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BIOMIMETIC MODELLING IN TEACHING THE DISCIPLINE "ECONOMICS OF LABOUR AND SOCIAL LABOUR RELATIONS"

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The article proposes an integrated biomimetic framework for teaching and applied modelling in the discipline of "Labour Economics and Social and Labour Relations". At its core is a combination of three ideas: stigmergic coordination as a mechanism of indirect interaction through "traces" in a shared environment (substitution market, change boards, access rules), swarm optimisation (Ant Colony Optimisation, ACO) as the dynamics of reinforcing "successful" employee assignments – change by analogy with pheromone routes and Physarum networks as a model of the evolution of a reference network of assignments, in which the conductivity of useful connections "thickens" and ineffective channels "dry up" thanks to simple rules of reinforcement and evaporation. The framework is designed specifically for educational and management situations where it is necessary to balance operational quality (full coverage of changes, compliance with standards, minimization of the "price" of the schedule) with people-centred guidelines (fair distribution of time, consideration of preferences, ergonomics of working time and predictability), recommended by international guidelines. It provides teachers with a visual tool to demonstrate how local rules (penalties, weights, restrictions) create macro-level equilibrium, and managers with a transparent methodology for constructing fair and resilient schedules that are acceptable to social partners. Theoretically, the article draws on contemporary trends in biomimetics in management and production systems, where self-organization, adaptation and resource allocation occur not according to command logic, but through local signals and minimal rules. Translated into the language of labour economics, this logic allows us to view the labour market and internal organizational schedules as networks that evolve in response to shortages/surpluses, preferences and regulatory constraints. The paper adopts a consistent, unified formulation of the problem in the form of a two-part graph "employees ↔ shifts", where each potential assignment corresponds to a cost function c(e) – a weighted sum of "hard" and "soft" components (night and holiday intervals, skill matching, preferences, overtime and fairness regulator (penalty for deviation of individual hours from the target range)). This formulation, firstly, makes the purpose of the model transparent to the audience and, secondly, allows the formation of a Pareto curve "quality ↔ fairness" and the selection of solutions acceptable to the parties to the social dialogue.

Keywords: biomimetic modelling, labour economics, social and labour relations, stigmergy, Ant Colony Optimisation (ACO), Physarum polycephalum, resilience, social dialogue.

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Introduction

The didactic module consists of two complementary lessons. The first, "Market of Change and Stigmergy," recreates the conditions of decentralised coordination through markers/traces: scarce changes "glow" brighter, participants compete/cooperate for "slots," and the teacher moderates the rules of signal honesty and limits. The second, “ACO/Physarum Simulator,” translates the intuition of stigmergy into a formal space: students adjust the weights of the “price” components, launch ACO or Physarum dynamics, observe how the necessary connections “thicken,” and evaluate decisions on the metrics panel. This pair of classes simultaneously develops systematic thinking (from local action to global patterns) and digital literacy in the areas of HR analytics and change management, which is a valuable learning outcome of the course “Labour Economics and Social and Labour Relations.”

Biometric models transfer the principles of self-organization, adaptation, resource allocation and coordination from biological systems (ecosystems, insect colonies, immune networks, vascular structures) to socio-economic analysis. Their strength lies in simple local rules (signals, “tags,” thresholds) that generate global order without rigid centralized control. Recent reviews in production systems and management demonstrate the explosive growth of biomimicry applications – from logistics to the design of sustainable organizations, with a focus on resilience, resource and energy efficiency, and flexibility to shocks [1; 2; 3; 4].

Methodologically, it is advisable to distinguish at least five classes of bio-inspired approaches relevant to the labour economy:

– swarm algorithms (ant/bee colonies) – searching for routes and schedules where “pheromone” reinforcements correspond to the best destinations and policies [5; 9; 12];

– physarum models – networks that “thicken” effective channels and “dry up” ineffective ones (useful for assignments and balancing time flows) [5; 13];

– stigmergy – indirect coordination through “tags” in a shared environment (message boards, substitution markets, application queues) [7; 8];

– epidemiological/network metaphors of risk – the spread of staff shortages and “chains” of disruptions (analogous to R_0 risk) for preventive planning of mixed changes and training [4];

– skill panarchy – adaptive r–K–Ω–α cycles at the individual/team/organisation/cluster levels (framework for reskilling policies and anti-fragile staffing strategies) [4].

The key advantages of biomimetic models for work lie in the combination of “hard” standards and “soft” preferences, in natural work with multiple criteria (efficiency, fairness, health, safety), and in explainability through the visual evolution of networks/ ”traces.” The versatility of these methods is confirmed in manufacturing, logistics, and educational and management contexts [1; 2; 3; 4].

Analysis of research and publications

Biomimetics in labour economics stems from a broader wave of work on transferring self-organization and adaptation mechanisms from biological systems to production and logistics processes. A review by Cohen et al. notes that nature-inspired approaches – from swarm algorithms to network metaphors – offer better manageability of complexity, energy and resource efficiency, and, most importantly, resilience in environments subject to shocks [1]. A new wave of publications emphasizes sustainable production, where biomimetics is conceived not as a mere “optimization trick” but as a framework for the regenerativity and renewability of systems [2; 4]. Management-oriented literature emphasizes the transition to an “ecosystemic” view of organizations – with horizontal connections, decentralization, and local decision-making rules [3]. Together, this creates a theoretical basis for rethinking the organization of labour as a network of roles, signals and constraints that evolves according to bio-like logic.

The second block of research is bio-inspired planning and scheduling algorithms. For tasks such as “employee-shift” and related production problems, swarm approaches (Ant Colony Optimisation, ACO) and derivatives are quite commonly used, which reproduce the “pheromone” dynamics of reinforcing successful decisions and “evaporating” unsuccessful ones [9; 12]. A number of studies show that ACO is suitable for both classic JSSP/FJSP and personnel scheduling, where it is important to combine “hard” standards with “soft” preferences [5; 9; 12]. A parallel line is Physarum models that mimic the behaviour of “smart slime mould”: useful channels “thicken” and ineffective ones fade away; this works well for network pathfinding tasks and can be interpreted as the dynamics of a reference network of destinations in work planning [5; 13]. In urban/infrastructure design, such approaches are already used as network “growth patterns” [11], which strengthens the argument in favour of their explainability to the audience of the academic discipline.

