Cyber-Physical System Improve by AI Models in Causal Approach for Energy Supply (on Transport) Systems

Alexey A. Bezrodniy*, Huang RuiQi*, Van Tszin†
**Belarusian State University*, Minsk, Belarus
†*Gubkin Russian State University of Oil and Gas*, Moscow, Russian Federation

***Abstract*—With the development of control materials and information technologies, cyber-physical systems have become a pivotal area for the description and improvement of large-scale interdisciplinary objects. These systems represent the integration of computing, networking, and physical processes, where embedded computers and networks monitor and control the physical processes, often with feedback loops where physical processes affect computations and vice versa. In today's society, as technology continues to advance, the challenges we face also become increasingly complex. Understanding and improving complex systems, such as energy supply and traffic management, require not only technological support but also a deep understanding of the "semantics" of these systems-namely, the meanings and relationships between components of the system. This paper aims to explore how semantic models built on cause-and-effect relationships can help us better understand and optimize complex systems, and how these models can enhance our comprehension and improvement of such systems.**

***Keywords*—models, algorithms, cyber-physical large-scale inter-disciplinary systems, artificial intelligence, cause-and-effect relations, semantics of solutions**

I. Introduction

By definitions — ancient greek ϰυβερνητιϰη as a skill of a ship driver, φυσισ as Nature and συστημααs whole, combined of parts — cyber-physical-systems (CPS) assume efficient control by information technologies considering physical properties of controllables. It is seen as a goal stage of complex system models (after socio-economic, human-machine) at the integration of computing into objects. CPSs are now used to deal with diversative source Big Data problem solutions by decomposition till parts sufficient for decision-making processes - objects automation, 3D-printing of unique items, artificial intelligence (AI), etc.

In AI models, analyzing structure and composition of systems to synthesize their best variants (AI Up-to-Down) and processing big data with smaller attention to the object's nature and generation of new regularities (AI Down-to-Up) are identified. It is purposeful to join said approaches, extending known petroleum supply (PS) aspects for energy supply on transport (EST) [1].

The concept of semantics, or $\sigma\eta\mu\alpha\nu\tau\iota\acute{\kappa}\varsigma$ (meaningful), in the realm of cyber-physical systems, extends far beyond the mere categorization of data. It encompasses the interpretation and understanding of data within a given context(so — how a systems work with them), allowing for a more nuanced and effective control over complex systems. The semantics of solutions, therefore, becomes crucial in achieving precise and anticipatory control mechanisms. By leveraging the semantics within cyber-physical systems, it's possible to bridge the gap between raw data and actionable insights, fostering systems that are not only reactive but also predictive (pro-active) and adaptive to their environments. This semantic layer enriches the decision-making processes, ensuring that the actions are taken at deeper understanding of the system's state and its interaction with the physical world.

By incorporating a semantic understanding into the core of CPS, we align closer with the ancient Greek notion of ϰυβερνητιϰη , navigating the vast seas of digital and physical data with the skill and insight of a seasoned ship's captain. It is within this framework that our investigation into energy supply on transport, underpinned by a rich semantic foundation, seeks to unveil new paradigms for control, efficiency, and innovation in the age of information and interconnectedness.

II. General task to control and develop complex systems

A system may be described by pair $\{K, D\}$, where $D = \{Gr, G\}$, Gr — graphs of controlling and control systems (CS), K — quality indicator, G — restrictions.

Transition from verbal to formal description of large-scale inter-disciplinary objects, interesting for investigation, is purposeful to do by causal models [2]–[4].

