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Integrated Model of Production and Engineering Chains in Smart Manufacturing Technologies in Industry 4.0 †

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Abstract: This study synthesizes a model of the main engineering and production chains in the Smart factory of Industry 4.0. This study has three main stages: an overview of the main definitions of the concepts "engineering and production chain" and "model", the generation of working definitions of these concepts for the purposes of this article, and synthesis of a model of the main engineering and production chains in the Smart factory of Industry 4.0. It was concluded in the course of the analysis that the defined six main engineering and production chains in the Smart factory of Industry 4.0 are part of its cyber–physical production system. The tools that support the Model of the main engineering and production chains in the Smart factory of Industry 4.0 are also synthesized in this article. The essential added value for science and production engineering of the Model in the main engineering and production chains in the Smart factory of Industry 4.0 are defined for the first time in the literature as an option to deepen the processes of re-structuring the real traditional physical production into a cyber–physical production process by integrating specialized software products in the operation of each of the defined chains and the entire cyber–physical production system.

Keywords: Smart factory; engineering production chains; cyber–physical production system

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1. Introduction

Changes in the economic environment, robust technological development, and the digitization of all sectors of socio–economic and public life have led to the need to define new terms, new concepts, and new models that adequately reflect the changes in the environment and its factors. Today, more and more concepts sound archaic and irrelevant to the changed macro-environment. The intensive technological, market, production, technical, engineering, economic, and financial changes are increasingly leading to the rejection of classic production methods at the expense of new engineering and production models and business models. Thus, the traditional physically based production system is restructured in terms of organizational–technical and engineering–technological aspects into a new type of production and organizational form—a cyber–physical production system.

According to some authors [1], the restructuring of traditional production into a cyber–physical production system is based on the application of four main concepts:

- a concept of computer-integrated production that achieves automation of production processes based on control and data exchange in the entire production process by using computers in a closed system;
- a concept of a computer-integrated enterprise that integrates all aspects of the company in a computerized automated system and serves as a tool to support the decision making in the fields of management, engineering design, marketing, and sales;
- a concept of factory automation consisting of the implementation of technologies and systems for automating the production process to increase productivity and reduce

costs, wherein the automation can involve only one operation or the entire production cycle, ignoring human intervention;
- a "just in time" concept, which is a management strategy that aligns supplies directly with the needs of the production plans and schedules, resulting in increased production efficiency and reduced waste.

These concepts are upgraded with engineering and technological resources such as information and communication technologies and form a new type of chain, cumulatively possessing production and engineering characteristics and features and determining the essence of the Smart factory of Industry 4.0. These chains are conscious, interactive, and efficient and are primarily associated with a certain degree of intelligence. This new type of chain also provides the framework for the "smart environment", which is one of the main distinguishing features of the Smart factory.

The definition of the essence, tasks, and functions of the engineering and production chains of the Smart factory of Industry 4.0 should be based on a review of the basic definitions of the concepts of "production chain" and "engineering".

According to several researchers [2–4], the production chain includes all processes that businesses use to turn raw materials into finished products that are ready for sale, and these processes include the supply of raw materials, production, quality control, distribution, and after-sales service. The development of technologies necessitates narrower production specialization and this is also associated with longer production chains which reflect the specifics of the highly specialized production process. At the same time, however, longer production chains are more vulnerable and riskier [5].

The foundation for the definition of the concept of "engineering system" should be the concept of "engineering". Many sources [6–12] define engineering as a practice, process, profession, and application of scientific knowledge. According to the United States Council of Professional Development Engineers, engineering means the creative application, cumulatively or independently, of scientific principles for the design, development, construction, and operation of structures, machines, apparatus, or production or work processes, for predicting their behavior under specific operating conditions. Based on the given definitions of the concept of "engineering", it can be concluded that this is unique and specific scientific knowledge aimed at the optimal transformation of certain resources to satisfy specific economic, consumer, public, social, or other needs.

According to the authors [13], systems engineering focuses on:

- the establishment, balancing, and integration of the goals for the success of the engineering and production units in the engineering work;
- the determination of the actual or expected needs of the users of the products of a certain engineering work;
- the elaboration of a model of the life cycle of the engineering work based on the operational concept and functionality of certain processes or products;
- overcoming the complexity, uncertainty, modification, and diversity in the engineering work by implementing a process approach and effective management structures;
- the generation and evaluation of concepts and architectures for alternative solutions in the engineering work;
- the modeling of a specific decision-making architecture at each phase of the life cycle of the engineering work;
- the design synthesis, verification, and validation of the engineering work.

