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OPTIMIZATION OF ENERGY CONSUMPTION IN DATA CENTERS BASED ON AN ONTOLOGICAL APPROACH

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Abstract. The article is devoted to the development and substantiation of an ontological approach to optimizing energy consumption in data centers under conditions of increasing complexity of their computational and engineering infrastructure. The limitations of traditional optimization methods caused by insufficient consideration of semantic dependencies between data center components, their operating modes, and management policies are analyzed. An applied domain ontology is proposed that provides a formalized representation of knowledge about data center structure, computational resources, engineering systems, workloads, and energy efficiency indicators. The paper performs a semantic decomposition of the domain into interrelated subsystems, identifies a subset of core concepts and relations of the general ontological model, and substantiates their use in the task of energy consumption optimization. A general scheme of the ontological approach is proposed, implementing a closed loop “data – knowledge – optimization – control” and ensuring the integration of the ontology with mathematical models and software-based management tools. The obtained results form a theoretical and methodological foundation for the development of intelligent energy management systems for data centers and can be applied in the design of energy-efficient and environmentally sustainable computing infrastructures.

Keywords: data center; energy consumption; optimization; ontological approach; applied ontology; semantic model; intelligent control systems; energy efficiency.

Анотація. Статтю присвячено розробці та обґрунтуванню онтологічного підходу до оптимізації енергоспоживання дата-центрів в умовах зростаючої складності їх обчислювальної та інженерної інфраструктури. Проаналізовано обмеження традиційних методів оптимізації, зумовлені недостатнім урахуванням семантичних залежностей між компонентами дата-центру, режимами їх роботи та політиками керування. Запропоновано прикладну онтологію предметної області, яка забезпечує формалізоване представлення знань про структуру дата-центру, обчислювальні ресурси, інженерні системи, навантаження та показники енергетичної ефективності. У роботі виконано семантичну декомпозицію предметної області на взаємопов’язані підсистеми, визначено підмножину базових понять і відношень загальної онтологічної моделі та обґрунтовано їх використання в задачі оптимізації енергоспоживання. Запропоновано загальну схему онтологічного підходу, що реалізує замкнений цикл «дані – знання – оптимізація – керування» та забезпечує інтеграцію онтології з математичними моделями і програмними засобами керування. Отримані результати створюють теоретичне та методологічне підґрунтя для побудови інтелектуальних систем керування енергоспоживанням дата-центрів і можуть бути використані при проєктуванні енергоефективних та екологічно сталих обчислювальних інфраструктур.

Ключові слова: дата-центр; енергоспоживання; оптимізація; онтологічний підхід; прикладна онтологія; семантична модель; інтелектуальні системи керування; енергоефективність.

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INTRODUCTION

The rapid development of cloud computing, big data services, artificial intelligence, and the Internet of Things leads to a continuous growth of computational workloads, which, in turn, results in a significant increase in the energy consumption of modern data centers. According to estimates by international analytical agencies, data centers consume a substantial share of global electricity, with a considerable portion of this energy used not directly for computation but for maintaining proper operating conditions of the infrastructure, particularly power supply and cooling systems. In this context, improving the energy efficiency of data centers is one of the key components of the sustainable development concept and “green” information technologies [1–3].

Existing approaches to optimizing data center energy consumption are predominantly based on classical mathematical optimization methods, heuristic algorithms, or machine learning techniques. Despite their effectiveness in certain scenarios, such approaches are generally focused on local parameters and do not provide comprehensive consideration of semantic relationships between data center infrastructure components, their functional roles, operating modes, and mutual constraints. This complicates the adaptation of models to heterogeneous environments, reduces the interpretability of the obtained solutions, and limits the scalability of optimization systems [4,5].

A promising direction for addressing these challenges is the application of an ontological approach, which enables the formalization of knowledge about the structure, operation, and energy characteristics of a data center in the form of a coherent semantic model. The use of ontologies ensures an explicit representation of relationships between hardware components, software services, workloads, and engineering infrastructure systems, and also creates prerequisites for integrating logical reasoning mechanisms with mathematical optimization models [6].

In this work, an approach to optimizing data center energy consumption is proposed, based on combining an ontological representation of the domain with mathematical models for optimal workload allocation and software tools for intelligent energy resource management. The data center ontology is used as a foundational knowledge layer for defining feasible regions of the optimization problem variables, dynamically accounting for constraints, and supporting decision-making processes under changing operating conditions.

