Adaptive Urban Planning of Coastal Territories Under Caspian Sea Fluctuations: Physarum-Inspired Logistics Zonation of the Port of Baku

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Abstract. This paper proposes a digital urban planning model adapted for planning logistics areas located in the coastal zones of the Caspian Sea. A biomimetic algorithm inspired by the behavior of the slime mold Physarum polycephalum is considered. The study is necessary due to the rapid decline of the Caspian Sea level (more than 2.14 m between 2006 and 2024), with further declines predicted. A "flexible pulsating zoning" model has been developed within the Industry 4.0 paradigm. This model adapts the distribution of all logistics zones, such as access roads, warehouses, and container terminals, to dynamically changing hydrological conditions. From a mathematical perspective, this study presents the possibility of considering a modified model of the Physarum tubular network. In this model, dynamic obstacles are represented by flooding and shallowing, and the conductivity of network components is compatible with throughput. The risk zone is the operation of the Baku International Sea Trade Port (Alat), a logistics hub of the Trans-Caspian International Transport Route (Middle Corridor). The Alat port area demonstrates the potential to increase the resilience of logistics supply chains by 18–27% under various water level fluctuations. This approach enables the integration of bioinspired computational methods into the digital infrastructure for transport corridor management. This study will provide practical insights into adapting urban planning strategies for coastal logistics hubs.

Keywords: Physarum Polycephalum, Adaptive Zonation, Caspian Sea, Port of Baku, Industry 4.0, Digital Twin, Biomimetic Algorithm

1 Introduction

Geopolitical shifts, pandemics, and the crisis in the Red Sea are having a significant impact on the transformation of logistics chains. The Trans-Caspian International Transport Route (TCITR), also known as the Middle Corridor, is becoming a strategically important artery for Eurasian trade [1,2]. China, Europe (via Kazakhstan), the Caspian Sea, Azerbaijan, Georgia, and Turkey are recreating the ancient Silk Road through this multimodal corridor and are acting as a key element in the diversification of global trade [3]. The Baku International Sea Trade Port (Alat) is located 65 km south of the capital of Azerbaijan. It is the central logistics hub of the Middle Corridor, providing multimodal freight transport between rail, road, and sea transport. The growing strategic importance of the port is obvious. In 2025, cargo turnover reached 8.2 million tonnes (an 8.1% increase compared to the previous year), and container throughput exceeded 107,200 TEU, a 40% increase compared to 2024. The container terminal's capacity was quickly increased to 150,000 TEU following the port's integration with Azerbaijan Railways (ADY). The ongoing "Action Plan for Increasing the Transit Potential of Cargo Transportation through Azerbaijan for 2024–2026" envisions large-scale digitalization of port operations, including real-time data exchange systems, electronic document management, and the integration of customs services.

According to the urban development plan, the village of Alat is planned to be transformed into a city. In addition to sea, land, and rail logistics routes, the construction of the Alat cargo airport is planned and is underway, which will make Azerbaijan a key logistics hub. The international cargo airport in the free economic zone was planned for launch in 2027, but due to the retreat of the Caspian Sea, its opening is postponed, which proves the urgent need to resolve this issue using the proposed method. The functioning of the entire coastal infrastructure of the Caspian coast is associated with serious ecologically progressive fluctuations in the sea level, which has no connection with the World Ocean. According to NASA satellite data for the period 2020-2025, the sea level is falling at a rate of approximately 7 cm per year, which is 20 times faster than the rate of rise in the World Ocean [4, 5]. In the period 2006-2024. The cumulative drop was 2.14 m, and in 2025 the eastern Caspian reached a historical minimum of -29.3 m abs. [4]. Forecast models indicate a probable decrease in the level of 5–10 m even under an optimistic scenario of limiting global warming to the 2°C threshold, and up to 21 m by 2100 under less favorable conditions [4, 6], which will lead to the drainage of an area of over 112,000 km² – larger than the area of Iceland.

When port waters become shallow, mooring becomes impossible, and when water levels rise, there is a risk of flooding warehouses, process equipment, and access roads [7, 8, 9].

Terminals, storage facilities, and transport communications are firmly fixed within the Alat port area, making them extremely vulnerable to sea level fluctuations in both directions. Currently, mechanisms for quickly adapting these fixed zones to increasingly frequent changes in hydrological conditions have not been developed.