Systems engineering as a concept encompasses the problem areas and solution options in a particular engineering work. The following is needed for the architectural and structural development of the engineering work:

- to analyze its constituent systems;
- to identify the elements and their interdependencies;
- to investigate the influence of the elements of the systems in terms of the behavior and efficiency of the entire engineering work;

- to define how all factors impacting the process of development are balanced to achieve an effective result.

Systems engineering ensures facilitation, guidance, and leadership to integrate the relevant fields of knowledge and specialized processes into a coherent effort, thus forming an appropriately structured development process that translates from concept into production, operation, evolution, and eventual disposal [13].

A working definition of the concept of a engineering and production chain can be created based on the overview and analysis of the concepts of "engineering", "systems engineering", and "production chain" as follows: a system of engineering and production processes aimed at or related to the transformation of physical assets into a finished final product through the use of specific engineering and production technologies, solutions, equipment, software, or another technological approach.

The definition of engineering and production chains in the Smart factory of Industry 4.0 should step on its characteristic feature—the "smart environment". On this basis, the engineering and production chains in the Smart factory of Industry 4.0 can be defined as a system of computer-integrated and automated engineering and production processes aimed at or related to the transformation of smart materials into a finished final smart product through the use of embedded systems, a network of connected different devices, sensors, and processors, and with an option to store and use data in a certain cyber–physical production system by using the capabilities of the Internet of Things and the Internet of Services (Figure 1).

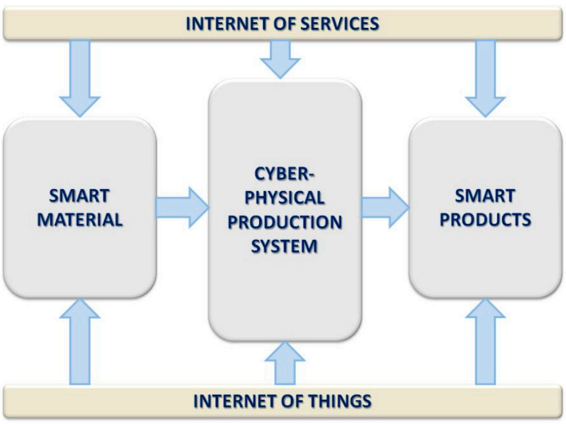

Figure 1. Functional structure of a modern Smart factory.

2. Object, Subject, Goal, and Main Tasks

The relevance of this study stems from the need to determine, define, and place in a system framework the main engineering and production chains in the Smart factory of Industry 4.0. Against the background of many developments related to the nature and organization of the modern Smart factory, there are insufficient studies of its basic engineering and production chains. This becomes even more relevant because it generates the specific added production and financial and economic value. This study is therefore relevant and caters to the needs of science.

The object of study in this paper is investigation of the engineering and production chains in the Smart factory of Industry 4.0.

The subject of the study is the modeling of the main engineering and production chains in the Smart factory in a single system.

The study aims to generate a model of the main engineering and production chains in the Smart factory of Industry 4.0.

The tasks of the current analytical work consist of the following:

- definition for the study of the concept of "engineering and production chain in the Smart factory of Industry 4.0";

- definition of the concept of "model" for this study;
- synthesis of a model of the main engineering and production chains in the Smart factory of Industry 4.0.

The following methods were used to achieve the tasks of the study and make the analysis: system analysis, synthesis, comparison, formalization, deduction, and correlation.

3. Defining the Term "Model" for the Study

The Model is generally a construction of a specific original (object) and is used for forecasting, testing, and analysis of a certain part of reality. The properties of the Model reflect the properties of the original object.

According to the encyclopedic dictionary [14], a model is a small but exact copy of something from the objective reality, most often in the form of a figure. A model can also be a description or an analogy used to visualize something that cannot be directly observed or, in other words, a theoretical projection of a possible or imagined system [14]. Thus, a model can be defined as information created by someone for someone who will use that information for some purpose. According to some authors [15], a model has three main characteristics: it is based on an original, it reflects only a specific part of the original, and it must be repeatedly used instead of the original to achieve a certain cognitive goal.

At the same time, a distinction should be made between a model and a copy, with a model being a description of something [16,17].