ANALYSIS OF LITERATURE DATA AND PROBLEM STATEMENT

The problem of reducing data center energy consumption has been the subject of active research over the past decades, driven by both economic factors and increasing requirements for the environmental sustainability of information technologies. The scientific literature proposes a wide range of approaches to energy optimization, which can be conditionally grouped into several main directions [7,8].

The first group comprises classical mathematical optimization models, including linear, nonlinear, and integer programming, which are used for optimal allocation of computational workloads among servers, minimization of power consumption, or reduction of peak loads. Such models make it possible to obtain formally optimal solutions; however, they are usually based on simplified assumptions regarding the data center structure and do not account for complex functional and semantic dependencies between its components. This limits their applicability in real, heterogeneous environments [9,10].

The second direction is represented by heuristic and metaheuristic methods (genetic algorithms, particle swarm optimization, simulated annealing, etc.), which provide acceptable solution quality under high-dimensional problem settings and limited computational resources. Nevertheless, these methods are typically weakly interpretable, sensitive to parameter selection, and do not guarantee stable results when the infrastructure configuration changes [9].

A separate group includes approaches based on machine learning and reinforcement learning, aimed at workload prediction, adaptive control of cooling systems, and automatic selection of energy consumption strategies. Although such solutions demonstrate high efficiency in dynamic conditions, their major drawback is the “black-box” nature, which complicates the explanation of obtained decisions, as well as the need for large volumes of representative training data [10].

At the same time, the literature increasingly pays attention to ontological and semantic models for describing data center infrastructure, its hardware components, software services, and energy characteristics. Ontologies enable formalization of domain knowledge, ensure consistent data representation, and support logical reasoning mechanisms. However, in most existing works, the ontological approach is used mainly for monitoring or configuration description and is rarely integrated directly with formal mathematical optimization models [7–9].

Thus, the analysis of literature sources indicates the lack of comprehensive solutions that combine semantically grounded knowledge representation, formal mathematical optimization methods, and software tools for intelligent energy management within a unified system. Table 1 presents a comparative analysis of the advantages and disadvantages of known methods [8–12].

Table 1 – Comparative characteristics of data center energy consumption optimization methods

Method Group	Brief Description	Advantages	Disadvantages
Classical Mathematical Optimization Methods (linear, nonlinear, integer programming)	Formal formulation of the energy consumption minimization problem with explicit variables and constraints	• formal rigor; • optimality guarantees (under given conditions); • clear interpretation of results	• simplified assumptions about data center structure; • poor scalability; • difficulty in handling heterogeneity and semantic dependencies
Heuristic and Metaheuristic Methods (GA, PSO, ACO, SA)	Search for near-optimal solutions without exhaustive enumeration	• suitable for large-scale problems; • no strict requirements on model form; • relatively simple implementation	• no guarantees of optimality; • sensitivity to parameter settings; • low interpretability of results
Machine Learning Methods (neural networks, regression models)	Prediction of workloads and energy consumption based on historical data	• ability to model nonlinear dependencies; • high adaptability; • effectiveness in dynamic environments	• requirement for large training datasets; • difficulty in explaining decisions; • risk of performance degradation under changing conditions
Reinforcement Learning Methods (RL, Deep RL)	Adaptive resource management through interaction with the environment	• self-learning capability; • online adaptation; • effectiveness in complex scenarios	• high computational complexity; • training instability; • difficulty in formalizing constraints
Rule-Based Systems	Control based on predefined rules	• simplicity of implementation; • predictable behavior; • high interpretability	• low flexibility; • poor scalability; • maintenance complexity as rule sets grow
Ontological and Semantic Approaches	Formalization of knowledge about data center structure and operation	• consistent	

PURPOSE AND OBJECTIVES OF THE STUDY

Despite the significant number of studies in the field of data center energy efficiency, the problem of developing a universal approach to energy consumption optimization that can adapt to the structural and functional heterogeneity of modern computing infrastructures remains unresolved. Existing methods do not adequately account for semantic relationships between data center components, which complicates the integration of heterogeneous models, limits the interpretability of decisions, and reduces management efficiency under dynamically changing workloads.

In this regard, a relevant scientific and practical task is the development of mathematical and software support for data center energy consumption optimization based on an ontological approach, which provides:

- a formalized representation of knowledge about the structure and energy characteristics of the data center;
- semantically grounded formation of constraints and parameters of the optimization problem;
- integration of logical reasoning mechanisms with mathematical optimization methods;
- adaptive software-based control of energy resources in real or near-real time.