The third layer is stigmergy as a mechanism of indirect coordination through “traces” in a shared environment (message boards, exchange markets, application queues). Empirical work in knowledge management and collaborative platforms shows that stigmergic signals can scale collective activity without rigid centralization [7], and engineering research in the world of robotics mimics these mechanisms to create sustainable collective behaviours [8]. For the labour economy, this means that “light” traces of demand/shortage (shortages “glow” brighter) can reduce the transaction costs of coordination in daily operations and at the same time serve as a visual teaching tool.

The fourth block is fairness, working time ergonomics, and participatory planning. International ILO reviews show a steady demand for flexible arrangements, work-life balance, transparent schedules, and predictable changes [10]. Applied research in healthcare and service industries is producing models that incorporate principles of fairness and co-design of schedules – from co-designing scheduling principles to assessing the effects of participatory planning on health and employment stability [15; 16]. Comprehensive reviews of industrial workforce planning are also moving from a "cost minimization" to a human-centered perspective, where fairness metrics are becoming paramount alongside operational quality [6; 14]. It is this evolution that is driving the integration of "fairness regularizes" into the cost function of assignments and the assessment of trade-offs between productivity, health and ethics in a single model.

Finally, integration works at the intersection of the above areas suggest comparing bio-inspired algorithms with "classical" mathematical formulations (MIP/mathe-heuristics) using a single set of metrics – coverage quality, weighted "price" of the schedule, inequality of hours (Gini), norm violations, speed of recovery after shock, institutional acceptability for social partners [12; 14–16]. This opens the way not only to technical benchmarking, but also to pedagogical applications – where students can observe the emergent dynamics of decisions and learn to form politically and ethically acceptable compromises.

A review of the literature provided a proven theory and case studies of biomimetics in operations [1–5; 11–13], tools for fairness and participation in schedules [6; 10; 15; 16], and stigmergy mechanisms as "easy" coordination [7; 8]. At the same time, there is a lack of a comprehensive framework that, in a single formulation: combines ACO and Physarum as alternative dynamics of self-organization, encodes fairness as a first-order regulator in the cost function itself, validates these approaches against the MIP benchmark on metrics of quality, resilience, and social acceptability, and translates all these elements into a didactic module for the course "Labour Economics and Social and Labour Relations." This article aims to fill this gap.

Thus, the main objectives of the study are to synthesise the theoretical foundations of biomimetics for work organization and to form a conceptual scheme "ant colony → schedule system"; to formulate a unified mathematical formulation of the assignment problem with a cost function that includes a fairness regulariser, and to describe the dynamics of ACO and Physarum as alternative mechanisms of self-organization; to construct a didactic module (simulations, tools, assessment rubric) for the course "Labour Economics and Social and Labour Relations"; to conduct a comparative assessment of ACO, ACO+fairness and Physarum relative to the MIP benchmark on metrics of coverage, weighted "price", Gini index, norm violations, and recovery time after shock; discuss implications for social dialogue (HR services, trade unions, employee councils) and outline limitations and directions for further research.

The purpose of the article

The purpose of the article is to develop and justify a biomimetic framework for teaching "Labour Economics and Social and Labour Relations," which combines stigmergic logic, swarm algorithms (ACO) and Physarum networks to build fair, resilient schedules and to demonstrate its validity on a coordinated panel of metrics for quality, fairness and speed of recovery.

Presentation of the main material

The development of modern technologies has a systemic impact on the formation of modern approaches to teaching the discipline of "labour economics and social and labour relations." Methodologically, two alternative (and mutually verifiable) dynamics of self-organisation are proposed. In ACO mode, "agent-ants" form destination routes; edges with low cost c(e) are reinforced by "pheromones," while "expensive" ones fade away, evaporation prevents frozen lock-in, and global/local reinforcement controls convergence. "Fairness" is introduced as a separate penalty in c(e) or as negative reinforcement in the pheromone update for "overfed" workers; this allows the model to be directly aligned with the principles of decent work and time ergonomics. The Physarum mode is conceived as a dissipative network with conductances De on the edges; conductivity increases in proportion to the useful flow of hours, decreases due to "evaporation," and after several iterations, a "reference" subnetwork of thick connections is formed, like a ready-made schedule that can be easily rearranged in case of shocks (cancellation of changes, illness). Both modes differ in their explanatory "language," but together they demonstrate to students how local amplification generates global order, and why small changes in criterion weights lead to systemic shifts in decisions.

To ensure scientific validity and relevance, the article proposes a comparative research design. Based on 3–6 months of shift logs, a two-part graph "employees ↔ shifts" is constructed with detailed restrictions (qualifications, limits, rest periods, night/holiday shifts, substitution and overtime rules). Next, sequential experiments are performed in three modes: basic ACO, ACO with a built-in fairness regulator, and Physarum dynamics. For correct benchmarking, an MIP benchmark (mixed integer programming) is added within the acceptable time and optimality for large instances. All models work with identical weights of the "price" components, and the hyperparameters ACO (α, β, ρ) and Physarum (λ, κ) are calibrated on training sub-sets and "frozen" before evaluation. This procedural alignment creates conditions for a "clean" comparison, where differences in results are interpreted as a consequence of self-organization mechanics rather than parameter "tweaking".

The metrics panel combines operational and socio-labour criteria (proportion of uncovered hours, weighted average "price" of the schedule, number of violations of standards, Gini index for hours worked; proportion of undesirable/night shifts per employee; recovery time after shocks as an indicator of resilience. To measure the institutional acceptability of the decision, experts (employer/trade union/employee council) additionally assess it on a Likert scale with open comments; expectations regarding compromises are consistent with the recommendations of the International Labour Organisation on work-life balance, flexible working arrangements and predictable schedules [10; 16]. It is proposed to perform statistical verification using bootstrapping with a 95% confidence interval, Wilcoxon–Mann–Whitney tests, and reporting of effect sizes (Cliff's δ), as well as taking into account computational costs. This design of metrics and procedures allows us to show that "fair" configurations are not only possible but also controllably achievable within a transparent model and realistic constraints.