General cause-and-effect (CE-) relation to develop CPSs is to achieve K by control as a structure formation (on strategical periods) and influences selection:

$$\begin{array}{rlcrl} \text{Cause:} & K & & \text{Effect:} & K* \\ > & & A(H,P,X,U,F) & < & \\ \text{Condition 1:} & G, w, S & & \text{Condition 2:} & G*, w*, \Gamma(X,U) \end{array}$$

Figure 1: General cause-and-effect relation to develop complex system

On Fig. 1 there is the following formalism (all sets except indexes):

- , A and F — functions, algorithms and control tasks on periods H;
- X — control means, U — relations between them, S — lifecycle stages;
- W — recourses (energy, control, material, techniques, finance, staff);
- G — also demands, influences of friendly and competitive environment;
- *, B — components after interaction (before — or without indexes).

In the general formulation a task usually is difficult to resolve due to high dimension, variety and diversity of components, non-linearity of their interaction, that provides necessity to create new and actualized known models.

III. Classical and cause-and-effect control model

CS models are determined by Cartesian product $F\colon C \times P \times H$, that elements match to number of organizational and technical control means $X(X_{pq}, p = 1..P, q = 1..Q)$ to resolve tasks $F_{ijk}\colon C_i \times P_j \times H_k$ in control loops (circuits) by execution of control functions $C(C_i, i = 1..I)$ for processes $P(P_j, j = 1..J)$ on $H(h_k, k = 1..K)$.

For comprehensiveness there should be build [1] inactive, control, decision-making, information, organization-technical subsystems structures resrectively $(G_r, G_{r1..4})$.

A task is resolved by formation of distributed system model, convolution on functions, periods, and processes (Ω-, C-, H-, P-synthesis), cutting useless (parasite) variants. For CPS it is considered control-by-control $F'\colon C_{cp} \times C \times H/G_{cp}$ with choosing C from $C^* = C \cup C_{cp}$, that provides P_j on H_k best by K.

To further refine this model, integrating semantic analysis into the classical and cause-and-effect control models introduces an advanced layer of understanding that transcends traditional control mechanisms. By incorporating semantics, the models gain the capacity to interpret complex interactions and causalities within the system, not just based on predefined rules but also on the contextual (at given conditions) meaning of actions and their impacts. This semantic enrichment allows for a dynamic adaptation of control strategies that are sensitive to the evolving state of the system and its environment.

Links between the model components are taken from theoretically proved, tested and/or intuitive CE-relations. They are structured on elementary cells (for operations), complexes (for processes) and Universum coverages (whole system).

Dimension of a task is decreased by an incident matrix like in table I.

On Fig. 2 for a 2-level CPS (object, net) in normal and abnormal modes there are relations in a CS, where Gr_2 of decision acts A_{ij} determines $Gr_{1,4}$ and Gr, Gr_3.

For EST-systems it is assumed, that within set of P_j ($j = 1..5$, 1 – supply and logistics, 2 – storage and operation, 3 – sales and marketing, 4 – support, service and maintenance, 5 – accounting/reporting) P_3 dominates (marketing paradigm, purpose-oriented approach) at typical set of C_i($i = 1..5$, 1 – data collection, 2 – situation identification, 3 – decision-making, 4 – execution, 5 – coordination).

Table I: Matching of classical and cause-and-effect control model

Multi-loop model component	Cause-and-effect model component			
	G	C	W	S
C	C~G	Identity	C~F_{CW}(W)	C~ F_{CG}(G)
P	P~ F_{PG} (G)	P~F_{PC}(C)	P~F_{PW}(W)	P~ ∑S
H	H~F_{HG}(G)	H~C	H~W	H~S
X	X~ F_{XC} (G)	X~ C	X~ W	X~F_{XS} (W)
G	Identity	G depends on C, W, S weaker («control by objectives »)		
W	W~G	W~C	Identity	W~ F_{WS} (G)
N	N ~ G	N ~ C	N ~ W	N ~ S
S	S ~ G	S ~ C	S ~ W	Identity

