Journal of Management & Technogy
e-ISSN: 2177-6652

NETWORK ENTERPRISE ARCHITECTURE BASED ON MULTIAGENT TECHNOLOGY

Cited as:
Telnov, Y., Kazakov, V., Danilov, A., & Fiodorov, I. (2024). Network enterprise architecture based on multiagent technology. *Revista Gestão & Tecnologia, 24*(2)

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Abstract
The architecture of a network enterprise for creating innovative products requires a software and technical platform for quickly configuring value chains with the involvement of the necessary business partners. It is proposed to use RAMI as an architectural framework for building a flexible and adaptive architecture of network enterprises, which is based on the use of digital twins and digital threads implemented in the form of asset administrative shells of industry systems of the 4th generation. The paper substantiates the use of multi-agent technology for implementing the architecture of network enterprises, which allows for the prompt and reliable configuration of value chains in accordance with changing needs. The paper summarizes the theoretical approaches and methodological principles of building multi-agent production systems related to the active and proactive modes of execution of microservices and the holonic organization of agents. Thus, horizontal and vertical integration of production and business processes at various levels of management of a network enterprise is ensured, the functional suitability, increases reliability and adaptability of the architecture of a network enterprise.

Keywords: network enterprise architecture, value chain, digital twin, digital thread, cyber-physical production system, asset administrative shell, multi-agent technology

Editor Científico: José Edson Lara
Organização Comitê Científico
Double Blind Review pelo SEER/OJS
Recebido em 21.09.2023
Aprovado em 04.04.2024

INTRODUCTION

The concept of network enterprises involves the broad involvement of various participants in joint economic activities, which form integrated ecosystems based on the use of unified software and technical platforms. At the same time, joint activities acquire the features of dynamically executed projects, the organizational structure of which is flexibly formed at various stages of the life cycle as the project is executed. The functioning of such enterprises in a distributed Internet environment determines the network nature of interaction, as a result of which enterprises become network-based.

The architecture of a network enterprise for creating innovative products involves configuring all its elements in accordance with new requirements and capabilities, which requires a software and technical platform for quickly configuring value chains with the involvement of the necessary business partners. It is proposed to use RAMI as an architectural framework for building network enterprises. The article analyzes the technological possibilities of using digital twins to implement the architecture of digital network enterprises. Such an architecture is built using a knowledge-based system, using a multi-agent system of interaction between participants of a network enterprise.

These features of digital network enterprises are fully reflected in the architecture being developed within the framework of a number of national programs related to the creation of a Plattform of Industrie 4.0 (Germany - Industrie 4/0) (Plattform Industrie 4.0, 2018), the Industrial Internet (USA – Industrial Internet Consortium) (Lin et al., n.d.), the development of digital factories (Russia-the National Technological Initiative, the Technet Association) (Association Tekhnet, n.d.), and a number of other countries.

Thus, in the digital transformation programs, the following principles are developed in the enterprise architecture (Plattform Industrie 4.0, 2018; Scheer, 2020; Schwab, 2016):

- all participants involved in the process share a common point of view and develop a common understanding of the jointly performed activities.
- the flexibility of network interaction of participants in joint activities implies the distribution of functions along the value chain, and the value is largely formed through the exchange of information.
- the product essentially becomes the result of network interaction, to the digital model of which all participants have access.

The digital model of the product and related production and business processes is becoming the central element of the digital enterprise architecture and has been called the digital twin. By a digital twin, we will understand a digital model of some asset (primarily a product or service), including specifications, design models describing the geometry, materials, structure and behavior, as well as, importantly, all current working documentation, up-to-date data on the creation and functioning of the asset: as-designed requirements, as-built, as-flown, as-maintained data, as well as inspection and calibration records (Minaev et al., 2019).

The term "Digital Twin" was first formulated by Professor Michael Greaves in 2011 on the basis of the idea of modeling dynamic objects of physical space in the information environment (Association Tekhnet, 2019; Grieves, 2016). According to the definition of M. Greaves, the concept of a digital twin consists of real and virtual spaces. The virtual space contains both all the information collected from the real space about the functioning of a certain asset, and a detailed description of the physical device or process from the point of view of the structural composition and functional behavior. The description provided by the digital twin should be "practically indistinguishable from its physical counterpart" (Grieves, 2016). At the beginning of the product life cycle, a virtual information image is first created, which is sequentially embodied first in a prototype (physical model), then in a prototype, an industrial product or a real service, about which data is collected, which is received in a digital model to eliminate possible problems and continuously develop the design and technological support of production.