Hypotheses are formulated in such a way as to test not only "who is better," but also why. First (H1), ACO with a fair regulariser reduces inequality (Gini) without significant loss of coverage quality or increase in "price"; second (H2), Physarum dynamics have a shorter recovery time after shock due to the "self-tuning" property of flows; thirdly (H3), varying the weights ωi\omega_iωi in the cost function generates predictable and stable changes in pheromone/conduction patterns, which is critically important for policy: increasing the weight of night-time or penalties for unfairness systematically shifts decisions towards health-preserving and ethically acceptable configurations. The content of these hypotheses does not contradict classical approaches (MIP), but rather complements them in situations where adaptability, explainability, and didactic clarity are required.

Special attention is paid to ethical safeguards and bias control. First, multiple independent runs with different initializations are used to eliminate the risk of local compromises. Second, bias is controlled inbuilt: a fairness regulariser is introduced into the cost function, and a dashboard of indicators (Gini, undesirable/nightly per employee, violations of norms) is introduced into reporting. Thirdly, transparency is ensured: each experiment is accompanied by "decision logs" recording the weights, rules and contributions of individual terms to the marginal cost of the assignment. This approach makes the model technically stable and legitimate in the eyes of social partners: decisions can be verified, explained and defended in the negotiation process without sacrificing production quality and ethical standards.

From a didactic point of view, the article's contribution lies in the fact that the proposed module "grounds" abstract optimization tools in specific learning activities: students adjust weights, experiment with constraints, observe convergence dynamics, and justify their choice of compromises. This strengthens policy analysis skills (how to change parameters to achieve a fairer schedule) and fosters a culture of ethical planning. For the teacher, the module is a ready-made "pedagogical bridge" from theory to practice, explaining why in complex systems direct "manual" control often gives way to the design of rules that allow the system to self-organize in the desired direction. At the same time, visual aids (network edge thickness, pheromone/conductivity map) simplify communication with the audience and enhance learning.

From a human resource management perspective, the framework offers three direct benefits. The first is the measurability and controllable increase in the redundancy of critical skills: the reserve indicator (how many employees are capable of performing one operation interchangeably) is naturally built into the cost of edges and becomes the basis for targeted reskilling. The second is fairness as a first-order constraint: models reduce imbalances, equalize hourly funds and increase the acceptability of schedules for employees/trade unions. Third, speed of recovery from shocks: ACO/Physarum networks reduce restructuring time without violating rest standards, which is especially important in sectors with turbulent demand. Together, this creates operational resilience, ethical legitimacy, and a basis for constructive social dialogue.

The originality and scientific contribution of the article lie in four points. First, in the holistic integration of stigmergy, ACO and Physarum within a single framework that directly encodes fairness into the cost function. Second, in the comparative design, which allows the difference between approaches to be interpreted precisely through the mechanics of self-organization. Third, in the didactic elaboration: lessons, tools, and an assessment section are proposed, making the framework reproducible in a university classroom. Fourth, in linking the results of modelling with the guidelines of international organizations on humane working time regimes – this provides not only "technical" optimization, but also politically acceptable solutions for social partners [10; 16].

The limitations of the study are directly related to the data and context. First, for some organizations, the set of employee preferences is incomplete or contains noise, in which case it is advisable to apply standardization and confidence coefficients in the relevant cost terms. Second, some constraints (e.g., unwritten rules of change) are less formalized than legal/contractual ones; this is compensated for by a "rule log" and a gradual transition to coding soft constraints as penalties. Third, comparisons with MIP for very large instances require time limits to ensure representativeness; therefore, the authors emphasize "qualitative" parity (uniform weights/constraints) as a condition for a fair benchmark. Finally, the results are sensitive to the weights of the criteria; however, it is precisely this sensitivity that is didactically useful, as it shows students how political and ethical decisions parameterize the space of possible outcomes.

In summary, the article demonstrates that biomimetic models are not just a metaphor, but an applied tool for teaching and practice in the field of labour. Thanks to simple and transparent rules of self-organization (reinforcement of useful channels, evaporation of ineffective ones, penalties for injustice), it is possible to obtain balanced, explainable and reproducible schedules that quickly link theoretical concepts (stigmergy, swarms, dissipative networks) with everyday HR and social dialogue practices. For teachers, it is a ready-made pedagogical toolkit, for managers – a methodological support in complex environments with turbulent demand, for employees and trade unions – a transparent procedure for agreeing compromises with fairness as the key objective. The framework is compatible with international guidelines on working time and quality of working life, and its experimental logic provides a basis for the transition from "manual" planning to managed self-organization, in which rules and weights openly determine socially desirable outcomes.

Biomimetics is particularly useful for teaching "Economics of Labour and Social and Labour Relations" because it develops several skills that are fundamental to the formation of a manager, namely:

– systemic thinking, since with this approach, the labour market can be viewed as a multi-level network of players and rules. Biomimetic simulations allow us to "see" how local decisions (rates, surcharges, night-time restrictions, employee preferences) crystallise into global results – employment, turnover, balance of shifts, quality of working life [1; 4];

– learning through action. Interactive models (swarms, Physarum) clearly demonstrate mode transitions – from stable to crisis – and give students tools for experimenting with policies and collective agreements, which can initially be played out as economic games and later actively implemented in work processes [5; 13];

– the integration of "soft" criteria – preferences, fairness, fatigue – can be easily coded as weights/penalties in the "price" function of the edge, which forms a culture of ethical change planning [9; 10; 15; 16];

– explicitness and transparency, as students can see why certain "ribs" have been strengthened (strong demand, relevant skills, "fair" hours), which is quite difficult to explain using other methodological techniques when analysing social dialogue with trade unions and employee councils [7; 15].

Systemic thinking. The labour market is a multi-level network (employees, enterprises, trade unions, the state). Biomimetics clearly demonstrates how local incentives (wage rates, schedules, access rules) shape collective outcomes – employment, turnover, fairness of shift distribution.

