_j \prod_{\ell=1}^{n} (\lambda_j - \lambda_\ell) \quad (t > 0). \]

Next we use the Erlang characteristics of the order \( n \):
\[ M[T_{(n)}] = M\left[ \sum_{i=1}^{n} T_i \right] = \sum_{i=1}^{n} \frac{1}{\lambda_i}, \quad D[T_{(n)}] = D\left[ \sum_{i=1}^{n} T_i \right] = \sum_{i=1}^{n} \frac{1}{\lambda_i^2}. \]

When describing the operation of DC in cross-docking and pick-by-line [21, 22] modes, these characteristics are not enough. Figures 1, 2 shows that with the same expectation and variance, the nature of the processes varies greatly. To formalize the processes of inventory and commodity movement, we additionally define a correlation function \( K(t,t') \) [23]. This is because pick-by-line technology is more sophisticated and provides a competitive advantage [24]. However, coordination is required between the logistics operator, supplier and consumer.

![Figure 1. Cross-docking technology.](image1)

![Figure 2. Pick-by-line technology.](image2)

5. **Mathematical model**

We use the pseudo-state method [25, 26]. We denote the time \( T_0 \) characterizing the process being in a subset of states \( U = \{s_0, s_1, \ldots, s_{n-1}\} \), where \( s_0 \) is the state at \( t=0 \). Then it is true: \( T_0 = \sum_{i=0}^{n-1} T_i \), and the distribution law of the quantity \( f_0 \) has the form \( f_0 = \sum_{i=1}^{n-1} \gamma_i \lambda_i e^{-\lambda_i} \quad (t > 0) \), where \( \gamma_i = \prod_{\ell=1}^{n} (\lambda_\ell - \lambda_i) \)
under the condition \( \sum_{i=0}^{n-1} \gamma_i = 1 \). To predict DC on the planning horizon [27], we find the characteristics of the stationary mode. Denote by \( r_m \) the probability of finding the system \( S \) in the pseudo-state \( U_m \): \( r_m = P\{S \subset U_m\} \), \( m = 0,1,2,\ldots \).
Then we have from:

$$r_m = p_m + \frac{1}{\alpha} p_m^{(k)} = p_m + \sum_{i=0}^{k} \frac{\lambda^i_m}{\alpha^i} p_m = p_m \sum_{i=0}^{k} \frac{\lambda^i_m}{\alpha^i},$$

assuming $a = \frac{\lambda^i_m}{\alpha^i} > 0$, one can find for $m = 0, 1, 2, \ldots$ the limiting values of $p_m$. To do this, we calculate [28] the values of $s_0, s_0^{(k)}, s_1^{(k)}, \ldots, s_m, s_m^{(k)}, \ldots$:

$$\lambda_0 p_0 = \mu p_1$$

$$(\lambda_0 + \mu) p_1 = \lambda_1 p_0^{(k)} + 2 \mu p_2$$

$$(\lambda_0 + m \mu) p_m = \lambda_m p_{m-1}^{(k)} + (m+1) \mu p_{m+1} m = 2, 3, \ldots$$

But since the assortment is limited, the last equation has the form: $m \mu p_m = \lambda_m p_{m-1}$. From here we get

$$r_m = \frac{P(m, \alpha)}{R(n, \alpha) + P(n, \alpha) \frac{1-\alpha}{\alpha}} , \quad r_e = \frac{R(n, \alpha) \frac{1-\alpha}{\alpha}}{P(m, \alpha) = \alpha^m e^{-\alpha}}.$$

The desired correlation function:

$$K_{i}(t, t') = M \left[ X(t) X(t') \right] - m_i(t) m_i(t') ; \quad M \left[ X(t) X(t') \right] = \sum_{i=0}^{\infty} p_i(t) m_{i,0}(t, t').$$

The obtained set of mathematical relationships allows modeling the operation of a network distribution center as a nodal element of a logistics system operating on the principles of a 3PL operator under the stochastic nature of incoming and outgoing goods flows [29, 30].

