Complex engineering object digital twins – power engineering smart transformation basic concept

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Abstract. The formation of information models and digital twins is a general element of the modern description of complex engineering objects. Their presence is already becoming a requirement of national and international technical regulation and contractual relations. The stage of forming separate digital twins within different stages of the life cycle has been passed and the approach has proven to be effective and in demand. The most striking example is BIM technologies. Now it is important to switch to complex end-to-end information models and digital twins for the full life cycle of complex engineering objects. This innovation becomes a universal tool for the interaction of all stakeholders in high-tech industries. Competence in technologies for working with complex information models and digital twins on the full life cycle of complex engineering objects is already a key competitive factor for high-tech engineering and operating companies in power production. This is a proactive trend in the formation of intellectual energy data space. It will lead to another cycle of improving the efficiency, safety, and economy of the industry and businesses.

1. Introduction
The fourth industrial revolution technologies [1] caused the transformation of engineering and business approaches to managing systems that make up the modern technological environment. The most important component of any modern technological sphere is the energy infrastructure and energy system. Power production is a system of systems (SOS) and includes some other full scale systems as elements. Different main subsystems can be identified in some details:
- energy generation subsystem which includes energy production facilities (thermal powerplants, nuclear powerplants, hydro powerplants, etc.);
- linear network power distribution infrastructure, main and local power lines (overhead lines with supports, underground cable lines, and others);
- electrical voltage transformer and power distribution system (which include electrical substation by different types, such as Transmission substation, Distribution substation, Collector substation, Converter substations, Switching station and some other specific types);
- end-users networks and equipment;
- other energy infrastructure territory facilities (for example, energy storage facilities, fuel and component warehouses, repairing facilities and other objects).

Most of these subsystems and their component objects are complex engineering objects (CEO). The most complicated and intricate CEO are nuclear power plants. And they are typical parts of the global energy generation sector. They are common in many countries, such as the USA, France, China, Japan, Russia, South Korea, Canada, Ukraine and some others. Nuclear power plants work in more than 30
countries just now. There were 451 working nuclear power reactors all over the world in the middle of 2018. Total capacity is about 394 GW [2]. Nearly 60 nuclear power reactors are under construction at the moment [3].

2. Methods

The engineering architecture, set of equipment, interaction algorithms and safety requirements for nuclear power plants are the most large-scale, complex and high-tech among all production facilities in the history of mankind. Therefore, it is advisable to implement the full life cycle of nuclear power facilities on the basis of the most modern industrial and information technologies.

The modern approach to life cycle management is based on an adequate realistic correspondence of the structure and regularities of functioning of an actual object and its digital information model. The modern concept of a digital information model varies widely among different authors and for different purposes. In our case, the most appropriate definition seems to be: “Information model (IM) is a set of structured and unstructured information containers that represent a complex reliable information source about a project (object evolution) at all or some stages of its life cycle” [4]. Partial digital information models have been used in industry and economics for several decades. They were gradually integrated into more complex ones in some cases. A remarkable example of technology development is BIM (Building Information Models). This approach is rapidly taking over areas of application in the design, construction and decommissioning of complex engineering objects [5]. Information models are elaborating on the operation and product manufacturing stage. It seems simple and natural to combine all these digital information models into a complete model that is unified for all stages of the life cycle of the CEO. In fact, this process is very difficult for many reasons. The main of them are:

- different purposes, objectives and efficiency criteria for different stages of the CEO life cycle [6,7,8,9];
- different creators and developers of digital information models (businesses and individuals) have different competencies and interests specific to each stage of the CEO life cycle;
- the engineering digital tools of various vendors are not fully compatible, especially at transmitting complex attribute information between digital information models;
- different data samples from the complete set are relevant at different stages of the CEO life cycle. Some data sets may not be used for a very long time, and then it becomes required again.

We need to associate the stages of the CEO life cycle with various information model structures and data classes in order to understand the future of CEO information modeling. The first complex stage is the creation stage. It combines design, construction and commissioning processes. The digital information model for these stages demonstrates the step-by-step model structure development and data accumulation. The base is a BIM model (Building Information Model), which primarily determines the spatial location of structures, equipment elements and engineering communications of objects. The BIM component does not represent a complete information model of investigated objects, processes and projects. Usually, we use project management systems, including classical management (time, resources, personnel, business processes). We need digital tools for system analysis and engineering (quality management, configuration management, collision management, etc.). Specialized digital tools for logistics modeling and assembling works visualization are used too. The structure of the information model thus includes a multidimensional spatial deeply attributed information about the object. Multi-level decomposition is enabled. Typically, there are four levels: object - the building - engineering system - the piece of equipment. Various engineering communications are important model elements too. All levels of the information model have a detailed system of attributes, including engineering and physical, logistics, and financial and economic parameters. The information model a priori provides the ability to track time points. The time variable is included both in the state of objects and in models of engineering and economic processes.

