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CYBER-PHYSICAL SYSTEMS IN FOOD PRODUCTION CHAIN

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Abstract
The article reviews the state-of-the-science in the field of cyber-physical systems (CPSs). CPSs are intelligent systems that include physical, biological and computational components using engineering networks. CPSs are able to integrate into production processes, improve the exchange of information between industrial equipment, qualitatively transform production chains, and effectively manage business and customers. This is possible due to the ability of CPSs to manage ongoing processes through automatic monitoring and controlling the entire production process and adjusting the production to meet customer preferences. A comprehensive review identified key technology trends underlying CPSs. These are artificial intelligence, machine learning, big data analytics, augmented reality, Internet of things, quantum computing, fog computing, 3D printing, modeling and simulators, automatic object identifiers (RFID tags). CPSs will help to improve the control and traceability of production operations: they can collect information about raw materials, temperature and technological conditions, the degree of food product readiness, thereby increasing the quality of food products. Based on the results, terms and definitions, and potential application of cyber-physical systems in general and their application in food systems in particular were identified and discussed with an emphasis on food production (including meat products).

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Introduction

The Strategy for Scientific and Technological Development of the Russian Federation, approved by Decree of the President of the Russian Federation dated December 1, 2016, No. 642, indicates the need for a transition to advanced digital intelligent production technologies, robotic systems, new materials and design methods, and the creation of systems for processing big data, machine learning systems and artificial intelligence.

The concepts of Industry 4.0 and Society 5.0 were introduced in 2011 and 2016 respectively, but digitalization of food systems began less than 5 years ago.

According to the Industry 4.0 concept proposed by physicist Henning Kagermann, the "fourth industrial revolution" is a means of increasing the competitiveness of the German processing industry through the increased integration of "cyber-physical systems" into factory processes.

As a result, one of the current trends is the development of cyber-physical systems for digital transformation, robotization of processes in the field of storage and processing of agricultural raw materials and food products. Digital transformation as the process of introducing modern digital technologies into business processes of production (processing) systems at all levels in practice will lead to the creation of a system of end-to-end IT/agro-biotechnological processes.

The purpose of this study is to give a comprehensive review of cyber-physical systems: purpose, history of creation, directions and prospects for use in the food industry.

Objects and methods

The authors conducted a search and a comprehensive analysis of publications using key phrases: "cyber-physical systems", "Industry 4.0", "smart industry", "smart production" in the Scopus, PubMed, MEDLINE, Web of Knowledge, Google Scholar, IEEE Xplore, Science Direct, eLibrary (RSCI) databases for the period of 2000 to August 2023.

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standard was chosen to ensure reproducibility of the selected information (http://www.prisma-statement.org/).

The identified publications were preliminarily analyzed by abstract. The inclusion criteria were as follows:

1. Scientific research on cyber-physical systems, their principles, architectures, implementation tools;
2. Conditions of use in industry;
3. Limitations of use;
4. Mainly publications in Russian and English.

The exclusion criteria were as follows:

1. Scientific articles, monographs published before 2000;
2. Publications related to Industry 4.0 tools (Big Data, IoT, Digital Twin, etc.) without the use of CPSs.

Terms and definitions

The term "Cyber-Physical Systems (CPSs)" was first introduced in 2006 by the Director of Embedded and Hybrid Systems of the US National Science Foundation (NSF), Dr. Helen Gill, at the "NSF Workshop on Cyber-Physical Systems" conference (October 16–17, 2006, Austin, Texas) to denote complexes consisting of natural objects, artificial subsystems and controllers.

Currently, the following definitions of the cyber-physical systems exist.

The book "Introduction to Embedded Systems — A Cyber-Physical Systems Approach" [1] states that CPSs represent the integration of computing with physical processes. The need to understand the interaction of the computational and physical process is noted. It is not enough to understand the computational and physical process separately. In other words, CPSs are monolithic connection of physical objects or phenomena and calculations combined into a network.