In general, the problem consists in minimizing the total energy consumption of a data center while satisfying specified computational workloads, complying with thermal, resource, and operational constraints, and accounting for semantic dependencies between infrastructure components defined by the domain ontology.

ONTOLOGICAL APPROACH IN ENERGY CONSUMPTION OPTIMIZATION PROBLEMS

Modern data centers are complex cyber-physical systems characterized by a multi-level structure, functional heterogeneity, and a large number of interrelated components. Under such conditions, classical mathematical models for energy consumption optimization typically operate with a limited set of parameters and do not provide comprehensive consideration of semantic dependencies between computational resources, engineering infrastructure, workloads, and management policies [6,13].

The ontological approach makes it possible to overcome these limitations by providing a formalized representation of domain knowledge in the form of a system of concepts, relations, and axioms. In the context of data center energy consumption optimization, an ontology serves as a semantic integration layer that links monitoring data, mathematical models, and software-based decision-making mechanisms within a single coherent conceptual framework [13–15].

The theoretical basis for ontology construction relies on the principles of knowledge representation theory, semantic modeling, and first-order logic. In the general case, a domain ontology is defined as an ordered triple [6,13]:

$$Ontology = \langle C, R, A \rangle,$$

where C - denotes the set of concepts (classes), R- represents the set of semantic relations between concepts, A - is the set of axioms and constraints that define the rules of interpretation.

For data center energy consumption optimization tasks, the conceptual model should encompass not only static structural elements but also dynamic characteristics associated with operating modes, energy consumption, thermal states, and workload behavior. The construction of a domain ontology for energy optimization is based on the following theoretical principles: hierarchy—the formation of a multi-level class structure reflecting the physical and logical organization of the data center; modularity—the division of the ontology into sub-ontologies (computational resources, cooling systems, power supply, workloads); formal definiteness—the specification of axioms and constraints ensuring logical consistency of knowledge; extensibility—the ability to enrich the ontology with new concepts without violating the existing structure; operationalizability—the orientation of the ontology toward practical use in optimization and control algorithms.

Adherence to these principles makes it possible to develop an ontological model suitable not only for describing the infrastructure but also for direct application in the processes of formulating and adjusting optimization problems.

From the perspective of ontological analysis, the domain of data center energy consumption optimization should be considered as a set of interrelated subsystems: the computational subsystem, which includes servers, processors, memory, and network components; the engineering subsystem, encompassing power supply and cooling systems; the workload subsystem, describing tasks, virtual machines, and services; and the control subsystem, which contains optimization policies, constraints, and control actions. Each subsystem is formalized as a set of classes and relations, while their interaction is defined through semantic links that reflect energy and functional dependencies (Figure 1).

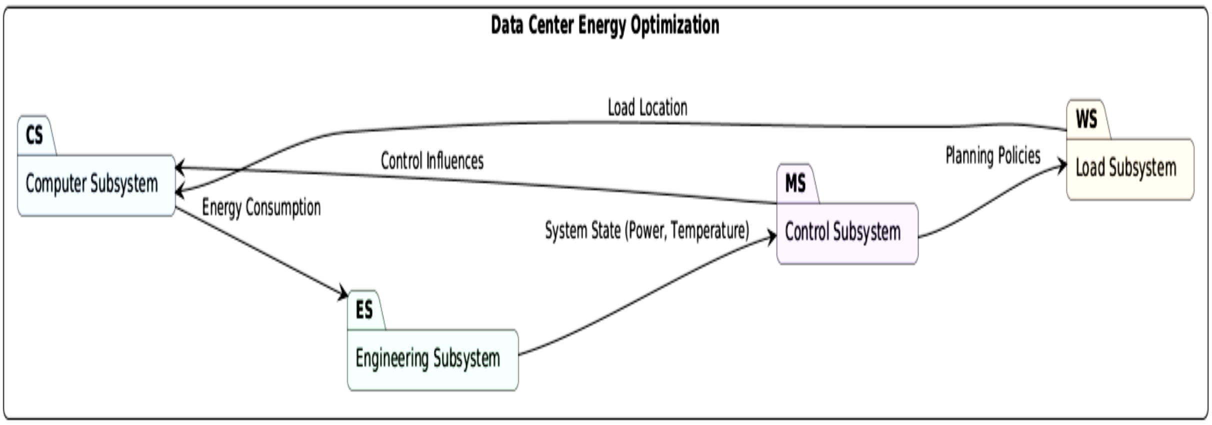

Figure 1 – Semantic Decomposition of the Domain

The general scheme of the ontological approach to optimizing data center energy consumption is based on the integration of knowledge-oriented domain representation with mathematical optimization methods and software-based control tools. Within this approach, the ontology is considered not only as a means of infrastructure description but also as an active component of the decision-making process, ensuring semantic consistency, adaptability, and interpretability of control actions.

