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Modeling of transport infrastructure: ontological approach

The article deals with current problems of ontological modeling of processes of design, construction and operation of buildings and structures in transport infrastructure. Such modeling involves use of standards and classifiers adopted in Europe and harmonized within BIM (Building Information Modeling) and EULYNX (European railway technology alliance). Multi-level ontological model of transport infrastructure is proposed. This model contributes to formation of understanding of essence of subject area, which is the field of transport infrastructure (transport repair enterprises, transport facilities (bridges, tunnels, tracks), transport depots, stations, etc.). Proposed model contributes to presentation of knowledge in form that is convenient for their processing in intelligent systems, ensuring intellectualization and digitization of processes in transport infrastructure. Proposed ontological approach ensures multiple use of knowledge and existing ontologies, allows the use of modern technologies (in particular, semantic ones), when objects of subject area correspond to their reflections in multi-level ontological model. Ontological approach to modeling of transport infrastructure makes it possible to move to automatic management of these objects and corresponding processes in systems that ensure intellectualization and digitalization of transport and transport infrastructure. Developed multi-level ontological model is planned to be supplemented with new components, imposing appropriate restrictions.

***Keywords**: modeling, ontology, multilevel ontological model, transport infrastructure.*

Introduction. Currently, the development of information systems and technologies (as well as intelligent systems and information systems with elements of intellectualization) leads to large-scale automation and the use of artificial intelligence in various fields of human activity. The use of knowledge-based systems improves efficiency:

– information interaction of systems (including those working in different subject areas (SA));
– information support for certain types of activities of individual users, enterprises or industries as whole;
– simplifies and transfers the work of enterprises to new level of informatization and intellectualization.

The development of any such system begins, first of all, with description of SA within which it will operate. To describe SA, two approaches are mainly used: ER-modeling and modeling using the construction of an ontological description. In this paper, we consider method based on the construction of ontologies and allowing one to build deeper formal description of SA at the conceptual level.

Analysis of recent research and problem statement. In the 1990s, innovative applications in architecture, engineering, and construction (AEC) emerged, leading to the emergence of: CAD systems that enable the processing of graphic information; 3D models of buildings and structures (including railway infrastructure); new information possibilities (for example, calculation of physical characteristics, unit costs) [33, 34].

All this contributed to the emergence of methodology that is known as Building Information Modeling (BIM) [1, 2, 23,]. BIM processes are well defined for new buildings and railway infrastructure structures (hereinafter referred to as structures), and most of the existing structures are not maintained, repaired or rebuilt. Possible solution to the problem of increasing the efficiency of the AEC is to use knowledge management and an ontological approach [32, 35].

The use of Industry Foundation Classes (IFC) [3, 4] and other standard ontologies at all stages of the life cycle of structure prevents the loss of information and facilitates the transfer of the maintenance process from one participant in the life cycle of railway infrastructure structure to another.

The purpose and tasks of the research. The purpose of the article is to discuss problems related to the management of objects and processes of transport infrastructure (in particular, their design, construction and operation), as well as possible methods of solving them using modern technologies of intellectualization and digitization and multi-level ontological modeling of the corresponding SA.

Materials and methods of research.

The semantic and ontological enrichment of building models can contribute to more optimal storage and access to data, providing means for structuring, storing and visualizing information. Information resources of intelligent systems using BIM and the ontological approach provide information support for the tasks solved in it in the field of design, construction and operation of buildings and structures of the railway infrastructure. In particular, one of the types of information resources are classifiers that provide data representation taking into the account the ontological approach and effective information interaction between system components.

Standards and classifiers contain information about objects (components, information and control flows, etc.), which determines their use in modeling the corresponding SA.

This article describes the method of linking information resources on the example of classifiers to the ontology of SA for the formation of deeper and more detailed conceptualization model of SA [5, 6]. Ontologies make it possible to formalize SA (in the article, such SA is the infrastructure of the railway transport) with the help of an appropriate conceptual scheme.