Learning through simulation. Students see dynamics in real time: how supply and demand signals (analogous to pheromones) intensify or fade away, how the network shifts between modes – from stable to crisis.

Integration of "hard" and "soft" constraints. Classical models often abstract from preferences, fairness, and fatigue. Biomimetic models allow these aspects to be woven into the "cost" of relationships and the process of self-organization, bringing learning closer to the real practice of HR and social partnership.

Explainability. The visual evolution of the network (thickening of "useful" connections, drying up of ineffective ones) helps to interpret the compromises of employment policy.

Global ILO reviews identify long-term trends: demand for flexible working hours, work-life balance, as well as more even distribution of hours and transparency of schedules [10], which directly reinforces the need for models that not only "minimize costs" but also inherently take into account fairness, preferences and employee health [15; 16]. Biomimetic approaches provide a natural mathematical framework for this (local reinforcement, fading of "incompatible" connections, dynamic network reformatting without "manual" micromanagement).

Recent studies show that the use of biomimetics in manufacturing processes can significantly increase the resilience and adaptability of technological and management systems. For example, the article Biomimetics in Sustainable Manufacturing: Towards a New Model for Enhancing Resilience proves that imitating natural mechanisms allows for the development of resilient, flexible, and resource-efficient production models [3]. In addition, biomimetic modelling in management enables organizations to develop as ecosystems – with decentralisation, feedback and regenerativity, which contributes to the construction of more resilient organizational structures (Ordonez-Iturralde, 2025) [3].

Let us consider how this might look in the context of increasing the attractiveness of metallurgical enterprises within the discipline of "labour economics and social and labour relations", which involves the following key stages: selecting a natural prototype that reflects adaptability in a turbulent environment (e.g., ant colonies (resource optimization) or symbiotic systems (interdependent stability)), transforming biological principles into business strategies, including decentralization of management, resource reservation, division of functions, synergy between departments, simulation of shock scenarios, i.e. modelling crises such as sharp increases in costs or supply disruptions, and testing the system's response by analogy with the adaptation of living organisms, implementing adaptive measures that form the basis for strategic flexibility, reducing risks and increasing investor confidence.

The ant colony model is best suited for analysis, and the conceptual diagram of biomimetic modelling is shown in the figure below.

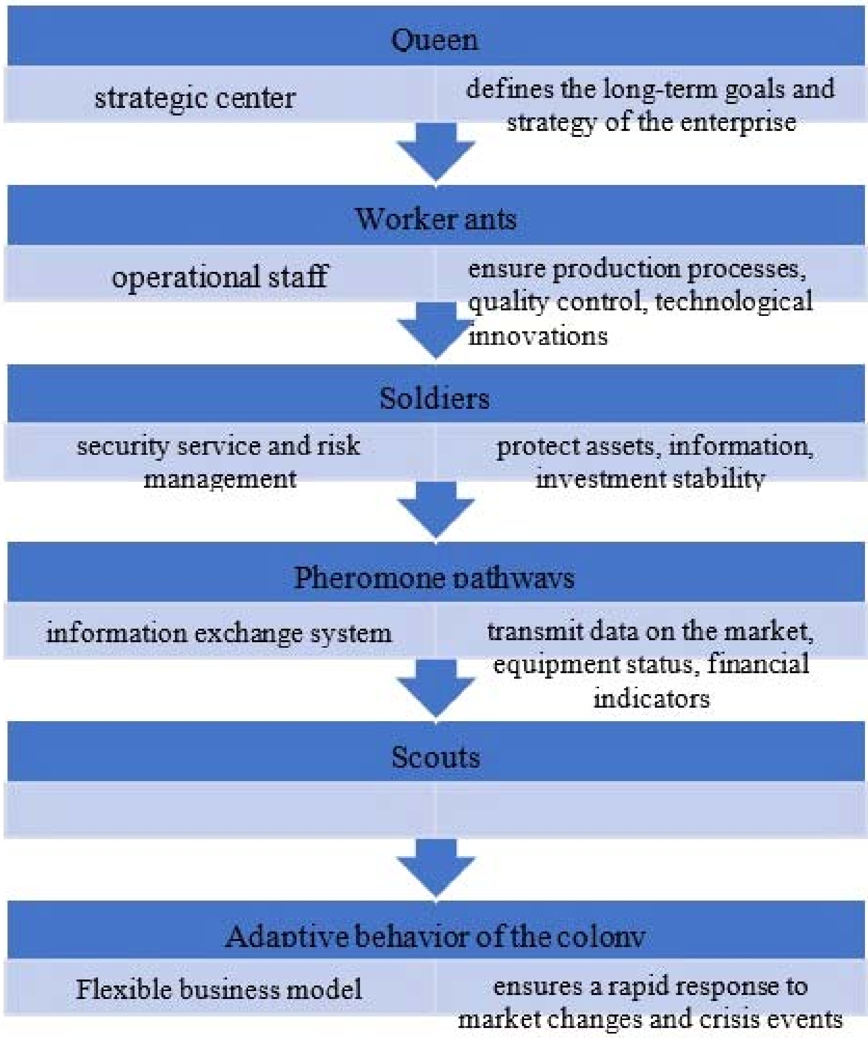

Fig. Conceptual diagram of biomimetic modelling based on an ant colony for a metallurgical enterprise

Source: compiled by authors

Based on the diagram used as a didactic bridge between biology and labour economics (analogue of an ant colony → business system), we adapt it to social and labour relations: strategic center (enterprise council/social partners), "worker ants" (teams), "soldiers" (occupational safety/compliance), "scouts" (recruiting/R&D), "pheromone trails" (IT scheduling system, substitution market), adaptive behaviour (flexible labour model) [1; 3].

Let us formulate the problem based on the following initial data: we have a bipartite graph

$$G=(P\cup S,\ E), \quad (1)$$

where P is employees (with qualifications, limits, preferences);
S is shifts (with requirements and standards);
E is potential assignments.

We assign a "price" to each edge $e\in E$:

$$c(e)=\omega 1\cdot night+\omega 2\cdot skill\ mismatch+\omega 3\cdot(5-preference)+\omega 4\cdot overtime+\omega 5\cdot injustice, \quad (2)$$

where ωi are political and didactic weights.