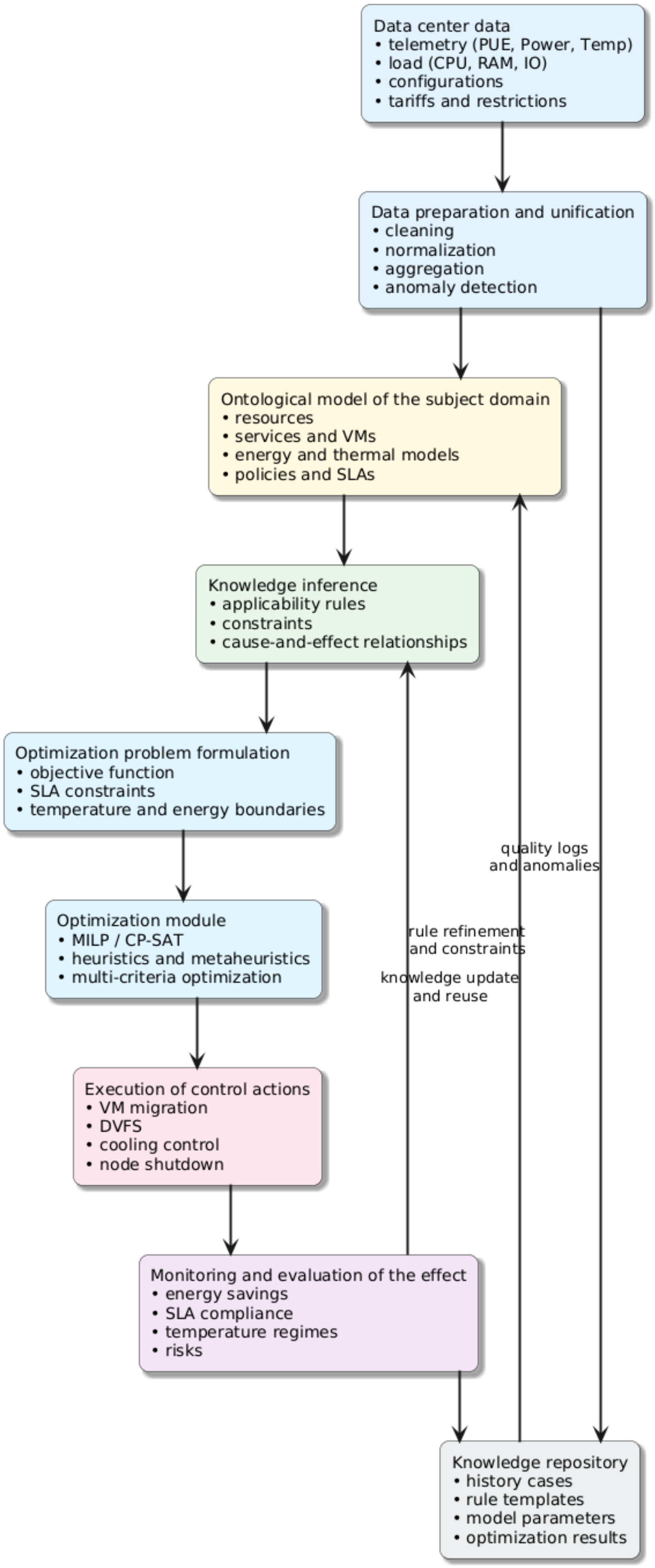

Figure 2 – General Scheme for Implementing the Ontological Approach for the Studied Domain

At the first level, a domain ontology of the data center is constructed, including concepts that describe computational resources, engineering infrastructure, workloads, and control mechanisms, as well as semantic relations between them. The ontology captures both structural characteristics of the system and functional and energy-related dependencies, providing a formalized representation of domain knowledge.

At the second level, the ontology is populated with up-to-date data obtained from data center monitoring systems. Indicators of power consumption, temperature, workload levels, and equipment status are interpreted in ontological terms and used to update its semantic state. In this way, a link is established between the abstract knowledge model and the real operation of the infrastructure.