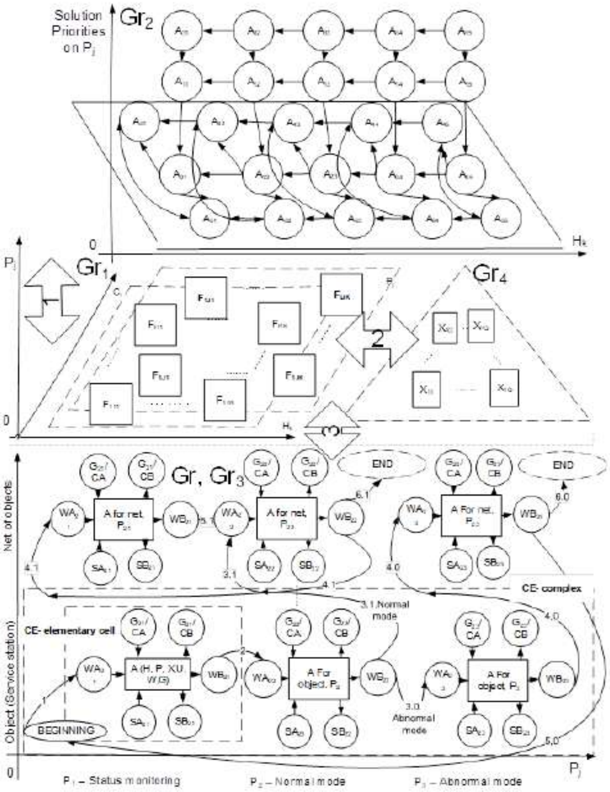


Figure 2: System structure at using of both classical and causal models

The synergy between classical control models and semantic analysis opens new avenues for developing intelligent cyber-physical systems. This combined approach not only enhances the precision and flexibility of control strategies but also ensures that systems are capable of understanding and reacting to their operational context in a more nuanced and effective manner. Consequently, it lays the groundwork for creating systems that are not only automated but also truly intelligent and responsive to the complex demands of modern infrastructure and societal needs.

At models co-using it is provided matching between

- elementary control tasks and cells of CE-relations F_{ijkpq} and $RC_{\text{phph}\to\text{phph}+1}$

$$F_{ijkpq} : C_i \times P_j \times H_k : X_{pq} \equiv \\ \equiv RC_{phph\to phph+1}(C, G, S, W), \quad (1)$$

- set of processes and CE-complexes

$$P_j \colon S_{ph1} \xrightarrow{F_{ijkpq}} S_{ph2} \cdots \xrightarrow{F_{ijkpq}} S_{phPH} \equiv \\ \equiv (RC_{A\to B}, U_{RC}), |RC|, |U_{RC}| \quad (2)$$

  $RC_{A\to B}$-set of elementary CE-cells, transforming system from A to B, URC – set of relations,$|RC|$ and $|U_{RC}|$ – matrixes of incidents and adjacency.

- structure models of sub-systems Gr Gr_{1-4}(graphs) and CE-components

$$P_j \colon S_{ph1} \xrightarrow{F_{ijkpq}} S_{ph2} \cdots \xrightarrow{F_{ijkpq}} S_{phPH} \equiv \\ \equiv (RC_{A\to B}, U_{RC}), |RC|, |U_{RC}| \quad (3)$$

  Order of resources w processing and status S changes as algorithmical solution finally determined by $Gr_5(X_5, U_5)$- coverage of Universum by links:

$$Gr_5(X_5, U_5) \colon \{(RC_{A\to B}, U_{RC}), |RC|, \\ |U_{RC}|, OA\}, j = 1..J, \quad (4)$$

  where $OA_{oa} \in \{OA_{oa}\}$ (oa=1..OA, 1 – beginning, 2 – operator, 3 – conditional pass, 4 – input-output). It is seen that number of models is decreased (Fig. 3).

