Automating Computations for the Digital Twin-based Design of an Integrated Energy System

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Abstract **— Integrated energy systems (IESs) based on traditional energy systems operating separately provide higher efficiency and reliability of energy supply to consumers. However, designing such systems poses significant complexity due to their intricate structure. A digital twin combines all the tools necessary for design in a single information space. To effectively simulate diverse equipment and integrate numerous methodologies alongside advanced mathematical models, software solutions supporting the digital twin paradigm must exhibit exceptional computational versatility. Automation of the computational subsystem development represents a promising strategy for addressing these challenges. This paper introduces a methodological approach for automating the development of the computational subsystem for a digital twin of an IES. The approach relies on advanced metaprogramming tools based on a software platform to automate the development process. Throughout the process, the Model-Driven Engineering concept is implemented, utilizing knowledge formalized in the form of ontologies. The digital twin, constructed using the presented methodological approach, facilitates computer-based and mathematical modeling of an IES in a virtual environment, enabling the exploration of its various configurations.**

Index Terms **— Digital twin, automation of computing process, automation of programming, Model-Driven Engineering, ontology, integrated energy system.**

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I. Introduction

Modern cities and industrial centers can boast a developed energy infrastructure, including fuel, electricity, heating, and refrigeration systems. These systems are of high social and economic importance. The creation of a new technological structure in the form of an integrated energy system (IESs) on the basis of several separately functioning energy systems can significantly expand their functionality, ensure the interchangeability of energy carriers, and implement a synergistic effect, thereby ensuring reliable, safe, cost-effective, and environmentally friendly energy supply.

IESs are sophisticated technical systems with extended networks and complex structural configuration. These systems include numerous energy systems, each incorporating subsystems that perform their functions: generation, transportation, distribution, and consumption of energy. Each of these subsystems consists of components with their sets of equipment.

Designing IESs is rather challenging because of their highly complex configuration, a wide range of equipment used, and a diverse set of mathematical models utilized to model it. Designing an IES often involves modeling all the subsystems, sets of their components and equipment, given technical and technological solutions for the integration of systems of various types. It is impossible to solve the problem of IES design without dedicated software, which creates conditions for increasing the efficiency of design, the quality of design solutions, and the automation of labor-intensive computational operations.

A high quality software tool for designing an IES should combine methodological, mathematical, and software support within a single information space where information links with the designed object are

implemented. At present, a tool with the specified characteristics corresponds to the concept of a Digital Twin (DT).

In order to effectively incorporate a digital twin into the design process, it is essential to ensure a high level of flexibility in its construction. This is mainly because it enables accurate modeling of a diverse array of equipment. It is also crucial to adjust the methods and algorithms used to a specific problem in the context of solving it. The approaches aimed at automating the construction of a digital twin of for integrated energy systems make it possible to overcome the described difficulties.

The paper proposes an original methodological approach to the automation of computations grounded in the digital twin representation of an IES. The structure of this approach is given. Additionally, we provide a technique for automated development of the computational subsystem of the digital twin and illustrate its utility via an example.

II. Description of the Problem and Formulation of Research Objectives

Mathematical modeling of integrated energy systems, which is carried out to design them, involves solving the subproblems that have common content and mathematical formulations. The methods, algorithms, and dedicated software used to solve them can therefore be of a universal nature. The software tools used however do not provide universality, which is due to the following reasons. Preparation for computation and the computation process encounter difficulties associated with the use of a whole host of mathematical models of equipment for the IES components. Software implementations of methods and algorithms are not separated from software implementations of models of IES components. As a result, it is arduous to adapt them to a specific set of equipment when solving practical problems since it is necessary to change the software components that describe the modeled equipment. Difficulties also arise in the development of methods and algorithms since they are not separated from the software implementation of equipment models. It is challenging to keep up to date the entire set of necessary software components that implement mathematical models of equipment for various IES subsystems.

The use of a component approach to create a digital twin of IES provides universal implementations of software components that can be reused in software development. To successfully apply this approach, it is crucial to establish clear principles for implementing the software components. These principles need to provide the segregation of methods and models, as well as their adaptability and seamless integration into a unified software system. This is essential to effectively solve applied problems.

The process of IES design involves the use of a wide range of methods and algorithms, each of which must be implemented as a software component. The IES consists of subsystems that perform various energy functions, each formed by components from a standard set of equipment. To model this equipment, it is necessary to develop software components that implement its models. As a result, we will obtain a set of components that must be organized into libraries. It will also be essential to give their universal description and develop a methodology for their automated integration into a single software system when solving an applied problem.

