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PROJECT-ORIENTED APPROACH TO MARITIME TRANSPORT SAFETY MANAGEMENT BASED ON A GRAVITATIONAL-INERTIAL MODEL

Nosov P., *Ph.D., Associate Professor, Head of the Department of Technical Cybernetics and Information Technology Named After Prof. R.V. Merkt, Odesa National Maritime University, Odesa, Ukraine; e-mail: pason@ukr.net; ORCID: 0000-0002-5067-9766.*

A project-oriented approach to maritime transport safety management at the macro level is proposed, based on a physical analogy with a gravitational-inertial model in which the mission of the multi-project is interpreted as a vertical axis, the execution rhythm ω_3 and process maturity I_3 form the momentum of the stable regime L, and the external environmental pressure H_t, G_t, S_t and the disturbance moment τ define the controlled precession Ω of the system. A system of generalized parameters and multi-project segments P_1-P_8 (regulatory compliance, ship traffic management, navigational infrastructure, human factor, cyber protection, environmental safety, emergency readiness, analytics and DSS) is developed, for which, using EMSA reports, weight matrices of impacts and a normalized matrix A are constructed that link the development levels of segments with the states $\{\omega_3, I_3, H_t, G_t, S_t, \theta, \tau\}$. On the basis of matrix B, which takes into account amplitudes and signs of effects, a weighted least-squares problem is formulated for the vectors Δp that provides the search for optimal changes in segment levels, while subsequent discretization $\Delta P_i \in \{-2,\ldots,2\}$ transforms them into interpretable expert recommendations on strengthening or unloading individual blocks of the multi-project. A software module in Python (NumPy, pandas, matplotlib) is implemented, which automates the calculation of the indicators L and Ω, classifies scenarios by stability, and generates tabular reports and plots for six typical scenarios of the European region, demonstrating the possibility of transforming crisis and stressed regimes into a new balanced state with increased momentum L and reduced precession frequency Ω.

Key words: *project-oriented approach; gravitational-inertial model; maritime safety multi-project; expert system; scenario analysis; project management; automation; Python; intelligent systems.*

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Introduction. The maritime transport sector is one of the largest in the world, as it accounts for more than 60% of total freight transportation. The performance of the sector is influenced by numerous factors, including the requirements of international organizations, flag States, shipping companies, ports, crewing agencies, and various supervisory services [1]. The current level of hazards and the risk space of maritime transport, in particular the human factor [2], reveal gaps in the theory and practice of project management at the macro level (state, industry clusters, large companies). These gaps are driven by growing organizational and technical complexity, instability of the external environment, and the high interdependence of operational processes.

Existing approaches mostly accumulate indicators (voyage delays, documentary non-conformities, incidents, deviations from routes), but do not provide an integrated controllable model and concept capable of explaining and predicting the evolution of the system, its stability, and the boundaries of controllability under external and internal disturbances. This leads to reactive decision-making, data fragmentation and the absence of transparent criteria by which transitions to unstable regimes of the maritime safety project can be recognized in due time. Thus, there arises a contradiction between the practical demand and the real conditions for organizing safe navigation on the part of international organizations, flag-state regulators and shipping companies that provide maritime transport services.

This situation necessitates the development of a concept and a project-oriented approach to maritime transport safety management that would allow one to assess and ensure:

1. An adequate level of integration between the operational execution rhythm, process performance and external pressure of norms and rules within a common space of controllable states and disturbances;
2. The introduction of formal, reproducible indicators of alignment with the project mission, enabling the establishment of stability thresholds for a company's project;
3. Operation based on open and verifiable data, with their intelligent processing, compatible with real supervision and operation practices;

4. The possibility of proactive decision-making in real time through resource reallocation, process reinforcement and risk prevention, based on transparent cause-and-effect relationships rather than ex-post indicators.

In practical terms, this study is oriented towards solving a specific applied problem, namely: the proposed gravitational–inertial model is implemented as a computable macro-level tool. The model is designed to transform measurable scenario data into discrete recommendations on reconfiguring the levels of eight safety segments at the level of the maritime sector or an individual shipping company. On this basis, it is planned to develop a Python (Anaconda JupyterLab)–based decision-support module, which, for scenarios in the European region, will automatically calculate the relevant indicators, verify stability thresholds, and output interpretable changes to the configuration of the maritime safety multi-project. Thus, the study not only introduces a conceptual framework but also addresses a concrete control problem: how to transfer a safety multi-project from crisis or stressed regimes into a new balanced state on the basis of formal optimization procedures.

Literature review. The issues outlined in the introduction highlight the need to develop a comprehensive concept for managing a maritime safety project at the macro level. Such concepts are typically described through analogies with processes or phenomena from physics and other exact sciences. In this context, models and concepts describing global processes in the maritime transport sector were analyzed.

In [3], the authors treat global freight flows as a complex network characterized by “scale-free” regularities, gravity-type flow dependencies and diffusion-like dynamics of propagation over network nodes. This approach provides physical intuition for macro-level management of risks and resilience in supply chains (propagation of disruptions, bottlenecks), and lays the groundwork for policies at the level of port clusters and corridors. In turn, [4] formulates safe navigation as an MPC problem with probabilistic (chance-constrained) limitations, where “safety” is represented by barrier functions/admissible sets; trajectories are generated by an EMA router and safety is ensured within the control loop (PSB-MPC).

Further analogies are found in [5], which describes a risk-oriented “decision field” consistent with COLREGs and proposes a risk measure for vessel encounters based on entropy weights and TOPSIS, where the geometry of ship interaction (DCPA, TCPA, relative courses/speeds) is aggregated into a scalar risk indicator. Another study that introduces spatio-temporal barriers (ship domain) and combines them with local path planning also defines a “trust zone” (ship domain). This continues the classical physical analogy with potential/repulsive fields for collision avoidance, but reinforces it with kinematic–geometric constraints and COLREGs requirements [6].

In conceptual modelling of safety processes in the maritime sector, a controlled “flow” structure (stock–flow system) is considered separately in [7]. The authors model port congestion using a system-dynamics approach: causal feedback loops between hinterland demand, throughput capacity and sets of governance measures (infrastructure, multimodality, “smart strategies”, interconnectivity). However, these approaches are not directly suitable for designing a comprehensive maritime safety project that explicitly accounts for the human factor, as they remain narrowly focused on specific processes within the maritime domain.

Instead, attention is drawn to physical analogies of a gravitational–inertial nature, where the state of the system depends on moments and forces that keep an axis aligned in response to external disturbances. Similar ideas have appeared in other societal domains. The first example was identified in a book review that introduces a political metaphor in which a “compass” sets the direction through science, while a “gyroscope” stabilizes via a policy of “limited conflict” and dialogue within communities of citizens. This provides a valuable framework for public policy, but the paper does not offer formalization or precise definitions for the model [8].

Subsequently, the notion of a “cultural gyroscope” was found in [9]. The authors treat the conceptual level of culture as the axis, the institutional/behavioral/artefact levels as the “flywheel”, the employee as a “particle” on the flywheel, and entrepreneurship as the driving force of rotation.

While this idea is conceptually interesting, it remains too abstract for application in large-scale project management systems for maritime safety. A similar idea appears in macro-social and economic analysis, where the author introduces the notion of a "gyroscope-like economy": systems that maintain quasi-equilibrium only due to high "rotation speed" – hyper-mobility of people, goods and capital; once rotation slows down, failures emerge [10].

A more formalized use of gyroscopic framing is presented in an article where the authors apply it to digital transformation. They sketch physical analogues and map them to controllable factors: moment of inertia ↔ urban infrastructure (carrier of stability), "angular velocities" ↔ target thrust and the mechanism of the economic cycle. However, the proposed model is predominantly descriptive and verification-oriented: it identifies that infrastructure, knowledge and the economy correlate with the "effect" of transformation. It relies on an empirical panel and demonstrates statistically significant coefficients for the "infrastructure–knowledge–economy" triad.

By contrast, the maritime sector requires a control-oriented model that explicitly defines regulators. In other words, what is needed is a controllable physical-type model with thresholds, laws of precession and gravitation, and a direct operational linkage to open maritime data and managerial actions. Such a model would be suitable not only for "explaining" but also for actively managing a company and an industry-level programme in real time.

Research objectives. Based on the literature review, it can be stated that although there exist effective approaches and conceptual analogues for describing individual processes in the maritime domain, they do not cover all aspects of maritime safety at the macro level, generally lack formalization and measurable indicators, focus on isolated subsystems of the sector, and do not take into account project life cycles and mission in a global representation.

For this reason, the development of a comprehensive concept within a project-oriented framework for maritime safety management is proposed, which should provide a reference, controllable dynamics with stable benchmarks and well-defined stability thresholds.