In [2], CPSs are systems that combine physical and computer-based or cyber components. The physical components are biological objects, as well as systems developed by man (for example, transport or energy systems). A physical component exists, functions, and interacts with its environment in a continuous or routine manner. A computational component includes systems and objects involved in the processing, transmission and controlling the information by computing means. These are algorithms implemented in software and digital systems interfaced with physical components through analog-to-digital converters (ADCs), digital-to-analog converters (DACs) and digital communication networks. Computational components are artificial systems that operate in discrete time or based on events. Sanfelice [2] notes that the complexity of integrating components in cyber-physical systems is due to the fact that the computational component is distributed throughout the system and is closely related to the physical component. Thus, CPSs are highly complex systems that combine continuous and discrete dynamics.

The following definition is given in [3,4,5]: CPSs are the junction of cyber (electrical/electronic) systems with physical object. CPS helps mechanical systems to sense the physical world, process that sensing as data on computers, make calculations, and inform the systems of actions to change the outcome of the process.

Trappey et.al. define in their work that "CPSs are a set of transformative technologies for managing interconnected physical and computational capabilities" [6].

According to Baheti et al. [7], cyber-physical systems refer to transformative technologies for managing interconnected systems between physical parameters and computational capabilities.

Shafiq et al. [8] agree that CPSs are "the convergence of the physical and digital worlds by creating global networks for businesses that include their equipment, warehouse systems and manufacturing facilities."

A number of studies suggest that CPS, as an emerging technology, has the potential to offer promising solutions to transform the operation and role of many existing industrial systems [9–14].

Gürdür et al. [10] note that the development of CPSs requires tool support for tasks associated with various engineering tasks at different stages of the product life cycle. These tools must evaluate product data based on internal and external dependencies. The study examines a method for visualizing the node-link diagram (NLD) in the CPS development chain. An assessment of the current compatibility status and various solutions for integration scenarios are provided.

Mao et al. [11] state that in the context of the Internet of Things (IoT) of an industrial enterprise, all objects, such as tools, materials, machines and persons, are networked by radio channels that have not only the capabilities of measurement, processing, communication and control, but also location information. To meet these requirements, the authors believe that future RFID systems will provide both reliable identification and high-precision positioning. In the paper, the authors propose an integrated asymmetric UHF/UWB reader transceiver for industrial IoT applications.

Yan et al. [13] proposed a new wearable wireless sensor network (WWSN) for health anomaly detection, discussed the network architecture, established a detection model, and developed a set of algorithms to support the operation of WWSN. Thus, changes in medicine will be due to the personalization of human data, and the system will select treatment individually.

Zhai et al. [14] presented a multi-frequency time division multiple access (MF–TDMA) protocol for a radio frequency identification (RFID) monitoring system in the industrial Internet of Things (IoT).

CPSs are industrial automation systems that integrate innovative functions via a network. Therefore, the operations of physical reality are connected with computing and communication infrastructures [5,8,15,16,17,18,19].

In [15], a unified framework for integrating CPSs into production is presented. The method of adaptive clustering is described as an advanced analytical method for interconnected systems, and a practical example of self-aware machines through CPS integration is shown.

Harrison et al. [16] consider the industrial context for the development of CPSs. Examples of engineering methods, approaches and tools that are currently available are provided. The study focuses on a set of tools for designing CPSs. An example is shown to explain how a component-based design toolkit may support an integrated approach to the virtual and physical design of automation systems throughout the life cycle. The method allows for the efficient integration of equipment from different suppliers and provides support for the specification, verification and use of such systems throughout the supply chain.

Jazdi [17] describes the significance of the Internet of Things and Services (IoT), its important role in professional and everyday life. The author notes that Industry 4.0 has already begun and directly affects our lives and business models, demonstrates software for an industrial coffee machine at the Institute of Industrial Automation. Future work is expected to focus on implementing a distributed remote application based on software agents.