The digital twin combines the entire set of methodological, mathematical, and software support for designing an IES and modeling it in a virtual environment, while ensuring the coordination of the characteristics with the real-world IES. The implementation of the IES digital twin requires developing a unified methodological approach to the automation of computations. This approach must consider the above-described difficulties in modeling these systems and deliver the following possibilities:

- Modeling the integrated energy systems with various types of energy systems included in them and sets of equipment;
- Accomplishing a range of tasks for designing IES on the basis of a single software platform;
- Automating computations on the basis of a digital twin of a IES when designing it;
- Separating the software implementations of methods (algorithms) and models of IES components to ensure their versatility and reusability.

III. Overview of Scientific Literature Related to the Research Topic

First presented by Grieves [1], the concept of digital twin included three components: the digital (virtual) part, the real physical product, and their connection. An overview of the history of digital twin development, its modern definitions and models, alongside six types of key enabling technologies are provided in [2]. Tao et al. [3]

expanded the concept of digital twin to five components, including data and service. In general, components of a product or product life cycle can be considered as digital twins. The difference between Product Lifecycle Management (PLM) technology and digital twin is explored in [4], where PLM is more focused on managing company components, products, and systems throughout their entire life cycle, while digital twin can represent a set of models for monitoring and processing data in real time. In some cases, it may be more appropriate to break the product or product lifecycle components into subcomponents, create several digital twins and establish relations between them [5]. The paper [6] is concerned with a 6-layer interoperability architecture in which low-level digital twins are combined into large high-level digital twins.

The study [7] discusses a five-dimensional digital twin model, which, according to the authors, has good applicability and scalability, and can also serve as a general model for applying digital twins in various fields. The same work attempts to explore and summarize commonly used digital twin technologies and tools. The paper notes that due to differences in formats, protocols, and standards, existing tools cannot be integrated and simultaneously used to solve a specific problem. The paper [8] addresses the problem of data standardization within the digital twin and proposes an approach to solving it.

Various scientific and industrial developments are examined in [9], identifying the implementation problems facing digital twin technology. One of the main disadvantages is the differences in the definitions and components of the digital twin. The work concludes that the development of machine learning and big data technologies has significantly influenced the formulation of the digital twin concept.

Currently, research is being actively conducted to develop a methodology for the creation and utilization of digital twins. The paper [10] proposes an approach to building an IT infrastructure for establishing intelligent systems to control the expansion and operation of energy systems. The approach relies on the results of systems studies for the energy industry and uses modern concepts such as digital twins and digital images. The paper [11] examines the state-of-the-art research into digital twins, with a focus on the key components, current developments, and main applications of digital twins in industry. The most important requirements for the digital twins of industrial power systems are identified in [12]. There is a growing number of works exploring the distinct characteristics of digital twin technology when applied to IES. In [13], the technical basis of the technology of digital twins of IES is discussed and its application is analyzed. The authors of [14] investigate an approach to the use of digital twin technologies in IES and propose an infrastructure for digital twin solutions based on hardware. In [15], the structure of the digital twin is proposed to solve the problems of the IES control. The paper also presents the process of automating the generation of a model to ensure that the digital model reflects the physical system in a virtual environment. The paper [16] explores the use of digital twin technology to model a regional integrated energy system when implementing the concept of "smart cities." The specific examples demonstrate that the practical implementation of digital twin technology not only optimizes the energy system but also brings a significant economic effect. In [17], a combination of digital modeling and real-time simulation technology is used to construct a digital twin intelligent architecture for an integrated energy system. In [18], the most important requirements for digital twins of IES in industrial energy systems are identified.

Some researchers propose the use of semantic networks to create a digital twin [19–21]. Ontologies can serve as a basis for the development of digital twins. Some papers focus on the examples of ontology application in implementation of digital twins. The authors of [22] analyze the control problems for the digital twin data. They propose using ontologies to solve these problems. This approach provides the flexibility of knowledge storage throughout the digital twin life cycle. The work [23] delivers a general architecture of digital twins of the industrial energy systems to ensure flexibility of these systems and optimize their operation. Ontologies are used to store information about resources and services. The researchers make use of a hierarchical design approach, which involves both a top-level ontology and a domain ontology. In [24], an ontology is considered as a representation of a digital twin in the context of cyber-physical systems. In [25], consideration is given to the prerequisites for applying the ontological approach to the construction of a digital twin, given the available results in the field of ontological engineering of energy systems.