The CEO information model for the productive operating stage has a completely different structure. The spatial arrangement of elements is almost invariable, although it is included in the background model. However, data about the technological modes of operation are incomparably more important at this stage. The digital model must include data about operating modes, failures, and malfunctions of
equipment and systems. The specialized model block describes maintenance and repair procedures. If hardware units or parts of them are replaced, the individualizing attributes at all levels of the model should be changed. In addition, the model provides for fixing the flows of material and energy resources, both irrevocably spent and circulating. A comprehensive digital model captures both engineering and physical parameters and the economic characteristics of the production process.

At the stage of reconstruction and modernization of an industrial facility, the information model is similar to the model at the construction stage. However, the starting state is not an empty production site, but a model with accumulated changes during operation. It will be necessary to perform a complex procedure of object inspection at the previous stages of technological development in order to fix this starting state.

For many objects of industry and engineering infrastructure of the human environment, the life cycle is very long. In most cases, a special decommissioning procedure is required. This is necessary even for industrial objects of standard purposes. In the case of high-risk facilities, such as those contaminated with chemicals or nuclear power facilities, the task of decommissioning is significantly complicated [10,11,12]. At the same time, the decommissioning stage will most require the full volume of data - project documentation, working documentation with the accumulation of changes and data on the course of operation. The information model inherited from previous stages of the life cycle can be effectively converted into a digital decommissioning model. This approach allows us to achieve the environmental, economic, and engineering efficiency of the final stage of the life cycle of a complex engineering object. However, the data required for decommissioning is quite different from the data obtained in the course of productive work. They can be obtained from design and operational data for special approval procedures, supplemented by the results of specialized integrated engineering surveys. Updated BIM models will be in demand again, taking into account wear, contamination, and destruction. Of particular interest is the analysis of the residual value of equipment and materials to determine economically, environmentally, and engineering efficient recycling technologies. Naturally, project management tools, information models of work production, and logistics organizations are again in demand at the final stage of the life cycle.

Russia is one of the largest exporters of turnkey nuclear power plants on the world market. It is the largest export item in the high-tech energy sector and a significant share of the world market. In recent years, national legislation in various countries has required the provision of digital information models [13]. This requirement is becoming a mandatory element of contracts for the construction of nuclear power plants and other engineering facilities on the world market. However, the legal requirements of different States are variable. Standardization of understanding information models is also not developed in engineering and business practice. This makes it difficult for the customer and the contractor to understand and interact on these points of the contract. As discussed above, the information models used at different stages of the life cycle are very different. These differences relate to both the detailed elaboration of information models and the data structure itself. The most obvious approach for the contractor is to build, use, and transmit information models of the construction stage to the customer. However, for the customer, this model is only of limited interest after the commissioning stage finish. Its need is to convert BIM into a complex digital information model of the operation stage. practice, this task has been set, but not fully resolved. BIM models are passed as information digital models. BIM models are in demand and effective for designers and builders. This format of information models is not sufficient for owners and operating organizations. In the future, they have to create a separate structure of information models, largely duplicating the earlier developed ones.

3. Results and discussion
For the transformation to intelligent energy power systems, the stages separated IM are no longer sufficient. The creation of end-to-end dynamic digital twins (DT) is required at the present stage. The digital twin includes time series of data corresponding to the instantaneous state of the modeled object. The data structure of the digital twin is based on the data structure of the digital model. At the same time, dynamic data series allow us to return and analyze the object's state at previous times. For the
effective use of the digital twin, it is important current values automatically regular in addition to the data series. Due to the large amounts of data describing complex engineering objects, the modern approach is to automatically extract data about the parameters of the engineering system and write them to the database of the digital twin. Even 15-20 years ago, the volume of data generated by a complex engineering object was too large for their full digital fixation throughout the entire lifecycle. Also, the cost of sensor and data transfer systems with stable data channels was unacceptably high. Currently, the technical and economic restrictions on continuous full-scale data collection and storage of digital twins are strongly minimized during the fourth industrial revolution. The expected engineering and economic effects of their use are large enough for widespread implementation [14]. The main obstacle to large-scale implementation of digital twins throughout the life cycle of complex engineering objects is the methodological problems of integrating content-based heterogeneous data that arise during successive stages of the life cycle in a single digital twin.