By analogy with a gravitational–inertial device embedded in a project macro-environment, such a conceptual model must have a vertical axis corresponding to the project mission; an angular deviation representing strategic drift; spin representing the operational execution rhythm; and a longitudinal moment of inertia reflecting process maturity and institutional capacity. In the model, the external moment of forces is treated as the aggregated pressure of norms, oversight and environmental events, while precession corresponds to the frequency of reprogramming and revision of policies and requirements. The reserve of stable motion is interpreted as execution inertia, which determines the system's ability to maintain course without breakdowns and emergency reorientations.

Normative "gravitation" in the model is represented by the requirements of international conventions, national regulations and safety standards; it pulls the system towards its mission and generates corrective influence only when deviations occur. Hence, the key controllable levers are: increasing project maturity, maintaining a uniform execution rhythm, and reducing external and internal pressure through risk prevention and harmonization of interpretations. At the level of a state, sector or maritime cluster, the impulses of subsystems are aggregated: the better the "mission axes" of individual programmer and organizations are aligned, the lower the need for frequent reprogramming under a given level of external pressure.

In this formulation, the physical analogy of a gyroscopic device is used not as a mere metaphor but as a clearly structured state space for the control problem. The mission axis, execution rhythm and process maturity are mapped to the variables θ, ω_3 and I_3, respectively, while the external pressure of norms and risks is mapped to the disturbance torque τ and the indices H_t, G_t and S_t. Accordingly, the control problem is formulated as governing the evolution of these physically interpretable variables so as to satisfy the stability condition $L \geq L_{crit}$ and to minimise the precession frequency Ω. In other words, the gravitational–inertial model serves as the mathematical backbone that links the practical task of maritime safety management to a well-defined dynamical system with explicit control laws.

The aim of this study is to develop and validate a controllable gravitational–inertial macromodel of maritime transport safety and to implement it as a software-supported tool for multi-project management. To achieve this aim, the following objectives are set:

1. To formalize the analogy between the physical gyrocompass device and the structure of the safety multi-project by defining a consistent system of aggregated indicators (ω_3, I_3, H_t, G_t, S_t, θ, τ, L);

2. To construct influence matrices that link the eight safety segments P_1–P_8 with these indicators on the basis of expert weights and EMSA data;

3. To formulate a stability threshold and controllability laws describing how changes in segment levels affect the momentum L and the precession frequency Ω;

4. To implement an optimization module in Python that solves a weighted least-squares problem and generates discrete recommendations for different regional scenarios;

5. To demonstrate, on six representative scenarios for the European region, how the proposed control mechanism transforms crisis and stressed regimes into a new balanced state.

Main part of the research. From the methodological point of view, the proposed model is operationalized through a sequence of clearly reproducible steps. First, EMSA accident investigation reports and related open statistics are analyzed to derive expert weights that quantify the influence of the eight safety segments P_1–P_8 on the macro-indicators (ω_3, I_3, H_t, G_t, S_t, θ, τ); these weights are encoded in Tables 2–4 and normalized to form the influence matrix A. Second, amplitude ranges for each macro-parameter are specified on the basis of engineering judgement, which yields the diagonal scaling matrix D and the signed influence matrix B. Third, six representative regional scenarios are constructed (Table 5) by fixing plausible combinations of ω_3, I_3, H_t, G_t, S_t, θ, τ that correspond to baseline, stressed and crisis regimes. Fourth, for each scenario the control problem $x^* - x^s = B\Delta p^s$ is solved in a weighted least-squares sense under the stability constraint $L \geq L_{crit}$. Finally, the continuous solution Δp^s is discretized into integer levels $\Delta P_i \in \{-2,...,2\}$, which are interpreted as expert recommendations to strengthen, maintain or unload the corresponding segments. Taking into account the above features of the gravitational–inertial concept, we then construct a set of variable parameters with controllable elements of portfolios, programmes and projects within large maritime organizations and cluster systems (Table 1).

Table 1 – Variable parameters of the gravitational–inertial concept

Physical variable/parameter	***Interpretation in project management (macro level)***
Vertical axis (upward direction)	Mission and strategic objectives
Angle θ	Deviation from the mission (strategic loss of project synchronization)
Spin ω_3	Working execution cadence (stable rhythm of planning/ delivery/ audits, throughput capacity)
Precession Ω	Cadence of managerial reorientations (frequency of priority/ policy revisions)
Longitudinal moment of inertia I_3	System maturity (standards, processes, competencies, IT infrastructure, institutional memory)
Transverse moment of inertia $I_\perp$	Stiffness of interactions between subsystems (unified regulations, inter-agency alignment)
Angular momentum $L = I_3\omega_3$	Systemic execution inertia (resilience to turbulence)
Gravitational moment $\tau = mgl\sin\theta$	Aggregate external pressure (regulatory functions, market, risk events, societal demands)
Gravity g	Aggregate set of IMO, flag State and international maritime safety norms and rules, ISPS Code, etc.
Losses $dE/dt \leq 0$	Operational losses (bureaucracy, duplication, “manual” approvals, technical debt)

The analogies in Table 1 are chosen so that each physical variable captures a distinct managerial role. The vertical axis of the spinning top corresponds to the mission and strategic objectives because it defines the reference direction in space relative to which all deviations are measured. The spin ω_3 reflects the execution cadence of the multi-project, as the rotation speed determines how much stabilizing inertia can be accumulated. The longitudinal moment of inertia I_3 is mapped onto process maturity: a more "massive" and structured safety system is harder to deflect from its course. The gravitational moment $\tau = mgl\sin\theta$ aggregates the pressure of regulatory, market and societal forces, which tend to pull the system back towards the mission axis when deviations occur. In this way, the physical structure of the model directly mirrors the architecture of macro-level maritime safety management.

Analogy between g and "normative gravity". Let introduce the normative gravity vector (2):

$$\mathbf{g}_N(t) = G(t)\mathbf{e}_z, \quad (1)$$

where $G(t) \geq 0$ represents the aggregated pressure of norms and rules, and $\mathbf{e}_z$ is the "mission vertical" (normative axis) fixed in space (2).

$$G(t) = k_g\left(\sum_{r\in R} w_r R_r(t) + \sum_{q\in Q} v_q Q_q(t)\right). \quad (2)$$

Here R_r is an indicator of the intensity of the corresponding regime (frequency and strictness of inspections, penalty coefficients, new mandatory requirements, security levels, etc.); Q is a group of situational factors (geopolitics, war risks, hydro- and meteorological conditions, social pressure); $Q_q(t)$ are normalized indices of the influence of such factors; w_r, $v_q \geq 0$ are influence weights; $k_g > 0$ is a scaling coefficient in the torque units of the model. The interpretation is that $G(t)$ is the "pull-to-vertical factor", i.e. the combined effect of norms and environment at a given moment (3).

$$|\tau| = mgl\sin\theta,\ |\tau_N(\theta,t)| = \left|-\frac{\partial V_N}{\partial\theta}\right| = mG(t)l\sin\theta. \quad (3)$$

Taken together, Eqs. (1)–(3) formalise the normative-gravity block of the model. Equation (1) defines the normative gravity vector $g_N(t)$ as a vector aligned with the mission axis $\mathbf{e}_z$ whose magnitude $G(t)$ represents the aggregated pressure of maritime norms and rules; Eq. (2) decomposes $G(t)$ into weighted contributions of regulatory regimes $R_r(t)$ and situational factors $Q_q(t)$; Eq. (3) converts this pressure into a gravitational torque $\tau_N(\theta, t)$ that increases with the deviation angle θ, capturing how mission misalignment generates corrective forces in the system.

We then assume that the corresponding relationships between $G(t)$, the gravitational torque and the system state hold. From this it follows that normative "gravity" does not generate a moment about axis 3, and therefore the projection $L = I_3\omega_3$ is preserved.

Law of controlled precession (macro level) (4).

$$\Omega_{sys} \approx \frac{\tau_{sys}}{I_{3,sys}\cdot\omega_{3,sys}}. \quad (4)$$

Equation (4) expresses the macro-level precession frequency Ω_{sys} as the ratio of the total disturbance torque τ_{sys} to the axial momentum $I_{3,sys}\omega_{3,sys}$; in other words, the higher the maturity $I_{3,sys}$ and execution rhythm $\omega_{3,sys}$, or the lower the disturbance torque τ_{sys}, the less frequently the multi-project has to be reprogrammed.

This leads to a direct organizational conclusion: in order to avoid "rocking" (an excessive frequency of project/portfolio reprogramming), it is necessary to increase system maturity $I_{3,sys}$ and maintain a stable execution cadence $\omega_{3,sys}$, while simultaneously reducing the external and internal torque τ_{sys} (risk prevention, harmonization of interpretations, transparency of decisions).