Since the major entities expressed their interest in digital twin technologies, the advancement of these technologies has accelerated significantly. As a result, new approaches and software tools have emerged to facilitate the

development of digital twins. Some of them will be discussed below. General Electric develops and implements industry-oriented digital twin technology based on the PREDIX platform [26]. Microsoft has proposed the Azure Digital Twins platform, which provides the construction of a digital twin [27]. The Paladin DesignBase platform [28] offers an exceptional opportunity to create a digital twin that enables the modeling, intricate analysis, and optimization of energy systems. An architecture proposed in [29] serves as the basis for the development of a digital twin platform.

Implementing digital twins involves complex software systems whose implementation requires the use of advanced approaches to software development. Such approaches are the subject of research by many specialists and are widely represented in the literature. The basis for modeling modern software is an object-oriented approach [30, 31]. The works [32–35] propose a methodology of Model-Driven Engineering (MDE) to automate the stages of software construction. This methodology is a set of approaches to the automated construction of complex software systems based on pre-developed models [36]. The MDE approach remains an area of ongoing innovation and intensive advancement today. Applying the MDE-based methods enables successful development of intricate software systems [37–40]. Approaches to automating the stages of software construction based on metaprogramming are described in [41–43].

IV. Methodological Approach and Its Components

This paper proposes a methodological approach to the automation of computations based on digital twins for solving a variety of IES design problems. The approach includes the following components:

- Principles of software platform development;
- Architecture of a software platform;
- Technique for automated construction of the computational subsystem of digital twins;
- Principles of ensuring the universality of software components.

A specific feature of the approach proposed to solve the IES design problems is the use of a single universal mathematical tool developed on the basis of mathematical models, methods, and algorithms of the theories of hydraulic and electrical circuits. In the methodological approach at issue, the mathematical tool is implemented in the form of libraries of software components that can be reused when constructing digital twins of various IESs. This makes it possible to overcome the challenges that come with a wide variety of IES equipment and numerous mathematical models used to describe it. Libraries of software components are part of the software platform developed in our study as a single basis for the automated construction of the IES digital twin.

The development of this software platform relies on the following principles.

- Automated construction of a digital twin based on the software platform in the context of IES design problems.
- Separation of software implementations of methods (algorithms) and models of IES components to ensure their universality and reusability.
- Standardization (within the platform) of interfaces of software components that implement methods (algorithms) and models of IES components, and their arrangement in the form of component libraries.
- Application of the MDE methodology and modern metaprogramming technologies within the software

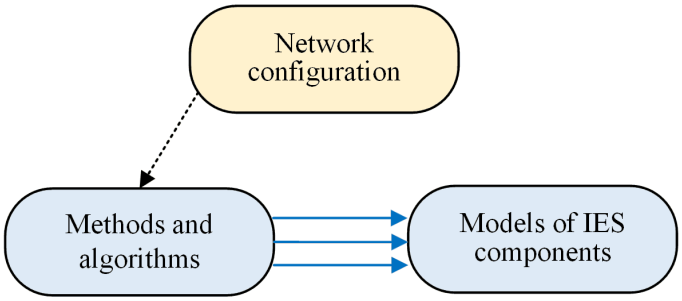

Fig. 1. Illustration of a system construction principle.