In expression 5, the preference scale is inverted into a penalty, i.e. the higher the employee's preference for change, the lower the penalty, and the lower the preference, the higher the penalty. The goal is to minimize the total "cost" of meeting the demand for changes while complying with regulations (hours, rest periods, collective agreement) and to balance individual hourly balances. This approach is consistent with recent work on incorporating preferences and fairness into schedules [12; 15; 16].

At each iteration, the "ants" build destination routes; the pheromone intensifies on edges with a low "cost" and fades on "expensive" ones. We use evaporation $\rho\in(0,1)$, local and global amplification, and for fairness, an additional negative reinforcement is used if the employee deviates from "fair" hours. ACO is systematically used in schedules (particularly medical ones), with positive results in terms of quality and adaptability [9; 12; 16].

The main educational advantage of this approach is that students can "see" how a change in ωi (e.g., an increase in night weight) immediately changes pheromone patterns and the final schedule. This is ideal material for discussing trade-offs between productivity, health, and fairness [10; 15].

In Physarum models, the conductivity of edge De increases proportionally to the useful flow and decreases due to "evaporation." In the educational task, we interpret the flow as the influx of hours according to "good" employee-shift matches. The advantage of this approach is its stable convergence to a "thick" support network that balances shift coverage and workload; it is also suitable for restructuring when a shift is cancelled or an employee is ill [5; 13].

This biometric course is covered in the discipline "Labour Economics and Social and Labour Relations" in particular through two interactive classes (60 minutes each), which have didactic materials, assessment and practical aspects for the course, as indicated below:

– practical exercise on topic 7, part 1 – Work organization: regulating working hours and workloads – "The market for change and stigmergy";

– tools: Miro/Trello/Google Sheets (Kanban methodology);

– steps: a) announce changes (those in short supply "glow" brighter – stigmergy); b) students suggest assignments/replacements; c) discuss how "traces" (labels) guide behaviour and where regulation (limits, rules) is needed;

– learning objective: explain indirect coordination and the risks of label manipulation [7; 8] – from process recording (note) to process line.

Practical exercise on topic 7, part 2 – Work organisation: regulation of working hours and work measures – "ACO/Physarum simulator". Input data: 30 employees, 7-day horizon, preferences (0–5), qualifications, limits. Experiments: a) basic ACO; b) model with increased fairness weight; c) shock scenario (–10% staff availability). Discussion: how the quality of schedules, Gini index of hours, % of violations of norms, and «recovery time» after shock change [9; 10; 12; 15; 16].

Learning outcomes are assessed according to the following logic:

– decision analytics (30%): correctness of formulation (constraints, weights), interpretation of compromises;

– ethical dimension (25%): whether fairness, health, and employee choice are taken into account (connection with ILO guidelines) [10];

– modelling (30%): reasoning behind the choice of ACO/Physarum, sensitivity experiments (ρ, ωi), quality of visualisations;

– communication (15%): clarity of presentation for social dialogue parties (HR, trade union).

The consequences of the proposed biomimetic approach for business practice naturally boil down to three interrelated vectors of action. First, the model allows for the measurement and controlled improvement of critical skill redundancy: the reserve indicator (how many employees are capable of performing one operation interchangeably) is built into the cost of assignments function and becomes the basis for targeted retraining and rotations. Second, schedule fairness is seen not as an “additional bonus” but as a first-order constraint: deviations of individual hours from the target range are coded through a penalty in the “price” function of the edge. This systematically reduces imbalances, increases acceptability for social partners and, as modern literature on staff scheduling and nursing schedules shows, improves time ergonomics and the quality of working life [12; 15]. Thirdly, the proposed framework increases the speed of recovery from shocks (sudden illness, peak demand, power outages): such events are interpreted as “micro-Ω” in the panarchy of skills, and ACO/Physarum network dynamics, through the evaporation and reconfiguration of “pheromones”/conductivities, reduce the time required to restructure the schedule without violating rest and collective agreement norms [4; 5; 13]. As a result, the company obtains a tool that simultaneously supports operational stability, social acceptability and an educational function: metrics for reservation, fairness and recovery time can be transparently communicated in the negotiation process and used as benchmarks for continuous improvement of employment policy.

For reasons of reliability and academic integrity, we accompany the proposed model with a clear verification procedure and ethical safeguards. First, to avoid getting stuck on local compromises, we obtain decisions as a consensus of several independent runs with different initializations and random seeds; additionally, we conduct stress tests with variations in the parameters α, β, ρ and penalty weights, as well as sensitivity analysis to changes in regulatory constraints. Secondly, we control bias not after the fact, but inbuilt: we introduce a fairness regulator into the “cost” function, and in our reporting we provide a panel of indicators – the hour distribution coefficient, the proportion of undesirable/night shifts per employee, the frequency of violations of rest norms, the “overload” index of departments, which allows us to construct a clear Pareto curve “schedule quality ↔ fairness” and select a compromise point acceptable to social partners, consistent with the principles of decent work and time ergonomics [15; 16]. Thirdly, we ensure transparency and reproducibility – each experiment is accompanied by a “decision log” recording weights, rules, violated/activated restrictions and the contribution of each component to the marginal “price” of the assignment; we anonymize the data, document the parameters and randomness for the repetition of results, and regularly subject the procedure itself to external audit with the participation of employee and employer representatives. This design makes the model not only technically stable but also legitimate from the point of view of social dialogue: decisions can be verified, explained, and defended in the negotiation process without sacrificing either production quality or ethical standards.

We verify the reliability and validity of the proposed framework through a research design that simulates real-life working conditions and, at the same time, allows us to separate the effect of biomimetic algorithms from alternative explanations. The empirical basis consists of change logs for 3-6 months, broken down by teams, qualifications, and roles; employee profiles (competencies, hour limits, legal/collective agreement restrictions, individual preferences for slots); rest and night/holiday work standards; rules for distributing overtime and substitutions. For each observation week, we construct a two-part graph “employees ↔ shifts” with an edge cost function that aggregates penalties for skill mismatches, working in “difficult” intervals, deviations from declared preferences, and from the target share of hours (fairness component). Next, we reproduce the flow of assignments using two bio-inspired mechanisms (swarm optimization (ACO) and Physarum networks) which, unlike rigidly centralized schemes, implement local rules for signal reinforcement/evaporation and therefore naturally adapt to changes in the environment [5; 12; 13].