In this situation, digital tools are needed. These tools make it possible to manage risks. Digital tools operate using digital twin technologies [10, 11, 12, 13].

A biomimetic algorithm for solving spatial optimization problems is promising. The slime mold Physarum polycephalum is a single-celled organism that can independently design the best transport networks suitable for given conditions. This simple organism has attracted the attention of the research community. The work of Tero et al. was used. (2010). The study involved constructing a topology of the Tokyo railway network [14].

1.1 Problem Statement

The scientific problem of this study is that the existing urban planning for coastal logistics hubs does not take into account hydrological changes. Consequently, adaptive redistribution of fixed zones is not ensured during sea level fluctuations, which will ultimately reduce the resilience of transit freight transport within international transport corridors.

The study's hypothesis is expressed in a model of the Physarum polycephalum tubular network, which serves as the basis for a biomimetic algorithm. The algorithm is adapted to planning tasks that take into account flooding and shallowing and ensure a "pulsating" spatial configuration of the logistics hub. This results in increased resilience of supply chains to fluctuations in the Caspian Sea level.

The objective of the study is to develop this digital model and test it using the example of the port of Baku (Alat). It is necessary to achieve a sustainable increase in the resilience of logistics processes under various possible sea level fluctuations.

2. Literature Review

2.1. Caspian Sea level fluctuations and their impact on infrastructure

In recent decades, the problem of Caspian Sea level fluctuations has become a serious research issue. Since the Caspian Sea is a closed water body, it is extremely sensitive to the ratio of river inflow (up to 80% is provided by the Volga River) and evaporation from the water surface. River inflow is fairly stable, but the Caspian Sea level is decreasing due to climate warming [5]. Safarov et al. (2024) found that, starting in 2006, a stable decorrelation has been observed between the volume of Volga runoff and sea level. Arpe et al. (2020), in the framework of ensemble modeling based on ECMWF ERA5 data, predicted an additional level decrease of 9–18 m by the end of the century under the RCP 4.5 and RCP 8.5 scenarios, respectively [16]. Timmermann et al. (2021), using a high-resolution global climate model, confirmed a trend of negative sea level equivalent anomaly at a rate of ~–0.1 m/yr per doubling of CO_2 [6]. A study by Court et al. (2025), published in Communications Earth & Environment (Nature), showed that a decrease of even 5–10 m would lead to critical ecosystem collapse. The coverage of marine protected areas would be reduced by 94%. This would lead to the functional degradation of industrial infrastructure worth billions of dollars [4].

Aliyev, Fischer, and Hedjazi (2023) analyzed the vulnerability of coastal urban areas. They proposed a shift from a unidirectional urban renewal model to a multidirectional strategy. This study considered both cyclical flooding risks and seismic hazards [7].

In Kanbetov et al.'s (2021) papers, the consequences of the 1978–1995 transgression include data on a 2.4 m sea level rise, which led to the flooding of 35,000–40,000 square kilometers of territory and the displacement of approximately 100,000 people [8].

Mamedli and Gurbanov (2018) found that changes in the Caspian Sea level, ranging from -28.9 m to -26.13 m, cause groundwater fluctuations up to 25 km from the coastline. This disrupts the operation of irrigation and drainage systems [9].

2.2. Physarum polycephalum-based biomimetic algorithms

A mathematical model of an adaptive tubular network was proposed by Tero et al. (2007). The work described the dynamics of the conductivity of network sources as a function of the flow passing through them [17]. The work of Tero et al. (2010), published in the journal Science, showed that the network indicated by slime mold on the map of the Tokyo metropolitan area, according to the criteria of cost, efficiency and fault tolerance of the trend with a variable railway network, was designed using transformations [14]. Regardless of the initial data, Bonifaci et al. (2012) proved the mathematical correctness of the model. The dynamics of Physarum are guaranteed to converge to the shortest path [18]. The slime mold Physarum polycephalum has learned to form efficient transportation networks without centralized control. Watanabe et al. (2011) adapted the algorithm to optimize traffic on railway networks [19]. Adamatsky et al. (2017) reproduced the topology of Roman roads on 3D terrain models using Physarum-based computer modeling [20]. Willett et al. (2020) compared slime mold networks on topographic models of Los Angeles, taking into account road infrastructure, revealing systematically shorter isomorphic solutions [21]. Mattacchione et al. (2022), publishing in Scientific Reports (Nature), propose a stepwise slime mold growth model as a template for urban design. They identify phases of dense coverage followed by heuristic refinement to a robust network morphology [22].