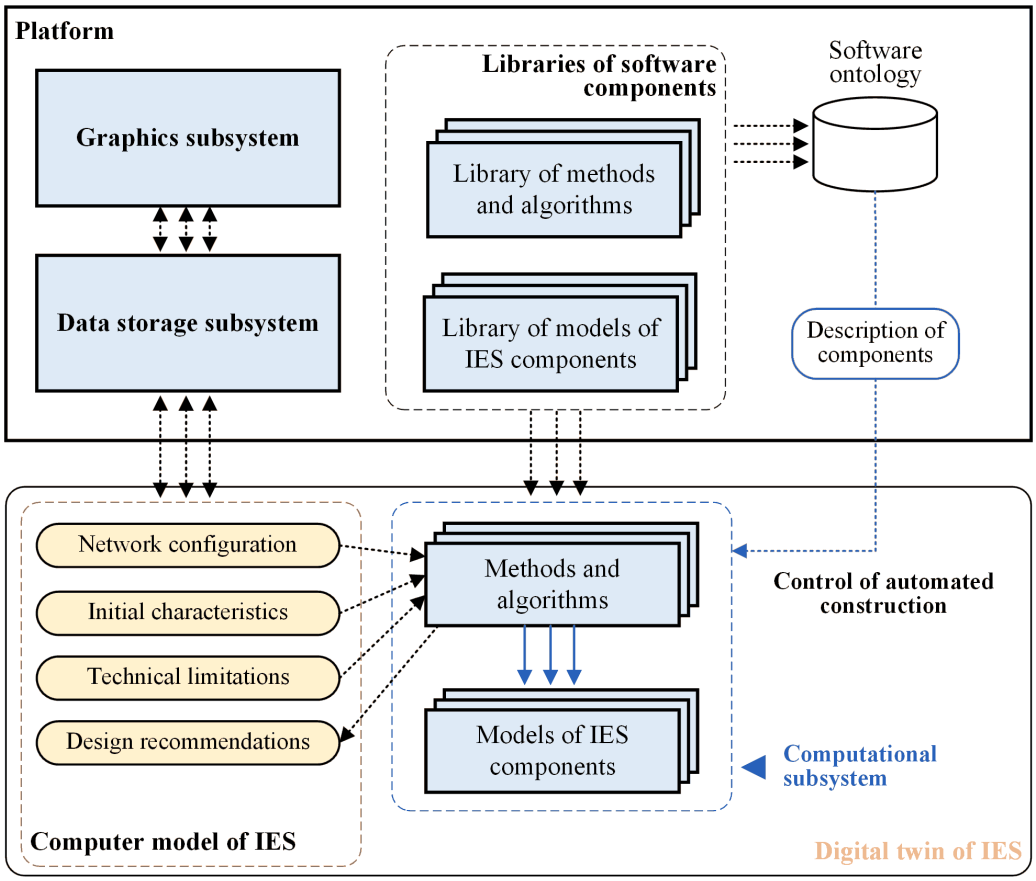

Fig. 2. Architecture of the software platform.

platform to automate the construction of a digital twin.

- Integration of methods for solving problems and models of IES components performed in the context of IES design problems, with this process controlled by knowledge organized in the form of a software ontology.

The universality of software implementation of the problem-solving methods and models of IES components is ensured by separating their software implementations. Their integration is performed in the context of solving an applied problem (see Fig. 1). Automated construction of the digital twin computational subsystem, within which the methods and models are integrated, leverages the concepts of the MDE approach. The specific feature of this approach is that the construction relies on a description of the structural configuration of the modeled system and a universal description of software components contained in the software ontology.

A software platform developed in the Java programming language is proposed for using as a single basis for automated construction. Its architecture, as shown in Fig. 2, includes the following components:

- Graphics subsystem;
- Data storage subsystem;
- Libraries of software components;
- Software ontology.

The graphics subsystem enables the development of a computer model of the IES, which reflects the structural configuration of the system, the initial characteristics of the components, technical limitations, and design recommendations for IES construction. This subsystem allows the user to view data in a readable form and make the necessary changes.

The data storage subsystem ensures the organization of work with various databases, which are used for storing and reusing computer models of IES, initial data and computation results, data on urban development projects.

The libraries of software components of the instrumental platform are categorized into the following functional groups.