3. "Global system": aggregation at the level of state/industry/cluster (5).

For a set of coordinated subsystems $i = 1.N$:

$$L_{sys} = \sum_i L_i,\ \tau_{sys} = \sum_i \tau_i,\ \frac{dL_{sys}}{dt} = \tau_{sys}. \quad (5)$$

With well-aligned mission axes (6):

$$L_{sys} \approx \left(\sum_i I_{3,i} \right) \omega_{3,sys}, \; \Omega_{sys} \approx \frac{\sum_i \tau_i}{\left(\sum_i I_{3,i} \right) \omega_{3,sys}}. \tag{6}$$

System stability threshold: $L_{sys} \geq 2\sqrt{I_{\perp,\mathrm{sys}} m_{ef} g l_{ef} \cos\bar{\theta}}$.

Here $I_{\perp,sys}$ the first coefficient characterizes the "transverse" stiffness of inter-agency links; $m_{ef} g l_{ef}$ the second is the aggregate "weight" of external pressure; $\bar{\theta}$ the third is the mean deviation angle. Equations (5) and (6) show that, when the mission axes of subsystems are aligned, their individual momenta L_i and disturbance torques τ_i are aggregated into the overall momentum L_{sys} and precession frequency Ω_{sys} of the maritime safety system. The stability inequality defines a minimum value of L_{sys} that must be maintained, meaning that only above this threshold can the system operate in a controlled-precession regime without falling into chaotic reorientations. The meaning is that there exists a minimally required "powerful momentum" L_{sys} (the product of maturity and rhythm), below which a controlled precession regime of projects becomes impossible.

4. Formal model of controlled dynamics

4.1. Continuous time (strategic level). A continuous-time model is introduced in the form of a dynamic system (7, 8).

$$\dot{\theta} = f\left(\theta, \Omega, \ldots\right) + d\left(t\right); \tag{7}$$

$$\dot{\omega} = -\alpha\omega_3 - \beta \mathrm{loss} + u_\omega, \; \dot{I}_3 = -\delta I_3 + u_I, \tag{8}$$

where u_ω – "fine-tuning of rhythm" (rhythm of planning/delivery, preventive maintenance, staffing);

u_I – investments in maturity (standards, procedures, competencies, digitalization);

α, β, δ – loss parameters;

$d(t)$ – disturbances (risk events, regulatory changes).

Equations (7) and (8) jointly describe the continuous-time dynamics of the strategic variables. The first equation specifies how the deviation angle θ evolves under the influence of precession and external disturbances, while the second governs the evolution of execution rhythm ω_3 and maturity I_3 as a balance between natural losses and managerial control actions u_ω and u_I.

4.2. Discrete time (tactical / operational level; step = control period) (9, 10).

$$\theta_{k+1} = \theta_k - K_p \theta_k - K_d\left(\theta_k - \theta_{k-1}\right) + g\left(\frac{\tau_k}{I_{3,k\omega_3,k}}\right) + v_k; \tag{9}$$

$$\omega_{3,k+1} = \left(1-\alpha\right)\omega_{3,k} + u_{\omega,k} - \beta \mathrm{loss}_k, \; I_{3,k+1} = I_{3,k} + u_{I,k} - \delta I_{3,k}, \tag{10}$$

where K_p, K_d form a "PD controller" for mission alignment, and v_k denotes noise/disturbances.

Equations (9) and (10) provide a discrete-time counterpart of the continuous model for a chosen control period. They show how, at each step k, the controller updates the mission angle θ_k, execution cadence $\omega_{3,k}$ and maturity $I_{3,k}$ in response to current deviations, disturbance torque and the selected control actions, thus operationalizing the strategic dynamics for practical planning cycles.

The objective function F_p (a class of controlled optimization problems) (11). This objective function penalizes large deviations of the key indicators θ, Ω and the energy-related term, as well as excessive control efforts u_ω and u_I; it therefore encodes the trade-off between achieving a stable regime and limiting the cost and intensity of managerial interventions:

$$F_p = \min_{u_\omega, u_I} \sum_k \left[\omega_\theta \theta_k^2 + \omega_\Omega \Omega_k^2 + \omega_E E_k^2 + \omega_u \left(u_{\omega,k}^2 + u_{I,k}^2 \right) \right], \quad (11)$$

subject to the dynamic constraints and the stability threshold $L_k \geq L_{crit,k}$. This is a natural place for applying predictive control methods.

The four controllability laws derived from the obtained relations define the logic of macro-level management. First, the precession law states that the frequency of reorientation Ω increases with growth in the total external disturbance moment τ and decreases as maturity I_3 and operational rhythm ω_3 increase; therefore, before initiating frequent meetings or reprogramming cycles, I_3 should first be reinforced and ω_3 stabilized. Second, the threshold law asserts that when the momentum of stable motion is insufficient ($L < L_{crit}$), the system enters "nutations" – chaotic reorientations and emergency directives; consequently, the condition $L \geq L_{crit}$ must be treated as a hard policy constraint. Third, the energy law fixes that any losses accelerate the depletion of L ($dE/dt \leq 0$), so eliminating sources of loss directly extends the resource of the stable regime. Fourth, the axis alignment law indicates that the smaller the average angular mismatch θ between subsystems ("aligned missions"), the better the individual momentum vectors L_i add up in a single direction and the lower Ω_{sys} becomes for the same τ. Taken together, these provisions establish a hierarchy of managerial actions: priority is given to increasing I_3 and ω_3, guaranteeing the threshold L_{crit}, systematically removing losses, and aligning subsystems around a common mission (Fig. 1).

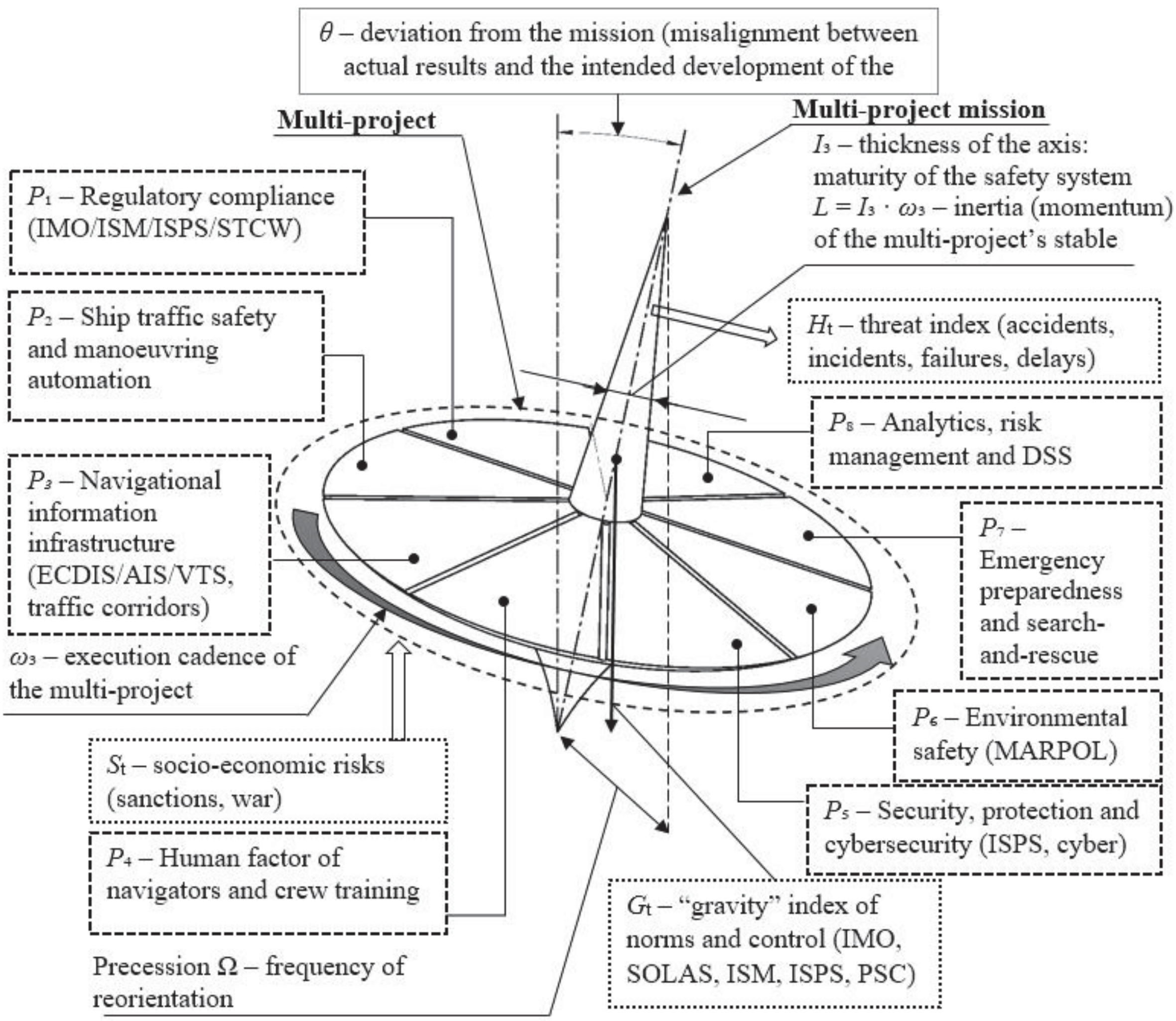

Figure 1 – Diagram of the dynamics of multi-project management in maritime safety

