Cyber-physical control system for integrated material flows

L N Borisoglebskaya¹, O Ja Kravets², O V Pilipenko¹ and V V Provotorov³

¹ Orel State University, Engineering centre of digital environment technologies for integrated security: telecommunications, communications and energy efficiency, 95, Komsomolskaya st., 302026, Orel, Russian Federation
² Voronezh State Technical University, 14, Moscow ave., Voronezh, 394026, Russian Federation
³ Voronezh State University, 1, University sq., Voronezh, 394006, Russian Federation

E-mail: sergeev2@yandex.ru

Abstract. The article is devoted to the development of applications for Industrial Internet of Things and their integration with Enterprise Resource Planning and Customer Relationship Management systems. This brings to a higher level interaction both of enterprises with each other and with consumers. These processes are most clearly revealed in commercial structure network. The prerequisite for IIoT implementation was the need to determine by the code of the goods not only the destination, but also the storage conditions and the period of realization. An important feature is the necessity to take into account a very short period between the production date and the Expire Date, during which Supply Chain Management is performed, generating storage, distribution, logistics and marketing problems.

1. Introduction
Effective management of commercial network business structures [1] became possible with the development of Web 3.0 networks, development of 4G wireless networks, VPN solutions, and, first of all, cloud services XaaS. This includes not only the widespread business-oriented SaaS (Software as a service) products, for example Microsoft Dynamics NAV from the MBS software family. Without M2M (Machine-to-Machine) digital algorithms, these processes cannot be effectively managed in conditions of complex network topology [2]. The network commercial structures, which were scattered geographically, needed, first of all, the information technologies IaaS (Infrastructure as a Service) and PaaS (Platform as a Service) and cloud computing models, for access of numerous divisions of companies to a single information and technological platform. The combination in the cloud operating system server, DBMS, connecting software, development and testing tools, served as the driver for the development of the largest network companies [3].

One of the major problems in the process of transition to digital inter-machine interaction in the scale of a commercial network was the optimization of all business components in a cross-functional mode. The sharp competition in this segment of entrepreneurship calls for the complex interaction of all top-level departments: procurement, production, marketing, transport, and logistics. Attempts to solve the optimization problem separately for each violate the overall balance and reduce the overall efficiency of the business.

The driver of development here is the penetration of digital technologies, the provision of artificial intelligence systems with sensory systems, the development of alternative wired and wireless...
channels, high-speed access to the global network, and the development of multiplatform business solutions available for replication.

In this regard, it is necessary to solve the problems, which are associated with the expansion of business in the transnational field of activity, and to ensure the development of computer digital infrastructure, high levels of 3PL (Third Party Logistics). At the same time, the core of server management systems is scientifically argued algorithms based on mathematical models and modern calculation methods. The world’s largest networks are now transnational corporations, and for real-time business data flows, the boundaries are transparent, while material ones, for example, transportation of goods or raw materials, are forced to face differences in legislation and other spheres. This inevitably leads to customs procedures and a number of restrictions when moving across state borders. We also have the distribution of processes in space.

2. Statement of the task of managing integrated flows

For the purposes of modeling the processes that occur in a commercial network, let us single out the concept of a physical network. It includes the nodes [4]. We introduce for them the concept of an interface that makes up the contact surface for mutual commercial activity. Each SKU (stock keeping unit) is provided with machine-readable barcode, QR (Quick Response Code) or RFID (Radio Frequency Identification) recognition markers. The use of EAN/UCC and ITF standards makes it possible to carry out the whole complex of operations on the physical interaction of network nodes regardless of their location.

The formation of optimal algorithms for the commercial network [5] is possible only if an adequate mathematical model [6] is constructed. The main priority is the task of clearly articulating the input and output characteristics when servicing integrated network flows. Such a set of data should be formalized by a vector of arguments, which are used in the mathematical modeling of each physical object to describe the inter-machine interaction. It is also necessary to determine a package of digital data for information exchange, and what kinds of sensors are involved in forming computer interconnection algorithms. In addition, the software needs to take into account the length of time in all processes.

3. Formalisation of the task by using digital technologies

Let’s consider an example of interaction of contact surfaces of commercial [7] services. You have to effectively use not only modern digital encodings, but also algorithms [8] of the external side of logistics 3PL [9]. First of all, we introduce the concept of a physical serving unit. For abstracting from specific content, let’s call it the interface item. For each item, we introduce a characteristic $\mu$ – the rate of service. Respectively, each business option has its own kind of service demands. Let’s introduce an indicator $\lambda$ – the flow demand rate. Since in a competitive environment the business tries to work with the maximum load, it is necessary to make a model [10] that takes into account the possibility of using all available resources for the work. This corresponds to the most rational rate of the company’s capacity utilization.

4. Mathematical substantiation of the solution method

To solve this problem, we apply a complicated algorithm of multiserver systems of QS-queueing system. In practice it is used as a bulk-service system, sharing [11]. At the same time, the rate of service increases in $s$ times: $\mu' = s\mu$, where $s$ is the number of points. One can write the equations of state of the system [12]:

$$
\begin{align*}
P_0 &= -\lambda P_0 + s\mu P \\
0 &= -(\lambda + s\mu)P_0 + \lambda P_{k+1} + s\mu P_{k+1}, \quad k = 1, 2, ..., s - 1 \\
0 &= -s\mu P_1 + \lambda P_{s+1}
\end{align*}
$$
From these equations we get:

\[ P_k = \left( \frac{\lambda}{s\mu} \right)^k P_0 \quad \text{for} \quad k = 0, 1, \ldots, s, \]

and since \( \sum_{k=0}^{s} P_k = P_0 \frac{1 - \psi^{s+1}}{1 - \psi} = 1 \), then we get the probability of servicing \( P_{\text{service}} \) and the average number of demands \( s \) in the system:

\[ P_{\text{service}} = 1 - P_0 \frac{1 - \psi'}{1 - \psi^{s+1}}, \quad \bar{s} = \sum_{k=0}^{s} kP_k = \frac{1 - \psi}{1 - \psi^{s+1}} \sum_{k=0}^{s} k\psi^k = \psi \frac{1 - \psi' [s(1 - \psi) + 1]}{(1 - \psi^{s+1})(1 - \psi)}. \]

These formulae allow determining the parameters of the system.

