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AN ONTOLOGY-DRIVEN KNOWLEDGE-BASED APPROACH TO COMPLEX SYSTEMS MANAGEMENT

The paper addresses the problem of managing a corporate network as a complex functional system, whose efficiency is determined by the consistency between the infrastructure structure, resource characteristics, and the requirements of application tasks. The feasibility of employing a knowledge-based approach, particularly ontology-based modeling, is substantiated for the formalization of corporate network structure and decision support in its configuration. A conceptual model of a corporate network is proposed, where the network is considered as a multi-level system of interconnected components, including network nodes, services, users, resources, operational parameters, and security constraints. Based on this model, a theoretical foundation for constructing a corporate network ontology is developed, ensuring a consistent representation of infrastructure entities, their properties, and relationships. Furthermore, it enables the formalization of interaction rules and logical constraints in the form of ontological axioms. The study proposes a formalized representation of the corporate network ontology in the form of a tuple-based structure, integrating sets of objects, parameters, states, task performance characteristics, and axiomatic constraints. On this basis, a parameter normalization model is developed, enabling the transformation of heterogeneous characteristics into a unified evaluation scale, taking into account the task context and ontological constraints. This facilitates the construction of an integral configuration quality criterion that incorporates resource, operational, and functional aspects. The main contribution of the work is the development of a method for ontology-driven configuration of a corporate network based on a set of tasks. The method relies on tuple algebra operations to generate a set of feasible configurations that satisfy structural, parametric, and axiomatic constraints, followed by the selection of an optimal configuration using multi-criteria evaluation. The proposed approach ensures transparency, reproducibility, and interpretability of the configuration process. Experimental studies were conducted for two types of corporate networks: a university information and telecommunication system and a network of a commercial enterprise. The results demonstrate that the proposed method significantly improves key performance indicators, including reduced service access latency, decreased computational resource load, fewer access conflicts, and enhanced compliance with security policies. The integral configuration quality criterion decreased by approximately 48–51%, confirming the effectiveness of the proposed approach. The proposed approach can serve as a foundation for the development of intelligent corporate network management systems, as well as for further advancement of optimization methods for complex information and telecommunication systems based on ontology-driven knowledge representation.

Keywords: corporate network; ontology-based modeling; network configuration; multi-criteria optimization; decision support systems; resource allocation; performance optimization; knowledge-based systems.

Introduction

In the context of the ongoing digitalization of the economy and the rapid development of information and telecommunication technologies, corporate networks serve as a fundamental infrastructure for the operation of organizations across various domains. They provide integration of computational resources, information services, users, and business processes into a unified environment that operates under conditions of dynamic workloads, evolving structures, and increasing requirements for performance, reliability, and security.

Accordingly, corporate networks should be considered as complex functional systems whose behavior is components and constraints of different nature [1].

The increasing complexity of corporate networks is accompanied by a growing complexity of configuration and management tasks. Traditional approaches based on static rules or local optimization techniques fail to provide sufficient flexibility and adaptability under multi-criteria operational requirements. In particular, the problem of coordinated allocation of computational resources among multiple application tasks becomes critically important, especially when these tasks significantly differ in their characteristics, priorities, and quality-of-service requirements [2].

In this context, the use of knowledge-based approaches, particularly ontology-based modeling, is highly promising. Ontological modeling enables the formalization of the corporate network domain as a structured system of knowledge. Ontologies provide explicit representation of infrastructure entities, their properties, relationships, and constraints, while also supporting logical inference of new knowledge based on predefined axioms. This creates the foundation for the development of intelligent network management methods that account for both structural and functional aspects of network operation [3].

Despite the considerable body of research in network management, resource optimization, and artificial intelligence applications, the integration of ontology-based approaches with formal methods for corporate network configuration remains insufficiently explored. In particular, further development is required for formalized representations of network ontologies that can be directly utilized within configuration algorithms, as well as for methods that transform ontological knowledge into formal models suitable for computational processing [4].

The objective of this paper is to develop a knowledge-based approach to managing complex corporate networks based on ontology-driven modeling and formal configuration methods. To achieve this objective, the following tasks are addressed: formalization of the corporate network as a complex functional system; development of a theoretical foundation for constructing a corporate network ontology; creation of its formalized representation; development of a method for ontology-driven configuration based on a set of tasks; and experimental evaluation of the effectiveness of the proposed approach [5-6].

Related works

Research on the application of ontologies in complex information systems forms several interrelated directions. The first direction is associated with general issues of ontology usage in corporate environments. Classical studies on enterprise ontology management emphasize that their primary role lies in the explicit representation of the semantics of heterogeneous information resources and in enabling meaningful interaction between systems that rely on different local data models. This perspective has laid the foundation for the transition from isolated information models to knowledge-based corporate environments [7,8].

A distinct research direction is represented by ontology-driven network management. In these studies, ontologies are employed to describe network entities, services, policies, and management behavior, as well as to support interoperability among components of the network environment. In particular, research on ontology-based network management demonstrates that ontologies are suitable for integrating management information, enhancing knowledge reuse, and supporting semantic analysis of network objects. However, these approaches are primarily focused on knowledge and policy representation rather than on the formal mapping of a set of tasks to a set of network configurations [9,10].

A significant contribution to semantic network management has been made by studies on ontology-based policy management. In these works, ontologies are considered as a means of unified representation of access rules, policy hierarchies, and context-dependent conditions of their application. These approaches have demonstrated the effectiveness of ontologies for formal policy specification, as well as for supporting flexible control of access and behavior in complex network systems. Nevertheless, the primary focus remains on policies as independent management objects, while the problem of holistic infrastructure configuration tailored to specific tasks remains insufficiently addressed [11,12].

Further development of this direction is associated with semantic models of access control and security. In particular, ontology-based models of context-aware access control demonstrate that ontologies are capable of integrating low-level contextual information with high-level decision-making policies. Similarly, recent studies on ontology-based risk and security modeling at the enterprise architecture level confirm that semantic approaches enable the identification of constraints and inconsistencies in the representation of risks, incidents, and security controls. For corporate network configuration tasks, this is particularly important, as security requirements must be considered not in isolation, but as an integral component of admissible configurations [13,14].

A direction more closely related to the formalization of network infrastructure involves the use of ontologies for constructing knowledge graphs and describing network configuration elements. For instance, in studies on high-level ontology networks for ICT infrastructures, a set of interconnected ontologies is proposed to cover configuration units, resources, and services within DevOps infrastructures. Another recent work on the YANG Server Ontology demonstrates that ontologies can be used for declarative construction of knowledge graphs from NETCONF/YANG-based network data sources. These results are highly relevant to the present study, as they confirm the practical applicability of ontologies for formalizing network artifacts and integrating them with declarative data processing mechanisms. However, these works primarily focus on the construction of network knowledge graphs and access to configuration data, rather than on the problem of selecting an optimal configuration under a set of tasks and axiomatic constraints [15,16].