1. The library of components, which contains

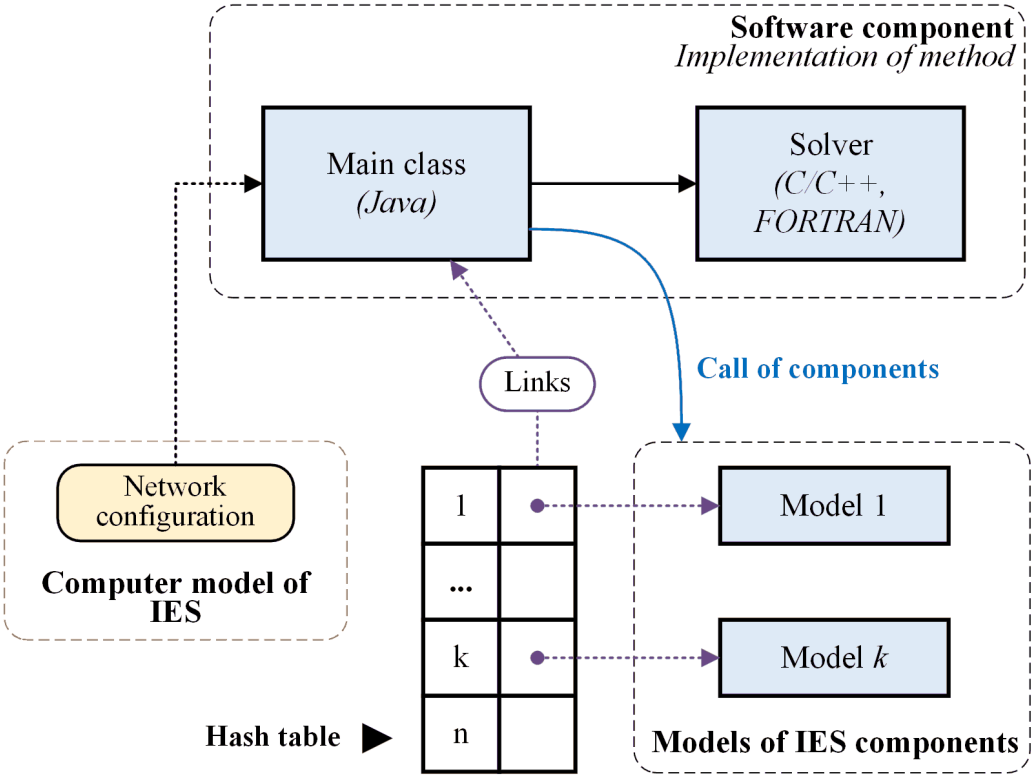

Fig. 3. Diagram of method and model integration.

implementations of mathematical methods and algorithms for solving the IES design problems.

2. The library of models of IES components, which includes software components implementing the models of components of various energy systems that constitute the IES.

The software ontology is designed to store the knowledge necessary to automate the development and use of the software. This ontology contains the description of:

- Software components that implement mathematical methods and algorithms for solving the IES design problems;
- Software components that implement the models of the IES components;
- Metadata (input and output parameters, description of data formats);
- Technologies and interfaces for access to program components.

The platform is used to build the IES digital twin in an automated mode. The digital twin includes (see Fig. 2):

- Computer model of IES;
- Software components that contain implementations of mathematical methods and algorithms for solving the IES design problems;
- Software components that implement the models of IES components.

To enable the dynamic integration of software components, a set of principles was formulated to ensure their universality. These principles are illustrated in Fig. 3. The solution proposed to provide a unified method for accessing the software components that are loaded into memory and implement the models of the IES components is as follows. Each IES component model has its unique identifier. The storage of the models is organized in a hash table, where the model identifier is used as a key, by which you can get a link to the software component that implements the corresponding model.

A software component that implements a method for solving a specific applied problem includes the main class in the Java language, which provides a single standardized access to the component (Fig. 3). In this case, it is possible to use auxiliary classes or computational modules implemented in compiled programming languages (C, C++, FORTRAN). During the computational process, the software component that implements the method for solving a specific applied problem receives the network configuration of the modelled system from the computer model. When calculating the parameters of a particular

