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DIGITAL TRANSFORMATION OF SUPPLY CHAINS INVOLVING WATER TRANSPORT

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ЦИФРОВА ТРАНСФОРМАЦІЯ ЛАНЦЮГІВ ПОСТАЧАННЯ ЗА УЧАСТЮ ВОДНОГО ТРАНСПОРТУ

At present, both global and domestic integrated systems of production and logistics relations among suppliers, manufacturers, carriers, and consumers are facing numerous challenges that are shaping processes in a state of uncontrolled chaos. Accordingly, the purpose of the article is to analyze the processes of uncontrolled chaos in supply chains involving water transport and to assess the role of digital technologies in controlling and mitigating them. The study finds that processes of uncontrolled chaos in supply chains involving water transport are systemic and arise from the simultaneous influence of internal and external factors that disrupt the predictability and coordination of logistics processes. These processes manifest as unpredictable delivery delays, periodic overloading or underutilization of port infrastructure, disruptions in interactions among supply chain participants, and the blocking or destruction of transport routes. It has been proven that under conditions of uncontrolled chaos, traditional approaches to managing waterborne supply chains are ineffective, as they do not ensure prompt responses to rapid, nonlinear changes in the external environment. These phenomena were particularly evident in domestic supply chains, which, after the onset of the full-scale military invasion of Ukraine by the Russian Federation, experienced numerous problems that disrupted-and continue to disrupt-the predictability and coordination of logistics processes, namely the blockade of the Black Sea and Azov Sea ports, the accumulation of vessels in queues at Danube ports, and the disruption of traditional shipping routes. At the same time, the study's results demonstrate that the digital transformation of supply chains is an effective tool for mitigating the manifestations of uncontrolled chaos. In particular, implementing real-time cargo monitoring systems, port resource planning systems, integrated shipping route management platforms, and big data analytics enhances transparency in logistics processes, improves coordination among participants, enables timely forecasting of delays, and optimizes the use of port and transport resources.

Наразі як глобальні, так і внутрішні ланцюги постачання, які становлять інтегровану систему виробничо-логістичних зв'язків між постачальниками, виробниками, перевізниками та споживачами, стикаються з численними викликами, що спричиняють процеси неконтрольованого хаосу. Відтак, метою статті є аналіз процесів неконтрольованого хаосу у ланцюгах постачання за участю водного транспорту та оцінка ролі цифрових технологій як засобу їх контролю та мінімізації. У межах дослідження встановлено, що процеси неконтрольованого хаосу у ланцюгах постачання за участю водного транспорту мають системний характер і виникають внаслідок одночасної дії внутрішніх та зовнішніх факторів, що порушують прогнозованість і координацію логістичних процесів. Такі процеси проявляються у вигляді непередбачуваних затримок доставляння, періодичного перевантаження або недовантаження портової інфраструктури, збоїв у взаємодії між учасниками ланцюга постачання, а також блокування або руйнування транспортних маршрутів. Доведено, що в умовах неконтрольованого хаосу традиційні підходи до управління водними ланцюгами постачання є малоефективними, оскільки не забезпечують оперативного реагування на швидкі та нелінійні зміни зовнішнього середовища. Особливо помітні ці явища у вітчизняних ланцюгах постачання, які після початку повномасштабного вторгнення рф в Україну зіткнулися з численними проблемами, що порушили прогнозованість і координацію логістичних процесів — зокрема блокуванням портів Чорного та Азовського морів, накопиченням суден у чергах у дунайських портах та порушенням традиційних маршрутів судноплавства. Дослідження довело, що цифрова трансформація ланцюгів постачання є ефективним інструментом пом'якшення проявів неконтрольованого хаосу. Зокрема, впровадження систем моніторингу вантажів у реальному часі, систем планування ресурсів портів, інтегрованих платформ управління судноплавними маршрутами та аналітики великих даних дозволяє підвищити прозорість логістичних процесів, покращити координацію між учасниками, своєчасно спрогнозувати затримки та оптимізувати використання портових і транспортних ресурсів.

Key words: production and logistics relations; digital transformation; chaos; port resource planning; water transport; digital transformation.

Ключові слова: виробничо-логістичні зв'язки; цифрова трансформація; хаос; планування ресурсів портів; водний транспорт; цифрова трансформація.