These definitions allow for us to draw a reasonable conclusion that the Model represents schemes, constructions, or algorithms created for cognitive purposes, which recreate a simplified image of objects from the objective reality, processes, or phenomena and reproduce their main properties and characteristics in a specific way. This means that the Model does not recreate all features of the object, process, or phenomenon that is modeled, but only the most essential and the most fundamental features that are important to fulfill the purpose of the modeling and that give the main purpose of the modeled image.

In this study, to generate a model of the main engineering and production chains in the Smart factory of Industry 4.0, "Model" is understood as a logical abstraction based on description, analysis, and synthesis made based on an analogy of a real object, process, or phenomenon from the objective reality and presented in the form of a drawing, figure, or algorithmic sequence, which reflects the essential qualitative features of the modeled image to satisfy specific cognitive goals.

For this study, the Model of the main engineering and production chains in the Smart Factory of Industry 4.0:

1. establishes ongoing trends in the development of various socio–economic processes in the Smart factory of Industry 4.0;
2. simply defines a broad system of functions, essentially expressing the most important causal relationships between the elements of the cyber–physical production system and between it and the elements of its environment;
3. makes it possible to evaluate the future values of all operating variables, thus creating real prerequisites for drawing up optimal plans and developing optimal production activities;
4. contains independent variables, key factors, endogenous indicators, and a set of methods that must be determined in advance [18];
5. sets the specific parameters of the future development of the Smart factory of Industry 4.0 through:

- the deterministic approach based on the unambiguous calculation of the estimated quantities;
- the stochastic approach based on the relationship between the quantities corresponding to interval or intermediate forecasts.

4. Model of the Main Engineering and Production Chains in the Smart Factory of Industry 4.0

Defining the term "Smart factory" for this article is the first step towards the proper and correct determination of its main engineering and production chains. Thus, the Smart factory of Industry 4.0 can be defined as a sustainable engineering and production model based on the use of the added value of the cyber–physical production system, integrating the physical and cyber environments into a system unity through communication-network-based relationships between people, machines, and robots based on the contact between physical systems and smart-based computers, tablets, devices, machines, equipment, sensors, and other technologies that make autonomous, independent, and human-independent decisions, influence the physical systems, and provide optimal results when reporting the changes and dynamics in the external and internal environments of the production system.

The main engineering and production chains in the Smart factory of Industry 4.0 can be synthesized by deducing the main elements of the structural architecture of the cyber–physical production system (Figure 2).

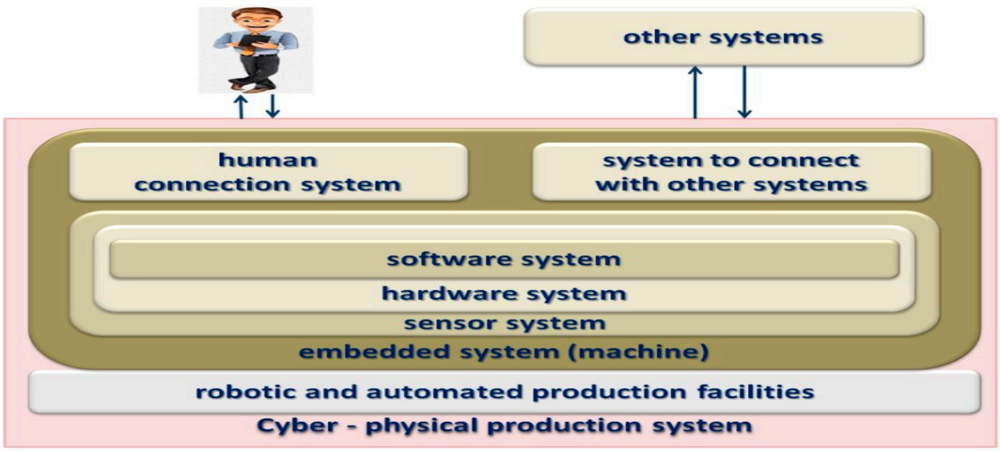

Figure 2. Systems that determine the main engineering and production chains in the Smart factory of Industry 4.0 [19].

The systems determining the essence, content, characteristics, and functions of the main engineering and production chains in the Smart factory of Industry 4.0 are:

- robotized and automated real production system;
- machine-embedded system;
- sensor system;
- hardware system;
- software system;
- human factor connection system;
- system for connection with other systems.

