Integrated Architectural Approach
to Ensuring Stability of Processes of the Digital Supply Chain

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Abstract. The revolutionary changes in the creation of platform-type models and strategies within the framework of Industry 4.0 have created new potential for the development of the economy and transport. The central place in the management of the digital supply chain (DSC) belongs to the models, structure and architecture of the system based on self-governing links - competence centers (CCs). The selected model for managing the system’s life cycle allows for more effective management of the central processing center at all stages through the integration of business processes and digital technologies, which allows for an integrated approach, simplifying the system itself and increasing its performance.

The term «organizational and technical sustainability» (OTS) is introduced in the article, which implies a balanced location of the DSC between control points at the stage of the life cycle. The proposed approach is focused on the use of the mechanism of «homeokinetic plateau». The homeokinetic plateau is the basic cybernetic mechanism for ensuring the state of dynamic stability of the system. As critical points characterizing the state of stability, a combination of the probability of the implementation of processes and their profitability with the identification of risk options for the life cycle stage is considered.

The mechanism of the homeokinetic plateau and tools considered in the article forms the structure of a comprehensive architectural approach, focused on innovative approaches to ensure stability and control of the continuity of the central processing center processes.

Keywords: Integrated architectural approach · Life cycle management · Digital supply chains

1 Introduction

A systematic and technological analysis of the problems of managing digital supply chains in the context of the global economic crisis and pandemic indicates serious problems in ensuring the sustainability of processes. The actualization of digital transformation, mechanisms and digital technologies (artificial intelligence, blockchain,
big data analysis and the Internet of things), revolutionary changes in the creation of platform-type models and development strategies within the framework of Industry 4.0, undoubtedly formed a new potential for the development of various sectors of the economy, including transport. Research in this area is quite intensive, but attention is focused mainly on the use of individual digital technologies in creating services for products and services with high added value [1, 2].

In the context of the application of digital technologies in Industry 4.0, a revision of the approaches to supply chain management (SCM) is necessary, the success of which depends on the transformation of all physical assets and their integration into the digital ecosystem together with partners involved in the value chain [3] and their hybrid control [4].

The central place in the design and management of the digital supply chain (DSC) will belong primarily to the models, structure and architecture of the high-speed system, and an important result of integration and interaction is the creation of a single organization with self-governing units - competence centers (CCs). The efficiency and stability of such an operating model will be associated with a combination of the hierarchy of the system and the network organization based on such CCs with a closed life cycle. The requirements for the stability of the processes of the applied life cycle model become the basic criteria in conditions of high environmental dynamics [5, 6].

For example, the provisions of the UN Global Compact, with regard to a sustainable supply chain, require integrated management of consequences and the promotion of best practices throughout the life cycle [7, 8].

The present stage of development of mankind is characterized by rather complex and contradictory processes of transition from the industrial to the information society and the digital economy. Modern digital technologies rely on new organizational forms of integration of transport systems and infrastructure on the principles of network interaction and autonomy, stability and integrity of physical and virtual objects.

The purpose of the article is to present the results of studies on the formation of an integrated model of digital transformation in the field of transport, covering the enterprise architecture, assets, products and business processes, combining the business and IT technologies into a single integrated system.

2 Methods of Problem Analysis and Materials for Research

As a scientific hypothesis, the authors consider the transformation of the DSCs based on the cybernetic model of self-regulation and stability. For the initial analysis of the problem, a crisis trend was taken to reduce the efficiency or breakdown of traditional supply chains and transportation processes using both different models and various digital technologies. For example, in the railway transportation sector, it was assumed that until 2030, container transportation would grow at an accelerating pace that outstrips market growth at a rate of about 6–8% annually. However, the crisis in the global economy, combining the global economic downturn with the rapid deglobalization caused by the COVID-19 pandemic and falling oil prices, shows a different picture. There was a significant drop in cargo turnover (−13.5% for January-February 2020). The global container shipping market in the I quarter of 2020 decreased by 4.7%; rail
freight decreased by more than 3%. This decrease was primarily due to lower imports
due to quarantine measures in China and some European countries, as well as reduced
consumer demand. And these trends will continue throughout this year, especially in
the II quarter. The total fall in GDP in 2020 may range from 3.8% to 10.2% [9].