Another related direction is represented by studies in which ontologies are applied for the description and discovery of network components or functions. For example, recent work in the field of in-network computing shows that an ontological model of functional and non-functional properties of network components enables semantic matchmaking and automated selection of components from centralized repositories. This approach is conceptually close to the one proposed in this study, as it also combines semantic resource descriptions with a selection procedure. However, in the cited work, the selection object is limited to individual in-network computing components, whereas this study considers the configuration of a corporate network as an integral structure that includes nodes, services, parameters, states, and ontological axioms [3, 6, 7, 17].

Thus, the literature analysis indicates that existing studies have established a solid foundation for the application of ontologies in corporate environments, network management, access control policies, semantic component description, and network knowledge graph construction. However, the problem of developing a unified method that simultaneously:

- relies on a formalized ontology of a corporate network;
- utilizes axioms as a mechanism for filtering admissible solutions;
- has a procedural interpretation based on tuple algebra operations;
- ensures the mapping of a set of tasks to a set of feasible configurations with subsequent selection of an optimal configuration, remains insufficiently explored. Addressing this gap constitutes the primary objective of the proposed study.

The conducted literature review has shown that existing approaches to corporate network management form several relatively independent directions, each emphasizing different aspects of the system, including resource-related, algorithmic, or semantic components. At the same time, there is no unified approach that ensures the consistent consideration of network structural characteristics, application task requirements, and logical constraints represented in the form of knowledge.

To more clearly identify these features and substantiate the need for developing an integrated approach to corporate network configuration, a generalized comparative analysis of existing methods was conducted. The results of this analysis are presented in Table 1.

Table 1

Comparative analysis of existing approaches to corporate network management

No.	Approach	Core Idea	Advantages	Limitations
1	Classical network configuration methods	Use of static rules and manual administration	Simplicity of implementation; transparency; low computational cost	Lack of adaptability; does not account for multiple tasks; poor scalability
2	Resource optimization methods	Optimization of individual parameters (CPU, RAM, bandwidth)	Effective for local tasks; well-formalized models	Ignores task semantics; lacks knowledge integration; limited to local optimization
3	AI/ML-based approaches	Application of machine learning for prediction and control	High adaptability; ability to process large datasets	Low interpretability; requires large datasets; difficulty in explaining decisions
4	Ontology-based network models	Semantic representation of network entities and relationships	Explicit knowledge representation; support for logical reasoning; flexibility	Lack of formalized configuration algorithms; weak integration with optimization methods
5	Policy-based management	Use of rules and access control policies	Formalization of constraints; flexible control mechanisms	Limited consideration of resource aspects; complexity of policy coordination
6	Semantic knowledge graphs	Construction of knowledge graphs for network data	Integration of heterogeneous data; support for analytical processing	Lack of mechanisms for optimal configuration selection; focused on representation rather than optimization
7	Proposed ontology-driven approach	Integration of ontology, axioms, and tuple algebra for configuration	Formal problem representation; interpretability; consideration of multiple tasks; multi-criteria optimization; use of axioms as constraints	Increased modeling complexity; requirement for ontology development

As shown in Table 1, existing approaches to corporate network management are either focused on the local optimization of individual parameters or concentrated on the semantic representation of knowledge without sufficient procedural interpretation. In particular, ontology-based models provide a high level of domain formalization; however, they lack mechanisms for the direct utilization of this knowledge in configuration tasks. Conversely, optimization and machine learning methods do not adequately account for the semantic structure of tasks and constraints.

The approach proposed in this paper integrates the advantages of these directions by combining ontology-based knowledge representation, axiomatic constraints, and formal operations of tuple algebra. This integration enables both interpretability and efficiency of the corporate network configuration process.

Purpose and objectives of the study

The objective of this study is to develop a knowledge-based approach to the configuration of a corporate network as a complex functional system. The proposed approach is based on the integration of ontology-driven modeling and formal configuration methods, enabling a consistent representation of network structure, task requirements, and logical constraints.

A corporate network is considered as a complex functional system composed of interconnected components, including network nodes, services, users, computational resources, and operational constraints. The configuration problem is defined as the task of determining an optimal network structure and parameter set that satisfies a given set of application tasks while adhering to resource limitations and logical constraints.

In this context, the key challenge lies in ensuring the coordinated consideration of heterogeneous factors, including structural dependencies, task-specific requirements, and domain knowledge represented in a formalized manner.

To achieve the stated objective, the following methodological steps are performed:

1. Formalization of the corporate network as a complex functional system, including the identification of its structural components, parameters, and operational states;
2. Development of the theoretical foundations of the corporate network ontology, ensuring a consistent and semantically rich representation of entities, relationships, and constraints;
3. Construction of a formalized tuple-based representation of the ontology, enabling its integration into computational procedures and configuration algorithms;
4. Design of an ontology-driven configuration method based on a set of application tasks, incorporating axiomatic constraints and formal operations of tuple algebra;
5. Experimental validation of the proposed approach, including the evaluation of its effectiveness in improving key performance indicators of corporate network operation.

Materials and methods

One of the most effective approaches to addressing the aforementioned problem is the ontology-based approach, which enables the representation of the domain as a formal knowledge system with clearly defined concepts, relationships, and constraints. Within this framework, a corporate network is considered not merely as a collection of technical components, but as a semantically structured system in which each entity has a defined role and interacts with other entities according to specified rules.

Figure 1 illustrates the interrelationship between the inherent characteristics of corporate networks, the fragmentation of knowledge sources, the limitations of traditional approaches, and the necessity of adopting an ontology-based approach. This approach serves as a foundation for formalized knowledge representation, logical reasoning, and the subsequent algorithmic interpretation of knowledge.

It is important to emphasize that, in this context, the ontology is not limited to a purely descriptive function. Rather, it serves as a formal foundation that enables logical reasoning, the identification of implicit dependencies, and the formation of consistent sets of solutions. Thus, the ontological model becomes not only a means of knowledge representation but also an instrument for knowledge processing.

The characteristics of corporate networks as an object of modeling define the requirements for constructing their ontology. First and foremost, this concerns the heterogeneity of resources, which necessitates a unified representation of diverse characteristics within a single model. At the same time, the dynamic nature of network operation implies that any model must account for temporal variability of parameters.

Additional complexity arises from the uncertainty associated with key characteristics, such as node workload or task execution time. In most cases, these parameters cannot be adequately represented as point estimates and are more appropriately modeled using interval values. This, in turn, requires an extension of classical approaches to knowledge formalization.

Furthermore, corporate network management processes are inherently multi-criteria, as decisions must be made by simultaneously considering multiple factors that are often conflicting. This necessitates the integration of ontology-based approaches with optimization methods.