Lee et al. [18] propose a unified five-layer architecture to implement CPSs. The article provides a practical guide for the processing industry to implement CPSs in order to improve product quality and system reliability using intelligent and failsafe equipment facilities.

The development of CPSs is associated with a new paradigm of technical systems. For implementation, the following is necessary: 1) online configuration for a set of systems; 2) coordinated functioning of interacting systems; 3) provision of appropriate infrastructure. Mosterman and Zander [19] focus on the second aspect, the collaboration function. In their study, they present a number of specific examples of CPSs, one of which is illustrated using a pick-and-place machine solving a distributed version of the Towers of Hanoi puzzle. The system includes a physical environment, a wireless network, parallel computing resources, and computing functions (service arbitration, various forms of control, and streaming video processing). The entire research is conducted at the computational model level aiming at contributing to the research agenda to develop next-generation systems.

The study by Putnik et al "What is a Cyber-Physical System: Definitions and models spectrum" [20] analyzed 44 scientific publications with different definitions of CPSs. Since there are many definitions, models, and structures of CPSs, this study focused on identifying their characteristics and classifying them by approaches or applications. An overview of definitions from the literature and their position in the presented synchronous spectrum of CPSs is presented. The classification is based on the basic characteristics, behavior and supporting technologies of CPSs.

Potential applications

The vast majority of authors in the studied publications agree that CPSs are related to the fourth industrial revolution. It is stated that it is the introduction of cyber-physical systems into industry that will contribute to the early transition from Industry 3.0 to Industry 4.0.

The fourth industrial revolution is closely related to the Internet of Things (IoT), cyber-physical systems (CPSs), information and communications technologies (ICTs), enterprise architecture (EA) and enterprise integration (EI).

A systemic analysis of researches [18,21,22,23] showed that the interoperability architecture of Industry 4.0 includes four levels: operational (organization), systematical (applicable), technical and semantic interoperability.

These four levels make Industry 4.0 and CPSs more productive and cost-effective. The interaction diagram between Industry 4.0 and CPSs is shown in Figure 1.

Interoperability indicates the common structures of concepts, standards, languages and relationships within CPSs and Industry 4.0. Systematical interoperability defines the guidelines and principles of methodologies, standards, domains and models. Technical interoperability brings together tools and platforms for technical development, IT systems, ICT environment and related software. Semantic interoperability enables the exchange of information between different groups of people, malicious application packages, and institutions at different levels.

Industry 4.0 interoperability requires specific principles to ensure the accuracy and efficiency of the entire process, i. e. accessibility, multilingualism, security, use of open-source software and multilateral solutions. Accessibility means that Industry 4.0 must offer equal opportunities for public access by participants without their discrimination. Multilingualism means that Industry 4.0 must support multiple languages to effectively deliver information and knowledge to CPSs. A security policy means that appropriate risk assessments and security measures are required. Multilateral solutions achieve Industry 4.0 interoperability by meeting the different requirements of different partners [24].

CPSs include microcontrollers that control sensors and actuators. Data and information are exchanged between embedded computer terminals, wireless applications,