Under these conditions, world GDP may increase by 4.2% in 2021, and growth in
advanced economies will be 3.9%. However, this forecast is accompanied by “extreme
uncertainty” taking into account the presence of various risks, including the risk of a
pandemic, the development of financial problems, and the general deterioration of the
situation in world trade [10]. Figure 1 shows the scenario of a delayed recovery in real
GDP. After the resumption of production, the possibilities of trunk transport, in par-
ticular railways, can be more actively used, which can provide, with lower risks than,
for example, other modes of transport, greater stability in the delivery of goods.

The current crisis situation is prompting businesses to redefine existing linear
supply chains with a focus on more adaptive and flexible networks (such as DSCs),
allowing production facilities to respond more quickly to changes in market demand,
which, in turn, is a significant competitive advantage [11, 12].

Responding to constantly changing conditions, classic supply chains using the
SCOR model began to actively transform into digital supply chains (DSCs), which
gives the organization the opportunity to use the full potential of the chain to ensure
end-to-end transparency of its operations, facilitate collaboration, increase
flexibility and optimize processes [3, 13].

Classical approaches in logistics, aimed primarily at planning and providing ser-
vices, do not have time to adapt to changes and begin to slow down development.
Therefore, it is important not only to create highly automated services, design a
logistics network and implement electronic digital workflow, but also to have a self-
regulatory mechanism based on data analysis and predictive risk management. Logistic
engineering, which acts as an integrator between business processes and digital technologies, allows you to combine the competencies of human experience and strategic thinking with big data analysis tools and artificial intelligence [14]. The logistics engineering function, based on the methodology of system and software engineering and enterprise architecture, with a constantly decreasing period of need for process reconfiguration, will allow you to link all parties involved in the logistics process and make the transition to “supergrid logistics”. Due to the structural and functional complexity of the facilities, the impossibility of effective modeling the forecasting of the state of the digital supply chain, the existing theory of systems and supply chain management has ceased to satisfy the needs of science and practice (business).

3 Theory and Practical Application

Due to the constant increase in the complexity of systems created by the humanity, a whole series of problems arise at various stages of the life cycle of the DSC and various levels of architectural detail. Among the problems distinguished are such as the heterogeneity of elements and processes, lack of integration and the need for an integrated approach to the application of business architecture and information and communication technologies. This requires a system-wide approach that ensures, on the one hand, the effective interaction of processes throughout the life cycle, on the other hand, the stable operation of all facilities and the supply chain as a whole.

Existing standards in the field of systems and software engineering contain initial tools for combining various process groups related to life cycle practices, determine the possibility of simplification for working with a complex system and describe its life cycle [15].

What is especially important in the framework of the study of the problem is that all stages correspond to control points for advancement and effectiveness (or loss) during the life cycle. To specify each element of the stage, practices (processes), resources, architectural descriptions, tools, manuals are included. In particular, the description of enterprise architecture (business architecture) exists in the form of reference models of organizational and technical systems and its components [16].

The development of systems theory, the concept of Industry 4.0., Systems engineering is aimed at improving the adequacy of various reference models. Various methodologies are used to model enterprise architectures (systems/networks), such as AVERM (Agile Virtual Enterprise Reference Model), VERAM (Virtual Enterprise Reference Architecture and Methodology), SCOR (Supply-Chain Operation Reference Model), ARCON (A Reference Model for Collaborative Networks), and several others. These reference models allow more efficient management of the enterprise and the DSC throughout the entire life cycle due to standardization of the organization, through the use of various methods and technologies, which allows for an integrated approach, simplification of the system itself and increasing its productivity.

The application of the architectural approach creates the conditions for sustainability and integration of the supply chain, which helps to reduce risks, and is an effective lever for introducing sustainable development policies on a global scale.
Taking into account that the main purpose of the digital supply chain is the high-speed joint and continuous use of various production, transport (physical) and information-digital assets, there is a need to include the principles of adaptation and self-organization in the management. An analysis of the work of the well-known XX century cybernetics S. Beer and existing studies have shown that limited self-organization and controlled instability of the system lies in the way of ensuring the dynamic interaction of various states of both the external environment and the autonomy of individual links forming the circuit of self-organization of the control system.