To distinguish the contribution of the methodology itself from the settings, we use a comparative design with three modes: basic ACO; modified ACO with a built-in fairness regulator (penalty for deviation of individual time funds from the “fair” range); and Physarum dissipative dynamics, where the conductivity of the edges increases proportionally to the useful flow of hours and decays in its absence. As a benchmark, we take a strict mathematical standard – a mixed integer programming formulation for assignments with time and legal constraints and typical “soft” penalties; for large-scale problems, we add the well-known matheventics, which combines the MIP core with heuristic search space pruning [12]. All models are run on identical data sets and with identical weights of the “price” components. The ACO (α, β, ρ) and Physarum (λ, κ) parameters are selected on training sub-sets and fixed before the main experiments. Such procedural control allows us to compare methods “on equal terms” and interpret differences as a consequence of the mechanics of self-organization, rather than just the outer shell.

We assess effectiveness and acceptability using a panel of metrics that reflects both operational and social-labour goals. The operational block includes the proportion of uncovered hours (norm to zero), the weighted average "price" of the schedule, and the number of violations of standards (rest, continuity, night limits). The social block measures the fairness of time distribution using the Gini index based on hours worked and the proportion of undesirable/night shifts per employee. Additionally, we record the "recovery time" after shocks (sudden staff shortages, peak loads), which in our context we interpret as an indicator of schedule resilience. For institutional acceptability, we use expert assessments from representatives of the employer/trade union/employee council on a Likert scale with open comments; we align expectations regarding priorities and compromises with the International Labour Organisation's international recommendations on work-time balance and flexible working arrangements [10; 16].

We formulate hypotheses so that they test not only "who is better" but also the mechanism of improvement. First (H1), we expect that the inclusion of a fairness regulator in the ACO will statistically significantly reduce the inequality of the distribution of hours (Gini) without a significant deterioration in the average "price" and coverage (the difference does not exceed a predetermined small effect size). This is consistent with empirical findings on working time ergonomics in participatory planning systems [12; 16]. Secondly (H2), we expect that Physarum dynamics achieve a shorter recovery time after a shock, since "thick" channels themselves redirect flows to relevant connections without a complete recalculation of the decision [5; 13]. Thirdly (H3), changes in the weights of the "price" components щі generate predictable and stable shifts in "pheromone"/ conductance patterns, which ensures policy controllability: increasing the weight of night-time or unfairness penalties systematically shifts the decision towards more ethical and health-preserving configurations without losing convergence.

We perform statistical verification on cross-validation blends of weeks with repeated stochastic runs. For each metric, we construct 95% confidence intervals using bootstrapping, test the differences between methods using non-parametric procedures (e.g., Wilcoxon–Mann–Whitney), and report not only p-values but also effect sizes (Cliff's δ). For time complexity and scalability, we record CPU time and convergence stability; for the MIP benchmark, we set the same time/optimality limits to avoid the "penalty" of large instances. We ensure reproducibility with an open "decision log": we record weights, hyperparameters, randomness seeds, data version, and, most importantly, the contribution of individual components to the marginal "price" of assignments so that social partners can reproduce and verify the conclusions.

Ultimately, we interpret the validity of the results in light of decent work policies: if models reduce inequality in working hours and shorten recovery time after shocks without violating rest standards, this indicates practical significance for collective bargaining and planning changes in sensitive sectors (healthcare, manufacturing, services) [10; 12; 16]. This design balances methodological rigour with realism of application: we do not simply "win" in metrics, but demonstrate a manageable and transparent procedure that combines productivity, health and fairness – precisely the benchmarks expected by modern labour policy.

Conclusions

Biomimetics provides a unified, explainable and practical framework for teaching "Labour Economics and Social and Labour Relations." It allows us to teach systematic thinking, model trade-offs between productivity, health and fairness, and design anti-fragile HR policies and sustainable schedules. Specific tools – ACO and Physarum – ensure adaptability, acceptability to social partners and consistency with current international guidelines on working time and quality of working life [1–4; 5; 7; 10; 12–16].

REFERENCES

1. Cohen, Y., Faccio, M., Galizia, F. G., Mora, C., & Pilati, F. (2023). Biomimicry in manufacturing and logistics systems: Review and challenges. *Journal of Manufacturing Systems, 68,* 65–81. DOI: https://doi.org/10.1016/j.jmsy.2023.05.003.

2. McNish, C. (2025). Biomimetics in sustainable manufacturing: Towards a new model for enhancing resilience. *Journal of Sustainable Manufacturing, Advance online publication.* DOI: https://doi.org/10.1016/j.susman.2025.100251.

3. Ordonez-Iturralde, D. (2025). Biomimetic management: What natural ecosystems can teach management. *Proceedings of the World Conference on Emerging Science, Innovation and Policy 2025.* DOI: https://doi.org/10.5281/zenodo.15844773.

4. Raman, R., Sreenivasan, A., Suresh, M., & Nedungadi, P. (2024). Mapping biomimicry research to sustainable development goals. *Scientific Reports, 14, Article 18613.* DOI: https://doi.org/10.1038/s41598-024-69230-9.

5. Cai, Z., Feng, Y., Yang, S., & Yang, J. (2023). A state transition diagram and an artificial *Physarum polycephalum* colony algorithm for the flexible job shop scheduling problem with transportation constraints. *Processes, 11*(9), 2646. DOI: https://doi.org/10.3390/pr11092646.

6. Burgert, F. L., Windhausen, M., Kehder, M., Steireif, N., Mutze-Niewohner, S., & Nitsch, V. (2024). Workforce scheduling approaches for supporting human-centered algorithmic

management in manufacturing: A systematic literature review and a conceptual optimization model. *Procedia Computer Science, 232,* 1573–1583. DOI: https://doi.org/10.1016/j.procs.2024.01.155.