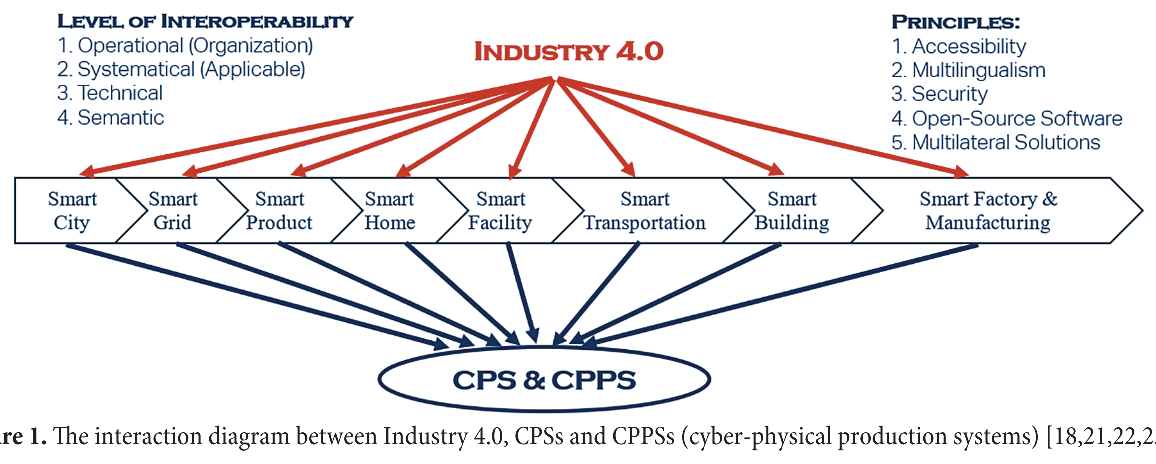

Figure 1. The interaction diagram between Industry 4.0, CPSs and CPPSs (cyber-physical production systems) [18,21,22,23,24]

homes, and even cloud services. A complex, dynamic and integrated CPS will support planning, analysis, modeling, design, implementation and maintenance in the manufacturing process [17,25]. CPSs are capable of increasing productivity, stimulating growth, changing labor productivity, and producing higher quality products at lower costs due to the collection and analysis of malicious data [26].

Since CPSs integrate information and materials, decentralization and autonomy play an important role in improving the overall performance of industrial production [27].

Ivanov et al. [28] state that to coordinate actions in production procedures and to achieve production optimization, dynamic models are needed in CPSs that describe changes in a system or process over time, take into account the influence of external factors, interactions with other elements of the system, and predict course of events and consequences. Based on the dynamic structure control mechanism, the authors develop a service-oriented dynamic model for dynamic scheduling and collaboration of CPS networks in Industry 4.0.

CPSs have characteristics such as timeliness, reliability, failure tolerance, security, scalability and autonomous operation [29,30,31].

Systematic reviews of CPS technologies [24,32,33] highlight the following areas of knowledge: real-time embedded systems, distributed computing systems, automated control systems for technical processes and objects, wireless sensor networks, Internet of Things (IoT), industrial Internet, machine-to-machine (M2M) interaction, fog and cloud computing, complex adaptive systems, holon (agent) production systems.

Figure 2 illustrates the product's impact and potential applications. Information technology and low-cost sensors offer new capabilities to improve the services [34].

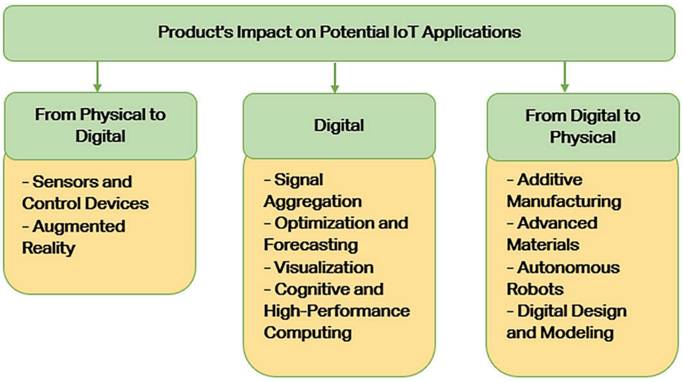

Figure 2. Product's impact and potential applications

In food production, CPSs consist primarily of three modules: 1) field device process; 2) production equipment process; 3) production management process using a service-oriented architecture for management [36].

Structure of CPSs

As noted in [24,36,37], CPS processes at the logical level are described in a formalized language and implemented using standard technologies for collecting, converting and storing information in information and communication systems. The physical level considers the implementation of CPS designed or adapted to interact with the expected operating environment to achieve one or more intended goals while respecting the limitations of the system. Communication between the logical and physical levels is carried out using converters: various sensing device, sensors that collect data about the physical state of the cyber-physical environment, the interpretation of which may be used to change the logical state of the system, as well as actuators that can influence the physical state of the environment. It is the converters that play a central role in CPSs, ensuring the interaction between physical and logical components.

