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DIGITAL TRACING IN LOGISTICS: SIMULATION OF SUPPLY CHAIN ELEMENT INTERACTION USING THE LOTKA–VOLTERRA MODEL

In the context of war and a crisis in logistics infrastructure, Ukraine has faced the urgent need to restructure its supply chains rapidly. The restoration of transport corridors, adaptation to EU requirements, and the increasing volume of humanitarian and military logistics have created a demand for transparency, flexibility, and predictability in logistics processes. One of the key aspects of this transformation is **digital tracing**, which enhances the transparency and controllability of the flow of goods, components, and materials. Recently, digital tracing technologies have become increasingly widespread, particularly through the use of the **Internet of Things (IoT)**, **Enterprise Resource Planning (ERP)** systems, and **Supply Chain Management (SCM)** tools. These technologies provide greater visibility, automation, and optimization of managerial decisions at various supply chain stages. However, introducing tracing into supply chains transforms information exchange mechanisms and alters the interaction between companies and their suppliers, requiring new approaches to modeling such processes. One such approach uses the Lotka-Volterra model[1], which is traditionally applied to describe the interaction between two populations. In logistics, this model can be adapted to study the dynamics of interaction between a company and its component supplier, considering the impact of digital tracing. The Lotka-Volterra model, also known as the predator-prey model, was developed to describe the interaction between two populations in an ecosystem. It consists of two differential equations that describe the changes in population sizes over time:

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[1] Cao, L., Halik, A., & Muhammadhaji, A. (2023). Further Studies on the Dynamics of a Lotka–Volterra Competitor–Competitor–Mutualist System with Time-Varying Delays. *Mathematics, 11*(13), 2902. https://doi.org/10.3390/math11132902

$$\frac{dM}{dt} = \alpha M - \beta MC, \ \frac{dC}{dt} = \delta MC - \gamma C,$$

where M(t) – is the population size of one group (e.g., the activity of the company); C(t) – is the population size of the other group (e.g., the activity of the supplier); α – is the natural growth rate of population M (company activity); β – is the competition or interaction coefficient between populations M and C; γ – is the natural decay rate of population C (supplier activity); δ – is the coefficient that defines how population M influences population C.

In the classical Lotka-Volterra model, the interaction between the two populations (the company and the supplier) is described using linear coefficients such as α, β, γ, and δ. These coefficients indicate the rate of change in the company's and the supplier's activity under certain conditions, such as natural growth or decay, and their interaction. However, digital technologies' impact on the development and decline of activity is nonlinear. Therefore, introducing exponential functions into the model will account for the sharp increase in the activity of both the company and the supplier as the level of tracing increases.

Thus, to describe the interaction between the company and the component supplier in the context of digital tracing, it is proposed to adapt the Lotka-Volterra model by introducing special parameters that account for the nonlinear nature of the impact of tracing on both the company and the supplier.

As a result, the following equations were proposed for the modeling:

$$\frac{dM}{dt} = \alpha e^{\delta T} M - \beta MC, \ \frac{dC}{dt} = \delta MC - \gamma e^{\theta T} C,$$

where M(t) – is the activity of the company, which changes depending on both external and internal factors; C(t) – is the activity of the component supplier; α – is the growth rate of the company's activity without interaction with the supplier; β – is the interaction coefficient between the company and the supplier; γ – is the decay rate of the supplier's activity without interaction with the company; δ – is the coefficient of the impact of tracing on the company; θ – is the coefficient of the effect of tracing on the supplier; T – is the level of digital tracing impact.

The system of equations presented models the changes in the company's activity levels and the component supplier over time, accounting for their interaction and the external influence of digital tracing (through parameter T). A set of parameters for the modelling was used, which conditionally reflects the characteristic dynamics of the interaction between a machine-building company and its component supplier within the context of Ukrainian manufacturing. The parameter values are based on empirical estimates and industry studies, considering the real functioning of medium-sized enterprises. In particular, the growth coefficient of the company without considering external interactions, α=0.4, corresponds to the average productivity growth rate in Ukraine's machine-building sector under stable demand conditions. The parameter β=0.02 represents the strength of the negative impact of supply shortages on the company's production activity. The low value of this coefficient indicates that manufacturing companies have a relatively stable supply structure or buffer stocks, which allow production to be maintained for some time even with reduced supplier activity. This aligns with the characteristics of Ukraine's machine-building sector, where local stocks and alternative supply sources are often used. γ=0.3 is the natural decay coefficient of the supplier's activity without interaction with the company. It reflects the tendency of the supplier's logistical or production activity to decrease if there are no external orders or stimulating influences from the consumer (the company). A value of 0.3 characterizes a moderate rate of decline in activity, which is typical for suppliers with a limited number of customers or those operating in unstable market environments, particularly in Ukraine's machine-building sector. The parameters δ and θ define the impact of tracing on the company and the supplier, respectively. The higher the tracing level, the faster the company and supplier can adapt to changing conditions, reducing the likelihood of delays and increasing supply chain efficiency. In our model, these parameters are set at 0.05 for the company and 0.04 for the supplier. The values of these parameters were selected based on a review of practical case studies in digital technology[2] impact and logistics[3]. The chosen values are small enough to maintain the model's realism – values that are too large would lead to uncontrolled growth in activity, which does not match practical observations.