5. Intelligent Program of the Server of Inter-Machine Interaction

The most difficult problem was to develop a mathematical model and form algorithms [13] as the basis of software. Here we need a methodology to form standards of interaction in the structural divisions of the commercial network [14], not only in the form of basic algorithms, but also among the practicing specialists of the system scientific approach, which is based on the application of the mathematical apparatus [15]. These kinds of control objects include passing demands sequentially through several interface items.

For algorithmization, let us first consider the problem in general. There is a network that includes the number of interface items \( M \) and one source of demands. In this case, demands coming out of the \( i \)-th system (\( i = 1, 2, \ldots, M \)) with probability \( \theta_j \) enter the system, or leave the network (\( j = 0 \)). From the source directly to the \( j \)-th system, demands are received with probability \( \theta_{0j} \). The matrix of transmissions, that is probabilities of receipt of demands from one system to another has the form:

\[ \theta = \begin{pmatrix} \theta_{ij} \end{pmatrix}, \quad 0 \leq \theta_{ij} \leq 1 \quad \text{for} \quad i, j = 1, 2, \ldots, M, \]

Also, a graph of transmissions is formulated. The vertices of this graph correspond to the points of the interface, the arcs indicate the possibility of a demand transition from one Queuing System to another, and the numbers on the arcs indicate the probability of this transition. First of all, it is necessary to determine the demand rate of flows in each system in the steady state. Then it is true:

\[ \lambda_j = \sum_{i=0}^{M} \lambda_i \theta_{ij} \quad j = 1, 2, \ldots, M \]

where \( \lambda_i \) is rate of source of demands. In the matrix form (1) has the form: \( \bar{\Lambda} = \{ \lambda_1, \lambda_2, \ldots, \lambda_M \} \), then \( \bar{\Lambda} = \bar{\Lambda} \bar{T} \). The rate of flows in the system depends on the source \( \lambda_0 \). The rank of the system of equations (1) is equal to \( M \) and from it one can determine:

\[ \lambda_i = \alpha_i \lambda_0 \quad i = 1, 2, \ldots, M \]

In a closed network, a finite number of demands and a transmission matrix \( T_i = \| \theta_{ij} \| \) will satisfy

\[ \lambda_j = \sum_{i=0}^{M} \lambda_i \theta_{ij} \quad \text{in case} \quad j = 1, 2, \ldots, M \].

The rate of flows in a closed network is determined by the total number of requirements. If we choose any, for example, \( i_u \) for the base one, we can determine:

\[ \lambda_i = \alpha_i^{(u)} \lambda_0 \quad i = 1, 2, \ldots, M \]
Thus, the invariance of the algorithm is achieved. In the steady state of an open network, the probability of finding a demand is determined as \( P = PT \). Hence we get: \( \frac{p_j}{p_o} = \frac{\lambda_j}{\lambda_n} = \alpha_j \). The relative frequency of passing through the interface point \( j \) for \( T \) is equal to \( \hat{p}_j = \frac{n_j}{N} \), where \( n_j \) is the number of demands in the system \( j \), \( N \) is the total number of demands in the network.

For a sufficiently large time interval \( n_j / n_o \rightarrow \alpha_j \). Thus, the requirements \( \alpha_j \) once pass through the system \( j \) before returning to the source. Therefore \( \overline{u} = \sum_{j=1}^{M} \alpha_j \overline{u}_j \), where \( \overline{u}_j \) is the average time spent in the system with the number \( j \).

The complexity of calculating networks is that the simplest flow of demands, which enter the elements in the network. Then, if the components circulate in the network. In this case, only those components \( M \), \( M \) support the level of emergent stocks, they predict purchases. Inter-...

6. Conclusion
The digital technology for the purposes of system management, forecasting, and the transition to advanced economic indicators is the main direction of increasing business efficiency. To solve such a large-scale task, there is already a developed technical base. It is based on digital technologies for the identification of any goods, materials, auxiliary activities. Equipping computers with numerous sensory devices allows receiving complete information not only about objects, their dimensions, weight, but also about storage conditions, travel routes, expire date. Also, without human participation, computer programs support the level of emergent stocks, they predict purchases. Inter-...
machine synchronization of network nodes today fully provides the level of third-party logistics 3PL. The organizational and technical platform allows integrating the information and physical space of the network business.

Software products continue to be improved, and, in addition to the XaaS solutions mentioned in the work and directly involved in flow management, the capabilities of hybrid cloud services, IDaaS, UCaaS (Unified communications as a service) systems, and cloud bursting technologies that take into account seasonal load variables are being used more extensively. This approach allows using multiplatform applications on mobile devices of both automatic systems and enterprise managers.

The mathematical model presented in this paper and analytical expressions allow transmitting the work to the level of inter-machine interaction with the use of computer coding. First of all, the benefits of the result are disclosed in the innovative field of third-party logistics with cross-docking or pick-by-line technologies.

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