Within multi-project management, the set of tasks can thus be represented as a coherent programme of actions. First, integration is ensured: alignment of the "axes" of all projects with a common mission, minimization of the average deviation θ, and strengthening of inter-agency interface stiffness (growth of $I_{\perp}$). In parallel, a maturity ramp-up plan for I_3 is implemented: updating procedures and regulations, developing a competence framework, and deploying unified digital registers with a fixed increment step of the maturity indicator. The execution rhythm is stabilized through cadence-based planning, regular audits and preventive cycles, the use of WIP limits, and avoidance of "peaks/valleys" in throughput, which keeps the "spin" ω_3 at the specified level. Resource allocation is organized as a balance between long-term investments u_I (in maturity) and operational support u_ω (for rhythm), with the aim of minimizing the frequency of reorientations Ω under the constraint $L \geq L_{crit}$.

Risk management is directed at reducing the disturbance moment τ through event prevention, early detection of deviations, and unified interpretation of requirements, organized according to a "single window" principle for incidents. The quality and continuous improvement loop is oriented towards minimizing the loss rate dE/dt via elimination of duplication, automation, and targeted efficiency audits with the construction of a "loss map" along the value stream. Stakeholder communications are supported through a consistent information policy and regular reviews centred on the core metrics $\{\theta, \Omega, \omega_3, I_3\}$. When external disturbances increase, controlled pivots are executed: the trajectory is deliberately changed while preserving the I_3 core and following a transition plan that maintains the "spin" ω_3 and does not violate the stability condition. In this formulation, the multi-project becomes both controllable (via the threshold L_{cr}) and measurable (via standardized indicators), ensuring reproducibility of management decisions at the macro level.

Thus, the proposed physical gravitational–inertial model is transformed into a multi-project governance architecture in which maturity and execution rhythm control the frequency of reprogramming, while elimination of "losses" prolongs the "life cycle" of the stable regime of the multi-project. This model is sufficiently rigorous and, at the same time, operational for implementation in real macro-level maritime safety management systems.

Within the proposed model, the internal state of the maritime safety multi-project is described by three basic parameters: the execution cadence ω_3 (the rhythm of operational cycles), the integral process maturity I_3, and the generalized momentum of the stable regime $L = I_3\omega_3$.

In this context, the execution cadence ω_3 denotes the regularity and throughput of operational cycles (planning, service, audits, corrective actions) expressed on a dimensionless scale from "fragmented and irregular" to "continuous and well-paced". The integral process maturity I_3 characterises the degree to which safety-related procedures, competencies, digital tools and institutional memory are formalised and consistently applied. The momentum $L = I_3\omega_3$ therefore represents the reserve of stable motion of the multi-project: high values of L indicate that the system can withstand external disturbances without frequent emergency reorientations. Throughout the paper, these terms are used in this precise operational sense.

To formalize the impact of individual multi-project segments (P_1–P_8) on these parameters, it is reasonable to introduce an expert weight matrix that reflects the relative importance of each segment in maintaining work rhythm, process maturity and the ability of the system to preserve a stable regime under disturbances (Tables 2–4). For expert assessment, we use EMSA reports [11].

The second block of model parameters reflects the interaction of the multi-project with the risk environment, which is described by the threat index H_t, normative "gravity" G_t, socio-geopolitical risk index S_t, and the aggregated disturbance moment τ. These variables characterize how strongly external factors (incidents, regulatory requirements, sanction regimes, geopolitical events) affect the system, forcing it to change its precession, rhythm and even its overall operating mode.

To construct the influence weight matrices in Tables 2–4, an expert elicitation procedure was performed with $m = 6$ experts for $n = 8$ segments $P_1 - P_8$ using a discrete scale $s_{q,i}^{(e)} \in \{0,1,2,3\}$, where q denotes a model parameter (e.g., ω_3, I_3, H_t, G_t, S_t, θ, τ), i is the segment index, and e is the expert index. Aggregated weights for each parameter were computed by averaging and normalizing [12, 13] (12):

$$\bar{s}_{q,i} = \frac{1}{m}\sum_{e=1}^{m} s_{q,i}^{(e)},\ a_{q,i} = \frac{\bar{s}_{q,i}}{\sum_{j=1}^{n} \bar{s}_{q,j}}, \tag{12}$$

where $a_{q,i}$ is the normalized contribution of segment P_i to parameter q.

Inter-expert agreement was assessed by converting scores into ranks and computing Kendall's coefficient of concordance W_q (separately for each parameter q). For each expert e, the scores $\left\{s_{q,i}^{(e)}\right\}_{i=1}^{n}$ were transformed into ranks $r_{q,i}^{(e)}$ (higher score implies higher priority). In the presence of ties, average ranks were used: if a tied group of size t occupies positions $k,...,k+t-1$, then each element is assigned (13):

$$r = \frac{k+\left(k+t-1\right)}{2}. \tag{13}$$

Next, aggregated ranks and their dispersion were computed as (14):

$$R_{q,i} = \sum_{e=1}^{m} r_{q,i}^{(e)},\ \bar{R}_q = m\cdot\frac{n+1}{2},\ S_q = \sum_{i=1}^{n}\left(R_{q,i} - \bar{R}_q\right)^2. \tag{14}$$

Kendall's coefficient with tie correction is (15):

$$W_q = \frac{12S_q}{m^2\left(n^3-n\right)-mT_q},\ T_q = \sum_{e=1}^{m}\sum_{g=1}^{G_e}\left(t_{e,g}^3 - t_{e,g}\right), \tag{15}$$

where $t_{e,g}$ is the size of the g-th tied group in expert e ranking and G_e is the number of tied groups. If needed, the statistical significance of agreement was assessed using the chi-square approximation (16):

$$\chi_q^2 = m\left(n-1\right)W_q,\ df = n-1. \tag{16}$$

Table 2 – Influence of multi-project segments P_1–P_8 on parameters ω_3, I_3, L (0 – minimal; 3 – key)

Multi-project segment	***Contribution to ω_3 (cadence, rhythm)***	***Contribution to I_3 (project maturity)***
P_1. Regulatory and legal compliance	1	3
P_2. Safety of ship traffic control; automation of collision avoidance and manoeuvring	2	2
P_3. Navigational information infrastructure (ECDIS/AIS/VTS)	2	1
P_4. Human factor and crew training	1	3
P_5. Security, protection and cybersecurity	1	1..2
P_6. Environmental safety	1	1
P_7. Emergency preparedness and SAR	1	2
P_8. Analytics, risk management and DSS	2	3

Expert assessment of the contribution of segments P_1–P_8 to these indices makes it possible to identify those areas through which external disturbances are transmitted into the multi-project most intensively.

Table 3 – Influence of multi-project segments P_1–P_8 on parameters H_t, G_t, S_t, τ

Multi-project segment	***Contribution to H_t (operational threats)***	***Contribution to G_t (normative "gravity")***	***Contribution to S_t (socio-geopolitical risks)***	***Contribution to τ (disturbance moment)***
P_1. Regulatory and legal compliance	1	3	1	2
P_2. Safety of ship traffic control; automation of collision avoidance and manoeuvring	3	1	0	2
P_3. Navigational information infrastructure (ECDIS/AIS/VTS)	3	1	0	2
P_4. Human factor and crew training	2	1	0	2
P_5. Security, protection and cybersecurity	2	2	2	3
P_6. Environmental safety	2	2	1	3
P_7. Emergency preparedness and SAR	2	1	1	1..2
P_8. Analytics, risk management and DSS	1..2	1..2	1..2	2

It should be noted that, in the proposed model, the angle θ is treated as an integral indicator of the multi-project's deviation from the mission and strategic goals of the maritime safety system. Unlike local performance indicators, θ reflects the cumulative effect of structural, operational and social disruptions across different segments. Therefore, it is reasonable to introduce a separate table that captures not only the notional "weight" of each segment's influence on θ, but also the qualitative nature of this influence, i.e. how a given block can realign or, conversely, systematically distort the "mission" vector.