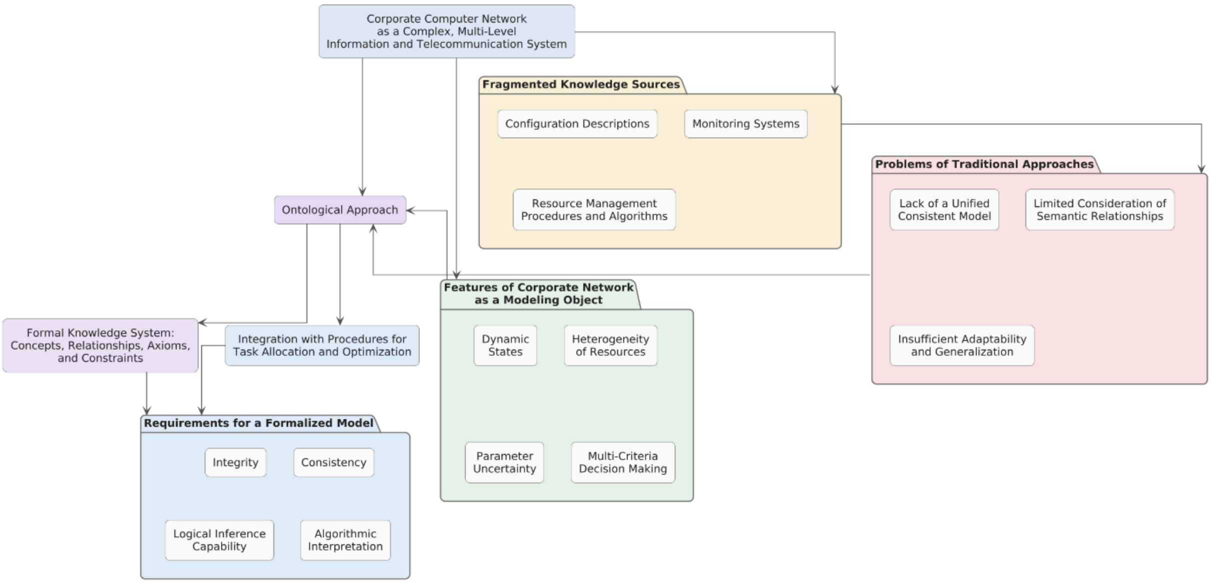

Fig. 1. Conceptual Framework of the Theoretical Foundations for Constructing a Corporate Network Ontology

The ontology of a corporate network is constructed as a multi-level system of classes that reflect different aspects of IT infrastructure operation. Its development is based on the transition from the physical level of network organization to the logical, functional, and organizational levels, and ultimately to the level of resource management and security. Such a hierarchical structure enables not only the description of the network architecture but also the representation of its operational processes in an integrated manner. The foundation of the ontology is formed by classes describing the physical network infrastructure, as illustrated in Figure 2.

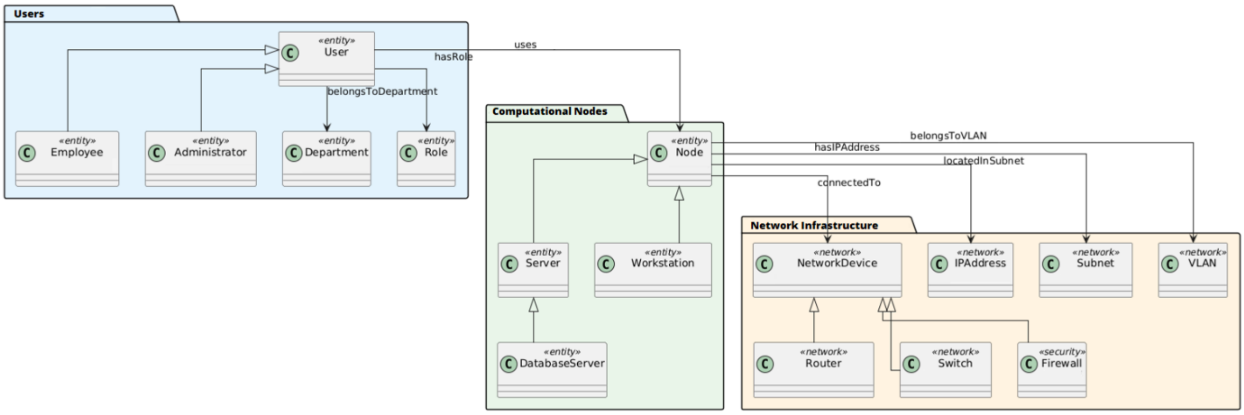

Fig. 2. Structure of Users, Nodes, and Network Infrastructure

Central to this context is the NetworkDevice class, which encompasses all devices responsible for the transmission and processing of network traffic. Within this class, specialized device types are distinguished according to their functional roles in the network. In particular, the Router class is responsible for routing data between networks, the Switch class enables packet switching within a local network, and the Firewall class performs access control and traffic filtering functions. The extension of this layer through the inclusion of the AccessPoint and LoadBalancer classes allows for the consideration of wireless communication and load balancing mechanisms, which are characteristic of modern corporate networks.

Interacting with network devices are computational nodes, which form the next level of the ontology. The generalized class at this level is Node, which represents any entity capable of performing computation or data processing. Within this class, the Server class denotes nodes that provide resources or services to other components, while the Workstation class describes user workstations. Further refinement through the VirtualMachine and Container classes enables the representation of virtualized environments. Additionally, the inclusion of the MobileDevice, Printer, and StorageNode classes extends the model to realistic network usage scenarios, where mobile clients, storage systems, and peripheral devices coexist.

The description of physical entities is insufficient without accounting for the logical organization of the network, which is defined through classes of network entities. The IPAddress class specifies the logical address of a node, determining its position within the network space, while the MACAddress class provides physical device identification. The Subnet and VLAN classes represent network segmentation mechanisms used to enhance efficiency and security. Furthermore, the Protocol class defines the rules for data transmission, whereas the Port and Session classes enable the formalization of specific interactions between nodes. In this way, the logical layer establishes a connection between the physical infrastructure and communication processes.

At this stage, it becomes possible to transition to the description of the functional aspect of the network, represented by classes of services and software components, as illustrated in Figure 3. The Service class generalizes all functionalities provided by the network, while its specializations, such as WebService, DatabaseService, MailService, and AuthenticationService, capture specific types of services. In this context, a server is no longer viewed solely as a technical node but assumes the role of a service execution environment. The Application class complements this model by representing application-level software, while the OperatingSystem class defines the fundamental execution layer of computational nodes. As a result, a comprehensive representation of the software environment of the corporate network is established.