PROBLEM STATEMENT

At present, both global and domestic supply chains, which constitute an integrated system of production and logistics relations among suppliers, manufacturers, carriers, and consumers, face numerous challenges, including fluctuations in demand and supply, security concerns, technological and infrastructure constraints, and the ongoing consequences of military conflicts. These factors have generated processes of uncontrolled chaos, manifested as unpredictable delays, periodic overloading or underutilization, disruption of transport routes, and breakdowns in the coordination of logistics participants' actions. Notably, these processes have been particularly pronounced in supply chains involving water transport, where systemic disruptions are caused by the blockage of sea routes and restricted access to port infrastructure, repeatedly creating situations in which normal coordination and predictability of logistics operations were impossible. At the same time, in this context, digitalization has emerged as a key tool enabling rapid restoration of functionality, transparency, and operational efficiency in the supply chain, and allowing the optimization of cargo movement via water transport. For instance, the implementation of real-time cargo tracking systems based on GPS and IoT allows port operators and carriers to respond promptly to situational changes, such as vessel delays due to weather conditions, sea route blockages, or port infrastructure overloads: vessels can be redirected, cargo allocation adjusted, and port congestion avoided, significantly reducing the risks of unpredictable delays and underutilization.

Dimension: Unpredictable cargo delays
Description: Cargo does not arrive at the scheduled time due to force majeure events, weather conditions, route blockages, or technical issues on vessels and in ports.
Manifestations in supply chains: Delivery delays to end customers, container accumulation at ports, disruption of shipping schedules, and increased logistics costs.

Dimension: Periodic overloading or underutilization of infrastructure
Description: Ports operate inefficiently, resulting in peaks and troughs in throughput capacity, when too many vessels arrive simultaneously or, conversely, berths and cranes remain idle.
Manifestations in supply chains: Accumulation of vessels in queues, delays in unloading and cargo handling, uneven utilization of port resources, and increased logistics costs.

General Dimensions of Uncontrolled Chaos

Dimension: Coordination failures among participants
Description: Supply chain participants fail to synchronize their actions due to outdated or incomplete information, technological constraints, and the lack of shared digital platforms.
Manifestations in supply chains: Untimely loading or unloading of cargo, conflicts between vessel schedules and port resources, increased idle time, and chaotic disruptions in deliveries.

Dimension: Destruction or blockage of transport routes
Description: Disruptions in routes caused by military conflicts, accidents, sanctions, or natural disasters, which prevent vessels from following traditional schedules.
Manifestations in supply chains: Delivery delays, overloading of alternative routes or ports, increased vessel idle time, shortage of available transport routes, and chaotic disruptions in logistics processes.

Figure 1. Dimensions of uncontrolled chaos in supply chains involving water transport

Source: developed based on [6; 8].

Thus, the use of digital technologies-such as transport management systems, the Internet of Things (IoT), blockchain, and big data analytics-not only automates key processes but also enables effective information management, thereby significantly reducing chaotic phenomena and enhancing the economic efficiency of transportation.

ANALYSIS OF RESEARCH AND PUBLICATIONS

The challenges of supply chain transformation have been investigated by scholars such as T.V. Nakonechna [4], O.M. Holovchenko, L.V. Mezina [2], A.V. Tserkovna, A.M. Rakhimi [7], A.V. Horban, and H.Yu. Kucheryuk [1]. In particular, they analyzed the features of ensuring logistics resilience in both traditional water transport and multimodal transport schemes. These researchers emphasized the importance of adapting traditional supply chain management methods to modern conditions, which include dynamic markets, demand fluctuations, globalization, and the integration of digital technologies into logistics.

Moreover, the studies by Yaxin Pang, Shenle Pan, and Eric Ballot highlight challenges related to improving the efficiency of water route planning, inventory optimization, and risk management in processes that, in contemporary theory, are interpreted as phenomena of "uncontrolled chaos."

At the same time, comprehensive research on the processes of uncontrolled chaos in supply chains involving water transport, as well as an assessment of the role of digital technologies in controlling and mitigating these processes, remains insufficiently addressed in the scientific literature. This creates both a theoretical and a practical gap that requires further investigation into integrating digital solutions into logistics processes and enhancing supply chain resilience.

FORMULATION OF THE ARTICLE'S OBJECTIVES

Accordingly, the aim of this article is to analyze the processes of uncontrolled chaos in supply chains involving water transport and to assess the role of digital technologies in controlling and mitigating them.

THE PAPER'S MAIN BODY

Within the study, the authors draw on principles of chaos theory to identify uncontrolled chaos in supply chains involving water transport as a systemic disruption, in which normal coordination and predictability of logistics processes are lost due to the simultaneous influence of internal and external factors [1; 6]. Practically, this manifests as:

1. Unpredictable delays — when cargo does not arrive as scheduled due to force majeure events, weather, security conditions, technical issues, or route blockages.
2. Periodic overloading or underutilization — when ports operate inefficiently, creating peaks and troughs in throughput capacity.
3. Coordination failures — when supply chain participants (suppliers, carriers, ports, distributors) fail to synchronize their actions due to outdated information or technological constraints.