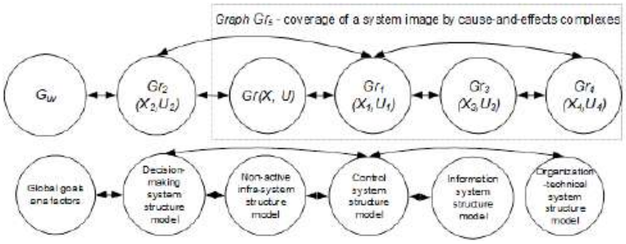


Figure 3: Dimension decrease of control (and system) model at algorithmical solution way

IV. Neural nets for causal system models

Artificial neural networks (NN) imitate human head mind structure as majority of interconnected elementary cells (neurons), executing many relatively simple operations in coordinated way. Information processing rules are given by LPR (leader of problems resolving), named also as decision-makers and experts.

At many-time using a NN is trained (control with information accumulation and analysis principle) with new regularities (knowledge) generation.

General structure of NN in modern understanding (e.g. of recurrent net with feedbacks and blocks of long short-time memory and convolution) may presented, accordingly to the opinion of authors as on Fig. 4.

Comparison and analysis of models, briefly presented on Fig. 2 and 4 shows about similarity of their structure and composition:

- elementary CE-cells (compatible NN nodes) with decomposition level, sufficient for LPRs for efficient control (layers and blocks) and coverage of a system Universum (whole NN);
- correction at new reports (data) coming, algorithmical solution (NN training);
- interrelated set of known models of subject field in Data (Knowledge) Base or D(K)B, forming the most general cause-and-effect relation (may be called as models of etalon processes), to which in NN match recurrent (RNN, modelling feedback), convolutional (CNN, dimension decrease with unproportionally lower quality lose), Long Short-time memory (LSTM, selection of alternative variants in conditions), Gated recurrent unit (GRU, variant of LSTM), etc.

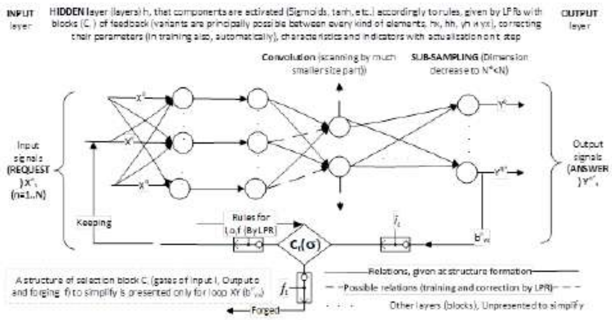


Figure 4: Structure model of a neural network with inter-element interaction

It permits to use developed mathematical support — software (and, sometimes, hardware for NN to model of operation and evolutional elaboration of CPSs by system cause-and-effect approach, that is good enough to investigate, control and improve of complex large-scale inter-disciplinary systems [2]–[4].

V. Task and methods to improve energy supply on transport

As a subject field one considers systems to supply energy on transport, on which development of State, Society and Man really depends one.

Most general cause-and-effect relations constituening semantics (σημαντιϰς,determening) are presented as follows:

- spatial distribution of the systems of high dimension and complexity;

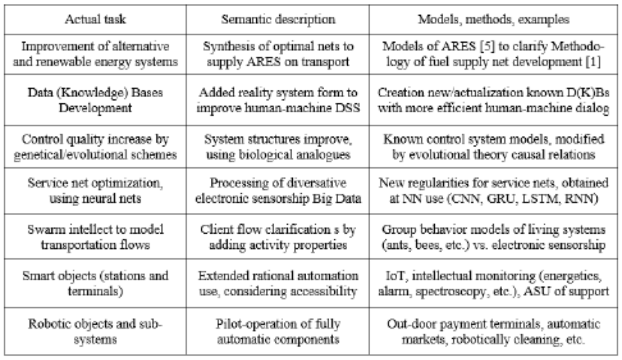
- huge data arrays (sets) of diversative data (clients, suppliers, macroeconomics);
- alternative and renewable energy sources (ARES), requiring efficient control systems at restrictions G_{ARES} on street-and-road (S-n-R) nets;
- vehicle transportation car diversity (TC) with exponential growth of numbers;
- hierarchical structure model — filling (charging) station, net, company – at net object location on Street-and-Road (S-n-Rs) and program (goal) oriented CS structure models;
- miniaturization of controlling and controllable components (narrow case CPS);
- trend of automation control system units (ASU) wide implementation, AI, decision support systems (DSS), Internet-of-Things (IoF), etc.