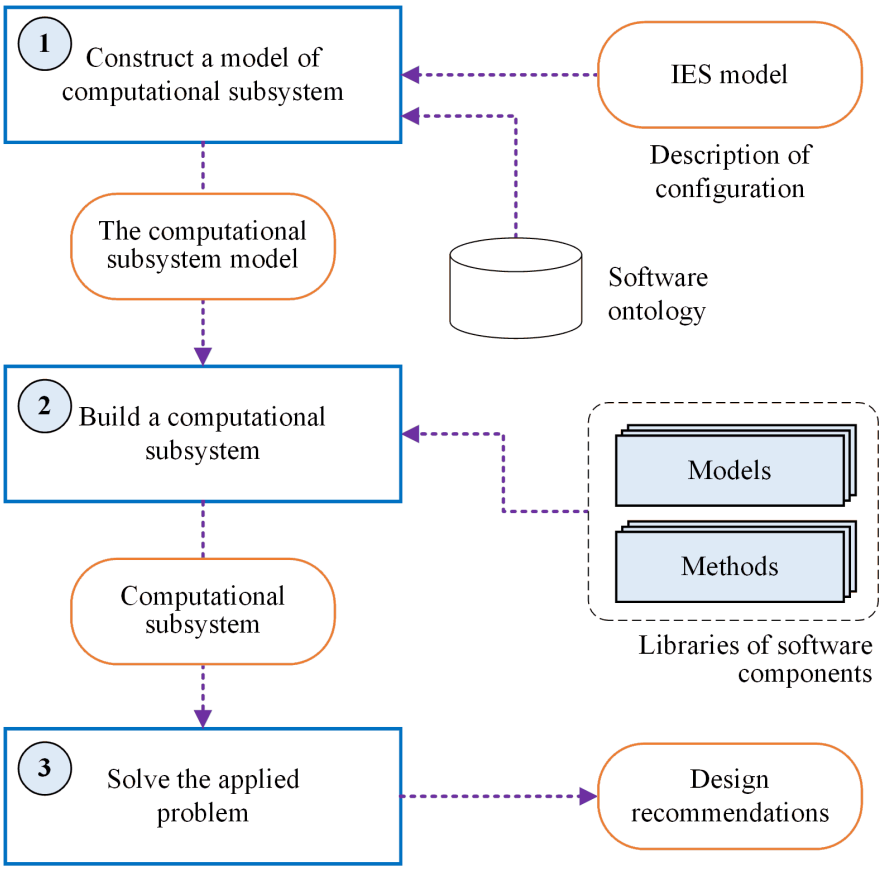

Fig. 4. The technique for the automated construction of the computational subsystem for the digital twin.

component, access to its model is performed from the hash table by its identifier.

V. Technique for Automated Development of a Digital Twin Computational Subsystem

In order to conduct calculations, it is first necessary to develop a computer model of a specific IES. This model must capture the properties of the network, including its structure, a set of equipment used and its properties, alongside parameters of the system components. This model is stored in the database for reuse. The applied problem is formalized, the set of equipment allowed for installation and the conditions for solving the applied problem are specified.

Automated construction of the computational subsystem for the digital twin is carried out in accordance with the technique proposed in this paper, which includes the following steps (see Fig 4).

Stage 1. Automated construction of a model of the computational subsystem. This stage involves building a model in an automated mode. This model describes the computational subsystem of the IES digital twin and represents a set of data structures that describe the computational subsystem.

The subproblems solved during this process are as follows:

1. Establishing a general problem-solving technique based on the description of the design problem, relying on the IES digital twin.

2. Identifying the software component that implements the problem-solving technique based on the software ontology.

3. Determining the methods and algorithms necessary for solving the problem according to the description of the technique.

4. Determining the software components that implement the necessary methods and algorithms, based on the software ontology.