6. Conclusions

The transition to digital technologies for supply chain automation of mechanical engineering production is possible with algorithms for control programs. The tracking of all inventory and commodity movement cycles based on digital shadow allows not only to control the entire forwarding cycle in online mode, but also to predict it. Integration of information from the manufacturer, consumer, machine-to-machine interaction of artificial intelligence systems, navigation of vehicles allows for 3PL outsourcing activities that are optimal from an economic point of view. The proposed algorithms are scalable, as well as invariant to the type of operations, including reverse logistics. For example, seaports that are accepting for safe custody, are engaged in the formation of consignments and other stevedore competences, act in a similar way, and their activities can be optimized. Such nodes as DC or local SW enterprises differ only in the dimension of the equations of mathematical formalisms. The results can be applied in a very wide class of supply problems. The proposed optimality criterion includes the concept of stockout, or out-of-stock, which is important for economic calculations.

Automation of the audit of the distribution center allows you to organize end-to-end interaction. Thus, the risks of losses caused by the difference in the intensity of shipments and the delivery schedule are reduced. Since digital technologies are implemented in all modern industries, all goods are provided with machine-readable markings not only in the form of QR or barcode, but also with RFID tags. Thus, you can specify additional information about the properties of the cargo, storage and transportation conditions, as well as expire date. The development of application programs using such information about the operation of an object, as well as its mathematical model, will provide a competitive advantage. The flow modeling technique is also promising for higher levels of logistics,
such as 4PL, 5PL. Such mathematical modeling and optimization algorithm will create a successful ecosystem. Practically significant results are the high efficiency of logistics activities.

References

[1] Provotorov V V, Sergeev S M and Part A A 2019 Solvability of hyperbolic systems with distributed parameters on the graph in the weak formulation Vestnik of Saint Petersburg University. Applied Mathematics. Computer Science. Control Processes 14(1) 107–17
[2] Yanenko M 2016 Cost-Based Brand Management International Business Management 10(26) 5991-5
[3] Sergeev S, Kirillova T and Krasyuk I 2019 Modelling of sustainable development of megacities under limited resources E3S Web of Conferences 91 05007
[4] Alexandrova I and Zhabko A 2018 A new LKF approach to stability analysis of linear systems with uncertain delays Automatica 91 173-8
[5] Krasnov S, Zotova E, Sergeev S and Draganov M 2019 Stochastic algorithms in multimodal 3PL segment for the digital environment IOP Conference Series: Materials Science and Engineering 618 012069
[6] Kravets O J, Barkalov S A, Butyrina N A, Sekerin V D and Gorokhova A E 2018 Processes of multidimensional classification of scoring objects with heterogeneous features based on the neural networks modeling International Journal of Pure and Applied Mathematics 119(7a) 875-9
[7] Kamachkin A M and Yevstafyeva V V 2000 Oscillations in a relay control system at an external disturbance Control Applications of Optimization 2000: Proceedings of the 11th IFAC Workshop 2 459-62
[8] Krasnov S, Sergeev S, Titov A and Zotova Y 2019 Modelling of digital communication surfaces for products and services promotion IOP Conf. Series: Materials Science and Engineering 497 012032
[9] Pilipenko O V, Provotorova E N, Sergeev S M and Rodionov O V 2019 Automation engineering of adaptive industrial warehouse J. Phys.: Conf. Ser. 1399 044045
[10] Provotorov V V 2015 Boundary control of a parabolic system with delay and distributed parameters on the graph International Conference "Stability and Control Processes" in Memory of V. I. Zubov (SCP) 126-8
[11] Aleksandrov A and Platonov A 2009 On stability and dissipativity of some classes of complex systems Automation and Remote Control 70(8) 1265-80
[12] Krasyuk I, Medvedeva Y, Baharev V and Chragaziya G 2019 Evolution of strategies of retail and technological systems under broad digitalization conditions IOP Conference Series: Materials Science and Engineering 1234 012124
[13] Provotorov V V 2008 Eigenfunctions of the Sturm-Liouville problem on a star graph Sbornik: Mathematics 199(10) 1523-45
[14] Krasyuk I A, Bakharev V V, Kozlova N A and Mirzoeva D D 2018 Staffing in the sphere of trade: the main issues and prospects of solution Proceedings of 2017 IEEE 6th Forum Strategic Partnership of Universities and Enterprises of Hi-Tech Branches (Science. Education. Innovations), SPUE 6 48-50
[15] Borisoglebskaya L N, Provotorova E N, Sergeev S M and Khudyakov A P 2019 Automated storage and retrieval system for Industry 4.0 concept IOP Conf. Ser.: Mater. Sci. Eng. 537 032036
[16] Artemov M A, Baranovskii E S, Zhabko A P and Provotorov V V 2019 On a 3D model of non-isothermal flows in a pipeline network Journal of Physics. Conference Series 1203 012094
[17] Provotorov V V, Ryazhskikh V I and Gnilitskaya Yu A 2017 Unique weak solvability of nonlinear initial boundary value problem with distributed parameters in the netlike domain Vestnik of Saint Petersburg University. Applied Mathematics. Computer Science. Control Processes 13(3) 264-77
[18] Kapustina I V, Kirillova T V, Ilyina O V, Razzhivin O A and Smelov P A 2017 Features of Economic Costs of Trading Enterprise: Theory and Practice *International Journal of Applied Business and Economic Research* **15**(11) 1-10