The main categories of components in CPSs are logical components, physical components, users, and converters, which include sensors and actuators.

Vatamaniuk and Iakovlev [38] presented a generalized set-theoretical model of CPS in their paper:

$$CPS = \langle Ph, Lg, Sens, Act, Hum \rangle \quad (1)$$

where Ph is a set of physical components;
Lg is a set of logical components;
$Sens$ is a set of sensors;
Act is a set of actuators;
Hum is a set of persons involved in the processes of CPS functioning or located within the cyber-physical environment and being the end users of the system.

According to the researchers, each functional component of CPS should have the following capabilities [39]:

- availability of computing power and software necessary to implement its own functions;
- availability of sufficient memory to store all the data necessary to carry out its own activities;
- ability to establish network connections with other system components and ensure targeted data transfer;
- ability to obtain and collect the necessary information about the state of the environment and other components of the system;
- ability to perform self-diagnosis in the context of identifying its own malfunction, as well as to inform related components in the event of such a malfunction.

Thus, each functional component is associated with a specific set of sensors, actuators and persons.

There are many architectures for CPSs. Highly detailed 5-level CPS configuration is presented in [34]. CPS consists of two main functional components: 1) advanced connectivity providing real-time data collection from the physical world and feedback from cyberspace; 2) intelligent data management, analytics and computing capabilities that form cyberspace. Figure 3 presents a generalized architecture of CPSs.

"Communication/Connection" is the first level towards achieving integration using such elements as sensors, actuators and protocols. Connections are necessary to create complex systems such as enterprise resource planning

(ERP), customer relationship management (CRM), and supply chain management (SCM).

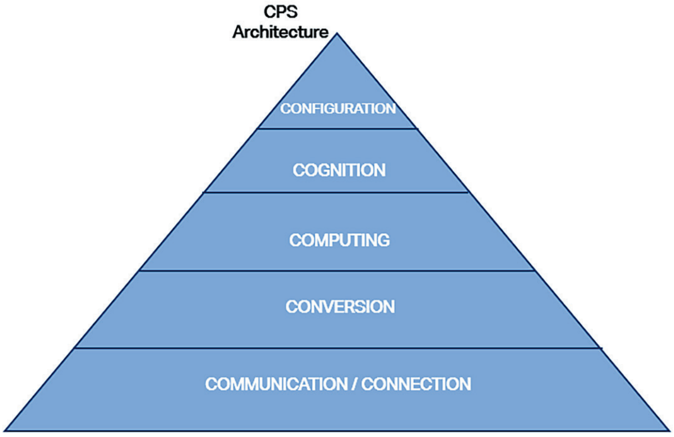

Figure 3. Generalized architecture of CPSs

"Conversion" is the second level. Interferences are filtered out based on information obtained from such sources as big data analytics and cloud computing.

At the third level, algorithms, software and computer infrastructures are used to analyze current data and predict the future behavior of the system or process.

"Cognition" is the fourth level that represents the knowledge collected at the above stages for decision making.

"Configuration" is the final, fifth level. There is a transformation of intelligence into action (moving from cyberspace to physical world).

The very first and simplest structure is proposed by Zachman [40] and shows that information should affect not only internal resources, processes and personnel, but also external resources of the organization. Along with this, Wolfert et al. [41] proposed a general information integration method based on service-oriented architecture (SOA) in agrifood supply chains. Närman et al. [42] proposed an analytical modeling method using a hybrid probabilistic relational model. Le and Wegmann [43] proposed hierarchical-oriented modeling with all stakeholders. Săsă and Krisper [44] proposed information-based analysis of business process support based on a systematic review of important aspects. Mamaghani et al. presented in their work [45] a conceptual model of enterprise IT architecture using Shannon entropy. Wang et al. [46] recommend using a hybrid multi-agent negotiation protocol in the implementation of virtual enterprises.