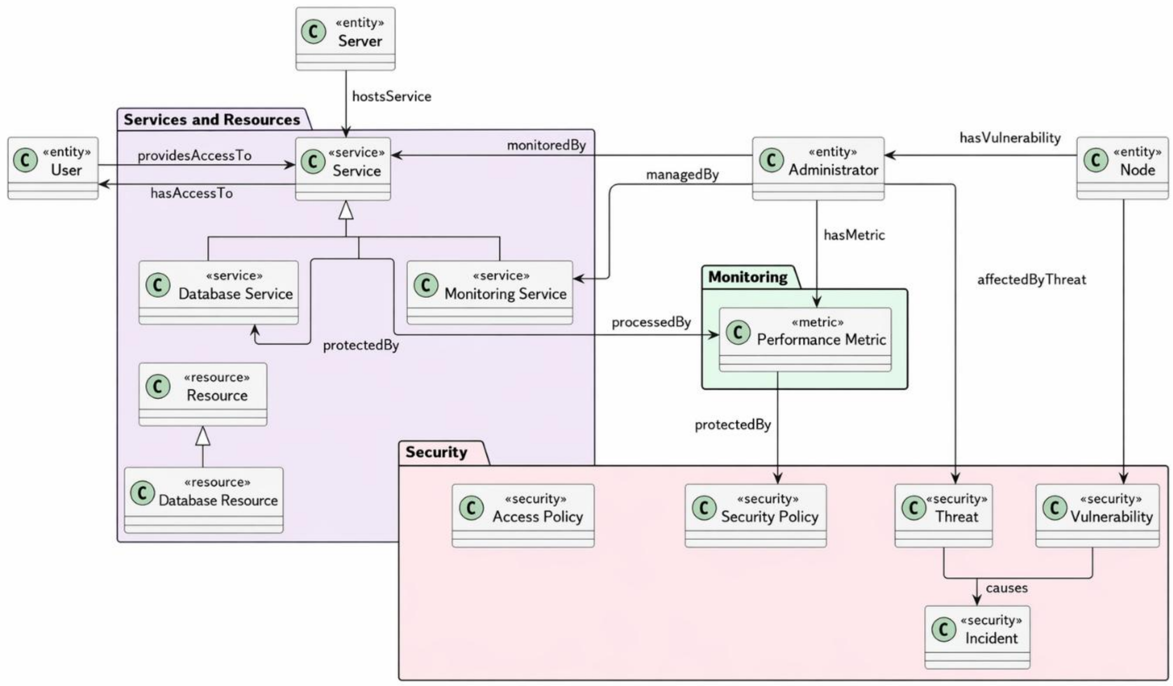

Fig. 3. Structure of Services, Resources, Monitoring, and Security

The final component of the structure is represented by classes that describe the system state and its behavior over time. The PerformanceMetric class generalizes performance indicators, while the CPUUsage, MemoryUsage, BandwidthUsage, and Latency classes provide detailed representations of different aspects of system load. The AvailabilityStatus class reflects the availability of nodes and services, whereas the Event and Alert classes enable the recording of system events and corresponding responses. In this context, the ontology extends beyond static description and becomes a tool for modeling dynamic processes.

As a result, this class structure forms a comprehensive ontological model of a corporate network, in which physical components, logical relationships, services, resources, users, and security mechanisms are integrated into a unified system. This integration provides the foundation for further formalization of relationships, construction of ontological axioms, and application of the model to tasks of analysis and optimization of corporate network operation.

Such classes acquire full meaning only when a system of semantic relationships is established among them, reflecting real-world interactions between components of the corporate network. It is precisely these relationships that transform a set of individual objects into a coherent ontological model suitable for logical reasoning, dependency analysis, and further formalization using tuple algebra.

Within the ontology of a corporate network, relationships perform several interrelated functions. First, they capture structural connections between physical and logical infrastructure elements. In addition, they define functional dependencies among users, services, and resources, as well as represent rules for access control, administration, and security. Consequently, the ontology can be used not only to describe the network configuration but also to interpret the processes of its operation.

One of the fundamental relationships is connectedTo, which describes the connection between one node or network device and another. This relationship represents the physical or logical topology of the network and enables the modeling of traffic transmission paths between its elements. For example, if a workstation is connected to a switch, and the switch is connected to a router, the sequence of such relationships can be used to analyze access paths to network resources or to identify critical infrastructure nodes.

Closely related to this is the locatedInSubnet relationship, which defines the membership of a node in a specific subnet. Unlike connectedTo, which captures topological interaction, this relationship represents the logical segmentation of the network. It is essential for modeling routing rules, access control policies, and network policy analysis. A similar role is played by the belongsToVLAN relationship, which establishes the association of a device or node with a particular virtual local area network. This allows the ontology to formally represent not only the physical structure of the network but also its virtual organization.

In general, the system of relationships within the corporate network ontology provides a formal integration of multiple levels of description. At one level, it represents the physical and logical structure of the network; at another, it models organizational relationships and access control rules; and at yet another, it enables the description of service operation, resource utilization, and security mechanisms. Owing to this multi-level system of relationships, the ontology becomes suitable for tasks such as logical reasoning, consistency verification, risk analysis, and the development of intelligent mechanisms for corporate network management.

Formalization of the Corporate Network Ontology

The transition from a conceptual description of a corporate network to its formalized representation is a necessary condition for constructing a system capable of automated analysis, logical reasoning, and decision support. Such a transition involves defining the structure of knowledge in the form of a formal model that captures not only the constituent elements of the network but also the patterns of their interaction, as well as the constraints that determine admissible modes of operation. Within the proposed approach, the ontology of a corporate network is considered as a formal system that combines domain description with mechanisms for its interpretation. This enables the transition from declarative knowledge representation to its use in procedural algorithms, particularly in tasks of optimizing the allocation of computational resources. Formally, the corporate network ontology can be represented as a tuple:

$$O_{net} = \langle D, M, U, P, S, E, A \rangle, \quad (1)$$

where each component reflects a specific aspect of the domain and performs a defined function in the process of knowledge formalization.

The first component is the set D, which defines the domain. It establishes the context within which the ontology is constructed and includes descriptions of network topology, functional elements, and external operating conditions. Formally, the domain can be represented as:

$$D = \langle id_D, dom \rangle, \quad (2)$$

where id_D uniquely identifies the domain, and domcontains its semantic description. It is important to emphasize that this component ensures the connection between the formal model and the real-world system.

The next component is the set M, which describes the structure of the network infrastructure. Unlike the domain, which defines the general context, this set specifies the system elements and their interconnections. Formally, it is defined as:

$$M = \langle id_M, Str_m \rangle, \quad (3)$$

where id_M is the identifier of a network element, and Str_m is its formalized description, including device types, configuration characteristics, and relationships with other elements. Thus, the set M serves as the structural framework of the ontology.

A particularly important component is the set U, which defines the objects of network usage. While M describes resources, UUU represents the processes of their utilization. This set includes tasks, services, and users interacting with network resources. Its formal representation is:

$$U = \langle id_u, Str_u \rangle, \quad (4)$$

where id_u identifies the object, and Str_u defines its characteristics, including resource requirements and execution conditions. Therefore, the set U establishes the link between network structure and operational processes.