The widely used formula of the classical logistic concept “the necessary goods - the right quality - at the right place - at the right time - at the lowest cost” turned out to be oriented mainly at the level of an individual enterprise and its functional areas. This approach turns out to be ineffective in the 21st century for manufacturers of products with high added value, for which the most important factors are not only the accelerated production and delivery (transportation) of new products, but also the sustainability of facilities throughout the entire digital supply chain in the face of incomplete information and an increasing rate of failed situations. Such solutions are more successfully implemented based on logistic engineering methods. According to the authors, logistics engineering is an activity based on system principles to ensure the functioning of artificially created objects and systems of industrial, transport, trade and information systems, covering all stages of the life cycle of logistics systems. The engineering cycle corresponds to the stages (structure) of the life cycle “planning - operation/logistic support - decommissioning” taking into account industry specifics.

In this article, the authors introduce the term «organizational and technical stability» (OTS), which implies the possibility of adaptation of the DSC relative to control points at a certain stage of the life cycle. The creation of such a mechanism for the stability of the DSC allows you to link the problems of the effective functioning of the processes within the framework of the functional and logistical cycle with the instrumental environment of logistic engineering (system engineering) based on the mechanism of the homeokinetic plateau.

To denote the state of dynamic equilibrium of a system in biology, the term “homeostasis” is used - it is a “set of interrelated rules of behavior of an organic system to maintain it in a stable state”, a derived term and system is a digital ecosystem. The process of introducing energy (control) into the system and the process of information processing have as their goal to stop the tendency of the system to transition to a state with higher entropy. These processes can be considered as attempts by the system to reach a state of equilibrium and maintain it, that is, to remain within the “homeokinetic plateau” [17, 18].

The homeokinetic plateau is the basic cybernetic mechanism for ensuring the state of dynamic equilibrium (stability) of a system. The plateau can be considered as a region of a relatively unstable state of the system (similar to homeostasis), in which the organic system tends to self-regulation (Fig. 2).
The ability of the system to remain in the area of stability is called the “survivability” of the system. Adaptive systems are those that “change their behavior in such a way as to remain in the field of stability even in the presence of external influences”. Thus, one of the most difficult problems is the establishment of critical points (boundaries) of stability in relation to various stages of the life cycle of the DSC.

Orientation of the digital supply chain model to the methods of logistic engineering and competence centers, as autonomous links of self-regulation, involves the creation of a mechanism focused on the requirements of safety and stability. Safety is one of the most important indicators of the quality and complexity of the functioning of transport and logistics systems [20].

Before the crisis in industry and transport, most systems remained at the level of “absolute risk” - the principle of “zero risk”. With this approach, the management system has no idea of the balance between profit and loss. With respect to logistics and supply chain management, the acceptable risk principle - the ALARA principle - “is as low as reasonably achievable” is developing. The fundamental goal of the criterion of “acceptable” risk is to increase the stability and efficiency of DSCs and transport and logistics processes based on the use of logistic engineering methods [21].

In relation to the organizational, technical and IT-areas of the supply chain, a number of dangers can be identified:

- insufficient structuring of processes, which reduces the effectiveness of their application in terms of predictability of development and management;
- reduction of the time required for decision-making and counteracting economic and technological hazards with the development of high-speed electronic communications and vehicles;
- technological advances have unpredictable consequences.

![Fig. 2. Homeokinetic plateau [19].](image)
Safety criterion is a comprehensive indicator, the extreme value of which characterizes the best (balanced) interaction of the elements of the digital supply chain with the used assets and processes at various stages of the life cycle. In the process of operation, critical parameters reflecting the state and dynamics of the structure of key competencies can subsequently change stepwise. To create a stable system from the point of view of the security criterion, it is necessary to determine the structure of the support system and critical points within the stages of the life cycle.

4 Results

Let us consider as critical points characterizing the state of stability, as a combination of risk (probability) of the implementation of the digital supply chain processes and total profitability (creating value for consumers). The combination of these factors will determine the range of the balanced state of the system. At risk of the DCSs and processes, a set of criteria will be considered, such as the effectiveness of order fulfillment in terms of meeting delivery deadlines, the quality of services provided, the range of supplies and costs within the 4D model [22].

The logic of risk analysis at the LC stage involves evaluating the reliability of the supplier-consumer chain of supply chains that form the CC. Reliability is understood as the ability of objects, processes to maintain the required properties and perform the intended functions for a certain period.