At the third level, the ontology is used as a source for forming the parameters and constraints of the mathematical energy optimization problem. Through logical reasoning mechanisms, admissible system configurations, active constraints, and control priorities are identified, enabling dynamic adaptation of the optimization model to the current state of the data center.

At the fourth level, the optimization problem is solved using appropriate mathematical or algorithmic methods. The obtained results have a semantic interpretation, as they are consistent with the ontological model and account for both energy-related and functional dependencies between system components.

At the fifth level, a set of control actions is generated, aimed at changing the operating modes of computational and engineering components of the data center. The implementation of these actions is carried out through software control interfaces, after which the effects of their application are again recorded by monitoring systems, thus closing the loop of ontology-oriented optimization.

Overall, the general scheme of the ontological approach implements a closed loop “data – knowledge – optimization – control,” within which the ontology plays a central role as an integration and interpretation mechanism. Such an organization of the optimization process makes it possible to improve the efficiency of energy resource utilization in data centers, ensure adaptation to changing operating conditions, and increase the transparency and justification of decision-making.

The structure of the applied ontology reflects the organization and logic of the formalized knowledge representation of the data center energy optimization domain and is shown in Figure 3. The ontology is considered as a multi-component model that integrates a conceptual description of the infrastructure, its energy characteristics, and control mechanisms into a single semantically consistent system.