Table 1. Impact of digital transformation on uncontrolled chaos in water transport supply chains

Digital process / technology	Mechanism of digital transformation impact on uncontrolled chaos	Uncontrolled chaos manifestations mitigated
Real-time cargo monitoring systems	Enables tracking of cargo and vessel movements online, allowing rapid response to schedule deviations	Delivery delays, overloading/queues, loss of coordination among participants
Integrated shipping route management platforms	Optimize vessel routes considering blockades, weather conditions, and port capacity	Route disruptions, port delays, cargo accumulation
Big Data Analytics	Forecasts peak loads, problem areas, and potential disruptions	Unpredictable delays, uneven port and vessel utilization
Port resource management systems	Optimize allocation of berths, cranes, and unloading equipment	Port queues, overloading/underutilization, unloading delays

Source: developed based on [1—3; 8].

4. Destruction or blockage of transport routes — caused by conflicts, accidents, sanctions, or natural disasters.

Overall, uncontrolled chaos is a situation in which a supply chain involving water transport ceases to operate according to predictable rules, and traditional management methods-such as planning based on historical data, annual or quarterly delivery schedules, static vessel routes, and standard coordination procedures among suppliers, carriers, and port authorities [5—6]-are unable to quickly restore balance and ensure the effective functioning of the chain (Fig. 1).

For example, if a key port is blocked due to a military conflict or natural disaster, vessels can no longer operate as planned, containers accumulate, queues form for cargo handling, and suppliers and customers lose synchronization, leading to delays throughout the entire chain and increased costs.

It should be noted that in domestic water-transported supply chains, such processes were relatively rare. For example, port blockages or significant vessel delays due to weather conditions or port maintenance occurred sporadically and did not cause systemic chaos in logistics operations [7]. However, following the military invasion of Ukraine, the frequency and scale of such phenomena have increased significantly. Examples include [1—3; 7]:

— Port blockages in the Black Sea and the Sea of Azov. Many Ukrainian ports (Mariupol, Berdyansk, Odesa, Mykolaiv) have been or remain partially blocked due to military actions, halting the export of grain, metals, and other cargo.

— Accumulation of cargo in queues. Specifically, river and partially operational sea ports face long vessel queues, resulting in unloading delays and container shortages. For instance, in the middle months of 2023, several dozen vessels were waiting to dock or unload at Danube ports near Ukraine (in Sulina and at the Bystre estuary), with waiting times at some ports ranging from 5 to 15 days.

— Disruption of shipping routes. The military conflict forces some vessels to change or bypass traditional routes due to the risks of blockade, minefields, and restricted port access. For example, vessels that traditionally sailed to Ukrainian Black Sea ports are now forced to reroute to Danube ports or use detours via Romania and Bulgaria.

At the same time, the practices of major international logistics operators and water carriers, such as Maersk, MSC, and CMA CGM, as well as the experience of Ukrainian port operators and logistics companies, have shown that the digital transformation of supply chains can partially mitigate, or even eliminate, the manifestations of uncontrolled chaos [8]. The use of real-time cargo monitoring systems, port resource management systems, integrated shipping route management platforms, and big data analytics enables timely forecasting of delays, optimization of unloading operations and vessel routes, improved coordination among supply chain participants, and a reduction of the negative impact of external factors, such as port blockages or vessel queues.

The specific impact of digital transformation on the processes of uncontrolled chaos within supply chains involving water transport is summarized in Table 1.

So, real-time cargo monitoring systems (Real-Time Tracking), such as Maersk's Remote Container Management (RCM), IBM Sterling Supply Chain, INTTRA Tracking, and MarineTraffic, allow continuous tracking of cargo and vessel movements, prompt detection of deviations from planned schedules, and timely management decisions to minimize delays and chaotic disruptions in the supply chain. For example, Maersk RCM enables online tracking of cargo locations, allowing it to be rerouted and schedules adjusted in the event of vessel delays.

Due to these advantages, these digital tools help mitigate the manifestations of uncontrolled chaos in water transport supply chains in the following ways:

— Delivery delays: Rapid response to schedule deviations allows for quick rerouting or redirection of cargo, reducing idle time.

— Overloading and queues: Monitoring enables even distribution of cargo across vessels and ports, preventing container accumulation in queues.

— Loss of coordination among participants: All supply chain participants have access to up-to-date, real-time

information, enhancing synchronization of actions and reducing chaotic disruptions.

Integrated shipping route management platforms, such as Kongsberg Maritime Fleet Management, Navis N4, StormGeo Fleet Operations Solution, and W?rtsil? Fleet Operations Solution, enable the planning, optimization, and adjustment of vessel routes while considering factors such as port blockages, weather conditions, port capacity, and navigation restrictions. For example, the Navis N4 platform automatically adjusts vessel allocation to berths based on their queue, cargo, and estimated time of arrival, significantly reducing the risk of delays and port congestion.

Due to their capabilities, these platforms mitigate the manifestations of uncontrolled chaos in the following ways:

— Route disruptions: Vessels can quickly alter or optimize routes in response to port blockages or hazardous areas.