Reliability indicators of logistic processes are data of probabilistic values in the interval $0 \leq P \leq 1$. Moreover, “0” is an indicator of complete cessation of operation (failure), and “1” is an indicator of complete interaction. Reliability of supply chain processes is understood as the probability that agreed results will be achieved within a certain period of time and within specified tolerances.

The task of calculating reliability indicators is solved using existing methods of probabilities and risks. In general, the reliability of delivery to the DSC is calculated as the difference:

$$P = 1 - P_{pfi}$$  \hspace{1cm} (1)

where $P$ is the reliability of the supply chain; $P_{pfi}$ – probability of failure to satisfy the application for supply or probability of failure by the $i$-th supplier.

When interacting with many CC, the formula (1) takes the following form:

$$P = 1 - \prod_{i=1}^{n} (1 - P_i),$$  \hspace{1cm} (2)

where $P_i$ is the reliability of the $i$th CC.

Given the operator’s profitability, probabilities and time of receiving the result (planned value) for all elements of the CC, the most effective ratio (structure) of the distribution of resources (assets) is determined to obtain the total added value. For example, a set of combinations for various CC elements. For elements of a CC we can get various options for added value.
In Fig. 3 there are two options for the structure of cost changes for the three CC processes (A, B, C), which provide for different states of the stability center of DSC, depending on the time of the change of critical parameters – profitability/risk of the functioning of the processes.

5 Significance of the Research Results

The models and tools considered in the article form the structure of a comprehensive architectural approach, focused on fundamentally new approaches for the sustainability of the DSC processes. In their properties and characteristics, they will approach the best practices of system and software engineering. As part of ensuring the integration of processes at various stages of the life cycle, joint management and interaction of participants in network logistics systems based on models of Internet technologies and information and communication technologies is carried out. Such interaction is focused on the functioning of the CC of a DSC based on the use of a single (compatible) organizational, technological and digital environment mainly within the framework of operating systems, i.e. at the operational level.

The system of complex architectural management proposed in the study based on the stability of processes, unlike traditionally used in practice reactive control systems that are focused on prompt response and subsequent prevention of incidents, involves preventing their occurrence through planning, implementation, verification and actions, the implementation of practical transformation (changes) the state of the object of the entire DSC. This approach is the development of the concept of proactive management of complex organizational and technical systems, to which the DSCs and their network versions belong.
6 Conclusions

Thus, a comprehensive-architectural approach to the DSC provides a digital transformation of the system as a whole based on the modeling and risk management of self-organizing CCs, ensuring the sustainability of processes and results. Thanks to the principles of integration and adaptation of autonomous modules (CC), opportunities are created to overcome the complexity of systems in the face of uncertainty and functioning in failed situations. The central place in the design and management of the DSC should belong to the models, structure and architecture of the system, and an important result of integration is the creation of a single organization with self-organizing autonomous links - competence centers.

The integrated architectural approach, in turn, provides a coordinated and fast interaction of processes and CCs in the digital supply chain based on the formation of a single trusting information environment through the integration of the life cycle stages of systems with a single architecture of business processes and IT. Modern enterprises and their supply chains, faced with rapid changes in the environment, are not able to use further traditional approaches and tools of forecasting and planning. A decisive transition is necessary to acceptable risk management methods linked to critical points both for an individual stage of the life cycle and for the DSC as a whole.

Proactive management, taking into account the comprehensive architectural approach to managing the DSC, provides a compromise between business goals and digital technologies, and creates the basis for the development and implementation of a strategy for their stable and productive functioning.

The transition of enterprises to a standardized life cycle system is a real way of economic excellence and digital development in modern conditions. The principles and standardization tools ensure consistency, convergence of various modeling methodologies and integration of various types of technological and business processes, ensuring high compatibility and integrity of the system.

The new technological structure of Industry 4.0, the model and mechanisms of the homeokinetic plateau are more close to modeling the stability processes of the centralized center in the conditions of the COVIT-19 pandemic and contribute to the increase of the “survivability” of the entire system. The scientific justification and principles for determining critical points (boundaries) of process stability according to the criterion of acceptable risk, creates the conditions for a predictive forecast of system behavior based on big data.

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