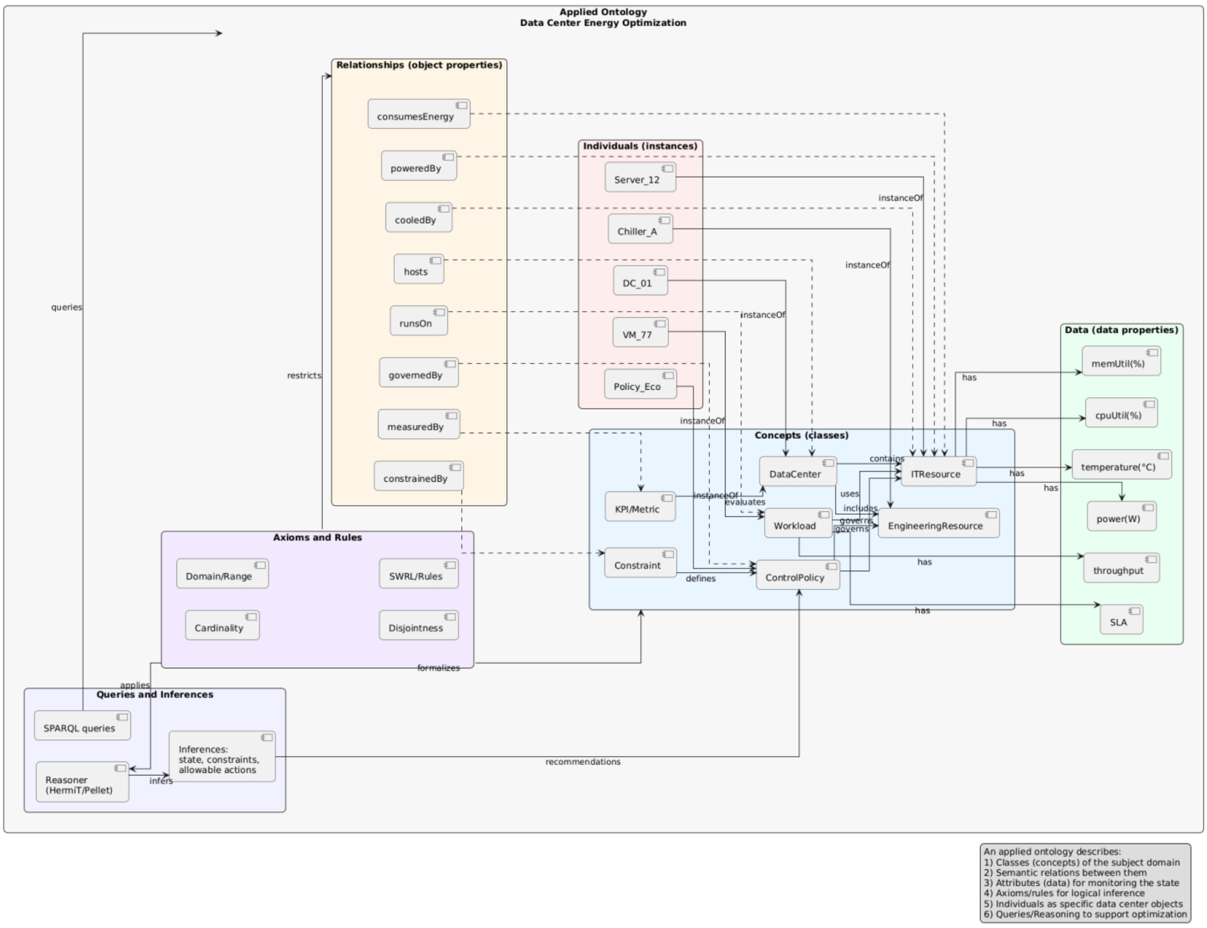

Fig. 3. Scheme of Applied Ontology Description (Data Center Energy Consumption Optimization)

At the core of the ontology, the level of concepts (classes) is distinguished, defining the basic notions of the domain. These include classes describing the data center as an integrated system, computational and engineering resources, workloads, control policies, performance indicators, and constraints. At this level, an abstract model of the data center infrastructure is formed, and the roles of its main components in the energy optimization process are determined.

The interaction between concepts is defined through semantic relations that formalize functional and energy dependencies between domain objects. In particular, relations are specified for workload placement on computational resources, energy consumption, interaction with cooling and power supply systems, and subordination of resources to control policies. Such relations ensure the coherence of the ontology and provide a foundation for subsequent logical reasoning.

The data property level is used to describe quantitative characteristics of objects, including power consumption, temperature parameters, resource utilization levels, and quality-of-service indicators. These properties link the ontological model with real measurement data obtained from data center monitoring systems and ensure the continuous updating of the system's semantic state.

The correctness and consistency of the ontology are ensured by a set of axioms and rules that define admissible constraints, value domains, and logical dependencies between concepts. The axioms make it possible to detect conflicting states, verify compliance with operational constraints, and formulate conditions for automated decision-making in the optimization process.

The level of individuals (instances) represents specific objects of a real data center, such as individual servers, virtual machines, cooling system components, or control policies. Individuals populate the ontology with actual data and ensure its applied orientation. An important component of the scheme is the query and logical reasoning mechanisms, which enable analysis of the current state of the data center, identification of active constraints, and generation of recommendations for optimal control actions. The use of semantic queries and logical inference ensures the interpretability of optimization results and their consistency with the formal knowledge model.

Thus, the applied ontology scheme reflects a holistic approach to organizing knowledge about the data center, within which conceptual modeling, data processing, logical reasoning, and support for energy consumption optimization processes are combined. This creates a theoretical and practical foundation for the development of intelligent energy management systems for modern data centers.

DISCUSSION OF RESEARCH RESULTS

The general ontological model of the data center energy consumption optimization domain covers a wide range of concepts and semantic relationships. To solve applied optimization problems, it is reasonable to a subset of basic concepts and relations that are directly involved in forming the mathematical model and control decisions. The key concepts of the ontological model include the following classes:

- DataCenter — a generalized concept describing a data center as an integrated computational and engineering system;
- ITResource — computational resources of the data center (servers, processors, memory, network components);
- EngineeringResource — engineering infrastructure, including power supply and cooling systems;
- Workload — computational workloads, tasks, services, or virtual machines;
- EnergyConsumption — characteristics of electrical energy consumption by individual components or by the system as a whole;
- ControlPolicy — control policies aimed at optimizing energy consumption;
- Constraint — operational, resource, and thermal constraints;
- Metric — performance indicators (energy efficiency, performance, SLA).
- The specified subset of classes forms the conceptual core of the ontology and represents both the physical components of the data center and abstract control and evaluation elements. The relationships between the basic concepts are formalized through a system of semantic relations, the main ones being:
- hasResource(DataCenter, ITResource) — the data center contains computational resources;
- hasEngineeringResource(DataCenter, EngineeringResource) — the data center includes engineering infrastructure;
- runsOn(Workload, ITResource) — a workload is executed on a computational resource;

- consumesEnergy(ITResource, EnergyConsumption) — a computational resource consumes energy;
- supportedBy(ITResource, EngineeringResource) — the operation of computational resources is supported by engineering infrastructure;
- governedBy(ITResource, ControlPolicy) — the operating mode of a resource is determined by a control policy;
- restrictedBy(ControlPolicy, Constraint) — control policies are constrained by operational requirements;
- evaluatedBy(DataCenter, Metric) — the state of the data center is evaluated using defined metrics.
- These relations reflect energy-related, functional, and control dependencies between system components and ensure the semantic consistency of the ontological model.
- The identified subset of concepts and relations is used as a semantic basis for:
- - forming variables and parameters of the mathematical optimization model;
- - automated identification of active constraints;
- - interpreting optimization results in domain-specific terms;
- - supporting adaptive control of data center energy consumption.
- Thus, the defined subset of concepts and relations serves as a linking layer between the abstract ontological model and applied optimization algorithms, ensuring the integrity and interpretability of the obtained solutions.