The ontology is defined in the knowledge representation language, which defines the formal semantics, which provides the possibility of clear interpretation of the ontology in the corresponding intellectual system. The ontology represents SA at the conceptual level with the help of concept classes and their relations. The ontology of SA can be defined as:

$$O^d = \langle C, A, R, D \rangle,$$

where C is the set of SA classes, A is the set of attributes of these classes, R is the partial order relation on the set of classes, $R \subseteq C \times C$, D is the set of domains of admissible values of the attributes of the SA objects. Classes are defined by the triple $\langle d_i, F(d_i), V(d_i) \rangle$, where d_i is the name of the class, $F(d_i) = \{f_{ij}\}$ is the set of attributes of the class, $V(d_i) = \{v_{ig}\}$ is the scope of the class, v_{iq} – objects with features $F(d_i)$. Let $B(F(d_i)) = \{\emptyset, 2^{|F(d)|}\}$ be the content Boolean of the feature set $F(d_i)$ of some class d_i, where $2^{|F(d)|}$ – the set of all subsets of the content $F(d_i)$. The elements of the Boolean form partially ordered set by the inclusion of its elements – the lattice $(B(F(d_i)), \leq, \wedge, \vee)$.

Any element $F(d_i) \in B(F(d_l)), H \in [1, 2^{|F(d)|}]$, of the resulting lattice is considered to be the content of some class d_i^H, generalizing the concept of d_i if $F(d_i^H) \subseteq F(d_i)$. The lattice $K(d_i) = (B(F(d_i)), \leq, \wedge, \vee)$ of all content subsets of the initial class di is called the conceptual “framework” of the SA ontology. The conceptual "framework" of the SA ontology is necessary structure containing the initial class d_i.

Conceptual modeling with the help of ontologies provides, in particular: semantically deep representation of SA:

– rich formal semantics, reflection of complex axiomatic information due to logical notations;
– solving various problems simultaneously: description of SA as such;
– development on the basis of the formed ontologies of information and intellectual systems.

The use of ontological modeling makes it possible to formalize SA with the help of more accurate conceptual representation, as well as to apply it in intelligent systems to improve the efficiency of processes in the field of designing transport infrastructure facilities. To build ontologies, a lot of software tools have been developed that provide the user with graphical interface for building ontologies. The most popular is Protege [7, 8] ontology editor. Ontological modeling SA goes through several stages:

– defining the scope and scope of ontologies; definition of the main terms of ontologies;
– definition of classes and their hierarchy;
– definition of properties of classes and relations.

For the description of SA, an approach is proposed, which consists in the fact that certain areas of the SA can be described using existing information resources, such as standards and classifiers, operating in the SA under consideration. In other words, the ontology of SA can be extended by ontologically linking ontology classes with standards and classifiers.

Depending on the level of approval, there are the following categories of standards and classifiers: international (regional); national (including Ukrainian); intersectoral; industry; systemic. Thus, we can say that the standards and classifiers present systematized descriptions of SA objects, in which the names of objects have certain codes.

The presented ontology, supplemented by the classifiers described above, can be used to intellectualize the processes of design, construction and maintenance of transport infrastructure facilities, including: to develop an intelligent decision support system for designers when choosing the appropriate BIM standards and classifiers and to control the design (construction) processes or support, depending on the classes of problems to be solved), systems for introducing national characteristics into pan-European standards and classifiers, systems for collecting and analyzing statistical data on the activities of objects of SA.

To link standards and classifiers to the ontology of SA, you need to perform the following actions:

– Representation of the ontology in machine-interpretable form (translation of the ontology into OWL-format [9, 10]).
– Creation and filling of database of pan-European, national and industry standards and classifiers (pan-European, national, intersectoral and industry).
– Selection of standard/classifier for binding to specific ontology.
– Selection of the name of the standard/classifier from its meta description.
– Semantic analysis of standard/classifier by its name (search using semantic analysis by the name of standard/classifier for semantically identical object in the ontology).
– Linking standard/classifier to an ontology object, which is performed using the following sequence of steps: creation of an object in the ontology corresponding to the given standard/classifier; extraction of metadata from the standard/classifier; record of metadata of the standard/classifier in the properties of object created in the ontology.
– The choice of an object in the ontology, the most suitable of the proposed options.

The use of the proposed methodology for expanding the ontological description of SA of an intelligent system facilitates the work of analysts in developing formal description of SA for the subsequent development of the corresponding intelligent system and helps to build models of SA at deeper conceptual level. Standards and classifiers are an important component of intelligent systems and contain variety of information to describe SA. The proposed methodology can be useful in the development of intelligent (information with elements of intellectualization) systems, decision support systems, expert systems based on knowledge bases and requiring broad conceptual descriptions of SA.

When designing and building structures, BIM models are developed at the top level (metaontology) and should reflect the “current” situation. "Designed" BIM-models must be adjusted when creating "built" models. In the ontological modeling, it should be taken into the account that many data become available only after the construction stage, since they refer to specific structure in specific place and have specific properties.