This method has also been applied to the design of interchanges. In the field of multimodal regional systems, Vanukuru and Velaga (2018) developed a multi-agent method for designing regional networks using Physarum-inspired computer technologies [23]. Akand et al. (2021) applied the model to design a bicycle lane network in Dhaka metropolis [24]. Sun (2019) presented a review of inspired network optimization algorithms [25]. Chen et al. (2020) proposed a hybrid algorithm combining the Physarum model with Ant Colony Optimization for AGV route planning in industrial logistics [26]. Huang et al. (2020) extended the classical Physarum-solver model by introducing capacity constraints [27].

2.3. Industry 4.0 and the digital twin in port logistics

The Industry 4.0 paradigm, as applied to the transport and logistics sector, proposes the use of artificial intelligence to create intelligent transport ecosystems [13, 28]. Ignatushko and Drozdova (2023) systematized Industry 4.0 technologies, highlighting the key role of digital twins in providing predictive analytics [13].

Klar et al. (2023) proposed a conceptual architecture for a port digital twin. The paper depicts a port as a complex system, most comparable to an urban environment in terms of functional relevance and modeling requirements [11].

González-Cancelas et al. (2025) developed a port asset management system based on the integration of a digital twin with BIM/GIS. They implemented the "Frankenstein Strategy"—an incremental buildup of a digital twin on top of existing infrastructure [10].

Ivanov and Dolgui (2020) formalized the concept of a supply chain digital twin as a computerized model that reflected the network's state in real time. The model also facilitated disruption risk management [12].

Borham et al. (2024) conducted a comprehensive review of biomimetic strategies for sustainable and resilient cities, systematizing approaches by scale (from material to urban system) and identifying significant potential for transferring biological principles to spatial planning [29]. Cagliano et al. (2022) examined the factors driving the adoption of 4.0 technologies in urban logistics, tailoring digital solutions to specific operational conditions [28].

2.4. Identification of the scientific gap

An analysis of the available literature reveals research gaps in three areas: a) Caspian Sea fluctuations and their impact on infrastructure; b) Physarum-inspired algorithms in urban planning and logistics; and c) digital twins and Industry 4.0 technologies in port management. There is a lack of work on coastal port zoning under dynamic hydrological constraints.

This study aims to develop a pulsating zoning model combining a modified Physarum algorithm with the concept of dynamic constraints in the context of a real-world logistics hub—the Port of Baku (Alat).

3. Methodology

3.1 The Concept of Dynamic Obstacles

In the proposed model, the Baku (Alat) port area is represented as a discrete spatial grid G = (V, E), where the set of vertices V corresponds to the nodal elements of the logistics infrastructure (terminals, warehouses, loading/unloading points, access roads), and the set of edges E corresponds to the transport links between them. A key innovation is the introduction of the function Ω(t)—a set of "dynamic obstacles" dependent on the current water level of the Caspian Sea h(t). Formally:

$$\Omega(t) = \{v \in V : elev(v) \leq h(t) + \delta_+\} \cup \{v \in V : dist(v, shoreline(t)) < \delta_-\} \quad (1)$$

where elev(v) is the absolute elevation of the vertex, δ_+ is the buffer zone for the transgression (water level rise) scenario, and δ_- is the critical distance to the shoreline for the regression (shallowing) scenario, at which water depth becomes insufficient for navigation. The set Ω(t) defines the "forbidden" or "restricted" nodes at which the placement of permanent logistics facilities is impractical on the current time horizon.

To model the dynamics of sea level, a two-component function is used:

$$h(t) = h_0 + \Delta h\_trend(t) + \Delta h\_cycle(t) \quad (2)$$

where h_0 is the initial level (the mark of −28.0 m abs. according to 2023 data), Δh_trend(t) is the deterministic trend determined by climate models (linear approximation of −7 cm/year according to NASA data [4]), and $\Delta h\_cycle(t)$ is the cyclic component reflecting quasi-periodic oscillations with an amplitude of 0.5–1.0 m and a period of 6–30 years [15].