Table 2 presents a subset of basic concepts and semantic relations of the general ontological model that are directly used in forming the mathematical problem of data center energy consumption optimization. The identified relations ensure consistency between the infrastructure structure, energy consumption characteristics, and control mechanisms, which enables the integration of the ontological model with optimization algorithms.

Table 2 - Subset of Concepts and Relations of the General Ontological Model

Class (Concept)	Semantic Relation	Related Class	Purpose of the Relation in the Optimization Task
DataCenter	hasResource	ITResource	Formalization of the data center's computational resource composition
DataCenter	hasEngineeringResource	EngineeringResource	Description of engineering infrastructure influencing energy consumption
Workload	runsOn	ITResource	Modeling of workload placement and migration
ITResource	consumesEnergy	EnergyConsumption	Linking a resource to its energy consumption profile
ITResource	supportedBy	EngineeringResource	Accounting for energy and thermal support of resources
ITResource	governedBy	ControlPolicy	Application of control policies to computational resources
ControlPolicy	restrictedBy	Constraint	Constraining control policies by operational and SLA requirements
DataCenter	evaluatedBy	Metric	Evaluation of data center operational efficiency
EngineeringResource	affects	EnergyConsumption	Accounting for the impact of cooling and power supply on energy consumption
Metric	reflects	EnergyConsumption	Formation of optimization criteria and objective functions

Figure 4 shows a graph of the applied ontology, in which the vertices correspond to concepts (classes) and generalized subsystems of the domain, while the edges represent semantic relations between them. The visualization is based on a force-directed layout, which provides automatic grouping of logically related elements and improves the perception of the model structure.

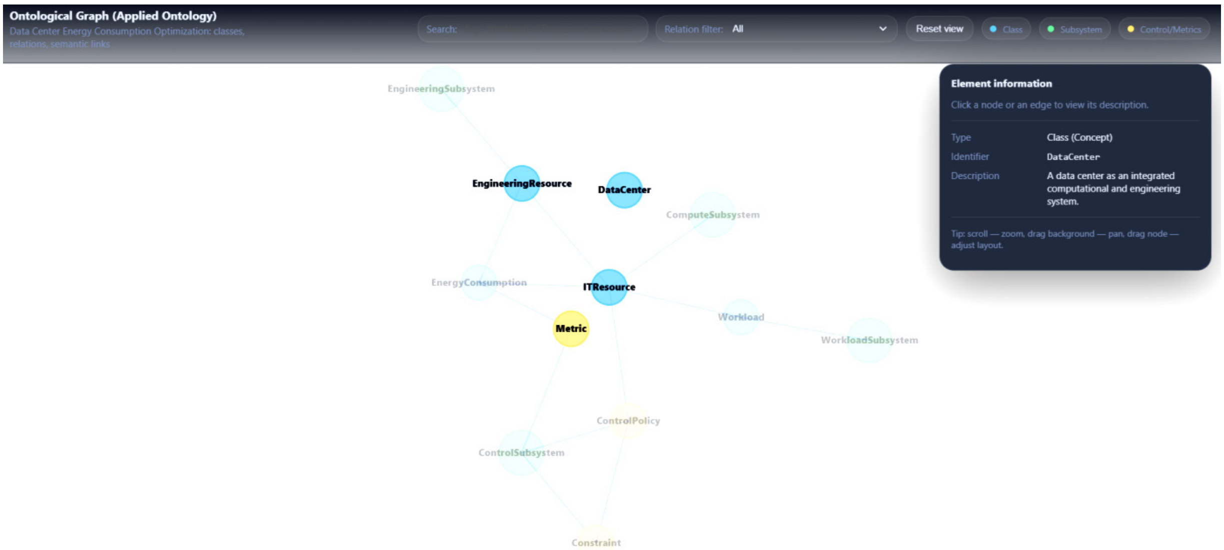

Fig. 4. Example of Ontological Graph Implementation

The ontology classes (DataCenter, ITResource, EngineeringResource, Workload, ControlPolicy, Constraint, Metric, EnergyConsumption) represent the key concepts required to describe the data center infrastructure, its energy characteristics, and control mechanisms. In addition, nodes representing subsystems (computational, engineering, workload, and control) are distinguished, reflecting the semantic decomposition of the domain and enabling visual structuring of the ontology.