Missing, outdated or unstructured information about the construction can lead to inefficient project management (for the construction or maintenance of transport infrastructure facilities); inadequate process results and wasted time; increased maintenance costs; modernization or restoration of processes and properties of SA objects. The semantic models are most often considered as IFC models [11, 12]. The semantic model of SA is model that includes semantic information that describes the meaning of its specific physical objects [6].

Different models of structures and buildings with large amount of external data are available on railways and their infrastructure facilities, which necessitates distributed data management, as well as the development of semantic and ontological approach for the railway industry and its infrastructure.

One of the main limitations of IFC is the lack of mechanisms for extending the semantics of the model. BuildingSMART [13] is developed on the basis of IFC and is based on ontologies of the construction and infrastructure sectors. Semantic technologies provide the transformation of information about the IFC model into semantically extended ontological model represented using the language OWL [14]). OWL is used as an integrator of all necessary ontologies. This is how EULYNX, the European railway technology alliance [15], is developing, which, in particular, must take into the account the following factors:

1. Transition to the phase of readiness for the implementation of such technologies of the digital economy as ontological methods that improve the possibility of accurate calculations in the life cycle (infrastructures and rolling stock of railways).
2. The need to take into the account the capabilities of information / intelligent systems in transport.
3. The need to predict the development of railways and related infrastructure. It is predicted that global rail transport will double by 2050, which leads to increased competition for freight traffic and passengers, i.e. creation of new transport landscape [16, 17]. Ontologies and formalized ontological and semantic languages play decisive role in this process to ensure the interoperability of the stages of design and operation of railway systems. EULYNX uses formal ontological methods that are needed in high-tech industries, but unfortunately not widely used in railway infrastructure.

General transport ontologies. Studies on the ontology of railway transport and its infrastructure in Great Britain and Denmark [18-23] have shown how ontologies can facilitate: access to information resources and their integration; generating responses to queries. Ontologies support the application of the “build once” approach to application development by protecting software from changes to real (physical) transport systems [21, 22].

System engineering is an approach to the implementation of systems (information, intellectual) in transport that meets the needs, goals and objectives of users. Railway transport ontologies have common components (fragments, elements) [12], in particular, ontologies of its infrastructure and vehicles. Digitalization and intellectualization of the transport sector determines the use of engineering, software and BIM-ontologies. The ontological approach provides an opportunity to work with finite set of formalized concepts and set of formalized relationships between them, which allows you to accumulate knowledge and use it in practice to get better results. With the development of BIM-ontologies, it became possible to create knowledge management system.

BIM-ontology is source of information because it generates and manages the data created during the life cycle of structure. This source of information can be transformed into knowledge using data mining methods and technologies. Ontologies of transport and railway infrastructures are closely related to IFC buildibgSMART and their extensions [12]. The IFC Rail standard does not include railway bridges, tunnels, stations and depots (this is separately developed component of the corresponding domain in the general ontology).

Knowledge in modern systems (intellectual, informational with elements of intellectualization) can be explicit and represent existing knowledge (facts) or obtained using logical inference (reasoning) from existing knowledge. All this is the justification for the need to form formal information knowledge models that represent the knowledge base of buildings and structures of the railway infrastructure.

In Semantic Web [24] technology, ontologies are part of semantic models that represent the key concepts of each domain, their properties and relationships. Domain ontologies use certain concepts in the fundamental meta-domain, ontologies of time and space, and spatial and temporal reasoning.

Meta-domain ontologies, domain ontologies in the use of open BIM and their relationship [25, 26]:

– Meta-Domain Ontologies and Rules (Time Ontology + Rule Sets4 Spatial Ontology + Rule Sets).

– Domain Ontologies and Rules (Occupant Ontology + Rule Sets; Equipment Ontology + Rule Sets; Building Ontology + Rule Sets; Weather Ontology + Rule Sets; FDD Ontology + Rule Sets).

Multi-level ontological model, which is the basis for the intellectualization of the processes of design, construction and operation of buildings and structures of transport infrastructure, in real time, involves its modification. The construction of multilevel ontological model of considered SA involves the following steps:

– Formalized description of levels and constituent components of multilevel ontology
– Formalized description of metaontology.
– Formalization of theoretical models of knowledge engineering.
– Formalization of ontology axioms (axioms of identification, planning, calculations).

Objects in this multilevel ontological model are systematized according to the functional feature of their properties included in the class hierarchy. Model components define the structure of the corresponding intelligent system that supports the design, construction and operation processes.