Table 4 – Influence of multi-project segments P_1–P_8 on deviation from mission θ

Multi-project segment	***Influence on θ (deviation from mission)***	***Brief description of impact on mission alignment***
P_1. Regulatory and legal compliance	2	Systematic non-compliance with IMO/ISM/ISPS/STCW requirements gradually diverts the system from its declared safety and reliability objectives.
P_2. Safety of ship traffic control; automation of collision avoidance and manoeuvring	2	Unsafe manoeuvres, COLREG violations and insufficient automation of collision avoidance directly undermine the mission of safe navigation.
P_3. Navigational information infrastructure (ECDIS/AIS/VTS)	2	Shortage or poor quality of navigational information leads to trajectories that do not match the target "safety corridors".
P_4. Human factor and crew training	2	Competence gaps, fatigue and typical navigator errors systematically shift operational practice away from the mission of safe and responsible fleet operation.

Continuation of table 4

P_5. Security, protection and cybersecurity	1	Security and cybersecurity incidents usually cause episodic, though sometimes sharp, deviations, without necessarily changing the long-term strategic vector.
P_6. Environmental safety	2	Ignoring environmental requirements contradicts the mission of sustainable maritime transport, creating a structural deviation from strategic goals.
P_7. Emergency preparedness and SAR	1	The level of emergency preparedness affects mainly the severity of consequences rather than the occurrence of deviations; therefore, its contribution to θ is indirect.
P_8. Analytics, risk management and DSS	3	This segment provides measurement, visualisation and controlled reduction of θ, turning the mission into a set of formalised criteria and regulatory actions.

We perform simulation modelling to assess how the states of the proposed model manifest themselves in the structural components of the maritime sector in the European region under six scenarios (Table 5).

We now carry out a numerical analysis for all scenarios. To this end, a formal calculation model is proposed, based on the data in Table 5 and the qualitative influence weights for segments $P_1 \ldots P_8$.

We first formalize the level of segments P_i. Let us introduce an activity level for each segment $p_i \in [0,3],\ i = 1,...,8$, where: 0 corresponds to a segment that is practically undeveloped / inactive;
3 corresponds to a segment that is maximally developed / prioritized; p_i is the quantitative representation of its influence.

After normalization we obtain scaled values $p_i^{`} = \frac{p_i}{3} \in [0,1]$.

Next, we construct the influence matrix from the tables and the state vector of the model. We take the vector of macro-parameters: $x = [\omega_3, I_3, H_t, G_t, S_t, \theta, \tau] \in R^7$, a $L = I_3\omega_3$ as a derived indicator. The weights from the tables are interpreted as coefficients: for each segment P_i we have weights on a 0…3 scale.

Table 5 – Summary data of simulation modelling for scenarios 1–6

Scenario	I_3	ω_3	H_t	G_t	S_t	θ°	τ	L_t	Ω	***Qualitative state***
1. Baseline stable	0.70	1.00	0.30	0.40	0.20	15	0.32	0.70	0.46	Stable, moderate precession
2. Norms tightening	0.70	1.00	0.30	0.70	0.20	18	0.44	0.70	0.63	Stable, but with increa-sing reprogramming frequency
3. Operational crisis	0.60	0.80	0.80	0.70	0.30	40	0.66	0.48	1.38	Unstable regime with “nutations”
4. Geopolitical shock	0.70	0.60	0.60	0.60	0.90	45	0.66	0.42	1.57	Unstable regime driven by external shock
5. Improvement programme	0.75	0.90	0.40	0.60	0.40	25	0.48	0.675	0.71	Transition towards a more stable regime
6. New balanced	0.85	1.0	0.20	0.50	0.30	10	0.34	0.935	0.4	Stable controlled precession regime

The data from Tables 2–4 are represented as normalized weights a_{ki}, obtained for example by dividing each raw weight by the sum of weights in the corresponding row (17).

$$a_{ki} = \frac{w_i^k}{\sum_{j=1}^{8} w_j^k}, \ k \in \{\omega, I, H, G, S, \theta, \tau\}. \tag{17}$$

In this way we obtain the influence matrix, which links the segment levels $P_1 \dots P_8$ to the macro-parameters of the "spinning top" model (18).

$$A = \begin{bmatrix} a_{\omega 1} & \dots & a_{\omega 8} \\ a_{I1} & \dots & a_{I8} \\ a_{H1} & \dots & a_{H8} \\ a_{G1} & \dots & a_{G8} \\ a_{S1} & \dots & a_{S8} \\ a_{\theta 1} & \dots & a_{\theta 8} \\ a_{\tau 1} & \dots & a_{\tau 8} \end{bmatrix} \in \text{Ÿ}^{7\times 8}. \tag{18}$$

Modelling over a time horizon with respect to the segment levels P_i. Can, in a static approximation, be written as $x = x_{\min} + D \cdot Ap$, where $p = [p_1, \dots, p_8]^T$ – is the vector of segment levels (normalized to [0,1]), $x_{\min}$ is the vector of minimal admissible parameter values, and $D = \operatorname{diag}(d_\omega, d_I, d_H, d_G, d_S, d_\theta, d_\tau)$ is a diagonal matrix of parameter amplitudes, i.e. the maximum range by which each parameter may change when all segment levels vary from $p_i = 0$ to $p_i = 1$.

For practical application, the model can be viewed as a mapping from an input scenario vector to an output vector of segment-level changes. The input consists of the current macro-parameters $x^{(s)} = [\omega_3, I_3, H_t, G_t, S_t, \theta, \tau]^T$ for a given scenario *s* and the corresponding target state x^*, which reflects the desired stability level (higher *L*, lower Ω, reduced risks). The model parameters include the influence matrix *B* and the priority matrix *W*, which are calibrated once from expert assessments and kept fixed. The outputs of the model are the continuous adjustment vector $\Delta p^{(s)}$ and its discretized form $\Delta P_i \in \{-2, \dots, 2\}$, which specify how much each segment P_i should be strengthened or unloaded. Thus, the proposed system explicitly separates fixed structural parameters, scenario-dependent inputs and decision outputs that can be directly interpreted by policymakers.

Therefore, for the risk parameters (H_t, G_t, S_t, θ, τ) it is reasonable to introduce a negative sign (19):

$$x_k = x_k^{\text{ref}} - d_k \sum_i a_{ki} p_i, \ k \in \{H, G, S, \theta, \tau\}, \tag{19}$$

where x_k^{ref} is the "worse" baseline level (without control), and strengthening the segments decreases the value of the parameter.

Equation (17) converts the expert scores w_j^k from Tables 2–4 into normalized influence coefficients a_{ki} that sum to one across segments for each macro-parameter *k*. The resulting matrix *A* in Eq. (18) collects these coefficients and links the development levels of segments P_1–P_8 to the macro-parameters of the "spinning-top" model. Equation (19) then adjusts the sign of the risk-related parameters so that strengthening the relevant segments corresponds to a decrease of H_t, G_t, S_t, θ and τ, which is consistent with their interpretation as threat and pressure indices.

In vector form, this property can be written as $x = b + Bp$, where *B* contains positive signs for ω_3, I_3 and negative ones for H_t, G_t, S_t, θ, τ.

In such an approach, if we take, for example, six scenarios with different multiproject parameters:

– the current state vector $x^{(s)}$,

– the desired (reference) state x^*.

Thus, we pose the problem $x^* - x^s = B\Delta p^s$,

where $\Delta p^{(s)}$ are the recommended changes of segment levels for scenario s.

Since the system is, as a rule, overdetermined (7 parameters, 8 segments) and partially contradictory, it is logical to formulate a least-squares problem with priority weights (20):

$$\min_{\Delta p^{(s)}} \left\| W\left(B\Delta p^{(s)} - \Delta x^{(s)}\right)\right\|_2^2, \ \Delta x^{(s)} = x^* - x^{(s)}, \ -p_i^{(s)} \le \Delta p_i^{(s)} \le 1 - p_i^{(s)}, \ i = 1,...,8. \qquad (20)$$

Thus we have the priority matrix of parameters: $W = \mathrm{diag}(w_\omega, w_I, w_H, w_G, w_S, w_\theta, w_\tau)$.

Then, conceptually, the solution can be represented in the form (21).