In the intricate web of cyber-physical systems, the most general cause-and-effect relations not only serve as the foundational skeleton but also weave the intricate tapestry of semantics (why systems exist and what for) that imbue these systems with meaning and purpose. The semantics, derived from these relations, go beyond mere functional descriptions, embedding systems with an understanding of their environment, objectives, and the potential impact of their operations. This semantic layers (following, e. g., M.Mesarovitch stratas and echelons), informed by the multifaceted interactions and outcomes of cause-and-effect dynamics, equips systems with the capability to interpret, adapt, and respond to the complexities of real-world challenges.

By integrating these cause-and-effect relations into the semantic framework, we enable systems to comprehend not just the ’what’ and the ’how’ of their operations, but also the ’why’ behind their actions. This deeper level of understanding is crucial for developing systems that are not only efficient and effective but also responsible and sustainable. It allows for the anticipation of potential consequences, the alignment of system operations with broader goals and values, and the adaptation to unforeseen challenges. Ultimately, the semantics constituted by these cause-and-effect relations transform cyber-physical systems from mere tools into intelligent agents capable of making informed decisions and contributing to the advancement of human society.

Actual tasks of EST-system improvement are presented in Table II.

Table II: Tasks of cyber-physical systems to supply energy on transports, models, methods



Actual task	Semantic description	Models, methods, examples
Improvement of alternative and renewable energy systems	Synthesis of optimal nets to supply ARES on transport	Models of ARES [5] to clarify Methodology of fuel supply net development [1]
Data (Knowledge) Bases Development	Added reality system form to improve human-machine DSS	Creation new/actualization known D(K)Bs with more efficient human-machine dialog
Control quality increase by genetical/evolutional schemes	System structures improve, using biological analogues	Known control system models, modified by evolutional theory causal relations
Service net optimization, using neural nets	Processing of diversative electronic sensorship Big Data	New regularities for service nets, obtained at NN use (CNN, GRU, LSTM, RNN)
Swarm intellect to model transportation flows	Client flow clarification s by adding activity properties	Group behavior models of living systems (ants, bees, etc.) vs. electronic sensorship
Smart objects (stations and terminals)	Extended rational automation use, considering accessibility	IoT, intellectual monitoring (energetics, alarm, spectroscopy, etc.), ASU of support
Robotic objects and subsystems	Pilot-operation of fully automatic components	Out-door payment terminals, automatic markets, robotically cleaning, etc.

After results, already presented in [2], in the said paradigm, the following advancements were achieved in the last several years, further embedding semantics into the core of cyber-physical systems:

- optimal service net structure for alternative and renewable energy sources (on the example of Hydrogen and compressed natural gas) [5];
  The development of an optimal service net structure, especially for alternative and renewable energy sources such as Hydrogen and compressed natural gas, represents a significant leap in applying semantic models. By understanding the intricate cause-and-effect relationships governing energy distribution and consumption, these systems can optimize service networks in a way that maximizes efficiency and sustainability.
- maintenance of service nets by the control principle <satisfaction to requirements> [6], implemented in petroleum supply companies in some regions of Russian Federation and Belarus;
  The maintenance of service networks based on the principle of satisfying requirements showcases the application of semantics in ensuring systems can interpret and act upon complex criteria. This approach leverages semantic understanding to tailor maintenance activities, ensuring that operational parameters align with specific needs and conditions, enhancing overall service quality and reliability.
- ASU of guarantied petroleum product supply implementation in net of 84 stations and 4 terminal of a petroleum company in Belarus, decreased number of dangerous operations on objects practically to zero and increased operational efficiency on them;
  Implementing an Automated System of Control (ASU) for guaranteed petroleum product supply, which significantly reduced the risk of dangerous operations and enhanced efficiency, exemplifies the role of semantics in risk management and operational planning. By semantically analyzing data

from various sources, the system can predict potential risks and optimize operations to mitigate them effectively.