The set of parameters P provides a quantitative representation of system characteristics, enabling the transition from qualitative descriptions to formal numerical evaluations required for decision-making. It is defined as:

$$P = \langle id_p, type_p, val_p \rangle, \quad (5)$$

where $type_p$ specifies the parameter type and val_p its value. In the context of corporate networks, these parameters describe computational resources such as CPU time, memory capacity, and bandwidth. An important feature is the possibility of representing parameter values as intervals, allowing uncertainty to be taken into account.

The set S represents network states and introduces the dynamic aspect of the model. While the previous components describe structure and characteristics, S captures temporal variability. Formally:

$$S = \langle id_s, cond_s \rangle, \quad (6)$$

where $cond_s$ describes the current state of the network. This component is essential for adaptive management, as it enables consideration of changes in load and resource availability. The set E defines task execution characteristics and establishes the relationship between resources and the outcomes of their usage. It describes performance indicators used for evaluating solutions:

$$E = \langle id_e, main_e, alt_e, rule_e \rangle, \quad (7)$$

where $main_e$ and alt_e represent primary and alternative characteristics, respectively, and $rule_e$ defines their interpretation rules. Finally, the set A includes methods and rules governing resource management processes. This component ensures the transition from static description to dynamic knowledge utilization:

$$A = \langle id_a, meth_a, oper_a \rangle, \quad (8)$$

where $meth_a$ specifies the method and $oper_a$ the set of operations implementing it.

The coordinated interaction of all these components forms an integrated ontological model in which structural, functional, and procedural aspects are combined into a unified system. An important feature is that each component can be used independently; however, maximum effectiveness is achieved through their integrated application.

Thus, the proposed formalization enables the representation of a corporate network as a multi-level knowledge system that combines declarative and procedural elements. To provide a formalized description of computational resource utilization processes, a set of ontological axioms A_k is introduced:

$$A_k = \langle a_1, a_2, \dots, a_k \rangle, \quad (9)$$

These axioms define constraints, rules, and dependencies among the elements of the ontology O_{net}. The introduction of an axiomatic system is essential for transitioning from a declarative description of the corporate network structure to its formal-logical interpretation, which enables automated knowledge inference, consistency checking, and decision support in computational resource allocation. Ontological axioms define the admissible solution space within which optimization is performed and establish the conditions for correct operation of the corporate network.

Ontology-Driven Method for Corporate Network Configuration Based on a Set of Tasks

Within the scope of this study, an approach to solving the stated problem is proposed based on a corporate network ontology defined by the tuple (1). Under this formulation, the configuration process is considered as a mapping of a task to a subset of ontology elements that satisfy both parametric requirements and logical constraints specified in the axiomatic base. Let us consider in more detail the process of formalizing the set of tasks:

$$T = \{t_1, t_2, \dots, t_n\}, \quad (10)$$

where T is the set of tasks considered within the corporate network. The introduction of the set T defines a formal task space relative to which the configuration problem is formulated. In this context, network configuration is treated as a task-dependent entity determined by its requirements. Each task is represented as:

$$t_i = \langle id_i, u_i, p_i, e_i \rangle, \quad (11)$$

where id_i is the task identifier; $u_i \in U$ is the usage object associated with the task; $p_i \subseteq P$ is the set of parametric requirements; and $e_i \subseteq E$ is the set of performance requirements. Representing tasks as tuples enables their direct interpretation within the ontology O_{net}, allowing the configuration process to be treated as an operation over ontology elements. The set of configurations is formalized as:

$$K = \{k_1, k_2, \dots, k_n\}, \quad (12)$$

where K is the set of admissible network configurations. This set defines the potential solution space, which is constrained by parametric, structural, and logical conditions. Each configuration is defined as:

$$K_i = \langle m_i, p_i^*, s_i, e_i^* \rangle, \quad (13)$$

where $m_i \subseteq M$ is the set of infrastructure elements; $p_i^* \subseteq P$ denotes configuration parameters; $s_i \subseteq S$ represents admissible states; and $e_i^* \subseteq E$ denotes expected performance characteristics. Thus, a configuration is interpreted as a consistent mapping of structural and dynamic network properties that satisfies task requirements. The mapping of tasks to configurations is defined as:

$$\Phi: T \to K, \quad (14)$$

where Φ is the configuration operator. This operator formalizes the configuration construction process as a mapping from the task space to the configuration space, which must be consistent with the ontological structure of the domain. The admissibility condition is defined as:

$$Valid(t_i, K_i, A) = 1 \iff \forall a_j \in a_j : A_{t_i} : a_j(t_i, K_i) = true, \quad (15)$$

where $A_{t_i} \subseteq A$ is the set of axioms relevant to task t_i. This condition defines the class of configurations that do not contradict ontological constraints. The inclusion of axioms ensures logical consistency and domain compliance of the resulting configurations. Next, consider the relational interpretation of ontology components M_{Rel}:

$$M_{Rel}(M_{Id}, M_{Type}, M_{Struct}), \quad (16)$$

where M_{Id} is the identifier of an infrastructure element, M_{Type} is its type, and M_{Struct} is its structural description. This relation defines the base set of resources used in configuration construction.

$$U_{Rel}(U_{Id}, U_{Type}, U_{Struct}), \quad (17)$$

where U_{Id} is the identifier of a usage object. This relation establishes semantic links between tasks and objects initiating network requirements.

$$P_{Rel}(P_{Id}, P_{Type}, P_{Value}), \quad (18)$$

where $P_{Id,}$ is the parameter identifier and P_{Value} is its value. This representation enables quantitative evaluation of configuration compliance.

$$S_{Rel}(S_{Id}, S_{Cond}), \quad (19)$$

where S_{Cond} describes the network state. This relation captures the dynamic aspects of network operation.

$$E_{Rel}(E_{Id}, E_{Main}, E_{Alt}, E_{Rule}), \quad (20)$$

where E_{Main} denotes primary characteristics, E_{Alt} alternative characteristics, and E_{Rule} interpretation rules. This relation formalizes task performance criteria.

$$Task_{Rel}(T_{Id}, U_{Id}, P_{Id}, E_{Id}), \quad (21)$$

which links tasks with corresponding ontology components.