Modern products and services include cyber-physical devices and embedded software that allow you to display the state of real objects in their digital counterparts online, generating big data that can be used to diagnose and predict the behavior of these objects in the future. Digital twins, along with the support of an information model of real objects, also include a set of mathematical and simulation models, the use of which allows you to play various variants of the development of the design of products before they are embodied in physical samples. From this point of view, digital twins are increasingly acquiring the characteristics of intelligent (smart) cyber-physical systems.

Digital twins work quite successfully with the cascade technology of creating products and services at separate stages of the life cycle, which are relatively isolated from each other: first design, then technological and design preparation of production, pilot production, industrial operation. In modern, more flexible production technologies, the production lifecycle is compressed, giving way to iterative design technologies that have found wide application in the development of purely software products. In this case, there is a need to manage the processes of creating products and services not only at separate stages, but also at several stages in the relationship, taking into account the possibility of managing several versions of manufactured products simultaneously. From this point of view, a set of digital models of products and services at certain stages of the life cycle are assembled into an integrated model, the so-called digital thread, with which you can manage the full life cycle of products and services with the involvement of all participants in joint activities (Bajaj & Hedberg, 2018; National Institute of Standards and Technology, 2022), and the enterprise is built on the basis of a system of interacting models (Model Based Enterprise) (Frechette, 2011). To increase the efficiency of the system of digital enterprise models, the article suggests a mechanism for ensuring their interoperability and scalability based on a multi-agent technologies (Telnov et al., 2020).

Using the RAMI framework to build a digital network enterprise architecture

For the completeness of the presentation of enterprises digital models, it is necessary to identify the main conceptual features, according to which it is possible to build an ordered system of descriptions that make up the enterprise architecture. The dynamic nature of the functioning of a modern model-based enterprise noted above causes the complexity of the enterprise architecture framework in comparison with the classical architecture of J. Zachman. In this regard, the most developed framework for describing the enterprise architecture is the reference model (framework) RAMI 4.0 (Reference Architectural Model for Industrie 4.0) (Plattform Industrie 4.0, 2018), as an architecture that reflects the essence of the digital transformation of the enterprise, from the point of view of three dimensions: the life cycle of products and services, implementation of various aspects of the enterprise functioning and the organization of production of products and services.

First of all, in the architecture of the enterprise, in contrast to the classical architecture of J. Zachman, introduces the dynamic aspect of the functioning of the enterprise associated with the life cycle of creating products and services, in which enterprises participate in joint activities on a dynamic basis.

Regarding network enterprises, in accordance with the architectural principles of RAMI, it is necessary to consider the interaction of participants in joint activities, each of which performs various operations in its own value chains, interacting with each other according to the "customer – supplier" type. Moreover, the composition of participants in the value chain can dynamically change during the implementation of the life cycle.

The second architecture dimension, which determines the implementation of various aspects of the enterprise, considers the activity of the enterprise from the perspective of the interaction of the digital and physical entities (worlds) of the product. So the digital entity of products involves: the definition of business needs for products (the answer to the question "What is the consumer willing to pay for?"), the formation of functional requirements for their execution (the answer to the question "What functions should the product perform?"), the definition of the necessary data for creating and using the product (the answer to the question " What data should the product provide?"), the specification of interaction (communication) with data (the answer to the question " How is access to data related to the product obtained?"), integration of the interaction of the digital and physical entities of the product (the answer to the question "Which parts of the product are available on the network in digital form?"). The physical entity of the product determines the interaction of the product with material technological processes (the answer to the question "How to integrate the product with the process in order to transfer it to the real world?").

The third dimension of enterprise architecture refers to the organization of production in a digital enterprise. In this dimension, the structure of material resources (assets) that are distributed among various participants in joint economic activity is considered. Traditionally, products, as the main material resources, consist of components that are manufactured on field devices with the participation of control devices, at separate stations and work centers, and all of these material resources form an enterprise. In modern digital enterprises, the distribution of assets across factories becomes flexible, flexible factories are formed, which interact with each other at the information level. In the same way, individual devices and products (parts) can interact with each other using the Internet of Things technology. Partner enterprises and consumers form a connected world through the network.