7. Zheng, L. N., Mai, F., Yan, B., & Nickerson, J. V. (2023). Stigmergy in Open Collaboration: An Empirical Investigation Based on Wikipedia. *Journal of Management Information Systems, 40(3),* 983–1008. DOI: https://doi.org/10.1080/07421222.2023.2229119.

8. Salman, M., Birattari, M., & Dorigo, M. (2024). Automatic design of stigmergy-based behaviours for robot swarms. *Nature Communications Engineering, 1*, Article 175. DOI: https://doi.org/10.1038/s44172-024-00175-7.

9. Matrenin, P. V. (2023). Improvement of Ant Colony Algorithm Performance for the Job-Shop Scheduling Problem Using Evolutionary Adaptation and Software Realization Heuristics. *Algorithms, 16(1),* 15. DOI: https://doi.org/10.3390/a16010015.

10. International Labour Organization. (2023). *Working time and work-life balance around the world.* Geneva: ILO. Retrieved from https://www.ilo.org/publications/working-time-and-work-life-balance-around-world.

11. Kay, R., Mattacchione, A., Katrycz, C., & Hatton, B. D. (2022). Stepwise slime mould growth as a template for urban design. *Scientific Reports, 12,* 1322. DOI: https://doi.org/10.1038/s41598-022-05439-w.

12. Achmad, S., Wibowo, A., & Diana, D. (2021). Ant colony optimization with semi-random initialization for nurse rostering problem. *International Journal for Simulation and Multidisciplinary Design Optimization, 12*, 31. DOI: https://doi.org/10.1051/smdo/2021030.

13. Bonifaci, V. (2013). Physarum can compute shortest paths: A short proof. *Information Processing Letters, 112(23),* 915–918. DOI: https://doi.org/10.1016/j.ipl.2012.09.005.

14. Pereira, D. L., Alves, J. C., & Moreira, M. C. (2020). A Multiperiod Workforce Scheduling and Routing Problem with Dependent Tasks. *Computers & Operations Research, 120,* 104930. DOI: https://arxiv.org/pdf/2008.02849.

15. Holton, S., Rasmussen, B., Long, K. et al. (2024). Developing nurse and midwife centred rostering principles using co-design: a mixed-methods study. *BMC Nurs 23,* 938. DOI: https://doi.org/10.1186/s12912-024-02522-7.

16. Turunen, J., Karhula, K., Ropponen, A., et al. (2022). The Time-Varying Effect of Participatory Shift Scheduling on Working Hour Characteristics and Sickness Absence: Evidence from a Quasi-Experiment in Hospitals. *International Journal of Environmental Research and Public Health, 19(22),* 14654. DOI: https://doi.org/10.3390/ijerph192214654.

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БІОМІМЕТИЧНЕ МОДЕЛЮВАННЯ У ВИКЛАДАННІ ДИСЦИПЛІНИ «ЕКОНОМІКА ПРАЦІ ТА СОЦІАЛЬНО-ТРУДОВИХ ВІДНОСИН»

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У статті запропоновано інтегровану біоміметичну рамку викладання та прикладного моделювання у дисципліні «Економіка праці та соціально-трудові відносини». В її центрі поєднання трьох ідей – стигмергійної координації як механізму непрямої взаємодії через «сліди» у спільному середовищі (ринок підмін, дошки змін, правила доступу), роєвої оптимізації (Ant Colony Optimization, ACO) як динаміки підсилення «вдалих» призначень працівник–зміна за аналогією до феромонних маршрутів та Physarum-мереж як моделі еволюції опорної мережі призначень, у якій провідність корисних зв'язків «товстішає», а неефективні канали «висихають» завдяки простим правилам підкріплення та випаровування. Рамка розроблена спеціально під навчальні та управлінські ситуації, де необхідно збалансувати операційну якість (повне покриття змін, дотримання нормативів, мінімізація «ціни» розкладу) з людиноцентричними орієнтирами (справедливість розподілу часу, урахування побажань, ергономіка робочого часу та передбачуваність), рекомендованими міжнародними настановами. Вона забезпечує викладачеві наочний інструмент для демонстрації того, як локальні правила (штрафи, ваги, обмеження) породжують макрорівневу рівновагу, а управлінцю – прозору методику конструювання справедливих і резильєнтних графіків, які прийнятні для соціальних партнерів. Теоретично стаття спирається на сучасні напрями біоміметики в менеджменті та виробничих системах, де самоорганізація, адаптація і розподіл ресурсів відбуваються не за командною логікою, а через локальні сигнали та мінімальні правила. Перекладена на мову економіки праці, така логіка дозволяє розглядати ринок праці і внутрішньоорганізаційні розклади як мережі, що еволюціонують у відповідь на дефіцити/надлишки, преференції та регуляторні межі. У роботі прийнято послідовну єдину постановку задачі у вигляді двочасткового графа «працівники ↔ зміни», де кожному потенційному призначенню відповідає функція вартості c(e) – зважена сума «жорстких» і «м'яких» компонентів (нічні та святкові інтервали, відповідність навичок, уподобання, понаднормові та регуляризатор справедливості (штраф за відхилення індивідуальних годин від цільового діапазону). Таке формулювання, по-перше, робить мету моделі прозорою для аудиторії, по-друге, дає змогу формувати криву Парето «якість ↔ справедливість» і відбирати рішення, прийнятні для сторін соціального діалогу.

Ключові слова: біоміметичне моделювання, економіка праці, соціально-трудові відносини, стигмергія, Ant Colony Optimization (ACO), Physarum polycephalum, резильєнтність, соціальний діалог.