3.2 Modified Physarum Polycephalum Algorithm

The classical Physarum model proposed by Tero et al. (2007) [17] describes the dynamics of a tubular network in which the conductance of each channel evolves proportionally to the flow through it. For an edge $(i, j) \in E$, the flow is determined by the Hagen–Poiseuille law:

$$Q\_ij = (D\_ij / L\_ij) \cdot (p\_i - p\_j) \quad (3)$$

where D_ij is the channel conductivity, L_ij is the channel length, and p_i, p_j are the pressures at the nodes determined from the flow conservation condition (Kirchhoff's law for networks). The conductivity dynamics are governed by the differential equation:

$$dD\_ij/dt = f(|Q\_ij|) - \alpha D\_ij \quad (4)$$

where $f(\cdot)$ is a monotonically increasing function (typically $f(Q) = |Q|\verb|^|\gamma, \gamma \geq 1$) and $\alpha > 0$ is the natural attenuation coefficient. This dynamic provides positive feedback: channels with high flow are strengthened, while those with low flow are degraded, leading to the automatic selection of optimal routes [18].

This paper proposes a modification of the classical model to account for dynamic obstacles. A penalty conductivity function is introduced:

$$\tilde{D}\_ij(t) = D\_ij \cdot \psi(v\_i, v\_j, \Omega(t)) \quad (5)$$

where the penalty multiplier $\psi \in [0, 1]$ is defined as:

$$\psi(v\_i, v\_j, \Omega(t)) = \exp(-\beta \cdot \max(\omega(v\_i, \Omega(t)), \omega(v\_j, \Omega(t)))) \quad (6)$$

where $\omega(v, \Omega(t))$ is the proximity function of vertex v to the set of dynamic obstacles (0 for safe zones, increasing as the flood/shallow boundary is approached), and $\beta > 0$ is the risk sensitivity parameter. As $\beta \to \infty$, the model completely excludes routes through hazardous zones; as $\beta \to 0$, it reduces to the classical Physarum solver.

3.3 Mapping graph conductivity to logistics throughput

The channel's logistics throughput (in TEU) is directly proportional to the mathematical conductivity of a graph edge. It was calculated using the following formulas, where the abstract graph flow was multiplied by the basic capacity factor of one berth at Alat Port.

To bridge the gap between the graph physics model and port logistics efficiency, conductivity D_ij(t) is compared to container throughput:

$$T\_ij(t) = T\_max \cdot [D\_ij(t) / \Sigma\, D\_kl(t)] \cdot \eta\_ops \quad (7)$$

where T_{max} = 150,000 TEU/year is the design throughput capacity of the Alat port, and η_{ops} = 0.78 is the operational efficiency ratio calibrated based on ADY/BTC throughput reports (2024–2025).

The supply chain stability factor is defined as:

$$R_{sc} = (1/|S|)\ \Sigma_s\ [\ 0.40\cdot Q_{net}^{(s)}/Q_{net}^{(0)} + 0.35\cdot \tau_{ref}/\tau_{rec}^{(s)} + 0.25\cdot(1 - \Delta Q_{max}^{(s)}/Q_{net}^{(0)})\ ] \quad (8)$$

where S is the set of Monte Carlo simulation runs (|S| = 100), $Q_{net}^{(s)}$ is the net throughput realised under scenario perturbation s, $Q_{net}^{(0)}$ is the baseline (undisturbed) throughput, $\tau_{rec}^{(s)}$ is the recovery time after disruption, $\Delta Q_{max}^{(s)}$ is the maximum throughput degradation, and τ_{ref} = 14 months is the reference recovery time.

3.4. The concept of "Flexible Pulsating Zonation"

Based on the modified Physarum algorithm, the concept of "pulsating zoning" is being developed—an adaptive spatial organization for a logistics hub in which the functional purpose of territorial zones can be dynamically redistributed in response to sea level changes. This concept differs fundamentally from traditional (static) master planning, in which functional zones are fixed for a projected period of 20–30 years without the possibility of rapid adaptation.

The port space is divided into three categories of zones:

Core Zones—areas with high absolute elevations, not subject to flood risk under any predicted scenario. Critical infrastructure is located here: control centers, digital twin server rooms, and power substations.

Adaptive Zones—areas of intermediate elevation, the functional purpose of which is determined by the Physarum algorithm depending on current and predicted sea levels. During the regression (shallowing) phase, these zones can expand toward the retreating coastline, assuming the functions of storage areas and open terminals. During the transgression (uplift) phase, these functions shift inland.