Semantic relations between concepts reflect functional, energy-related, and control dependencies, including workload placement on computational resources, energy consumption, support of resources by engineering infrastructure, application of control policies, and evaluation of data center operational efficiency. Edge labels ensure an unambiguous interpretation of each relation.

The use of an applied ontology as the semantic core of a data center energy consumption optimization system opens a number of promising directions for further development from both theoretical and applied perspectives. The ontological model provides a formalized and interpretable representation of knowledge about data center infrastructure, creating a foundation for building intelligent, adaptive, and scalable control systems.

One of the key prospects is the integration of the ontology with artificial intelligence and machine learning methods. The ontological model can be used for semantic interpretation of learning outcomes, for shaping the state and action spaces in reinforcement learning tasks, and for constraining the solution search space based on expert knowledge. This makes it possible to combine the high adaptability of intelligent algorithms with the explainability and formal consistency inherent in the ontological approach.

An important direction is the extension of the ontology toward digital twins of data centers. A formalized representation of the infrastructure structure, operating modes, and energy characteristics allows the ontology to serve as a knowledge backbone of a digital twin, supporting scenario simulation, energy consumption forecasting, and assessment of the effects of control actions prior to their actual implementation.

The ontology also creates prerequisites for unification and standardization of data center descriptions, which is particularly relevant for heterogeneous and distributed computing environments. The use of a common ontological vocabulary ensures interoperability between different monitoring, optimization, and control systems and simplifies the integration of new components and services.

Another promising application of the ontological approach lies in decision support and strategic planning tasks. The ontology can be employed to analyze long-term energy consumption trends, evaluate the effectiveness of investments in infrastructure modernization, and generate recommendations for transitioning to more energy-efficient and environmentally sustainable solutions.

Special attention should be given to the potential use of the applied ontology in the context of regulatory requirements and sustainability policies. The formalized representation of energy indicators and corresponding constraints enables automated compliance monitoring with energy efficiency standards, environmental regulations, and reporting requirements, which is particularly important for large-scale data centers and cloud service providers.

Thus, the applied ontology for data center energy consumption optimization demonstrates significant potential for further development and practical implementation. Its use facilitates the transition from isolated algorithmic solutions to comprehensive knowledge-oriented control systems capable of improving energy efficiency, enhancing transparency of decision-making processes, and adapting to the dynamic operating conditions of modern data centers.

CONCLUSIONS

The paper addresses a relevant scientific and practical problem of optimizing data center energy consumption under conditions of increasing complexity of computational and engineering infrastructure. It is shown that traditional energy optimization approaches based solely on mathematical or algorithmic methods do not adequately account for semantic dependencies between data center components and limit the adaptability of control systems in dynamically changing operating conditions.

An ontological approach to data center energy consumption optimization is proposed, based on a formalized representation of domain knowledge in the form of an applied ontology. A semantic decomposition of the domain is developed, allowing the data center to be represented as a set of interrelated computational, engineering, workload, and control subsystems, between which energy-related, functional, and control dependencies are defined.

A subset of basic concepts and relations of the general ontological model is identified, which is directly used in the optimization task. It is shown that this subset ensures semantic consistency between the data center infrastructure structure, energy consumption characteristics, and control policies, and can serve as a basis for forming variables, parameters, and constraints of the mathematical optimization model. A general scheme of the ontological approach is developed, implementing a closed loop “data – knowledge – optimization – control,” in which the ontology performs the role of an integration and interpretation mechanism.

The obtained results confirm the feasibility and effectiveness of using an ontological approach for building intelligent data center energy consumption optimization systems. The proposed solution provides a theoretical and methodological foundation for further integration with mathematical optimization methods, artificial intelligence algorithms, and the digital twin concept, and can be applied in the design of energy-efficient and environmentally sustainable computing infrastructures.

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ЮРІЙ ПОПИК, МАРЕК ПЛЕС

ОПТИМІЗАЦІЯ ЕНЕРГОСПОЖИВАННЯ В ЦЕНТРАХ ДАНИХ НА ОСНОВІ ОНТОЛОГІЧНОГО ПІДХОДУ

Західноукраїнський національний університет, Академія Сілезії