— Port delays: The system enables even distribution of vessel arrivals, reducing queues and waiting times.

— Cargo accumulation: Optimization of arrivals and cargo handling prevents container buildup at berths and in port waters.

Big Data Analytics, such as IBM Sterling Supply Chain, SAP Logistics Business Network, Oracle SCM Cloud, and StormGeo Fleet Weather Analytics, allows the forecasting and prevention of supply chain disruptions by integrating and processing data on vessel and container movements in real time, port throughput and unloading resources, weather conditions and maritime risks, and historical data on delays, queues, and accidents. For instance, the StormGeo Fleet Operations Solution enables large shipping companies to forecast weather-related delays and optimize vessel routes before departure from the port.

In the context of Ukraine, such tools could help mitigate the manifestations of uncontrolled chaos in the following ways [6—8]:

— Unpredictable delays: Forecasting of problematic areas and peak loads enables timely adjustments to vessel routes and arrival schedules.

— Uneven port and vessel utilization: The system predicts potential vessel queues at ports and optimizes cargo and vessel allocation, preventing congestion and resource overloading.

— Coordination failures among supply chain participants: Access to real-time analytical data enhances synchronization between port operators, carriers, and customers.

In practice, maritime analytics data show that near the Greater Odesa ports (Odesa, Chornomorsk, Pivdennyi), dozens of vessels were waiting at various times during 2024—2025 for entry or departure to load or unload cargo. Thus, big data analytics would be particularly useful for forecasting potential port congestion and digitally mapping available berths (i.e., automated identification and visualization of free or potentially available berths in specific time intervals, taking into account vessel type, cargo characteristics, and available port resources [7—8]), which would significantly reduce idle time and improve the efficiency of water transport supply chains.

Port Resource Management Systems (PRMS), such as Navis N4 Resource Planner, Tideworks Terminal Operating System, TOS Kongsberg, and SAP Port Management, provide comprehensive optimization of port resource allocation, including berths, cranes, storage facilities, and unloading equipment. They integrate data on vessel arrival schedules, cargo types, personnel availability, and equipment condition, enabling near-real-time coordination of port operations.

PRMS resources are capable of mitigating the manifestations of uncontrolled chaos in water transport supply chains in the following ways:

— Reduction of vessel queues: The system optimally allocates berths and berthing times, preventing simultaneous arrivals of multiple vessels and reducing waiting time in port waters.

— Reduction of port infrastructure overload: Efficient use of cranes and unloading equipment avoids bottlenecks during peak periods and ensures even utilization of resources.

— Improvement of coordination among participants: All stakeholders (port operators, shipowners, and freight forwarders) have access to up-to-date operational information, reducing the risk of uncoordinated actions and operational disruptions.

In the context of Ukraine, the implementation of port resource management systems could serve as an effective tool to reduce chaotic manifestations in the Danube and Black Sea ports, where, due to the military conflict, there are uneven vessel flows, a limited number of available berths, and increased load on port infrastructure.

Thus, digitalization can be considered a key direction for enhancing the resilience of water transport supply chains under conditions of high uncertainty by providing features such as: transparency and access to up-to-date real-time information; forecasting and proactive planning; resource utilization optimization; improved coordination among participants; and increased flexibility and adaptability.

CONCLUSIONS

The study established that the processes of uncontrolled chaos in supply chains involving water transport are systemic and arise from the simultaneous influence of internal and external factors, disrupting the predictability and coordination of logistics processes. These processes manifest as unpredictable delivery delays, periodic overloading or underutilization of port infrastructure, disruptions in interactions among supply chain participants, and the blocking or destruction of transport routes.

It has been demonstrated that, under conditions of uncontrolled chaos, traditional approaches to managing water transport supply chains are largely ineffective because they do not provide timely responses to rapid, nonlinear changes in the external environment. These phenomena were particularly pronounced in domestic supply chains, which, following the full-scale military invasion of Ukraine by the Russian Federation, experienced numerous problems that disrupted-and continue to disrupt-the predictability and coordination of logistics processes, including the blockade of ports in the Black Sea and the Sea of Azov, vessel accumulation

in queues at Danube ports, and disruptions to traditional shipping routes.

At the same time, the study's results show that the digital transformation of supply chains is an effective tool for mitigating the manifestations of uncontrolled chaos. In particular, implementing real-time cargo monitoring systems, port resource management systems, integrated shipping route management platforms, and big data analytics increases transparency in logistics processes, improves coordination among participants, enables timely forecasting of delays, and optimizes the use of port and transport resources.

Thus, the digitalization of water transport supply chains is considered a key approach to enhancing their resilience under conditions of high uncertainty, creating the prerequisites for reducing uncontrolled chaos and ensuring more stable operation of logistics systems even amid military, economic, and infrastructural shocks.

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