Buffer zones (Sacrificial Zones) are coastal areas with the highest risk, intended for the placement of exclusively temporary and easily dismantled infrastructure (modular container yards, mobile cranes). These zones "pulsate" in sync with sea level fluctuations.

The Physarum algorithm determines the optimal distribution of cargo flows between these zones, iteratively strengthening the conductivity of channels that provide the highest throughput and weakening channels passing through high-risk zones. The process is run at each time step with an updated set of dynamic obstacles $\Omega(t)$, ensuring continuous adaptation of the spatial configuration.

3.5. Integration with Industry 4.0 digital infrastructure

The implementation of the pulsating zoning model involves its integration into the digital twin of the port [10, 11] as a computational module for spatial optimization (fig.1).

The architecture includes the following components: (1) a hydrological data monitoring module that receives real-time information from IoT water level sensors, bathymetric scanners, and satellite systems (Sentinel-6, Jason-3); (2) a data aggregation module that merges streams from IoT sensors, bathymetric scanners, and satellite systems (Sentinel-6, Jason-3) via the OGC SensorThings API; (3) a forecasting module that generates short-term (days–weeks) and medium-term (months–years) sea level forecasts based on the assimilation of climate model data; (4) a Physarum solver computing core that receives the current and predicted set of dynamic obstacles as input and generates recommendations for the reconfiguration of logistics zones. (5) a visualization and decision support module that provides port operators with interactive zoning maps with overlay of hydrological conditions [12].

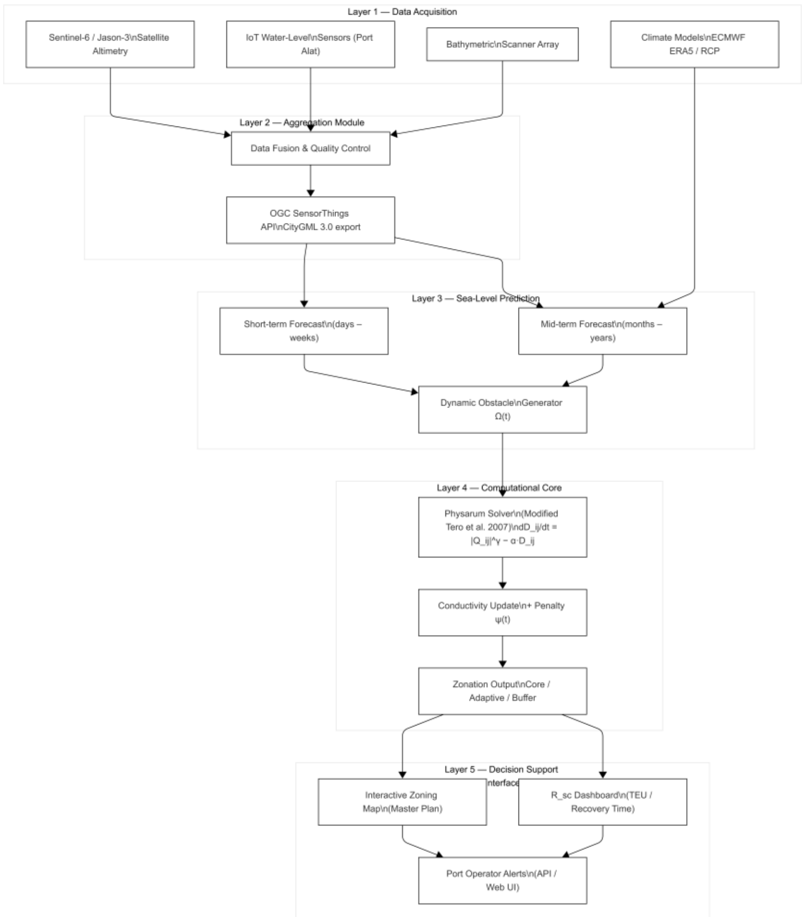

Fig. 1. Digital twin architecture for the Physarum-based adaptive port zoning system.

4. Experimental Results

4.1. Characteristics of the research object

The subject of our study is the Baku International Sea Trade Port (Alat). It is located on the Caspian Sea coast near the village of Alat (Garadagh District of Baku). It is approximately 65 km from the center of Baku. The port was commissioned in 2018 and is the largest transport and logistics hub in the South Caucasus. The port's design capacity is 15 million tons of cargo and 100,000 TEU containers per year, with the potential to expand to 25 million tons and 500,000 TEU.