Food system applications

Digital engineering technologies are increasingly adopted by the food and processing industries and agriculture. This is not only due to the use of sophisticated robotic technology in carrying out technological operations and processes, but also due to the use of engineering concepts in relation to the food product.

It should be noted that food production based on CPSs is a very complex heterogeneous system including several types of physical systems and many computing and communication models.

Cyber-physical system of the food system life cycle should integrate smart technologies at each stage using various tools.

Smart technologies include distributed CPSs, open API (application programming interface) and fog computing network.

From a hardware point of view, a distributed system is a set of interconnected autonomous computers or processors; from a software point of view, it is a set of independent processes (executable software components of a distributed system) interacting by messages to exchange data and coordinate their actions.

CPSs are complex distributed systems driven or controlled by computer algorithms tightly integrated with the Internet and its users. The technological basis of which is the Internet of things (IoT) or "thin Internet" technologies. Thin Internet is a general term for the growing number of physical devices around the world that are connected to the Internet and, ultimately, to each other; a networked world of interconnected devices, objects and persons.

Open API is a new web technology such as Simple Object Access Protocol (SOAP). It is necessary for interoperability in the food supply chain, where CPS-managed service system may also adapt to any tracking in a managed services environment with another CPS through centralized system integration.

Fog computing, also known as fogging, is a new paradigm operating directly at the edge of the network that extends the capabilities of cloud computing running on machine-to-machine communications based on a large-scale and geospatially distributed programming model to efficiently operate a network of smart physical objects for the future Internet-applications without human intervention [47,48].

There are a lot of studies and scientific publications related to tracking food products throughout the supply chain. Aung and Chang [49] provided in their study extensive information on safety and quality tracking in the food supply chain.

Pizzuti et al. [50] specify the description by presenting an ontology of forward (track) and backward (trace) traceability of food products (Food Track and Trace Ontology, FTTO). The main goal of the proposed FTTO is to integrate the most representative food concepts involved in the entire supply chain (SC) into a single ordered hierarchy capable of integrating and linking the main functions of food traceability. FTTO consists of four modules: food, services, processes and supply chain participants.

Kang and Lee [51] proposed and developed a new set of services called tracking services (TS) using the EPCglobal certified EPCIS system. EPCglobal Architecture Framework is a standard for connecting distributed RFID systems in the supply chain. The system allows tracing the entire chain of product movement and integrates with other systems including external ones.

Overall, it should be noted that companies gain a sustainable competitive advantage through the implementation of innovative food traceability systems [52].

In a review study, Suprem et al. [53] discuss the application of technology systems in agriculture and food processing, such as embedded computing, robotics, wireless technology, GPS/GIS (Geographic Positioning System/ Geographic Information System) software and DBMS (Database Management System). The article describes: 1) soil sampling methods and their application; 2) mapping fields and yields using GPS and GIS; 3) harvesters and future research in robotic harvesters; 4) food processing and packaging technologies, such as traceability and RFID tags; 5) application of a sensor network; 6) data management and execution systems; 7) automation and control standards.

A review article by Bosona and Gebresenbet [54] on the modern food supply chain concludes that future research should be focused on: 1) integrating food traceability with logistics; 2) technological aspects of FTSs (Food Traceability Systems); 3) connections between the traceability system and food enterprises; 4) standardization of data collection and information exchange; 5) awareness raising strategies; 6) continuity of information flow and effective communication of traceability information to consumers and other stakeholders; 7) connections between different FTS drivers; 8) strategies for improving FTSs; 9) development of systems for assessing the effectiveness of FTSs.