Based on this chain relationship between various structural elements of the architecture of the Smart factory of Industry 4.0, six main two-way engineering and production chains can be synthesized, which determine its production processes:

- chain of "resource planning–provision of resources";
- chain of "available resources–production planning–production capacity planning–control of the capabilities of production facilities";
- chain of "production planning–production process planning–operational production–control of production processes and operations";
- chain of "strategic control–operations and production control";
- chain of "production process–quality testing–production management software–operations and production software";
- chain of "quality testing–transport and commercial logistics".

The defined basic engineering and production chains in the Smart factory of Industry 4.0 are an inseparable foundation of the cyber–physical production system. These engineering and production information flows underpin the Model of the main engineering and production chains in the Smart Factory of Industry 4.0 and draw data from embedded and physical systems operating in real-time [20]. This is achieved through a systematic set of smart engineering systems, artificial intelligence, cloud technologies, communication systems, blockchain, management tools, additive materials, big data sets, the Internet of Things and Services, cloud computing, social platforms, and physical production systems (Figure 3).

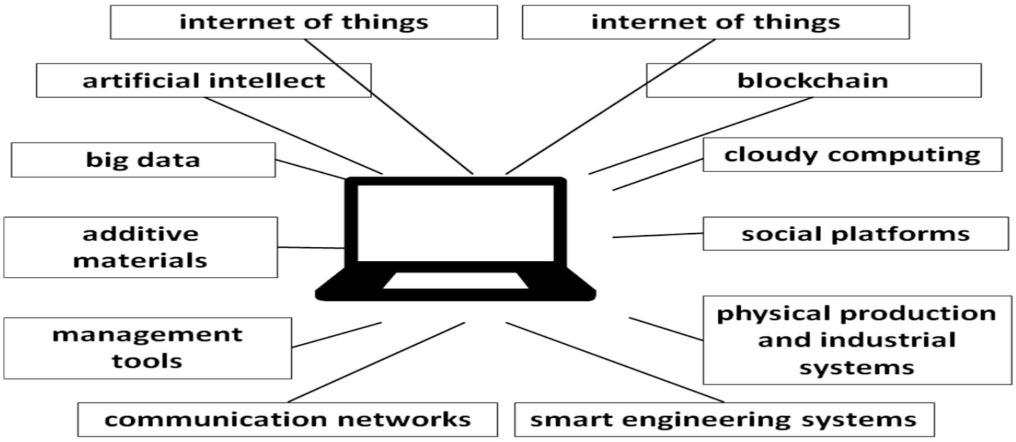

Figure 3. Tools supporting the Model of the main engineering and production chains in the Smart factory of Industry 4.0.

The synthesized Model of the main engineering and engineering production chains in the Smart factory of Industry 4.0 is the result of its interdisciplinary integration of physical and cyberspace, digital, and physical semantic laws, real physical and virtual production, and management processes. The main engineering and production chains in the Smart Factory of Industry 4.0 communicate utilizing automated information as well as physical and electronic network flow, leading to:

- the actual separation of autonomous and independent production processes;
- independent analysis, coordination, and regulation of these processes through self-regulated control;
- the integrated possibility of transmission, exchange of, and feedback from the information flows along the "robot -machine–human" axis.

The bi-directionality of the connections in the Model of the main engineering and production chains in the Smart factory of Industry 4.0 is achieved with self-developed software or software applications, enabling the intelligent automated flow of the processes in it (Figure 4).

Some of the main software applications facilitating the connection between the main engineering and production chains in the Model are:

- PLM Services enable the management of product lifecycles by quickly and easily connecting processes, people, and data throughout the product lifecycle and by capturing critical business information and integrating tools and processes to reap benefits at every stage of the product development;
- Service Control Manager is a special system process from the Windows NT family that starts, stops, and interacts with Windows service processes and allows for interaction with Service Control Manager through a defined API that enables the management of the services provided by Windows;
- CRM Services manage customer relations and are a strategy that contributes to managing customer interactions based on the streamlining of processes and the increase in profitability;

- CMS Services deliver unique software solutions for managing compliance and provide cost-saving solutions for collecting, reviewing, and sharing compliance materials and documentation at the account level;
- ERP Services are a software that connects multiple processes and enables the exchange of information between them by providing planning of enterprise resources based on day-to-day business activities such as accounting, supplies, project management, risk and compliance management, supply chain operations, enterprise performance management, planning, budgeting, forecasting, and reporting of the organization's financial results.