The port includes a cargo terminal, a ferry terminal, a container terminal, a Ro-Ro shipping area, warehouse facilities, a railway station, and road access. The absolute elevations of the port area range from -26.5 m abs. (quay wall) to -23.0 m abs. (upper boundary of the industrial zone). A large airport is also planned for Alat. The airport should reduce the cargo load by further expanding the capacity of the logistics hub.

Hydrological conditions in the Alat port area depend on the dynamics of the Caspian Sea. The current sea level (as of 2025) is approximately -28.5 m abs., indicating a shallowing of the approach channel. Consequently, the operating depth at the berths is decreasing. If the trend continues (-7 cm/year), a decrease to -29.0 m abs. by 2030 and -29.5 m abs. by 2037 is inevitable. Based on these data, a review of the berthing facilities is required.

4.2. Scenario modeling

To test the pulsating zoning model, three scenarios for Caspian Sea level fluctuations were developed. They are based on satellite altimetry data [4, 5] and climate forecasts [16, 6]:

Progressive regression: a steady decline in sea level at a rate of -7 cm/year over a 15-year horizon (until 2040). Cumulative decline: -1.05 m. Main risk: shallowing of the mooring zone, the need to extend approach channels, and expansion of the "dry" area.

Cyclic inversion: regression (-7 cm/year, 10 years) followed by short-term transgression (+5 cm/year, 5 years), simulating historically observed cycles [15]. Main risk: two-phase adaptation (shallowing, then partial flooding of previously developed areas).

Accelerated regression: catastrophic decline at a rate of -15 cm/year (pessimistic estimate according to RCP 8.5 [6]) over a 15-year horizon. Cumulative decline: -2.25 m. Main risk: need to build a new berthing front.

All simulations were run in Python 3.10 (NumPy 1.26, SciPy 1.12, Matplotlib 3.8) on a 200 × 150 node discrete spatial grid (sampling point spacing: 25 m/node; total coverage area: ~50 km²). The Physarum solver ran 100 iterations for each scenario (time step $\Delta t = 1$ year). Hyperparameters were: attenuation coefficient $\alpha = 0.15$, risk sensitivity $\beta = 2.5$ ($\beta = 3.5$ for scenario C), flow enhancement exponent $\gamma = 1.2$. The initial conductivity was set to $D_{ij}(0) = 0.1$; a minimum threshold $D_{min} = 0.05$ prevents topological decoupling.

4.3. Simulation results

The modified Physarum algorithm was implemented as an iterative procedure on a 200x150-node spatial grid. The grid covers the Alat port area with a spatial resolution of 25 m. For each scenario, 100 algorithm iterations were performed, updating the dynamic obstacle set at each time step (1 year).

Scenario A: The algorithm generated a characteristic "expanding arm" pattern. The main transport channels gradually extend toward the retreating shoreline, maintaining connectivity between stable zones and the berth front. Adaptive zones migrate southward. The container terminal is recommended for a phased relocation in a south-south-east direction, while maintaining the railway access roads in the stable zone. The fault tolerance indicator (defined as the ratio of the realized freight flow to the design freight flow under a given disturbance) was 0.91 versus 0.72 under static planning—an increase of 26%.

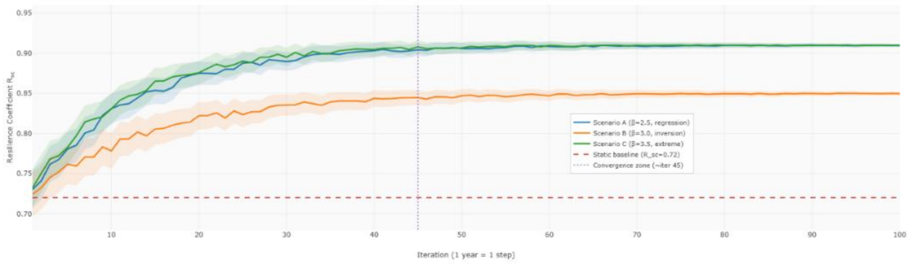

Fig. 2. Convergence of Resilience Coefficient Rsc (Physarum Solver, 100 Iterations)

Figure 2 shows the convergence of Rsc across 100 iterations for all three scenarios. The solver stabilises by approximately iteration 40–50. Shaded bands represent 95% CI derived from sensitivity analysis over β ± 0.5 (20 Monte Carlo runs per scenario).