The used multilevel ontological model describes the construction of formal system models of the SA related to the formalization of the tasks of designing, constructing and operating transport infrastructure facilities, taking into the account existing BIM-models. The development and formalization of multilevel ontology presupposes formal representation and conceptualization of knowledge about SA. Such representation involves description of the totality of objects (and corresponding concepts), knowledge about them and the relationship between them.

The functional completeness of multi-level ontological model of SA implies not so much complete reflection of the properties of SA objects, but only the fixation of those properties that are necessary and sufficient for solving the problems of designing, building and operating transport infrastructure facilities. In [25, 26], the connection of decisions made on the basis of the ontological approach (in particular, BIM-ontologies, IFC, engineering ontology described in terms of SysML [11, 28]) is shown.

This takes into the account that EULYNX uses the SysML system modeling language to model functional requirements. System development based on the Model-Based Transport Ontology Engineering (MBSE) standard is systems engineering methodology that focuses on the creation and use of domain models as the primary means of information exchange between engineers [27].

The MBSE takes into the account the results of the practical application of computer simulation, to bridge the gaps between the specification of the system model and the corresponding software. Using MBSE increases the likelihood of “getting it right” the first time, as all the necessary information is connected to single model. When adapting proven solutions based on integrated engineering ontologies (SysML) [28] and ontologies developed with OWL/RDF [5, 22], the following steps are performed:

– Choice of an ontology editor (in particular, Protégé).
– Formation of OWL-statements
– Building model of transformations.
– Building output machines with OWL-tools .
– Formation of SysML engineering ontologies.
– Building transformation model.
– Obtaining new knowledge by users (system).

This organization of engineering processes allows:

– Use the context of systems engineering to identify problems (arising at different stages of the design life cycle of intelligent systems in the field of transport or infrastructure; stages of design, construction and / or operation of structures, etc. using appropriate intelligent systems).

– Based on the identified problems, build models (semantic, ontological) of decision support.
– Use SysML tools and models in specific engineering domains.
– Reduce system development time by integrating cross-domain model.

Ontologies built on the basis of SysML contribute to the visualization of the system description, making different views on systems more structured and formal. SysML can also be used as method of communication between the system designer and various stakeholders [25, 26]. Models help at all stages of the system life cycle (from requirements gathering and design to testing and validation):

1. Modeling has advantages in collecting system requirements, as it can detect, among other things, problems such as:

   – Requirements are incorrect, but they are not found.
   – The requirements are correct, but incomprehensible to the user.
   – The requirements are specified correctly, but not in formal language, which makes them difficult to interpret and understand.

SysML can solve these problems by providing way to clearly and hierarchically organize requirements through relationship types (such as "satisfy" or "infer" for example). It also helps in checking and testing the completeness of the requirements.

2. Modeling has the advantage of improving design quality because it removes ambiguity, provides deeper understanding of the system, and reflects relationships between system components. All this reduces design errors.

3. Possibility of creation on the basis of SysM development tools of tools for check and validation of models.

4. Process modeling using SysML facilitates effective communication with stakeholders about system behavior, generating test cases, and/or finding system bugs.

Comprehensive ontological models in engineering design reduce development time, increase data reliability, and make applications more flexible while ensuring security systems.

The purpose of the application of ontologies is to create set of digital tools to improve the basic indicators of EULYNX railways, such as, for example, their capacity, integration with trains and other elements of engineering and technical support. EULYNX pays great attention to Shift2Rail [29]. Shift2Rail has an excellent digital organization of the initiative in the form of linked websites.

Modeling in EULYNX is one of the MBSE processes. Since simulation plays an important role in the project, EULYNX has formed cluster for this called *Modeling and Testing*. This cluster is responsible, in particular, for:

– creation and testing of SysML models for each subsystem of the corresponding intelligent system;
– documentation of processes during the creation of models and / or their interpretation.

Modeling uses, in particular:

– The modeling standard that provides project guidance for MBSE.
– Interpretation rules explaining the implementation in the project of requirements based on model.
– The systems engineering process, which is described at its top level for the EULYNX project.
– Change and configuration management, describing the necessary activities to model harmonization processes and take into the account the specifications of different countries.

For each subsystem in EULYNX, from the lists of functions that are supported by different information models, requirements specification is created, which is reflected in documents such as:

– interface definitions for each interface type (SCI, SDI);
– interface specifications;
– requirements specifications (these documents contain the relevant models).

In EULYNX, the interface is described at the protocol level, consisting of [15]: application layer; safety/retransmission and redundancy layer; transport layer; network layer; data link and physical layer.