- co-projection and co-development of stations and terminals net [6], that in an application permitted to decrease quantity of terminals, necessary to serve a regional net, optimized there structure (minimal outages of both equipment and clients) and decreased cost of only construction on 12,5 %

  The co-projection and co-development of station and terminal networks highlight the semantic-driven approach to system design and optimization. Through a deep understanding of the system's goals and requirements, this approach enables the reduction of unnecessary infrastructure, leading to cost savings and increased efficiency without compromising service quality.
- investigation of general information-logical schemes to model energy supply on base of genetic algorithms, forecasting of petroleum product logistics by various kind back propagation NN models, added reality to improve interaction in human-machine decision-support systems, etc.

  The exploration of information-logical schemes and the application of genetic algorithms and neural network models for forecasting in energy supply systems underscore the importance of semantics in modeling and simulation. These semantic-rich models facilitate more accurate predictions, improving decision-making and interaction within human-machine decision-support systems by providing a deeper contextual understanding of operational data and trends.

In particular, only initial modeling by genetic algorithms (GAs) application accordingly to the scheme, presented on Fig. 5, efficiency of simulation and the subject field KPIs are increased on 5-10 % and more. Hence, GAs, with their ability to perform global searches through selection, crossover, and mutation, looking well-suited to identify optimal or near-optimal system configurations that balance performance requirements with operational stability and adaptability.

Furthermore, integrating semantic analysis into this process enhances the capability of GAs by providing a richer contextual understanding of the system components and their interactions. By incorporating semantics, the genetic algorithm can evaluate not only the quantitative performance metrics but also the qualitative aspects of system configurations. This involves analyzing the meaning and relevance of various system parameters and states in relation to the overall objectives, such as energy efficiency, sustainability, and user satisfaction. For instance, a semantic layer could help the GA prioritize configurations that align with sustainable practices or adapt to user preferences, beyond mere numerical optimization.

This enriched modeling approach, where semantics and genetic algorithms work in tandem, enables a more holistic optimization of cyber-physical systems. By understanding the "why" behind system behaviors and configurations, as informed by semantic analysis, and leveraging the "how" of achieving optimal configurations, as facilitated by GAs, we achieve a more robust, adaptable, and intelligent system design. This dual approach not only improves simulation efficiency and KPIs but also ensures that the system's evolution is aligned with strategic goals, user needs, and environmental considerations, thus contributing to a more sustainable and user-centric ecosystem.

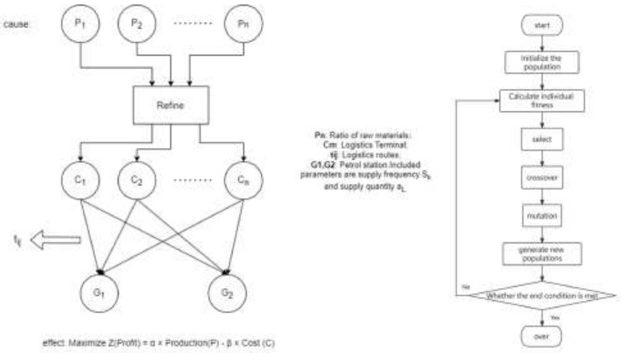


Figure 5: A structure of an elementary petroleum product net for genetical algorithm

So far, interaction of models related to energy supply systems (on transport) may pe presented as on Fig.6, where current tasks are marked by gray and/or bold.