Equation (20) formulates the problem of finding the change vector $\Delta p^{(s)}$ that minimises the weighted discrepancy between the desired parameter shift $\Delta x^{(s)}$ and the shift generated by segment adjustments $B\Delta p^{(s)}$, subject to capacity bounds for each segment. Equation (21) provides the closed-form solution of this weighted least-squares problem and is used in the software module to compute recommended changes for each scenario.

$$\Delta p^{(s)} = \left(B^T W^2 B\right)^{-1} B^T W^2 \Delta x^{(s)}. \qquad (21)$$

We proceed to ranges of adjustments depending on the scenario parameters.

For a practical solution $\Delta p^{(s)}$ it is advisable to move to discrete levels of intensity. To this end, we introduce the normalized magnitude of change for each segment: $r_i^{(s)} = \left|\Delta p_i^{(s)}\right|$.

Further, we set threshold levels for different scenarios:

$0 \le r_i^{(s)} < 0.1$ – "maintain the current level", $\Delta P_i = 0$;

$0.1 \le r_i^{(s)} < 0.2$ – "moderately strengthen/weaken", $\Delta P_i = \pm 1\, level$;

$r_i^{(s)} \ge 0.2$ – "significantly strengthen/weaken", $\Delta P_i = \pm 2\, level$.

The sign $\Delta p_i^{(s)}$ indicates which adjustment mode to assign:

– strengthen the segment (if $\Delta p_i^{(s)} > 0$);

– unload/simplify (if $\Delta p_i^{(s)} < 0$), which is important for scenarios where the system is overloaded.

Thus, for each scenario s the algorithm provides: set $x^{(s)}$ → determine the target x^* → choose the priority matrix $W^{(s)}$ → solve the least-squares problem for $\Delta p^{(s)}$ → reclassify $\Delta p^{(s)}$ into discrete recommendation levels for each P_i.

During corrective actions, L and the stability threshold must be taken into account. Thus, we separately monitor: $L = I_3 \omega_3$, $L_{кр}$ – the specified threshold.

After determining $\Delta p^{(s)}$, through the formulas for ω_3 and I_3 we obtain (22):

$$\omega_3^{new} = \omega_3^{(s)} + \Delta\omega_3^{(s)}, \ I_3^{new} = I_3^{(s)} + \Delta I_3^{(s)}, \ L^{new} = I_3^{new} \cdot \omega_3^{new}. \qquad (22)$$

Equation (22) maps the recommended segment changes into updated values of execution rhythm ω_3^{new}, maturity I_3^{new} and the resulting momentum L^{new}; these quantities are then compared with the stability threshold to verify whether the controlled scenario has indeed been moved into a stable regime.

In cases where $L^{new} \ge L_{crit}$, the system signals that the set Δp is insufficient – it is necessary either to increase the target values of ω_3, I_3, or to add the constraint $L^{new} \ge L_{crit}$ to the optimization problem.

Thus, we further proceed to the software implementation of the expert system for analyzing the state of the multiproject of maritime safety management.

Within the framework of the study, a full-fledged software module in Python was implemented and designed as a standalone script. At the beginning of the code, the main libraries are imported: `os` for working with the file system, `numpy as np` for vector computations, `pandas as pd` for tabular data structures, and `matplotlib.pyplot as plt` for plotting. A constant `RESULTS_DIR = r"...\Resalt"` is defined, after which the results folder is automatically created, if it does not yet exist, by means of `os.makedirs(RESULTS_DIR, exist_ok=True)`. The input data arrays are then formed: the scenarios are specified as `pd.DataFrame({...})` with the columns `"Scenario", "I3", "ω3", "Ht", "Gt", "St", "θ", "τ"`, as well as control fields `"L_paper"` and `"Omega_paper"`. The control indicators are computed using vector operations `scenarios["L_calc"] = scenarios["I3"] * scenarios["ω3"]` and `scenarios["Omega_calc"] = scenarios["τ"] / scenarios["L_calc"]`, after which the table is saved to a file by `to_csv(..., encoding="utf-8-sig")`.

The next block of code is responsible for constructing the model matrices. The influence weights of segments $P_1 \dots P_8$ are described by separate `np.array` arrays (`W_omega, W_I3, W_Ht, W_Gt, W_St, W_tau, W_theta`), which are combined into a “raw” matrix using `np.vstack`. Row-wise normalisation is implemented via the division operation `weights_raw / weights_raw.sum(axis=1, keepdims=True)` using broadcasting; the result is then converted into a DataFrame `A_df = pd.DataFrame(A,index=param_names, columns=[f"P{i+1}" for i in range(8)])`. The parameter amplitudes are specified in the vector `d_vec = np.array([...])`, and the signs are specified in the array `signs = np.array([+1, +1, -1, -1, -1, -1, -1])`. The influence matrix B is formed by the compact command `(signs[:, None] * d_vec[:, None])* A` and then saved to a file via `B_df.to_csv(...)`. To specify the importance of the parameters, a diagonal priority matrix is used, `W = np.diag(W_diag)`, where `W_diag = np.array([1, 1, 1, 1, 1, 1, 1])`.

The core of the expert system is implemented in two functions. The function `compute_recommendations(x_current, x_target, B, W, segments, thresholds=(0.1, 0.2))` takes the current and target state vectors, converts them into NumPy arrays (`np.asarray(..., dtype=float)`), computes the difference `delta_x = x_target - x_current`, and solves a weighted least-squares problem via `np.linalg.solve(BW.T @ BW, BW.T @ rhs)`, where `BW = W @ B` and `rhs = W @ delta_x`. The segment modification vector `delta_p` is then formed, together with the intensities `r = np.abs(delta_p)` and the discrete levels `deltaP_disc`, which are determined by conditional operations on arrays (`deltaP_disc[(r >= t1) & (r < t2)] = 1`, etc.) and are converted into textual recommendations. The new configuration of parameters is calculated as `x_new = x_current + B @ delta_p`, and all results are stored in a DataFrame `rec_df = pd.DataFrame({...})`.

The second function, `classify_state(...)`, implements a simple logical classifier that, based on thresholds for `L`, `Omega`, `Ht`, `St`, and `θ`, returns a textual category of the state (“Stable controlled precession”, “Conditionally stable”, “Unstable”). In the main loop `for idx, row in scenarios.iterrows():` the program sequentially processes all scenarios, accumulates the new states in `new_states`, aggregates the recommendations via `pd.concat(all_rec_dfs,ignore_index=True)`, and exports the consolidated results to the files `new_states_after_control.csv` and `segment_recommendations_all_scenarios.csv`. The final visualisation block uses matplotlib: plots are constructed with `plt.plot(...)`, `plt.bar(...)`, labels are configured (`plt.title, plt.ylabel, plt.xticks(rotation=20)`), and then saved as PNG files `L_by_scenario.png`, `Omega_by_scenario.png`, and `DeltaP_scenario3_operational_crisis.png` via `plt.savefig(os.path.join(RESULTS_DIR, "..."), dpi=300)` followed by `plt.close()`. This demonstrates that a complete software tool has been developed, which combines tabular analytics, linear algebra, and graphical presentation of results within a single code base. As a result of the simulation modelling, the plots shown in Figs. 2–4 were obtained.

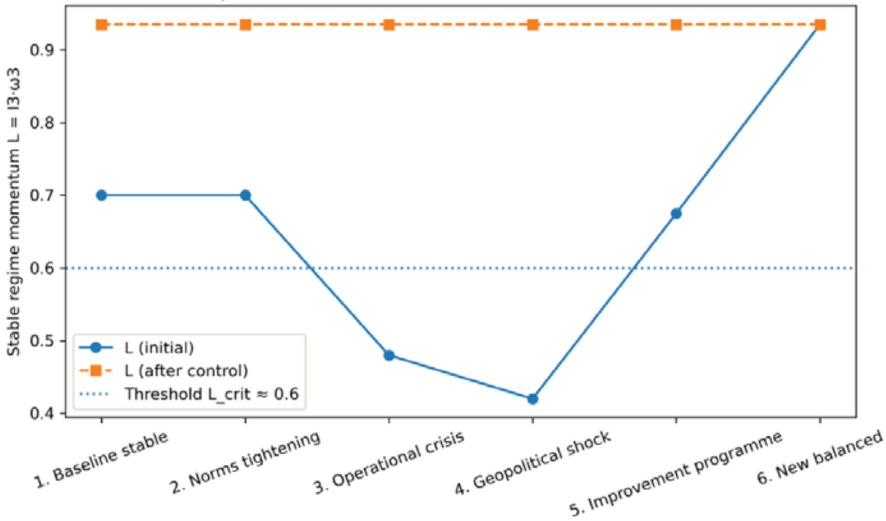

Figure 2 – Stable-regime momentum *L*

Figures 2–4 visualise the dynamics of the model for the six scenarios introduced in Table 5. For each scenario, the "initial" point corresponds to the uncontrolled state $x^{(s)}$, while the "after control" point is obtained by applying the recommended changes ΔP_i and recomputing L and Ω according to the formulas in Section 4.2. Thus, the trajectories on the plots explicitly show how the optimisation procedure changes the momentum of the stable regime, the precession frequency and the configuration of segment levels over the scenario set.