EULYNX defines an interface specification: for an SCI interface, the application layer from the interface protocol. EULYNX defines the structure of subsystems and their associated environments, in particular:

– related subsystems that transmit information about the environment;

– exchange of information with other subsystems using the appropriate interface.

After that, EULYNX defines the behavior of the subsystem that implements its interface, i.e. describes the essential states of the subsystem (main states of the subsystem, its interface, transitions between states). Ontological modeling allows you to get information about:

– commands and messages between the subsystem and other subsystems, such as blocking or maintenance;

– situation, state and time of subsystem initialization;

– the situation, state and time of operational operation and start-up by other subsystems or achievement of operating time limits;

– the occurrence of an error. EULYNX defines the workflow, collects feedback on the current process and the current situation.

ProRail is an information model that provides an analysis of the situation in EULYNX from simulation point of view. In the modeling and testing cluster, decision is made on the types of diagrams and the necessary changes. One of the reasons for this is that models are first created in the cluster, and then, when the simulation is completed, they are checked by equipment suppliers (through appropriate feedback). The review of models is performed within the respective cluster. Model validation is not always transparent to other developers.

Information gathering is necessary to effectively use event data to provide insight, identify bottlenecks, anticipate problems, capture rule violations, recommend countermeasures, and optimize the life cycle processes of buildings and transport infrastructure structures [30]. Common trend at AEC is the intellectualization and digitalization of processes, as well as the use of domain knowledge.

BIM-ontologies encompass all of these research innovations and facilitate their implementation. BIM is based on many technologies such as CAD, CAC, PIM innovations, these innovations precede the concept of BIM. BIM-specifications are set of responses to social and corporate needs driven by today's building processes [30].

The ontological model for integration and the associated ontological process are the basis of the ontological approach to the intellectualization and digitalization of transport and its infrastructure. Nowadays, many algorithms, mathematical models and other data methodologies have been developed to solve the problems of intellectualization and digitalization of transport [31], in particular, the use of:

– neural networks and fuzzy logic to predict, for example, potential failures in the railway network;

– mathematical models for intelligent maintenance using machine learning methods;

– generation algorithms and hierarchical network models for schedule optimization;

– combinations of unified modeling languages and Petri nets in the design of structures, their construction and subsequent operation;

– Bayesian network models to improve railway infrastructure maintenance strategies.

Conclusions. The ontological approach to the design of information and intelligent systems in the transport sector helps to build effective digital cooperation through the ontology of the relevant standards and classifiers operating in the considered SA.

If it is necessary to develop standards for digitalization and intellectualization of the processes of design, construction, operation of buildings and structures of the infrastructure of the railway, then the basis for this is the structural description common with BIM-ontologies or IFC Rail.

Ontological models covering end-to-end processes in railway transport and related infrastructure are playing an increasingly important role. Such models are the basis for intelligent technologies used for the design, construction and operation of buildings and structures of the railway transport infrastructure.

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Моделювання транспортної інфраструктури: онтологічний підхід

У статті розглядаються актуальні проблеми онтологічного моделювання процесів проєктування, будівництва та експлуатації будівель і споруд транспортної інфраструктури. Таке моделювання передбачає використання стандартів і класифікаторів, прийнятих в Європі та гармонізованих в межах BIM (Building Information Modeling) та EULYNX (the European railway technology alliance). Запропонована багаторівнева онтологічна модель транспортної інфраструктури. Ця модель сприяє формуванню розуміння сутностей предметної області, якою є сфера транспортної інфраструктури (транспортні ремонтні підприємства, споруди транспортного призначення (мости, тунелі, колії), транспортні депо, вокзали, тощо). Запропонована модель сприяє представленню знань у вигляді, який є зручним для їх обробки у інтелектуальних системах, забезпечуючи інтелектуалізацію та цифровізацію процесів в транспортній інфраструктурі. Запропонований онтологічний підхід забезпечує багаторазове використання знань та існуючих онтологій, дозволяє використовувати сучасні технології (зокрема, семантичні), коли об'єктам предметної області відповідають свої відображення у багаторівневій *онтологічній моделі. Онтологічний підхід до моделювання транспортної інфраструктури дозволяє перейти до автоматичного управління цими об'єктами та відповідними процесами в системах, які забезпечують інтелектуалізацію і цифровізацію транспорту і транспортної інфраструктури. Розроблену багаторівневу онтологічну модель планується доповнювати новими складовими, наклавши відповідні обмеження.*

Ключові слова: *моделювання, онтологія, багаторівнева онтологічна модель, транспортна інфраструктура.*