Based on relations (10)–(21), the following formalized algorithm for corporate network configuration is proposed. The first operation selects infrastructure elements matching task requirements:

$$R_1 = \sigma_{M_{Struct} \models p_i}(M_{Rel}), \quad (22)$$

where σ is the selection operator and $\models$ denotes compliance. This step reduces the resource space to potentially relevant elements. Next:

$$R_2 = R_1 \bowtie_{M_{Id}=U_{Id}} U_{Rel}, \quad (23)$$

$\bowtie$ ensures consistency between resources and usage objects.

$$R_3 = R_2 \bowtie_{U_{Id}=P_{Id}} P_{Rel}, \quad (24)$$

incorporates parametric characteristics.

$$R_4 = \sigma_{P_{Type} \in ReqTypes(t_i) \wedge P_{Value} \geq ReqVals(t_i)}, \quad (25)$$

filters configurations according to parameter constraints.

$$R_5 = R_4 \bowtie_{M_{Id}=S_{Id}} S_{Rel}, \quad (26)$$

accounts for network states.

$$R_6 = \sigma_{S_{Cond} \in AllowedStates(t_i)}(R_5), \quad (27)$$

filters admissible operational modes.

$$R_7 = R_6 \bowtie_{E_{Id}} E_{Rel}, \quad (28)$$

$$R_8 = \sigma_{a_1 \wedge \ldots, \in a_q}(R_7), \quad (29)$$

verifies ontological consistency. The resulting configuration relation is:

$$ConfigRel_i = \pi_{M_{Id}, U_{Id}, P_{Id}, S_{Id}, E_{Id}}(R_8), \quad (30)$$

where π is the projection operator. The configuration quality is evaluated by:

$$J(ConfigRel_i) = \alpha_1 J_P + \alpha_2 J_S + \alpha_3 J_E, \quad (31)$$

where $\alpha_1, \alpha_2, \alpha_3$ are weighting coefficients. The optimal configuration is defined as:

$$K_i^* = arg \min_{K_i \in \phi(t_i)} J(K_i) \ , \quad (32)$$

$arg\ min$ which minimizes the objective function over admissible configurations.

Figures 4 illustrate the overall architecture of the ontology-driven network configuration method, consisting of declarative and procedural components.

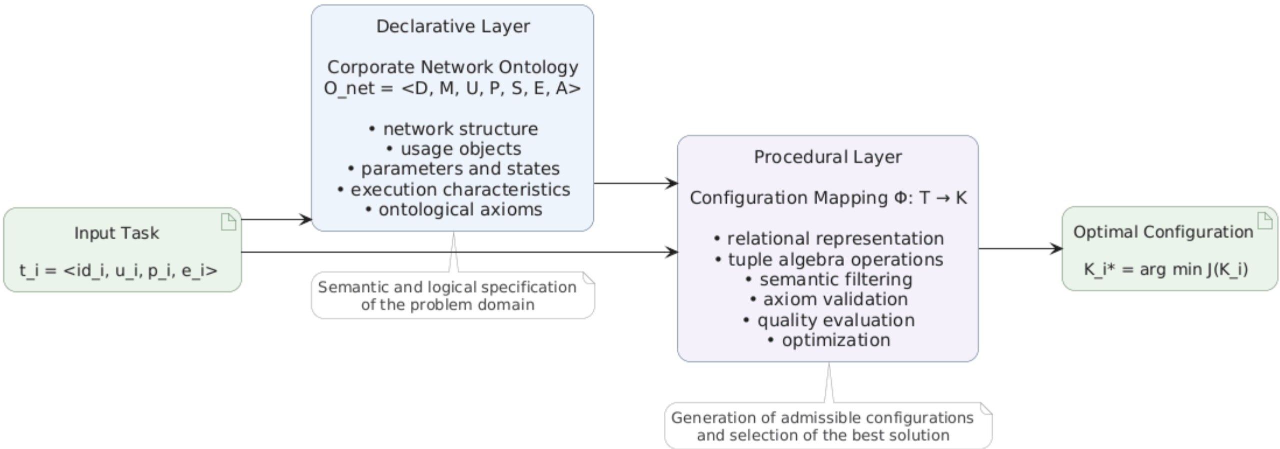

Fig. 4. Implementation Scheme of the Ontology-Driven Corporate Network Configuration Method

The declarative component defines the ontology structure, while the procedural component implements task-to-configuration mapping using tuple algebra operations, axiom validation, and optimization. The proposed method integrates an ontological approach with relational algebra, enabling the configuration process to be formalized as a sequence of rigorous operations over relations. Unlike traditional approaches focused primarily on parametric characteristics, the proposed method emphasizes ontological axioms, which define admissibility in terms of logical, functional, and security constraints.

This approach ensures not only compliance with task requirements but also consistency with the domain structure described by the ontology O_{net}.

Experiments and Results

The experimental validation of the proposed method was conducted in two application environments differing in functional purpose, network structure, service composition, and workload profile. One of the experiments was carried out on the corporate network of the West Ukrainian National University, where educational, administrative, and information service tasks predominate. The objective of the experiments was to determine whether the method, based on a corporate network ontology and tuple algebra, is capable of constructing a configuration that better satisfies task requirements compared to an initial or intuitively formed configuration. Within the experimental framework, the following indicators were evaluated: task resource consumption, compliance of nodes with task requirements, server load levels, service access latency, an integral configuration quality criterion, and the number of configurations eliminated by ontological axioms. In the first experiment, the problem of ensuring the operation of a distance learning and electronic testing system under peak load conditions was considered. This scenario is typical for a university environment, as it involves simultaneous access by a large number of users and requires the operation of web services, authentication services, database servers, and file resources.

Task T_1 corresponds to a mass online testing scenario. The following requirements were specified:

- number of concurrent users: 850;
- minimum required number of logical CPU cores: 24;
- required RAM: 64 GB;
- required storage capacity for active services: 500 GB;
- minimum segment bandwidth: 1 Gbit/s;
- required services: learning platform web service, authentication service, and database server;
- mandatory implementation of a learning segment isolation policy and access logging;
- maximum allowable average latency: 120 ms.

Table 2 presents the parameters of the network nodes of the West Ukrainian National University used in the experiment.

Table 2

Network Node Parameters of the West Ukrainian National University (WUNU)

Node ID	Type	CPU (cores)	RAM (GB)	Storage (GB)	Bandwidth (Mbps)	Status	Hosted Services
EDU-SRV-01	Application Server	16	32	500	1000	Normal	LMS Web
EDU-SRV-02	Application Server	24	64	1000	1000	Normal	LMS Web, Auth
EDU-DB-01	Database Server	16	64	2000	1000	Normal	DB
EDU-DB-02	Database Server	32	128	4000	1000	Partially Loaded	DB
AUTH-SRV-01	Authentication Server	8	16	250	1000	Normal	Auth
FILE-SRV-01	File Server	12	32	6000	1000	Normal	Files
NET-SEG-A	Network Segment	—	—	—	1000	Normal	VLAN-Academic
NET-SEG-B	Network Segment	—	—	—	100	Normal	VLAN-Admin

For each node, ontology classes, attributes, and relations such as *hostsService*, *hasCPUCapacity*, *hasMemoryCapacity*, *locatedInSubnet*, *protectedBy*, and *hasAvailabilityStatus* were defined. The structured representation of the ontology elements, in contrast to an unstructured description, ensures an unambiguous interpretation of each entity and its role in the configuration process by decomposing data according to the components of the set O_{net}.