Recalling food products, especially perishable or gourmet foods, is extremely expensive for a company. It is associated both with direct financial and reputational losses. A study by Piramuthu et al. [55] illustrated the importance of more details in both forward and backward traceability. The appropriate levels of responsibility between participants in the production and supply chain are determined depending on the identification speed of contamination and its source. The recall of contaminated products is tracked using radio frequency tags.

RFID tags have been successfully applied and described by Parreño-Marchante et al. [56] to trace the movement of aquaculture. RFID tags are combined with environmental data collected through wireless sensor network (WSN) infrastructure. By reducing the time spent on monitoring, the company's performance (in a pilot project) increased by 89% to 95%.

Olsen and Aschan [57] describe a method of process mapping (a graphical description of the material and information flow of value stream creation in the form of flow charts using special symbols and a description of data obtained from measurements or statistics) in a processing plant throughout the entire traceability chain. This method helps to standardize company reporting and supply chain reporting, and also allows for comparisons and benchmarking. The study focuses on identifiers and conversions. Once the process has been mapped and systematic information loss have been identified and bottlenecked, new or improved software should be installed to improve the food traceability system.

Using a vegetable supply chain traceability system as an example, Hu et al. [58] use the Unified Modeling Language along with a set of suitable templates, i. e. a series of Unified Modeling Language class diagrams.

Lack of process automation is the main reason why special high-resolution tracking tools are difficult to implement. Lavelli [59] describes a promising algorithm for implementing traceability in enterprises with a low level of automation.

Based on the above, in a food traceability system based on CPSs, it is necessary to coordinate the actions of internal and external parties, i. e. both network and distribution systems must be used.

Example of a food supply chain monitoring and traceability system

Food production based on CPSs includes all elements that have industrial automation capabilities. This includes an intelligent system model, intelligent programmable logic controllers (PLCs), sensors, actuators, cameras, subsystem control units, etc.

A three-layer food production system based on CPSs includes: 1) physical level with cyber capabilities deeply embedded in physical processes; 2) network level to strengthen cybersecurity; 3) service level for distributed operational services.

Chen [35] proposed intelligent CPS for food production based on the value stream, the diagram of which is presented in Figure 4.

The food traceability system in the supply chain is divided into 5 levels: 1) operational level; 2) level of traced points; 3) level of details; 4) level of stakeholders; 5) technological level (process level).

The first level (operational) consists of transport, packaging, production or processing of the food product with a traceability process in place. From raw materials to the sale of a product to the consumer, more and more detailed traceability information needs to be collected at the stakeholder level.

The final, fifth level (receipt of raw materials) describes: sowing/irrigation for the farmer, growing agricultural crops, animals and poultry for the manufacturer, slaughter/meat processing for the processer, harvesting/packaging for the distributor, processing/repackaging for the retailer.

In Russia, the life cycle of a food product differs from that presented in Chen's work [35].

Thus, a value stream management (VSM) model is presented, i. e. a cyber-physical systematic approach integrated into processes at the corporate and global levels using a fog computing network for traceability and improving the efficiency of the company. At the same time, a feature of VSM is the formation of a product based on the customer's request, the business capabilities of all participants in the chain and the customer's degree of satisfaction with the final product.