For the study, three scenarios of digital tracing were chosen: T=0.0 – a logistics system without digital support, typical for traditional companies

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[2] Ning, L., & Yao, D. (2023). The Impact of Digital Transformation on Supply Chain Capabilities and Supply Chain Competitive Performance. *Sustainability*, *15*(13), 10107. https://doi.org/10.3390/su151310107

[3] Helo, P., & Thai, V. V. (2024). *Logistics 4.0 – Digital transformation with smart connected tracking and tracing devices. International Journal of Production Economics*, *275*, 109336. https://doi.org/10.1016/j.ijpe.2024.109336

without automated document management; T=0.4 – partial digitalization, reflecting the implementation of local digital solutions without end-to-end integration in the supply chain; T=0.8 – a high level of tracing with the integration of information flows between all participants in the logistics process. This gradation allows the analysis of how varying degrees of digitalization affect the interaction dynamics between the company and component suppliers.

Numerical modeling was performed using the GNU Octave software environment, which provides efficient tools for solving systems of differential equations. This environment allowed the implementation of the adapted Lotka-Volterra model, performing a parametric analysis of the impact of digital tracing, and visualizing the results for different scenarios of the level of digital technology implementation in logistics (Figures 1 and 2). The results of the numerical modeling demonstrate the oscillatory nature of the dynamics of both the company's and the supplier's activity over time, which corresponds to the typical behavior of a Lotka-Volterra system. The constructed graphs show that with the increase in digital tracing, the amplitude of activity oscillations increases, and the average activity level rises. The oscillations are explained by the interdependent nature of supply and production: the increase in the activity of one element leads to a rise in the other, followed by a decline, and the cycle repeats.

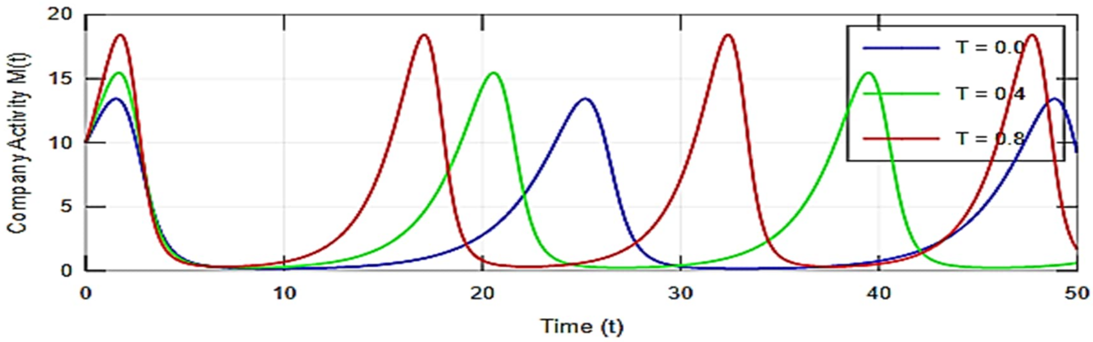

Fig. 1. Impact of Tracing on the Company Dynamics using the Lotka-Volterra Model

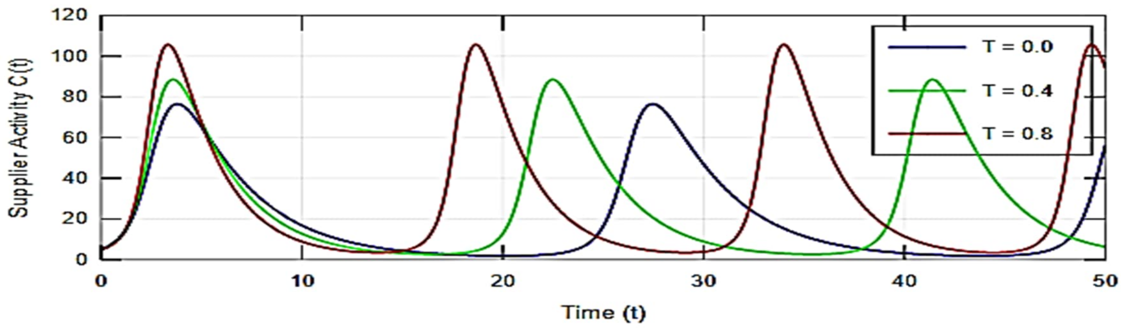

Fig. 2. Impact of Tracing on the Supplier Dynamics using Lotka-Volterra Model

Thus, modeling using the adapted Lotka-Volterra model showed that implementing digital tools can reduce uncertainty in the supply chain, stabilizing production processes. The results emphasize the importance of integrating digital tracing into logistics, especially in global changes and increasing demand for delivery speed and accuracy.

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1. Cao, L., Halik, A., & Muhammadhaji, A. (2023). Further Studies on the Dynamics of a Lotka–Volterra Competitor–Competitor–Mutualist System with Time-Varying Delays. *Mathematics*, *11*(13), 2902. https://doi.org/10.3390/math11132902
2. Ning, L., & Yao, D. (2023). The Impact of Digital Transformation on Supply Chain Capabilities and Supply Chain Competitive Performance. *Sustainability*, *15*(13), 10107. https://doi.org/10.3390/su 151310107
3. Helo, P., & Thai, V. V. (2024). *Logistics 4.0 – Digital transformation with smart connected tracking and tracing devices. International Journal of Production Economics, 275,* 109336. https://doi.org/10.1016/j.ijpe.2024.109336

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STRATEGIC GUIDELINES FOR THE DEVELOPMENT OF BUSINESS LOGISTICS SERVICES

In today’s globalized and unstable business environment, logistics services are not just an additional service, but a key strategic element of business competitiveness. Businesses seeking not only to survive but also to grow are forced to rethink their attitude to logistics as a support function that is increasingly transforming into a driver of innovation and cost optimization.