The mechanism of formation of flexible production structures is largely determined on the one hand by the needs of product lifecycle management (the first dimension), and on the other hand by the various aspects of the enterprise (the second dimension). The third dimension of the architecture for the use of assets determines the production capabilities that affect the implementation of the production and the organization of the life cycle. Thus, all three dimensions of the digital network enterprise architecture are interdependent.

The connecting link in the three dimensions of the digital enterprise architecture is digital twins and digital threads, which allow for information support of the process of interaction between participants and resources at all stages of the life cycle. In the Industry 4.0 architectural framework, such a tool for integrating the digital and physical world is a software tool called "Asset Administration Shell" (Plattform Industrie 4.0, 2019, 2022). Let's consider the possibilities of digital twins in more detail.

With the help of the asset administration shell (AS), any material assets (resources) can be described: products and parts that provide devices, equipment and their components, devices, exchanged documents, contracts, orders. Each asset in AS has a unique identification, a set of properties that can be grouped by functional submodels for a specific use. For example, a car is described by a set of submodels in accordance with specific use cases (functional areas): fuel supply subsystem, power supply subsystems, traffic support subsystem, etc. In some cases, the set of use cases can be expanded, for example, additional maintenance subsystems. In these cases, the network of participants in joint activities may expand.

Along with the properties of AS, it supports (Plattform Industrie 4.0, 2019):

- Operations that do actions.
- Events to observe properties.
- References to external data sources or files.
- References to other Administration Shells and their parts (submodels, properties), also from external partners in the value chain.
- Capabilities of the asset, description of method calls.
- Sets of properties.

The properties of assets can expand as the resource is developed and used. During the development process, a simulation of the functioning of the resource can be carried out. The results of monitoring the asset during operation are also recorded in the AS.

AS supports the full life cycle of an asset and provides a description of the value chain, managed and protected access to information and integration with other material resources. Functional submodels can be basic (standardized), reflected in product data catalogs, and free (specialized) for the creation of specific values, reflected in agreements between participants in the value chain. Basic submodels reflect identification, technical, operational and documentation characteristics, free submodels, as a rule, describe the data of processes, interaction features, checks, etc.

The participants of the value chain exchange packages of protected files, each of which can correspond to separate submodels and properties of AS, in XML, JSON, .aasx formats. At the same time, it can be represented in OPC UA, AutomationML and RDF. The presented tools have found a fairly wide practical application.

At the same time, the autonomous nature of the interactions of digital twins based on AS has both positive aspects from the point of view of automation of technological processes without direct human involvement in some cases, and disadvantages from the point of interaction between components. In addition, the mechanism of interaction of digital twins is not universal enough, and in each case has a different implementation. From this point of view, it would be useful to use more universal multi-agent technologies of component interaction (Telnov et al., 2022).

Application of multi-agent technology for building the architecture of a network enterprise

The classical architecture of the enterprise management system is hierarchical (Cruz Salazar et al., 2019). At the lower level is the management of physical assets (enterprise equipment) with the reaction time to events in milliseconds and seconds. At the next level of the SCADA - hardware and software complex for data collection and dispatching control, the execution of technological processes for creating products with a reaction time to events of up to a minute is controlled. At the level of production process management (MES – manufacturing executive system) (as a rule, at the shop floor level), operational scheduling and monitoring of production processes are carried out, optimizing the execution of many production orders in a time interval from an hour to one day. At the enterprise resource management level (ERP - Enterprise Resource Planning), operational management and accounting of production is carried out on a time interval calculated in days, which is set depending on the type and nature of production.

The use of digital twins based on multi-agent technologies in cyber-physical production systems radically changes the architecture of the management system of network enterprises. The paper (Almada-Lobo, 2015) examines the application of the principles of decentralization, vertical integration, connectivity and mobility, big data analytics in production process management systems from the point of view of digitalization. The creation of a common information model for the interaction of digital twins for all levels of management allows using microservice technology to integrate of production and business processes (Cruz Salazar et al., 2019). For example, the result of product design and development of production plans at the level of product types in the ERP system becomes the basis for operational planning and production management in the MES system, and accordingly, the result of planning and organization of the production chain at the MES level later becomes the basis for its execution at the level of technological management and control. In turn, the accumulation and analysis of digital data on the functioning of technological lines makes it possible to modify the organization of production chains at the operational level and designs and plans for the production of products at the tactical level. At the same time, the cyber-physical production system implements not only technological production processes, but also serves the execution of business processes related to enterprise management at various levels.