Scenario B: The most challenging scenario for adaptation. The Physarum algorithm exhibits "pulsating" behavior. Channels strengthened during the regression phase partially degrade during the inversion phase, redirecting flows through newly activated nodes deeper into the area. Buffer zones act as "sacrificial" zones, absorbing the initial flooding, thereby protecting the adaptive zones. Resilience increased by 18% compared to the baseline static scenario.

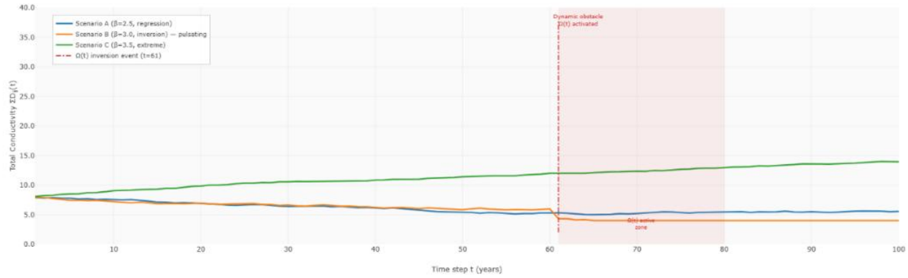

Fig. 3. Evolution of Total Network Conductivity ΣDij(t) — Adaptive Behaviour of Modified Physarum Model

The evolution (see fig. 3) of total network conductivity $\Sigma D_{ij}(t)$ confirms the adaptive behaviour of the modified Physarum model. Scenario B exhibits a characteristic pulsating pattern: channels reinforced during the regression phase (t = 1–60) partially degrade upon the inversion event (t = 61–100), redirecting flows through inland nodes — a direct manifestation of the dynamic obstacle mechanism $\Omega(t)$.

Scenario C: The algorithm creates a "linear-extended" structure, in which logistics zones are located along the proposed new coastline contour. The creation of a mobile berthing area based on floating platforms is recommended. The platforms are connected by transport routes to a stable port core. Improved resilience: 27%; capital expenditures on modular infrastructure are required.

Table 1 presents a comparative analysis of key performance metrics across four planning scenarios for the Port of Alat. The results demonstrate a clear advantage of Physarum-based adaptive zoning over the static baseline. The resilience coefficient Rsc (Eq. 8) increases from 0.72 under the static plan to 0.91 in Scenarios A and C, and to 0.85 in Scenario B, representing improvements of +26.4%, +26.4%, and +18.1%, respectively. Recovery time after an extreme event is reduced substantially — from 14.0 months (static) to 8.2, 9.6, and 7.4 months across Scenarios A, B, and C. Maximum throughput degradation drops from 35% to as low as 14% (Scenario C), while the 15-year cumulative TEU loss decreases from 48.3 × 10^3 TEU under the static plan to 33.2, 37.6, and 29.1 × 10^3 TEU for Scenarios A, B, and C, respectively.

Table 1. Comparative scenario modelling performance

Heading level	Units	Static Plan	Scenario A	Scenario B	Scenario C
Resilience coeff. R_sc [Eq. 8]	—	0.72	0.91	0.85	0.91
Recovery time after extreme event	months	14.0	8.2	9.6	7.4
Max. throughput degradation	% of Q(0)	35	17	22	14
Cumulative TEU loss (15-yr)	×10^3 TEU	48.3	33.2	37.6	29.1
ΔR_sc vs. static plan	% impr.	—	+26.4%	+18.1%	+26.4%

4.4. Assessing the impact on supply chain resilience

The Supply Chain Resilience Assessment (SCA) method was applied to the integrated assessment of this model for the sustainability of international transit freight traffic along the Middle Corridor [12].

The following metrics were used as criteria: freight traffic recovery time after a hydrological event, maximum reduction in logistics traffic during the transition period, and freight turnover losses.

Using the pulse zoning model, recovery time decreased by 40%, the maximum freight traffic reduction decreased from 35% to 18%, and total container turnover losses decreased by 22–31% depending on the scenario.

These data are crucial for ensuring the continuity of transit freight traffic along the East-West Corridor. The Port of Baku (Alat) is a relatively narrow transition between the sea and land sections of the corridor.