[19] Avdonin S and Kurasov P 2008 Inverse problems for quantum trees *Inverse Problems Imaging* **2**(1) 3973-91

[20] Borisoglebskaya L N, Provotorova E N and Sergeev S M 2019 Promotion based on digital interaction algorithm *IOP Conf. Ser.: Mater. Sci. Eng.* **537** 042032

[21] Aleksandrov A, Aleksandrova E and Zhabko A 2016 Asymptotic stability conditions of solutions for nonlinear multiconnected time-delay systems *Circuits, Systems and Signal Processing* **35**(10) 3531-54

[22] Karelin V V 2010 Penalty functions in the control problem of an observation process *Vestnik of Saint Petersburg University. Applied mathematics. Computer science. Control processes* **4** 109-14

[23] Kamachkin A M, Potapov D K and Yevstafyeva V V 2016 Existence of solutions for second-order differential equations with discontinuous right-hand side *Electronic Journal of Differential Equations* **2016** 124

[24] Zhabko A P, Nurtazina K B and Provotorov V V 2019 About one approach to solving the inverse problem for parabolic equation *Vestnik of Saint Petersburg University. Applied mathematics. Computer science. Control processes* **15**(3) 322-35

[25] Krasyuk I A, Krymov S M, Medvedeva YuYu, Chernisheva A M and Lashko S I 2017 Marketing management in retail chains *International Journal of Applied Business and Economic Research* **15**(12) 83-91

[26] Podvalny S L, Provotorov V V and Podvalny E S 2017 The controllability of parabolic systems with delay and distributed parameters on the graph *Procedia Computer Science* 12th. *International Symposium Intelligent Systems* **2017** 324-30

[27] Aleksandrov A and Zhabko A. 2003 On stability of solutions to one class of nonlinear difference systems *Siberian Mathematical Journal* **44**(6) 951-58

[28] Zabko A P, Provotorov V V and Balaban O R 2019 Stabilization of weak solutions of parabolic systems with distributed parameters on the graph *Vestnik of Saint Petersburg University. Applied mathematics. Computer science. Control processes* **15**(2) 187-98

[29] Lvovich Ya E, Tishukov B N, Preobrazhenskiy A P, Pitolin A V and Kravets O Ja 2019 Complex-Structured Objects Optimization During Modeling on the Population Algorithms Adaptation Basis *International Journal on Information Technologies and Security* **3** (11) 41-50

[30] Nedyalkov I, Stefanov A and Georgiev G 2019 Studying and Characterization of the Data Flows in an IP-Based Network *International Journal on Information Technologies and Security* **1** (11) 3-12