5. Making a list of modeled equipment based on the description of the network configuration of the IES digital twin.

6. Determining software components that implement

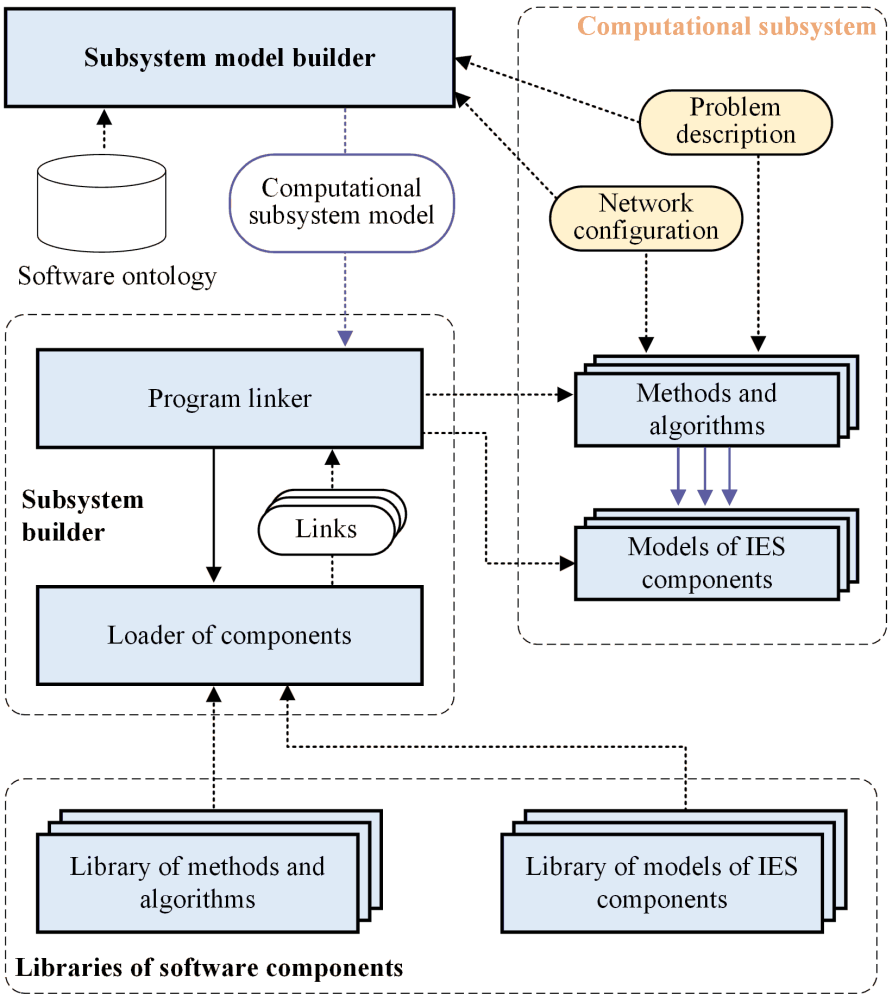

Fig. 5. General diagram of constructing the computational subsystem of the digital twin.

models of the necessary IES components based on the software ontology.

7. Loading the description of the necessary software components from the software ontology.

8. Building the data structures that describe the necessary software components.

9. Developing a general model of the computational subsystem under construction.

Stage 2. Automated construction of the computational subsystem for the digital twin based on its model using modern metaprogramming tools.

This stage involves solving the following subproblems:

1. Configuring the software component loader to work with the required libraries of components.

2. Loading software components that implement the general problem-solving technique, mathematical methods and algorithms.

3. Building the data structures for storing the software components loaded at the previous step.

4. Loading software components that implement the models of IES components.

5. Building the data structures for storing the software components loaded at the previous step.

Stage 3. Application of the digital twins in the development of recommendations for designing IESs.

This stage suggests solving the applied problems. In the course of this process, the methods and models of IES components are integrated.

The diagram of the software components interacting during the automated construction of the digital twin computational subsystem in accordance with the proposed technique is shown in Fig. 5.

The automated construction of the IES digital twin computational subsystem relies on advanced metaprogramming tools. Reflection is used, which is a type of metaprogramming and is an extension of the object-