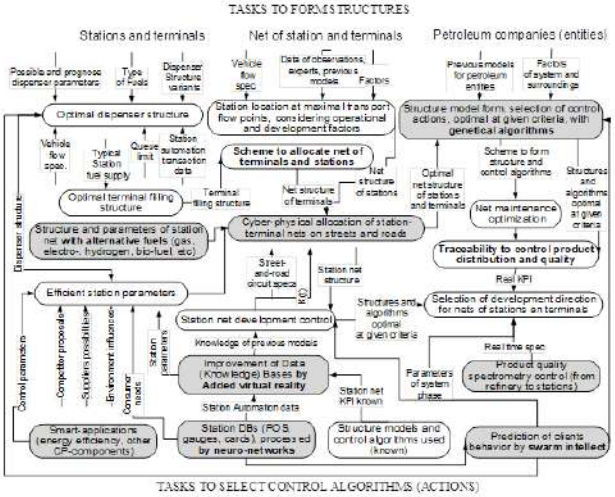


Figure 6: A structure of tasks and models for energy supply systems on transport

VI. Conclusion

1) Cyber-physical systems reflect a modern view on complex objects and their nets, that causes actuality

of their improvement to resolve efficient control tasks for large-scale inter-disciplinary cases.

2) Application of system causal structure models and artificial neural networks together permit to increase quality of investigations, control, and development of cyber-physical systems, due-to development of software packages for nerual networks and computer power.
3) Since the causal approach has a universal application, it may permit to investigated and improve systems of, practically. any kind, taking into consideration their inner languages, rather indefinite but important interactions between elements and verbal description of they characteristic, and control parameters, that constitutes semantics of object (events, phenomena and processes) images for their further modelling .formal description and mathematical modeling.
4) For systems to supply energy on transport as example, above models are being developed, tested or piloted, with such features as co-projection of controlling and controllable parts, wide cyber-physical component implementation, artificial intelligence using both in Up-to-Down and Down-to-Up variants and continued clarification at new reports coming, that is also applicable in other types of nets.
5) At synthesis of efficient control structures within so-called Principal component analysis dimension reduction by clustering/classification and summarizing there may be also applied some other methods of optimization tasks theory and practice – parcel solution trees, emergency combination of events, etc. as, probably future technique of AI, investigations to be continued.
6) Semantic analysis enabled us to identify hidden causal relationships and behavioral patterns within the system, offering a deep-level method of understanding systems. This understanding goes beyond mere data analysis to encompass grasping the meanings behind system behaviors, providing a new perspective for system design and optimization.
7) Utilizing semantic information, we demonstrated how to optimize decision-making processes in complex and dynamically changing environments. Mining the semantic layer allows the system to anticipate and adapt to future changes, achieving intelligent and adaptive decision-making, essential for building systems that are effective over the long term and highly adaptable.

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РАЗВИТИЕ КИБЕРФИЗИЧЕСКИХ СИСТЕМ С ПОМОЩЬЮ МОДЕЛЕЙ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА В РАМКАХ ПРИЧИННО-СЛЕДСТВЕННОГО ПОДХОДА НА ПРИМЕРЕ ОБЪЕКТОВ ОБЕСПЕЧЕНИЯ ЭНЕРГИИ (НА ТРАНСПОРТЕ)

Безродный А.А., Жуйци Х., Цзинь В.

С развитием управления, теории материалов и информационных технологий кибер-физические системы можно считать целевой парадигмой для описания и совершенствования сложных междисциплинарных объектов. Данного рода системы подразумевают интеграцию вычислительных мощностей управления с обратной связью непосредственно в сетевые распределённые структуры. В современном мире бурно развивающихся технологий их создание с требуемым качеством на примере обеспечения энергией на транспорте, требует не только надлежащего технического обеспечения, но и глубокого понимания смысловой составляющий – предназначения, структур и состава компонент и их взаимосвязей. Работа имеет цель показать как семантические модели на основе причинно-следственных связей могут помочь при оптимизации сложных систем, обеспечивая их комплексное представление и дальнейшее развитие.

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