The plot of the stable-regime momentum L shows that, in the initial state, scenarios 3 ("Operational crisis") and 4 ("Geopolitical shock") have L values below the threshold $L_{crit} \approx 0.6$, while scenario 5 lies close to this boundary, which corresponds to unstable or borderline regimes. After control is applied, all six scenarios converge to the same level $L_{new} \approx 0.935$, which significantly exceeds the threshold, i.e. the model drives any scenario into a stable, balanced regime.

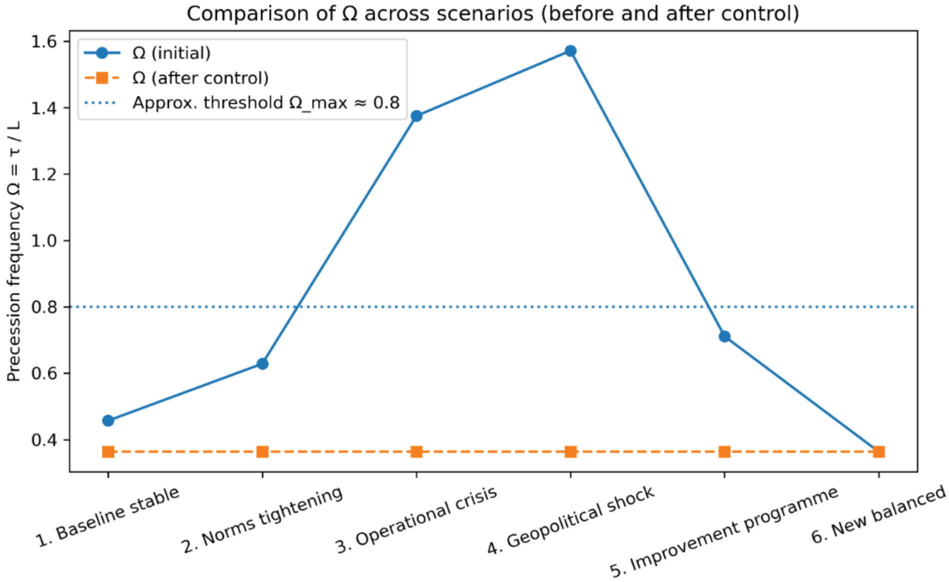

Figure 3 – Precession frequency Ω

The plot of the precession frequency $\Omega = \tau / L$ shows that, before control, scenarios 3 and 4 significantly exceed the recommended threshold $\Omega_{max} \approx 0.8$ (reprogramming frequency > 1.3–1.5), while scenario 5 approaches a critical level. After applying the control actions, all scenarios have the same value $\Omega_{new} \approx 0.36$, which is well below the threshold, meaning that the system moves into a calm, well-controlled regime with infrequent reconfigurations.

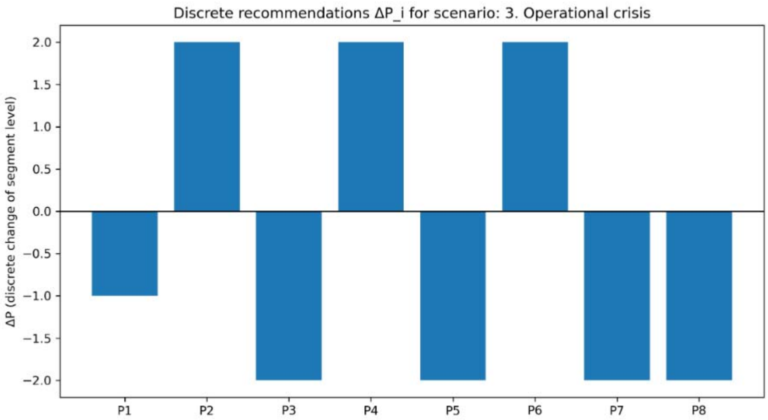

Figure 4 – Bar chart of discrete recommendations ΔP_i

The bar chart of discrete recommendations ΔP_i for the “Operational crisis” scenario illustrates how efforts are redistributed across the segments. The model suggests moderately reducing the load in the regulatory compliance segment (P_1), significantly strengthening segments P_2, P_4, and P_6 (manoeuvring, human factor, environmental safety), and significantly simplifying/unloading P_3, P_5, P_7, and P_8 (navigational infrastructure, security and cybersecurity, emergency readiness, analytics and DSS). This change profile proves sufficient to move the scenario out of operational crisis into the same stable “new balanced” state as for the other scenarios.

A separate program-generated report of the calculations by scenario is formed (Fig. 5).

```
Check of L and Ω against Table 5 (paper vs calculated):
                Scenario  L_paper  L_calc  Omega_paper  Omega_calc
0       1. Baseline stable    0.700   0.700         0.46    0.457143
1      2. Norms tightening    0.700   0.700         0.63    0.628571
2     3. Operational crisis    0.480   0.480         1.38    1.375000
3     4. Geopolitical shock    0.420   0.420         1.57    1.571429
4  5. Improvement programme    0.675   0.675         0.71    0.711111
5           6. New balanced    0.935   0.935         0.40    0.363636
```

```
Normalised influence matrix A (row sums = 1):
       P1     P2     P3     P4     P5     P6     P7     P8
ω3  0.091  0.182  0.182  0.091  0.091  0.091  0.091  0.182
I3  0.194  0.129  0.065  0.194  0.097  0.065  0.065  0.194
Ht  0.061  0.182  0.182  0.121  0.121  0.121  0.121  0.091
Gt  0.240  0.080  0.080  0.080  0.160  0.160  0.080  0.120
St  0.133  0.000  0.000  0.000  0.267  0.267  0.133  0.200
θ   0.133  0.133  0.133  0.133  0.067  0.133  0.067  0.200
τ   0.114  0.114  0.114  0.114  0.171  0.171  0.086  0.114
Row-sum check: {'ω3': 1.0, 'I3': 1.0, 'Ht': 1.0, 'Gt': 1.0,
```

```
Matrix B (with amplitudes and signs):
       P1     P2     P3     P4     P5     P6     P7     P8
ω3  0.045  0.091  0.091  0.045  0.045  0.045  0.045  0.091
I3  0.058  0.039  0.019  0.058  0.029  0.019  0.019  0.058
Ht -0.036 -0.109 -0.109 -0.073 -0.073 -0.073 -0.073 -0.055
Gt -0.096 -0.032 -0.032 -0.032 -0.064 -0.064 -0.032 -0.048
St -0.093 -0.000 -0.000 -0.000 -0.187 -0.187 -0.093 -0.140
θ  -5.333 -5.333 -5.333 -5.333 -2.667 -5.333 -2.667 -8.000
τ  -0.046 -0.046 -0.046 -0.046 -0.069 -0.069 -0.034 -0.046
```