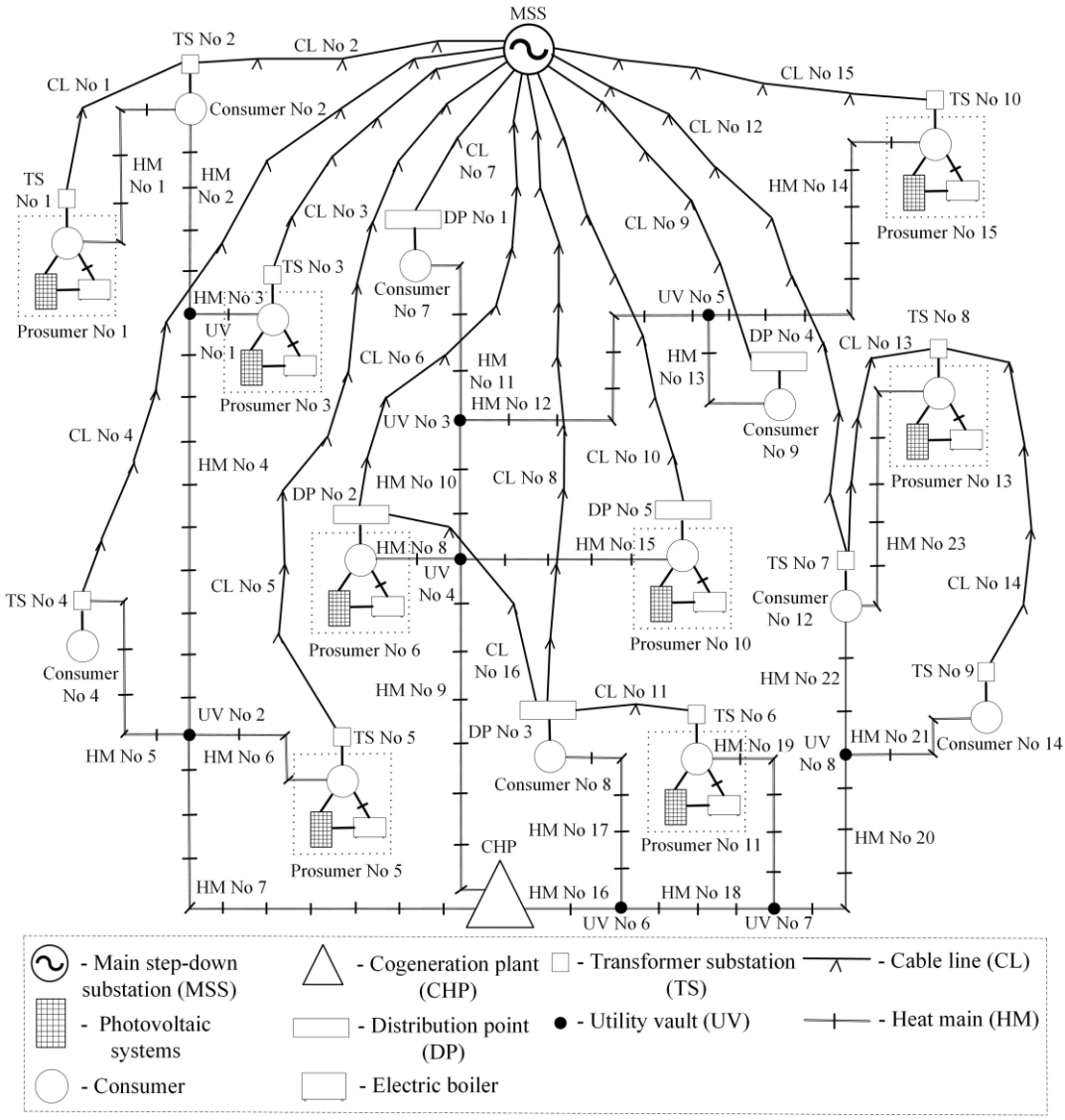

Fig. 6. Scheme of the Irkutsk microdistrict IES.

oriented programming paradigm. Reflection allows operations that cannot be performed in the classical object-oriented programming. The most important of them are studying classes during program execution; determining their fields, methods, and constructors; creating new instances of objects by class name using constructors; setting and getting values of fields by their name; calling methods by their name and argument description; working flexibly with arrays and containers (collections). With the help of reflection, the components are dynamically connected to the designed software system and configured to solve the applied problem.

VI. Testing the Methodological Approach

The methodological approach proposed in this paper is used for the software implementation of a software platform prototype to solve the IES design problems. The digital twin for the IES of an Irkutsk microdistrict was constructed based on the platform. The calculated scheme of the system is shown in Figure 6. The currently functioning electricity and heating systems are taken as a basis. Additionally, to address one of the possible options for their expansion, prosumers with their electrical and thermal energy sources are also added. The presented scheme includes the following entities: seven traditional consumers; eight prosumers; eight electric boilers for heat

generation; eight photovoltaic systems for generating electrical energy; sixteen cable lines; twenty-three heat mains; one centralized electrical energy source, and one district thermal energy source.

The developed software platform prototype was used to carry out a computational experiment on the IES expansion. Based on the calculations, a compromise solution was found to allocate power between centralized and distributed energy sources in the IES. The capacity of centralized sources in the electricity and heating systems was 35 MW and 54 Gcal/h, respectively. With these values, there is no increase in the cost of supplying centralized energy to consumers. In this case, the total costs will be USD 21 715 for heating, and USD 18 168 for electricity supply.

The conducted computational experiment shows the operability and efficiency of the proposed solutions, which helped reduce the total cost of energy supply to consumers by redistributing power between the centralized and distributed generation sources in the course of the IES expansion.

VII. Conclusion

Integrated Energy Systems (IESs) grounded in the conventional energy systems operating separately ensure higher efficiency and reliability of energy supply to the consumer. Designing them, however, can be a challenging task due to their complexity. Digital twins enable the integration of all the essential design tools within a single information space. The software tools that implement the IES digital twins and are developed to design them require high flexibility in organizing computations. This requirement is crucial for modeling various types of equipment, necessitating a wide range of methods and mathematical models. Automating the development of the computational subsystem emerges as an effective solution for addressing the identified challenges. The paper proposes a methodological approach to automate the development of the computational subsystem for the IES digital twin. The proposed approach leverages the advanced metaprogramming tools based on a software platform. Throughout the development process, the MDE concept is implemented, utilizing formalized knowledge represented through ontologies.

The key components of the proposed methodological approach aimed at automating the development of the computational subsystem for the digital twin are presented. They encompass the principles for building a software platform and designing its architecture; devising a technique for automated construction of the computational subsystem for the digital twin; and ensuring the adaptability of the software components.

The digital twin generated by applying the proposed methodological approach facilitates computer and mathematical modeling of the integrated energy system in a virtual environment, enabling the exploration of its various configurations. This modeling, relying on the digital twin of IES, makes it possible to adopt adaptable and efficient IES design approaches, offering design recommendations to guide the construction of real-world IESs.

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