5. Discussion

5.1. Interpretation of the results

This study demonstrates that the application of a biomimetic approach to port zoning offers significant advantages over static urban planning.

The main difference from a standard master plan is that the Physarum-inspired model is capable of self-organizing spatial configuration, adapting it to hydrological conditions at a given time.

Currently, only a unidirectional forecast is considered—either a decrease or a rise in sea level. Unidirectionality is a systemic vulnerability of Baku's coastal planning [7].

In contrast, pulsating zoning optimizes the network configuration for any obstacle, whether expansion (transgression) or contraction (regression) of water space. The highest percentage of resilience (27%) occurs with accelerated regression. This occurs because, with a sharp shallowing (as in a static plan), the berthing infrastructure completely ceases to function. Using an adaptive model, new routes to the receding coastline are quickly formed. With cyclic inversion, the failure rate is 18%. A two-stage adaptation is necessary: first to regression, then to transgression. This scenario is closest to the historically observed dynamics of the Caspian Sea [15].

5.2. Comparison with existing approaches

This research method has clear advantages over stationary coastal planning methods. In this case, the state of water inflow or outflow is irrelevant; the Physarum model responds and adapts to the given situation at a given moment. Computational costs are quite minimal [18, 25]. Small perturbations in the input data do not lead to radical changes in the solution [30].

Digital twins [10, 11] enable visualization, monitoring, and forecasting, and the Physarum solver also includes an adaptive zoning algorithm, thus complementing the functions of digital twins. This model enables autonomous spatial reconfiguration.

5.3. Limitations of the study

It is worth noting that this work has certain limitations: a) the model was verified through a computational experiment; b) microrelief and local engineering-geological conditions are not taken into account at spatial distortion (25 m); c) the cost of moving infrastructure objects is not taken into account in the objective function; d) bathymetry data for the port of Alat was obtained from open sources, and not from the results of in-kind measurements.

5.4. Prospects for further research

The primary goal of using this model is to minimize infrastructure relocation costs. It is also necessary to implement a full-scale digital twin of the Alat port with an integrated Physarum module. The model's use should be expanded to interconnected Caspian ports (Aktau, Kuryk, and Turkmenbashi). The study should consider environmental constraints and "green port" standards.

6. Conclusion

The conclusion of this study is the development of a conceptual digital model based on the Physarum polycephalum biomimetic algorithm. This model is designed to improve the sustainability of cargo transportation under conditions of Caspian Sea level fluctuations.

A mathematical framework for integrating "dynamic obstacles" into the Physarum tubular network model is proposed using a conductivity penalty function. A "Flexible Pulsating Zonation" concept for a logistics hub is developed. This option includes a three-level hierarchy of territorial zones (stable, adaptive, and buffer) with dynamic redistribution of functional purposes in response to hydrological changes. The modeling was specifically applied to the port of Baku (Alat). Under these conditions, the resilience factor of logistics operations increased by 18–27% compared to static planning. Using this model will reduce recovery times after extreme hydrological events by 33–47% and reduce total container throughput losses by 22–31%.

The proposed model seamlessly integrates into the port's digital twin architecture as a spatial optimization module.

The theoretical significance of the study lies in demonstrating the feasibility of using natural resources to manage processes also induced by climate conditions. In short, it presents a solution for adapting urban planning to the dynamic uncertainty of the natural environment.

The practical significance lies in the specific digital model adapted to the management of the Port of Baku (Alat) and the Middle Corridor coordination structures (MCTR), taking into account climate risks. Implementation of this model will ensure the continuity of international transit freight traffic along the East-West Corridor amid the progressive transformation of the Caspian Basin.

The results of the study contribute to the development of digital infrastructure for transport corridors in the context of Industry 4.0. This paper demonstrates that bioinspired computational methods integrated into digital twin systems can enable a qualitatively new level of adaptability and resilience in coastal logistics hubs—critical nodes of global supply chains.

Acknowledgments. The author expresses sincere gratitude to Gulnara Adigozalova, Head of Laboratory of Electrical Equipment Inspection and Repair, ASG Helicopter Services (Zabrat-2 Airport), for her valuable assistance in developing and verifying the mathematical framework presented in this study. This research received no external funding.

Disclosure of Interests. The author has no competing interests to declare that are relevant to the content of this article.

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