In addition, automated recommendations were generated for each scenario (Fig. 6).

```
SCENARIO: 1. Baseline stable
Current state x^(s): {'ω3': 1.0, 'I3': 0.7, 'Ht': 0.3, 'Gt': 0.4, 'St': 0.2, 'θ': 15.0, 'τ': 0.32}
Desired state x*:    {'ω3': 1.1, 'I3': 0.85, 'Ht': 0.2, 'Gt': 0.5, 'St': 0.3, 'θ': 10.0, 'τ': 0.34}

Recommended changes of segment levels P1–P8:
                                   Segment  delta_p_continuous  intensity_r = |delta_p|  deltaP_discrete                Recommendation          Scenario
P1. Regulatory compliance (IMO/ISM/ISPS/STCW)             -1.467                    1.467               -2 significantly decrease segment 1. Baseline stable
  P2. Traffic safety & manoeuvring automation              6.436                    6.436                2 significantly increase segment 1. Baseline stable
 P3. Navigational information (ECDIS/AIS/VTS)             -6.282                    6.282               -2 significantly decrease segment 1. Baseline stable
            P4. Human factor & crew training               0.727                    0.727                2 significantly increase segment 1. Baseline stable
    P5. Security, protection & cybersecurity              -0.874                    0.874               -2 significantly decrease segment 1. Baseline stable
           P6. Environmental safety (MARPOL)              -0.770                    0.770               -2 significantly decrease segment 1. Baseline stable
               P7. Emergency readiness & SAR               1.905                    1.905                2 significantly increase segment 1. Baseline stable
        P8. Analytics, risk management & DSS               1.185                    1.185                2 significantly increase segment 1. Baseline stable
```

```
SCENARIO: 3. Operational crisis
Current state x^(s): {'ω3': 0.8, 'I3': 0.6, 'Ht': 0.8, 'Gt': 0.7, 'St': 0.3, 'θ': 40.0, 'τ': 0.66}
Desired state x*:    {'ω3': 1.1, 'I3': 0.85, 'Ht': 0.2, 'Gt': 0.5, 'St': 0.3, 'θ': 10.0, 'τ': 0.34}

Recommended changes of segment levels P1–P8:
                                   Segment  delta_p_continuous  intensity_r = |delta_p|  deltaP_discrete                Recommendation            Scenario
P1. Regulatory compliance (IMO/ISM/ISPS/STCW)             -0.185                    0.185               -1    moderately decrease segment 3. Operational crisis
  P2. Traffic safety & manoeuvring automation             14.734                   14.734                2 significantly increase segment 3. Operational crisis
 P3. Navigational information (ECDIS/AIS/VTS)             -9.326                    9.326               -2 significantly decrease segment 3. Operational crisis
            P4. Human factor & crew training               1.212                    1.212                2 significantly increase segment 3. Operational crisis
    P5. Security, protection & cybersecurity              -3.308                    3.308               -2 significantly decrease segment 3. Operational crisis
           P6. Environmental safety (MARPOL)               7.032                    7.032                2 significantly increase segment 3. Operational crisis
               P7. Emergency readiness & SAR              -2.148                    2.148               -2 significantly decrease segment 3. Operational crisis
        P8. Analytics, risk management & DSS              -3.409                    3.409               -2 significantly decrease segment 3. Operational crisis
```

```
SCENARIO: 5. Improvement programme
Current state x^(s): {'ω3': 0.9, 'I3': 0.75, 'Ht': 0.4, 'Gt': 0.6, 'St': 0.4, 'θ': 25.0, 'τ': 0.48}
Desired state x*:    {'ω3': 1.1, 'I3': 0.85, 'Ht': 0.2, 'Gt': 0.5, 'St': 0.3, 'θ': 10.0, 'τ': 0.34}

Recommended changes of segment levels P1–P8:
                                   Segment  delta_p_continuous  intensity_r = |delta_p|  deltaP_discrete                Recommendation               Scenario
P1. Regulatory compliance (IMO/ISM/ISPS/STCW)             -0.227                    0.227               -2 significantly decrease segment 5. Improvement programme
  P2. Traffic safety & manoeuvring automation             -7.526                    7.526               -2 significantly decrease segment 5. Improvement programme
 P3. Navigational information (ECDIS/AIS/VTS)              7.216                    7.216                2 significantly increase segment 5. Improvement programme
            P4. Human factor & crew training               2.817                    2.817                2 significantly increase segment 5. Improvement programme
    P5. Security, protection & cybersecurity               2.536                    2.536                2 significantly increase segment 5. Improvement programme
           P6. Environmental safety (MARPOL)              -2.900                    2.900               -2 significantly decrease segment 5. Improvement programme
               P7. Emergency readiness & SAR              -0.277                    0.277               -2 significantly decrease segment 5. Improvement programme
        P8. Analytics, risk management & DSS               1.535                    1.535                2 significantly increase segment 5. Improvement programme
```

Figure 6 – Results of scenario-based modelling of the expert proposal

The resulting automated recommendations may be useful when implementing corrective actions at the macro level of the maritime safety multiproject operation [14–18].

The scientific contribution of this work is threefold. First, a physically consistent gravitational–inertial macro-model of maritime safety is formulated, in which the mission, execution rhythm, process maturity and external pressure are embedded into a single controllable state-space with an explicit stability threshold L_{crit}. Second, a new system of aggregated indicators and influence matrices is proposed that connects eight safety segments $P_1 - P_8$ with the macro-parameters (ω_3, I_3, H_t, G_t, S_t, θ, τ, L) and allows one to derive scenario-specific recommendations by solving a weighted least-squares problem under stability constraints. Third, a full software implementation of the model in Python is developed, which integrates data ingestion, linear-algebra computations, optimization and visual analytics, and demonstrates, on real-world inspired scenarios, how crisis and stressed regimes can be systematically transformed into a stable controlled precession regime.

In contrast to the above works, which either employ physical metaphors in a qualitative way or focus on specific subsystems of the maritime domain, the present study develops a fully formalized and computable gravitational–inertial model tailored to macro-level maritime safety management. The control laws, stability threshold and optimization procedure are derived explicitly within this model and are not borrowed from existing gyroscopic analogies. At the same time, standard building blocks such as least-squares estimation and PD-type regulation are used in a classical manner and are referenced accordingly, while the integration of these elements into a coherent multi-project governance framework constitutes the principal original contribution of the paper.

Conclusion. Therefore, the results reported here should be regarded not as a restatement of known physical models, but as a new project-oriented methodology that rigorously combines the gravitational–inertial analogy, aggregated safety indicators and software-supported scenario optimization for maritime transport safety.

The project-oriented approach based on the gravitational–inertial model proposed in this study forms an integrated framework for managing maritime transport safety at the macro level. The model incorporates a system of aggregated parameters (execution rhythm ω_3, process maturity I_3, threat indices H_t, normative “gravity” G_t, socio-geopolitical risks S_t, strategic deviation θ, disturbance torque τ and the impulse of the stable regime L), as well as multiproject segments P_1–P_8 that represent key safety domains – from regulatory compliance and the human factor to cybersecurity, environmental safety and DSS. Based on expert weights, influence matrices were constructed and a Python software module was developed that automates scenario assessment, solves a weighted least-squares problem to determine optimal changes in segment levels, and provides discrete recommendations on their strengthening or unloading. Simulation of six typical scenarios for the European region showed that application of the proposed control mechanism makes it possible to transform both crisis [19, 20] and stressed regimes into a stable balanced state with an increased impulse L and a reduced precession frequency Ω, thus ensuring proactive corrective actions at the maritime safety level.

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Носов П. С. ПРОЄКТНО-ОРІЄНТОВАНИЙ ПІДХІД У ЗАВДАННЯХ УПРАВЛІННЯ БЕЗПЕКОЮ МОРСЬКОГО ТРАНСПОРТУ ЗА ПРИНЦИПОМ ГРАВІТАЦІЙНО-ІНЕРЦІЙНОЇ МОДЕЛІ

У даній статті запропоновано проєктно-орієнтований підхід щодо управління безпекою морського транспорту що спирається на фізичні аналогії гравітаційно-інерційної моделі. В огляді літератури, показано, що традиційні підходи зосереджуються на окремих показниках і процесах морського транспорту: затримки, інциденти, невідповідності, однак це не надає цілісної керованої концепції сукупності проєктів безпеки та їх стійкості до зовнішніх і внутрішніх збурень.

У рамках статті розроблено формалізовану систему узагальнених параметрів, що включає в себе ритм виконання $\omega_З$, *зрілість* $I_З$, *індекси загроз* H_t, *нормативної «гравітації»* G_t, *соціально-геополітичних ризиків* S_t, *стратегічне відхилення* θ, *момент збурень* τ, *імпульс стійкого режиму* L. *Окремо додано сегменти мультипроєкту* P_1-P_8, *що охоплюють нормативну відповідність, керування рухом, навігаційну інфраструктуру, людський фактор, охорону й кібербезпеку, екологічну безпеку, аварійну готовність і СППР. Це дало можливість на основі експертних ваг побудовано матриці впливів і сформулювати закони керованості, порогові умови стійкості та критерії для мультипроєктного керування.*

Окремою частиною дослідження є розробка і застосування програмного модуля на мові Python (Anaconda JL), який реалізує задачі зважених найменших квадратів, автоматично оцінює імовірні сценарії та генерує експертні рекомендації щодо стабілізації стану безпеки морського транспорту. Результати імітаційного моделювання показали, що запропонований підхід дає змогу зменшувати загрози кризових режимів, наближати їх до стійкого збалансованого стану з підвищеним імпульсом L.

Практичне значення роботи полягає в тому, що модель може бути інтегрована в цифрові платформи моніторингу, використовувати відкриті дані EMSA, служб і контролюючих відомств у портах, компаніях та слугувати основою для формування складних мультипроєктів безпеки галузі морського транспорту, узгоджених із місією судноплавних компаній і міжнародних морських організацій.

Ключові слова: *проєктно-орієнтований підхід; гравітаційно-інерційна модель; мультипроєкт безпеки мореплавства; експертна система; сценарний аналіз; управління проєктами; автоматизація; Python; інтелектуальні системи.*

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