The cyber-physical production system assumes, first of all, the organization of asset management of production, aimed at their self-organization and coordination in the relevant production and business processes based on the use of Industrial Agent technology (Multiagent technology).

Thus, in (Cruz Salazar & Vogel-Heuser, 2022), the following main abilities of industrial agents (IA) in the construction of cyber-physical production systems (CPPS) are distinguished:

- Autonomy, as the ability of an IA to independently achieve goals in an uncertain environment in an automatic way without external interference.
- Reactivity, as the ability of an IA to respond promptly to requests for processing information about the environment, that is, the efficiency of monitoring and interaction with other IA.
- Proactivity, as the ability of an IA to take the initiative in making decisions and processing information when achieving a goal.
- Predictability, as the ability of IA to predict future results of actions taking into account actions in previous tasks and self-learning based on historical information.
- The ability of operational interaction of IA with decision makers, as the ability to carry out human-machine integration in production processes.

In the industrial sphere, the listed abilities of industrial agents provide such most important properties of CPPS (Cruz Salazar et al., 2019) as:

- adaptability and flexibility of new products and services in response to changing market needs in dynamic business ecosystems;
- rapid reconfiguration of the production system, which involves changing the structure, as well as individual components of the production chains to ensure the adjustment of equipment and functionality for the production of a family of products in response to sudden changes in market or regulatory requirements;

- reliability of the functioning of production systems in terms of achieving the required level of maturity, fault tolerance, recoverability, availability, compliance with quality requirements that affect the ability of the software to maintain the required level of performance under specified conditions for a certain period of time.

The works (Komesker et al., 2022; Vogel-Heuser et al., 2021) consider aspects of the implementation of multi-agent systems based on the concept of the fourth generation industry and administrative asset shells (AS, Administration Shell). The development of a multi-agent interpretation of AS is associated with active and proactive modes of their use (Belyaev & Diedrich, 2019), since the passive mode of accessing AS submodels provides only a display of the state of asset properties in the form of data or a description of the functions performed.

The active mode of using AS involves setting a set of microservices that, in accordance with the RAMI architecture (Plattform Industrie 4.0, 2018), determines the interpretation AS as a reactive agent. In the works of (Karnouskos et al., 2020) microservices can be both mandatory (integration, communication, organization and access to AS data) and optional, providing functions for data collection, diagnostics of states, configuration of processes, evaluation of limitations related to the specifics of a particular domain.

The addition of microservices at the business level, which are designed to make decisions on the selection of a set of operations, optimize the configuration of production and business processes, compile work schedules, and monitor is provided by a proactive mode of using AS and converting AS into intelligent agents, requiring the organization of a knowledge base and heuristic decision-making algorithms. Microservices of decision-making can cause the connection of software modules of MES and ERP systems at a certain time horizon at the level of the workshop and enterprise, respectively.

Access to the microservices of administrative shells is carried out through directories (registers) belonging to the administrative shells of assets. To organize the interaction of components within a single chain of operations, the i4.0 Language is used, which provides messaging between components (Belyaev & Diedrich, 2019). In this case, one AS of the component can either request the execution of some action (request) from another AS, or perform some action (provide).

The construction of multi-agent production systems must meet the following requirements (Komesker et al., 2022):

- Modularity of the structure of products, processes and resources and the corresponding administrative shells, which reflects the formation of submodels and components of physical resources and determines the basis for their coordination to ensure a sustainable production process;

- The autonomy of the IA, which assumes the provision of adaptability, reconfigurability, monitoring and conclusions, which allows you to quickly respond to unforeseen changes in accordance with monitoring situations and timely decision-making.
- Scalability of the production system, taking into account the growth of demand for products due to the expansion of the set of IA and the establishment of relationships between them.
- Interoperability as the ability to support vertical and horizontal communication and information interaction of heterogeneous IA components supported in different software environments.
- Recursiveness of mechanisms for planning and controlling the execution of production and business processes at various levels of asset decomposition.