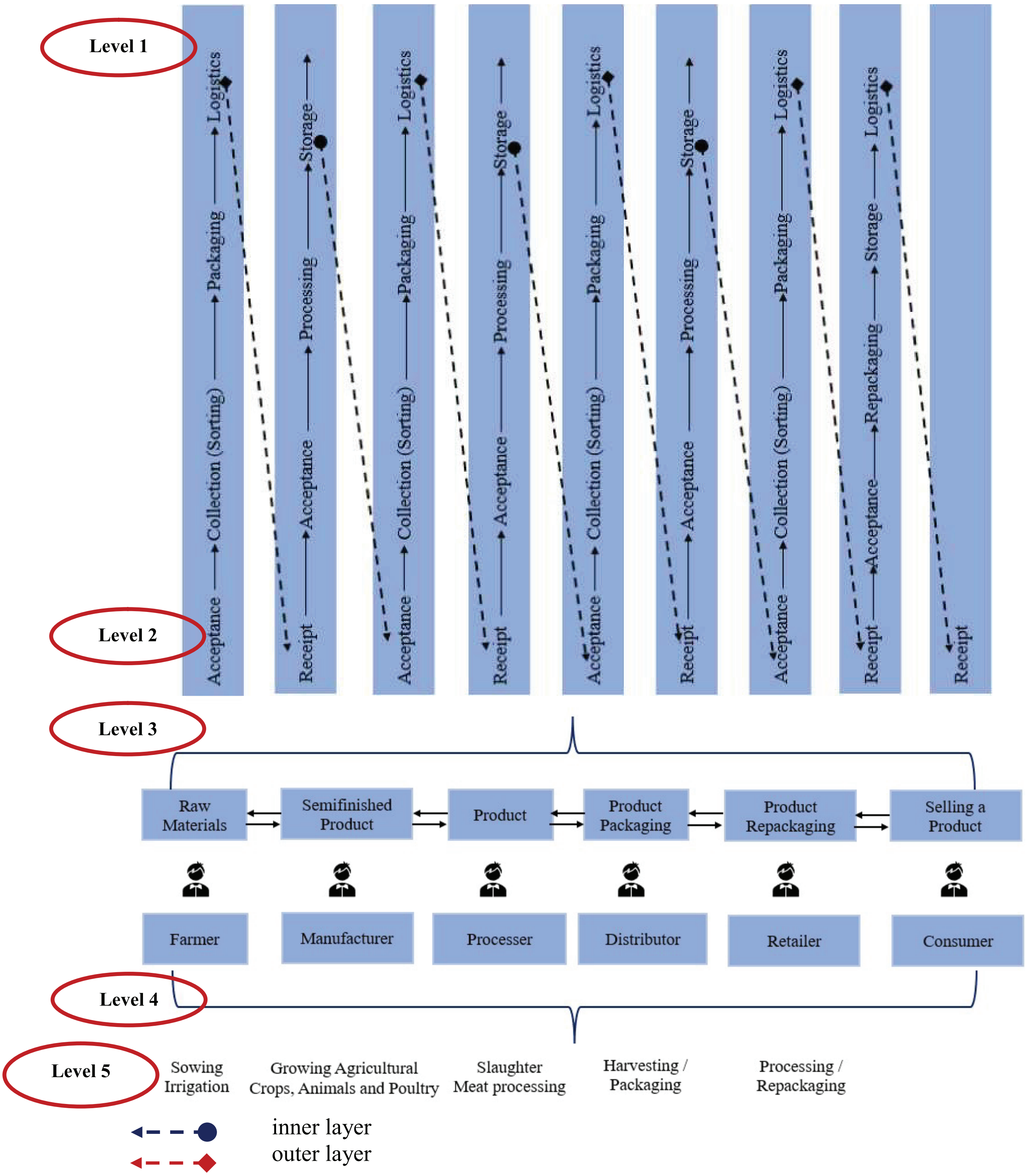

Figure 4. Hierarchical food traceability diagram

Conclusion

Digital transformation, or implementation of digital technologies into industrial production in general, and into the life cycle of food systems in particular, is expected to contribute to the sustainable development of industry. It is noteworthy that the use of cyber-physical systems in food production will help to increase the share of qualified personnel capable of creating and managing CPSs, opposite to mechanization and even automation of technological processes aimed at facilitating the work of lower-skilled personnel.

It is expected that at each stage of the food product life cycle (including meat products) specific tools will be used, from predictive analytics and big data analysis (Big Data, Data Mining), neural networks, fogging and artificial intelligence to the development of digital twins for food products (meat products), technological operations and the technological process as a whole. Due to differences in the stages of a food product life cycle (including meat products) and technological approaches at enterprises in Russia, the hierarchical traceability using CPSs must be adapted and adjusted for specific conditions.

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