Table 3 illustrates the step-by-step processing of network infrastructure elements through the sequence of configuration method operations.

At the R_1 level, structural compatibility between node descriptions and the task type is verified. For task T_1, only learning environment servers, database servers, and authentication servers located within the appropriate network segment are considered relevant. At levels R_2 and R_3, nodes are matched with usage objects and task parameters. This requires that each node is associated with the necessary services (LMS, DB, or Auth) and possesses sufficient attributes for further analysis. At level R_4, compliance with parametric requirements is verified. In particular, minimum thresholds for CPU, RAM, storage capacity, and bandwidth are applied. At this stage, node EDU-SRV-01 is excluded due to insufficient resources. Levels R_5 and R_6 consider the current state of nodes. This stage is crucial in dynamic environments, as even resource-capable nodes cannot be included if they are overloaded or degraded. Consequently, node EDU-DB-02 is excluded due to violation of the admissible state axiom. At level R_7, execution characteristics such as latency and expected service quality are evaluated. However, the final decision regarding node inclusion is made only after verifying ontological axioms at level R_8, including resource sufficiency, service availability, admissible state, and compliance with the network segment. As a result, the final relation $ConfigRel$

includes only nodes that have successfully passed all filtering and validation stages. For task T_1, these are EDU-SRV-02, EDU-DB-01, and AUTH-SRV-01, which together form a feasible and optimal configuration for online testing. The resulting configuration relation for task T_1 can be expressed as:

$$ConfigRel_{T_1} = \left\{ \begin{matrix} (M_2, U_3, P_{cpu}, S_1, E_1), \\ (M_3, U_3, P_{db}, S_1, E_1), (M_5, U_4, P_{auth}, S_1, E_1) \end{matrix} \right\}$$

Table 3

Knowledge-Oriented Analysis of Configuration Formation for Task T_1

Node Id	M_{Rel}: Node and Characteristics	(R_1): Structural Compliance $M_{Struct} \vDash p_i$)	(R_2–R_3): Matching with Usage Objects and Parameters	(R_4): Parametric Compliance	(R_5–R_6 Admissible Network State	(R_7): Performance Characteristics	(R_8): Axiom Verification	Inclusion in ($Config$ Rel)
M_1	EDU-SRV-01, ApplicationServer, CPU=16, RAM=32, Storage=500, BW=1000	Yes	Linked to LMS	No (CPU and RAM below task requirements)	—	—	—	No
M_2	EDU-SRV-02, ApplicationServer, CPU=24, RAM=64, Storage=1000, BW=1000	Yes	Linked to LMS, Auth	Yes	State: Normal	ResponseTime = 96 ms	All axioms satisfied	Yes
M_3	EDU-DB-01, DatabaseServer, CPU=16, RAM=64, Storage=2000, BW=1000	Yes	Linked to DB	Yes	State: Normal	DB response acceptable	All axioms satisfied	Yes
M_4	EDU-DB-02, DatabaseServer, CPU=32, RAM=128, Storage=4000, BW=1000	Yes	Linked to DB	Yes	State: HighLoad	Latency acceptable	Admissible state axiom violated	No
M_5	AUTH-SRV-01, AuthServer, CPU=8, RAM=16, Storage=250, BW=1000	Yes	Linked to Auth	Yes	State: Normal	Auth response acceptable	All axioms satisfied	Yes
M_6	COL-APP-02, ApplicationServer, CPU=24, RAM=64, Storage=1000, BW=1000	No	—	—	—	—	—	No
M_7	COL-DB-01, DatabaseServer, CPU=16, RAM=64, Storage=2000, BW=1000	No	—	—	—	—	—	No
M_8	COL-LOG-01, LoggingServer, CPU=8, RAM=16, Storage=1000, BW=1000	No	—	—	—	—	—	No

Following structural, parametric, and security-based filtering, the method generated three feasible configurations for task T_1, as presented in Table 4. Configuration K_1 was found to be resource-constrained: although it formally provided the required services, the use of node EDU-SRV-01 resulted in excessive load. Configuration K_3 was eliminated due to violation of the network state axiom, as node EDU-DB-02 operated under high load. Configuration K_2 was identified as optimal, satisfying all ontological axioms and yielding the lowest value of the integral criterion. Table 5 presents a comparison of performance indicators before and after applying the proposed method.

The results demonstrate a significant improvement in all evaluated metrics. The most notable reductions were observed in authentication failure rates and database access conflicts, confirming the effectiveness of incorporating functional and logical constraints within the ontology-based approach. The decrease of the integral configuration quality criterion from 0.81 to 0.42 indicates improved alignment between the configuration, task requirements, and the current network state.

Table 4

Feasible Configurations for Task (Online Testing) T_1

Configuration	Application Server	DB Server	Auth Server	Segment	Axiom Satisfaction	Average Latency (ms)	CPU Load (%)	Integral Criterion (J)
K_1	EDU-SRV-01	EDU-DB-01	AUTH-SRV-01	NET-SEG-A	Partial	148	91	0.79
K_2	EDU-SRV-02	EDU-DB-01	EDU-SRV-02	NET-SEG-A	Full	96	73	0.42
K_3	EDU-SRV-02	EDU-DB-02	AUTH-SRV-01	NET-SEG-A	State axiom not satisfied	102	68	0.61

Table 5

Comparison of Performance Indicators Before and After Applying the Proposed Method for the WUNU Network

Metric	Initial Configuration	Optimal Configuration K_2	Change
Average Access Latency (ms)	151	96	−36.4%
Average CPU Load of Application Server (%)	92	73	−20.7%
Authentication Failure Rate (%)	4.8	1.3	−72.9%
Database Access Conflict Rate (%)	3.1	0.9	−71.0%
Resource Utilization Coefficient	0.94	0.78	−17.0%
Integral Quality Criterion (J)	0.81	0.42	−48.1%

Figure 5 presents a normalized comparison of the corporate network performance indicators before and after applying the configuration method for the online testing task. The normalization was performed with respect to the values of the initial configuration, allowing all indicators to be mapped onto a unified scale [0,1] and ensuring their consistent comparison.

The analysis of the graph demonstrates a significant improvement across all performance metrics following the application of the proposed method. The most pronounced reductions are observed in the authentication failure rate and database access conflict rate, which confirms the effectiveness of incorporating both functional and logical constraints within the ontology-based approach.