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BIOMIMETIC MODELLING IN TEACHING THE DISCIPLINE “ECONOMICS OF LABOUR AND SOCIAL LABOUR RELATIONS”

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The article proposes an integrated biomimetic framework for teaching and applied modelling in the discipline of “Labour Economics and Social and Labour Relations”. At its core is a combination of three ideas: stigmergic coordination as a mechanism of indirect interaction through “traces” in a shared environment (substitution market, change boards, access rules), swarm optimisation (Ant Colony Optimisation, ACO) as the dynamics of reinforcing “successful” employee assignments – change by analogy with pheromone routes and Physarum networks as a model of the evolution of a reference network of assignments, in which the conductivity of useful connections “thickens” and ineffective channels “dry up” thanks to simple rules of reinforcement and evaporation. The framework is designed specifically for educational and management situations where it is necessary to balance operational quality (full coverage of changes, compliance with standards, minimization of the “price” of the schedule) with people-centred guidelines (fair distribution of time, consideration of preferences, ergonomics of working time and predictability), recommended by international guidelines. It provides teachers with a visual tool to demonstrate how local rules (penalties, weights, restrictions) create macro-level equilibrium, and managers with a transparent methodology for constructing fair and resilient schedules that are acceptable to social partners. Theoretically, the article draws on contemporary trends in biomimetics in management and production systems, where self-organization, adaptation and resource allocation occur not according to command logic, but through local signals and minimal rules. Translated into the language of labour economics, this logic allows us to view the labour market and internal organizational schedules as networks that evolve in response to shortages/surpluses, preferences and regulatory constraints. The paper adopts a consistent, unified formulation of the problem in the form of a two-part graph «employees ↔ shifts», where each potential assignment corresponds to a cost function c(e) – a weighted sum of “hard” and «soft» components (night and holiday intervals, skill matching, preferences, overtime and fairness regulator (penalty for deviation of individual hours from the target range)). This formulation, firstly, makes the purpose of the model transparent to the audience and, secondly, allows the formation of a Pareto curve «quality ↔ fairness» and the selection of solutions acceptable to the parties to the social dialogue.

Keywords: biomimetic modelling, labour economics, social and labour relations, stigmergy, Ant Colony Optimisation (ACO), Physarum polycephalum, resilience, social dialogue.

REFERENCES

1. Cohen, Y., Faccio, M., Galizia, F. G., Mora, C., & Pilati, F. (2023). Biomimicry in manufacturing and logistics systems: Review and challenges. *Journal of Manufacturing Systems, 68,* 65–81. DOI: https://doi.org/10.1016/j.jmsy.2023.05.003.

2. McNish, C. (2025). Biomimetics in sustainable manufacturing: Towards a new model for enhancing resilience. *Journal of Sustainable Manufacturing, Advance online publication.* DOI: https://doi.org/10.1016/j.susman.2025.100251.

3. Ordonez-Iturralde, D. (2025). Biomimetic management: What natural ecosystems can teach management. *Proceedings of the World Conference on Emerging Science, Innovation and Policy 2025.* DOI: https://doi.org/10.5281/zenodo.15844773.

4. Raman, R., Sreenivasan, A., Suresh, M., & Nedungadi, P. (2024). Mapping biomimicry research to sustainable development goals. *Scientific Reports, 14, Article 18613.* DOI: https://doi.org/10.1038/s41598-024-69230-9.

5. Cai, Z., Feng, Y., Yang, S., & Yang, J. (2023). A state transition diagram and an artificial *Physarum polycephalum* colony algorithm for the flexible job shop scheduling problem with transportation constraints. *Processes, 11*(9), 2646. DOI: https://doi.org/10.3390/pr11092646.

6. Burgert, F. L., Windhausen, M., Kehder, M., Steireif, N., Mutze-Niewohner, S., & Nitsch, V. (2024). Workforce scheduling approaches for supporting human-centered algorithmic management in manufacturing: A systematic literature review and a conceptual optimization model. *Procedia Computer Science, 232,* 1573–1583. DOI: https://doi.org/10.1016/j.procs.2024.01.155.

7. Zheng, L. N., Mai, F., Yan, B., & Nickerson, J. V. (2023). Stigmergy in Open Collaboration: An Empirical Investigation Based on Wikipedia. *Journal of Management Information Systems, 40(3),* 983–1008. DOI: https://doi.org/10.1080/07421222.2023.2229119.

8. Salman, M., Birattari, M., & Dorigo, M. (2024). Automatic design of stigmergy-based behaviours for robot swarms. *Nature Communications Engineering, 1*, Article 175. DOI: https://doi.org/10.1038/s44172-024-00175-7.

9. Matrenin, P. V. (2023). Improvement of Ant Colony Algorithm Performance for the Job-Shop Scheduling Problem Using Evolutionary Adaptation and Software Realization Heuristics. *Algorithms, 16(1),* 15. DOI: https://doi.org/10.3390/a16010015.

10. International Labour Organization. (2023). *Working time and work-life balance around the world.* Geneva: ILO. Retrieved from https://www.ilo.org/publications/working-time-and-work-life-balance-around-world.

11. Kay, R., Mattacchione, A., Katrycz, C., & Hatton, B. D. (2022). Stepwise slime mould growth as a template for urban design. *Scientific Reports, 12,* 1322. DOI: https://doi.org/10.1038/s41598-022-05439-w.

12. Achmad, S., Wibowo, A., & Diana, D. (2021). Ant colony optimization with semi-random initialization for nurse rostering problem. *International Journal for Simulation and Multidisciplinary Design Optimization, 12*, 31. DOI: https://doi.org/10.1051/smdo/2021030.

13. Bonifaci, V. (2013). Physarum can compute shortest paths: A short proof. *Information Processing Letters, 112(23),* 915–918. DOI: https://doi.org/10.1016/j.ipl.2012.09.005.

14. Pereira, D. L., Alves, J. C., & Moreira, M. C. (2020). A Multiperiod Workforce Scheduling and Routing Problem with Dependent Tasks. *Computers & Operations Research, 120,* 104930. DOI: https://arxiv.org/pdf/2008.02849.

15. Holton, S., Rasmussen, B., Long, K. et al. (2024). Developing nurse and midwife centred rostering principles using co-design: a mixed-methods study. *BMC Nurs 23,* 938. DOI: https://doi.org/10.1186/s12912-024-02522-7.

16. Turunen, J., Karhula, K., Ropponen, A., et al. (2022). The Time-Varying Effect of Participatory Shift Scheduling on Working Hour Characteristics and Sickness Absence: Evidence from a Quasi-Experiment in Hospitals. *International Journal of Environmental Research and Public Health, 19(22),* 14654. DOI: https://doi.org/10.3390/ijerph192214654.