The paper (Karnouskos et al., 2020) analyzes the application of industrial agent technology in practice from the perspective of the implementation of known characteristics of automated systems:

- Functional suitability of IA refers to the extent to which an individual product or production system provides functions that meet the stated and implied needs when used under certain conditions. Currently, most of the developed multi-agent CPPS have the nature of prototypes.
- Work efficiency in terms of achieving productivity in relation to the amount of resources used under given conditions is achieved under dynamic conditions that determine adaptability and the ability to self-organize compared to traditional production systems.
- Compatibility from the point of view of information exchange between system components is ensured by structured interaction protocols that support dynamic changes in terms of reconfiguration and deployment of both the physical system and the software solution, and in this respect they surpass traditional production systems in flexibility.
- Usability involves adapting the decision-making processes embedded in industrial agents to specific operational scenarios, depending on the application conditions.
- Reliability of IA use. Agent-based solutions demonstrate a high level of cyber-physical reliability due to their autonomy. However, in the case of systemic violations and coordinated external attacks, the development of additional reliability support tools is required.

- Agent security largely depends on the supported platforms, services, and interaction patterns used, and is currently not fully implemented.
- The convenience of maintenance, which involves carrying out modifications of a product or production system to improve, correct or increase efficiency, is facilitated by the modular nature of agents, and on the other hand, encounters problems of maintenance of the digital platform itself.
- The portability of IA, which characterizes the possibility of transferring a system, product or component from one hardware, software or other operating environment to another, is more effective than traditional systems due to the inherent properties of autonomy and compatibility with various operating environments as a result of the implementation of interaction protocols.

The analysis of the listed features of multiagent technology at the present stage of development shows that, first of all, it is necessary to develop research in terms of ensuring their functional suitability by developing operational scenarios depending on the classification of application conditions, requirements for ensuring reliability and safety of interaction of components of the production system. At the same time, the greatest importance in this article is attached to the implementation of such properties as adaptability/flexibility, reconfigurability and reliability the value chain of network enterprise.

The implementation of these properties is based on the introduction of the holonic production paradigm (Komesker et al., 2022; Sakurada et al., 2022), according to which the principles of flexible horizontal and vertical integration of production are implemented on the basis of multi-agent interaction. Thus, in accordance with the structure of the products, roles and responsibilities are distributed between the enterprises participating in the network enterprise and the corresponding software agents who can participate in parallel in several value chains. Vertical holarchy of assets by type: equipment (workplace), production line, workshop, enterprise also allows for flexible planning and management of production and business processes. Thus, thanks to the use of multi-agent technology, the advantages of modularity, decentralization, autonomy, scalability and reuse of software components and assets of network enterprises are achieved.

CONCLUSION

The analysis of the possibilities of implementing the architecture of a network enterprise based on the RAMI framework (reference model) has shown that the fully dynamic properties of a network enterprise for building a value chain in accordance with the changing needs of a competitive market environment can be fulfilled by using a combination of digital twins and multiagent technologies.

The creation of cyber-physical production systems based on the implementation of digital twins using multi-agent technologies allows you to quickly accumulate and analyze digital data on the functioning of value chains and organize them at the operational level, as well as plan production at the tactical level by connecting external applications of MES and ERP systems.

Active and proactive modes of using administrative asset shells as reactive software agents are implemented using a set of microservices that, in accordance with the RAMI framework, implement all layers of architecture, allow performing data collection functions, state diagnostics, process configuration, evaluation of limitations associated with the specifics of a particular subject area, that is, the possibility of full-featured management of dynamically developing production systems of network enterprises.

The analysis of the implementation of the principles of flexible horizontal and vertical integration of production when building the architecture of network enterprises based on multi-agent technology at the present stage of development shows that it is necessary to develop research in terms of ensuring their functional suitability by developing operational scenarios depending on the classification of application conditions, requirements for reliability and safety of interaction of components of the production system. At the same time, the tasks of implementing the holonical organization of interaction between agents of a network enterprise are of paramount importance.

ACKNOWLEDGMENT

The research was carried out at the expense of the grant of the Russian Scientific Foundation No. 22-11-00282.

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