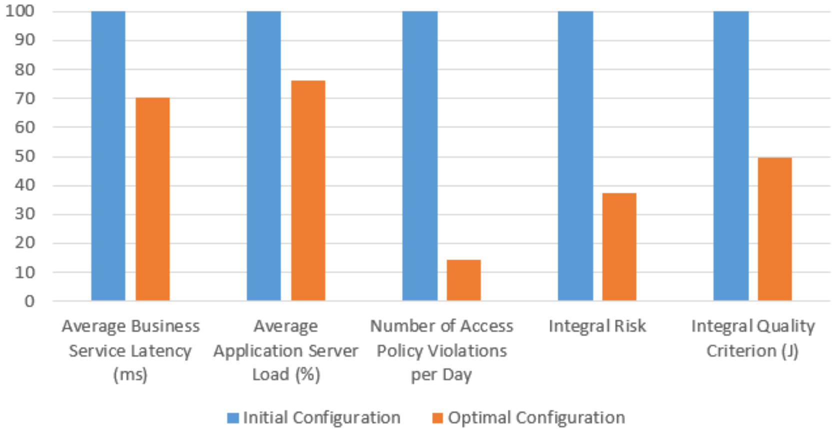

Fig. 5. Comparison of Performance Indicators Before and After Applying the Method (Task)

Overall, the obtained results confirm that the ontology-driven approach not only enables the identification of feasible configurations but also significantly enhances the efficiency of problem solving. In particular, reductions in average latency and conflict rates for authentication and database services highlight the practical effectiveness of the proposed method.

Conclusions, limitations, and future work

This paper proposes a knowledge-driven approach to the management and configuration of corporate networks, which are considered as complex functional systems. The approach is based on ontology-based modeling, providing a formalized representation of network components, their properties, relationships, and constraints within a unified semantic structure. A formalized ontology model of a corporate network is developed in the form of a tuple-based structure that integrates domain objects, parameters, system states, task execution characteristics, and axiomatic constraints. The proposed representation ensures knowledge consistency and interpretability while enabling its direct use in algorithmic procedures. In addition, a model for normalizing heterogeneous parameters based on the ontological context is introduced, allowing them to be mapped onto a unified evaluation scale for subsequent multi-criteria analysis.

Based on these principles, a method for ontology-driven configuration of corporate networks is developed. The method relies on tuple algebra operations to generate a set of feasible configurations, taking into account structural, parametric, and axiomatic constraints. The selection of the optimal configuration is performed using an integral quality criterion that considers resource utilization, network state, and task execution efficiency.

The results of experimental studies conducted on different types of corporate networks confirm the effectiveness of the proposed approach. In particular, a reduction in service access latency, a decrease in computational resource load, and a reduction in the number of access conflicts and security policy violations were observed. The integral configuration quality criterion decreased on average by 48–51%, demonstrating the practical applicability of the proposed method. Thus, the proposed approach provides a consistent integration of ontology-based knowledge representation and formal optimization methods, enabling efficient solution of corporate network configuration problems. The obtained results can serve as a foundation for the development of intelligent decision support systems in the field of network infrastructure management.

Future research directions include extending the proposed approach to dynamic and real-time network environments, integrating machine learning techniques for adaptive parameter tuning, and further development of ontology models for scalable distributed infrastructures.

ADDITIONAL INFORMATION

AUTHOR CONTRIBUTIONS

Conceptualization, A.M. and Y.P.; methodology, A.M. and Y.P.; software, Y.P.; validation, Y.P.; formal analysis, Y.P.; investigation, A.M.; resources, A.M.; data curation, Y.P.; writing -original draft preparation, A.M. and Y.P.; writing review and editing, A.M. and Y.P.; visualization, A.M.; supervision, A.M.; project administration, A.M. All authors have read and agreed to the published version of the manuscript.

DECLARATION ON THE USE OF GENERATIVE ARTIFICIAL INTELLIGENCE TOOLS

In preparing this work, the authors used Grammarly and DeepL Translate to check grammar and spelling, paraphrase, and rephrase individual sentences. After using these tools, the authors reviewed and edited the content and take full responsibility for the content of this publication.

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ЗНАННЯ-ОРІЄНТОВАНИЙ ПІДХІД З ВИКОРИСТАННЯМ ОНТОЛОГІЙ ДО УПРАВЛІННЯ СКЛАДНИМИ СИСТЕМАМИ

У статті розглянуто задачу управління корпоративною мережею як складною функціональною системою, ефективність якої визначається узгодженістю між структурою інфраструктури, характеристиками ресурсів та вимогами прикладних задач. Обґрунтовано доцільність використання знання-орієнтованого підходу, зокрема онтологічного моделювання, для формалізації структури корпоративної мережі та підтримки прийняття рішень щодо її конфігурації.

Запропоновано концептуальну модель корпоративної мережі, яка розглядається як багаторівнева система взаємопов'язаних компонентів, що включає мережеві вузли, сервіси, користувачів, ресурси, параметри функціонування та обмеження безпеки. На цій основі розроблено теоретичне підґрунтя побудови онтології корпоративної мережі, що забезпечує узгоджене представлення об'єктів інфраструктури, їх властивостей і відношень, а також дозволяє формалізувати правила взаємодії та логічні обмеження у вигляді онтологічних аксіом.

У роботі запропоновано формалізоване представлення онтології корпоративної мережі у вигляді кортежної структури, яка інтегрує множини об'єктів, параметрів, станів, характеристик виконання задач та аксіоматичних обмежень. На основі цього підходу розроблено модель нормування параметрів, що забезпечує приведення різнорідних характеристик до єдиної шкали оцінювання з урахуванням контексту задачі та онтологічних обмежень. Це дозволяє перейти до побудови інтегрального критерію якості конфігурації, який враховує ресурсні, експлуатаційні та функціональні аспекти.

Основним результатом роботи є розробка методу онтологічно-керованої конфігурації корпоративної мережі на основі множини задач. Метод базується на використанні операцій алгебри кортежів для формування множини допустимих конфігурацій, які задовольняють структурні, параметричні та аксіоматичні обмеження, а також на подальшому виборі оптимальної конфігурації за допомогою багатокритеріальної оцінки. Запропонований підхід забезпечує прозорість, відтворюваність та інтерпретованість процесу конфігурації.

Проведено експериментальні дослідження для двох типів корпоративних мереж: університетської інформаційно-телекомунікаційної системи та мережі комерційної компанії. Результати експериментів показали, що застосування методу дозволяє суттєво покращити ключові показники функціонування мережі, зокрема зменшити затримку доступу до сервісів, знизити навантаження на обчислювальні ресурси, зменшити кількість конфліктів доступу та порушень політик безпеки. Інтегральний критерій якості конфігурації зменшився приблизно на 48–51%, що підтверджує ефективність запропонованого підходу.

Запропонований підхід може бути використаний як основа для побудови інтелектуалізованих систем управління корпоративними мережами, а також для подальшого розвитку методів оптимізації складних інформаційно-телекомунікаційних систем на основі онтологічного представлення знань.

Ключові слова: корпоративна мережа; онтологічне моделювання; конфігурація мережі; багатокритеріальна оптимізація; системи підтримки прийняття рішень; розподіл ресурсів; оптимізація продуктивності; знання-орієнтовані системи.