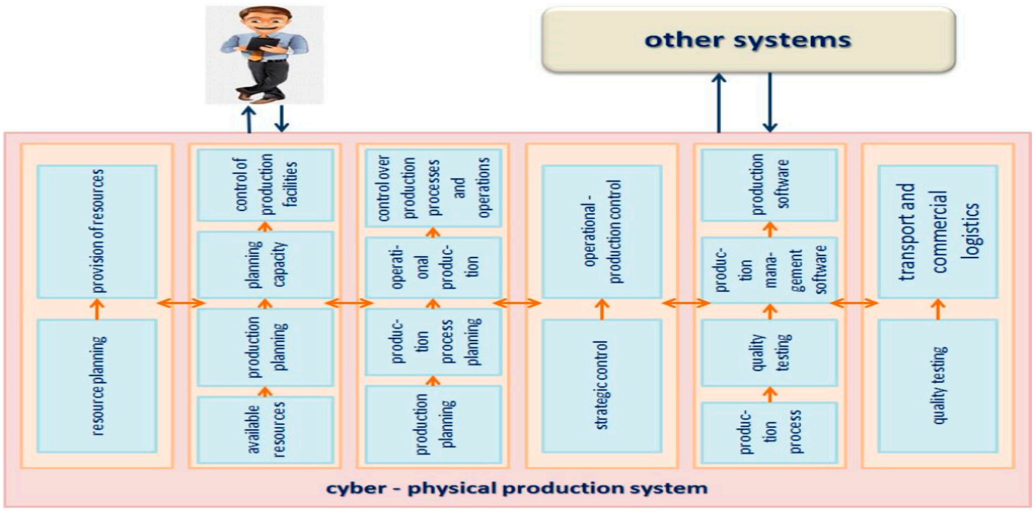

Figure 4. Model of the main engineering and production chains in the Smart factory of Industry 4.0.

5. Conclusions

The Model of the main engineering and production chains in the Smart Factory of Industry 4.0 developed in this article is a logical abstract synthesis by the analogy of the related engineering and production processes in the Smart Factory of Industry 4.0. It is descriptive and is generated based on analysis that reflects the most important qualitative, information technology, logistics, and management characteristics of the real cyber–physical production system. The purpose of this model is to provide knowledge about the main engineering and production chains in the Smart factory of Industry 4.0 and to facilitate the options for restructuring the real physical production systems into cyber–physical production systems.

Based on the above, the Model of the main engineering and production chains in the Smart factory of Industry 4.0 is a significant prerequisite for the development of digital computer-integrated production that uses information and communication technologies in the production processes. The basic engineering and production chains defined in the Model exchange information with each other and coordinate their actions. The Model of the main engineering and production chains in the Smart factory of Industry 4.0 is a basis for developing further the digitalization and automation of production and contributes to a sustainable and fast production process, corresponding to an environment where the possibilities for errors are kept to a minimum.

The Model of the main engineering and production chains in the Smart Factory of Industry 4.0 outlines the connections and interactions between the main processes in the cyber–physical production system that lie at the heart of the Smart Factory of Industry 4.0 and defines:

- the method for extraction, storage, processing, and presentation of data;
- the approaches, mechanisms, and tools for monitoring the state of the engineering and production structure and restructuring and/or changing the processes in the Smart factory of Industry 4.0;

- the algorithms for unifying the main components, elements, and information flows that enable the processing of data in the Smart factory of Industry 4.0.

The Model of the main engineering and production chains in the Smart factory of Industry 4.0 cumulatively bring together engineering, production, management, logistics, finance, and marketing. On this basis, the definition of the six main engineering and production chains in their structure contributes to the possibility of developing and implementing specific software products that ensures the main functions of the chains and the related activities. The added value of the defined Model of the main engineering and production chains in the Smart factory of Industry 4.0 for the science is expressed in the enabled digital transformation of more and more production units and the acceleration of the digitalization of production based on the outlined connections and interdependences between the six main engineering and production chains defined in the model.