*Figure 1.* Transformation separated information models & digital twins for different lifecycle stages to complex end-to-end ones.

The previous approach to creating information models was to create a data structure specific to each stage of the lifecycle. Then the initial data was taken selectively from the final model of the previous stage. Unclaimed data were archived and partially lost. In practice, until recently, both electronic and paper archives were used. In some cases, digital archives were referred to as unrecognized digital scans of paper documents. If it was necessary to use data from the early stages of the lifecycle, fragmentary re-entry of information was performed. The structure of the information model is re-constructed in a modified and truncated format. Selecting and re-entering some specific data of the previous digital twin is done selectively, in many cases manually. This procedure simultaneously leads to the loss of model reliability and increases the operating costs of working with information. The described scheme for working with a digital twin is shown in figure 1, variant A. Currently, technological and methodological readiness allows us to work with a single end-to-end digital twin of a complex engineering object within the framework of the dynamic complexity of the data structure of information models throughout the full life cycle. This perspective approach is shown in figure 1, option B. This approach makes it possible to create an end-to-end digital twin of a complex engineering object for analysis procedures, predictive
modeling, and management of technological, engineering, and business processes throughout the lifecycle. Currently, work with large energy facilities is in the transition stage to a new methodology for building digital twins. This process will simultaneously improve safety and technical manageability, as well as reduce operating costs for the full life cycle of the object. Within the framework of nuclear power, this approach requires end-to-end interaction and full information openness between the subjects of design, construction, operation, reconstruction, and decommissioning. This task is currently realized and implemented by Russian GK Rosatom's divisions in the external and internal markets of nuclear power facilities. Among energy generating facilities, nuclear power stations are the points of advanced implementation of end-to-end digital twin technology on the full life cycle. This is primarily due to several specific requirements:

- security and reliability of NPP operation [15,16,17,18];
- mandatory approval of all changes in design and technology by the developer, international and national Supervisory authorities;
- a complex, highly regulated and controlled procedure for decommissioning radiation-hazardous facilities.

The consequence of this advanced development is a deep study and large-scale testing of the technology of digital information models and end-to-end digital twins of extremely complex objects on the example as NPP. It is also important that the market of engineering and operational services in the energy sector should include entities that have different approaches and technologies. An example of this experience will allow you to thoroughly analyze the advantages of working at a new technological level. Besides, there are real enterprises-carriers of a new generation of technology.

It is important to understand that the end-to-end approach to the formation, filling and use of digital twin data implies the accumulation of data and their dynamic structuring without loss at time intervals of about a hundred years. At various stages of the lifecycle, a full set of procedures will be implemented for working with the structure of the information model, as well as with dynamic data sets of the digital twin. These procedures include long-term storage of structured data, their usage without modification and addition, modification and addition of the data structure, as well as building up time series of data.

**Figure 2. Information model (IM) and digital twin (DT) life cycle.**

G – data generation, T – transformation, U – usage, S – storing;

S1 - design, construction and commissioning stage, S2 - productive operation stage,
S3 - modernization and reconstruction stage, S4 – after-reconstruction productive operation stage,
S5 – Decommissioning stage.
at all stages of the object's lifecycle. The general scheme of working with data and its structures within the full lifecycle is shown in figure 2.

4. Conclusion
Thus, one can conclude the world-wide transition that is taking place before our eyes from big disparate data sets to a new complex entity when describing engineering objects on their full lifecycle. Integrated information models and end-to-end digital twins are becoming universal tools for the interaction of all stakeholders in high-tech industries just now. In the energy industry as a whole and the power generation facilities sector, the nuclear power segment is currently one of the main leaders in this area. The inevitable almost complete coverage of engineering and technical infrastructure and the main business processes of the energy sector with integrated end-to-end digital twins will lead to another cycle of increasing the efficiency, safety, and economy of the industry. Competence in technologies for working with complex information models and digital twins in the full life cycle of complex engineering facilities is already a key competitive factor for high-tech engineering and operating companies in the power industry. In the foreseeable future, this trend will only increase.

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