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References

1. Hozdić, E. SMART factory for Industry 4.0: A review. *Int. J. Mod. Manuf. Technol.* **2015**, *7*, 28–35.
2. Manufacturing Supply Chains Explained. Available online: https://www.netsuite.com/ (accessed on 8 September 2023).
3. Pietrzyk, M.; Madej, L.; Rauch, L.; Szeliga, D. *Computational Materials Engineering, Achieving High Accuracy and Efficiency in Metals Processing Simulations*; Elsevier Inc.: Amsterdam, The Netherlands, 2015; pp. 69–151. [CrossRef]
4. Schlimbach, J.; Ogale, A. Out-of-autoclave curing process in polymer matrix composites. In *Manufacturing Techniques for Polymer Matrix Composites (PMCs)*; Woodhead Publishing Series in Composites Science and Engineering; Woodhead Publishing: Sawston, UK, 2012; pp. 435–480.
5. Levine, D.K. Production chains. *Rev. Econ. Dyn.* **2012**, *15*, 271–282. [CrossRef]
6. Lopez-Cruz, O. An Essential Definition of Engineering to Support Engineering Research in the Twenty-First Century. *Int. J. Philos.* **2022**, *10*, 130–137. [CrossRef]
7. Lopez-Cruz, O. Por qué historia y filosofía en las carreras de ingeniería. *Hojas De El Bosque* **2018**, *4*, 61–67. [CrossRef]
8. De Vries, M.J. Engineering science as a "discipline of the particular? Types of generalization in engineering sciences. In *Philosophy and Engineering*; Springer: Dordrecht, The Netherlands, 2009; pp. 83–93.
9. El-Zein, A.H.; Hedemann, C. Beyond problem solving: Engineering and the public good in the 21st century. *J. Clean. Prod.* **2016**, *137*, 692–700. [CrossRef]
10. El-Zein, A.H.; Hedemann, C. Engineers as problem solvers: A deficient self-definition for the 21st century. In Proceedings of the 6th International Conference on Engineering Education for Sustainable Development, Cambridge, UK, 22–25 September 2013.
11. Downey, G. Are engineers losing control of technology? From "problem solving" to "problem definition and solution" in engineering education. *Chem. Eng. Res. Des.* **2005**, *83*, 583–595. [CrossRef]
12. Goldman, S.L. Compromised exactness and the rationality of engineering. In *Social Systems Engineering: The Design of Complexity*; García-Díaz, C., Olaya, C., Eds.; Wiley Series in Computational and Quantitative Social Science; Wiley: Hoboken, NJ, USA, 2017; pp. 11–30.
13. Systems Engineering. Available online: https://www.incose.org/ (accessed on 15 September 2023).
14. Zenkert, J.; Weber, C.; Dornhöfer, M.; Abu-Rasheed, H.; Fathi, M. Knowledge Integration in Smart Factories. *Encyclopedia* **2021**, *1*, 792–811. [CrossRef]
15. Del Gallo, M.; Mazzuto, G.; Ciarapica, F.E.; Bevilacqua, M. Artificial Intelligence to Solve Production Scheduling Problems in Real Industrial Settings: Systematic Literature Review. *Electronics* **2023**, *12*, 4732. [CrossRef]
16. Kuhne, T. What is a Model? ResearchGate.Net. Available online: https://www.researchgate.net/publication/30814656_What_is_a_Model (accessed on 1 January 2024).
17. Zakeri, Z.; Arif, A.; Omurtag, A.; Breedon, P.; Khalid, A. Multimodal Assessment of Cognitive Workload Using Neural, Subjective and Behavioural Measures in Smart Factory Settings. *Sensors* **2023**, *23*, 8926. [CrossRef] [PubMed]
18. Teplická, K.; Khouri, S.; Mudarri, T.; Freňáková, M. Improving the Quality of Automotive Components through the Effective Management of Complaints in Industry 4.0. *Appl. Sci.* **2023**, *13*, 8402. [CrossRef]

19. Vogel-Heuser, B.; Bayrak, G.; Frank, U. Agenda CPS-scenario Smart Factory (Agenda CPS-Szenario smart factory). In *"Increased Availability and Transparent Production" ("Erhöhte Verfügbarkeit und transparente Produktion")*; Vogel-Heusser, B., Ed.; University Press: Kassel, Germany, 2014; pp. 6–21.
20. Ryalat, M.; ElMoaqet, H.; AlFaouri, M. Design of a Smart Factory Based on Cyber-Physical Systems and Internet of Things towards Industry 4.0. *Appl. Sci.* **2023**, *13*, 2156. [CrossRef]