Functional safety of cyber-physical production of the Industry 4.0

D A Zakoldaev¹, A V Gurjanov², A V Shukalov¹ and I O Zharinov¹

¹ Faculty of Information Security and Computer Technologies, Saint Petersburg National Research University of Information Technologies, Mechanics and Optics, 49, Kronverksky Av., Saint Petersburg, 197101, Russia
² Department of Aviation Instrumentation Systems and Training Systems, Saint Petersburg State University of Aerospace Instrumentation, 67, Bolshaya Morskaia str., Saint Petersburg, 190000, Russia

E-mail: mpbva@mail.ru

Abstract. An actual task has been studied to develop science and technical organization measures to provide functional safety of an Industry 4.0 smart factory. Functional safety is an industrial company property to provide continuous manufacturing of item designing components should some emergency cases in production happen. There is a typical structure of cyber and physical production and some schemes (a cluster scheme and a matrix scheme) to provide company functional safety by applying reserve cyber and physical systems. Reserve cyber and physical systems could be part of automatic technological line and is engaged should some primary equipment components are failed. It is clear that cyber and physical system reserving method selection depends on necessary level of functional safety in the Industry 4.0 smart factory.

1. Introduction

To organize modern item designing production equipped with cyber and physical systems (CPS) [1, 2] includes a continuous item manufacturing technological cycle completion. Technological cycle continuity is based on inter-machine interaction technologies for CPSs, which are realized with the results acceptability of some technological operations completion [3].

The production division functional safety property defines the Industry 4.0 smart factory behavior equipped with CPS components in the physical level and software components (cloud services and applications) placed in the company virtual space [4, 5]. The cyber and physical dualism leads to the smart factory functional safety provision must be done technically and with the proper software with necessary machines and the company informative redundancy [2].

The smart factory functional safety may be evaluated with quality and quantity according to the standards methods. The smart factory cyber and physical systems provision requires to create a standard of the new generation functional safety provision which are compatible with digital economy standards [6, 7].

The smart factory functional safety provision is based on the cyber and physical production decomposition into the components, threat analysis and risk assessment of the components failure probability including the CPS diagnosis and components functional behavior scenarios development under different exploitation conditions [8, 9]. That why the smart factory functional safety must be
studied into the exploitation environment behavior in which the CPS is working inside the production company [10].

2. Cyber and physical production typical structure
The Industry 4.0 smart factory item manufacturing technological route is defined into technological documentation and requires step by step completion in multi-operational CPSs [11] some technological operations. The typical cyber and physical production structure scheme is given in figure 1.

![Diagram of Industry 4.0 cyber and physical production typical three-level scheme](image)

**Figure 1.** The Industry 4.0 cyber and physical production typical three-level scheme (AWP – Automatic Work Place).

Material transportation, components and some assembly units (parts) among working positions of multi-operational CPSs is done by the robotized transport system. Controlling commands and data are being transferred to the CPS and to the transport system through the communication environment interfaces from the cloud services and applications. Materials and components storage and the ready product storage manufactured in a cyber and physical production is done with the cases of dry storage access to which has the robotized transport system.

Smart factory item manufacturing physical environment is the hierarchy lower level in the three-levels structure of an Industry 4.0 cyber and physical production. The smart factory communication environment is the hierarchy middle level of the company structure [12].

Cyber and physical production cloud services and applications is a set of programs in a remote server to ensure the following production functions in a smart factory [13, 14]:
- automatic completion in CPSs some technological operations and the technological route in general;
- cyber and physical systems and robotized transport system control based on the algorithms of the artificial intelligence (the self-organization of technological equipment);
- production data processing, analysis and smart factory operator display which characterize the condition of production tasks completion and all CPSs condition and other.

Smart factory cloud environment is the third hierarchy level (upper) of a cyber and physical production.

The linear way of CPS connection into a technological chain shown in figure 1 is the simplest way from the practical realization point of view but this way has the worst properties of cyber and physical production reliability. If a CPS sequence component fails, the whole technological line will be shut
down. To increase the cyber and physical production reliability they need to develop different schemes of CPS reserving which when a CPS fails may transmit (re-assign) the technological functions to the working CPSs. The CPS environment dynamic re-assignment of production tasks is the property of cyber and physical production reliability and is done by the informative and machine redundancy which the smart factory designer puts in the company structure.

The smart factory machine redundancy [2] requires to include into company infrastructure some different purposes CPSs which copy out the actions of some other CPSs. The CPSs duplication is like the production «cold reserve» and it is engaged if the primary CPSs fail. Normally they duplicate production CPSs with the low values of reliability. According to the method of CPS reserving there are matrix, cluster and some other schemes of such reserving in production.

The implementation of machine redundancy in a cyber and physical production is a strong requirement of the Industry 4.0 smart factory functional safety. The production machine redundancy key feature is some additional components in the smart factory structure which are not necessary if the production line CPSs function normally.

The smart factory informative redundancy is to duplicate in the production company infrastructure the connection channels, cloud services and applications placed in several physical devices of the virtual environment (servers).

Cyber and physical production informative redundancy is the Industry 4.0 smart factory communication environment property where the production data are being transmitted several times through the connection channels. So connection means duplication in a smart factory leads to the duplication of production data. The production data duplication is a mean of data integrity protection which is important for self-organizing cyber and physical systems.

3. Cyber and physical production matrix structure

The Industry 4.0 cyber and physical production matrix scheme is given in figure 2. The primary production unit of a smart factory matrix structure is a section equipped with one type of cyber and physical systems which are connected among each other with a communication environment of inter-machine interaction.

![Figure 2. The Industry 4.0 cyber and physical production matrix structure (IoT – Internet of Things).](image)

CPSs of each type is engaged only for one technological route of item manufacturing within which the robotized transport system transports materials and components inside the workshop. This kind of scheme may complete at the same time in production several different in complexity and type technological operations of some technological routes engaging some working sets of CPSs.

If one technological section CPSs fail its production function can be done by neighbor CPSs of the
same section, which excludes the significant delays of item transportation by the transport system. To realize practically such a reserving scheme all CPSs must be loaded up with the production tasks in the level not higher than 70% where the production tasks of a failed CPS could be carried out by other CPSs until this one is repaired.

Cyber and physical production matrix structure provides the acceptable risks of CPS failure and good level of reliability when the production efficiency if all CPSs initially functions well never will be maximum possible (In comparison for example with the production linear structure).

4. **Cyber and physical production cluster structure**

The Industry 4.0 cyber and physical production cluster scheme is given in figure 3. The primary production unit of a smart factory cluster structure is a section equipped with different types of cyber and physical systems from which a linear chain could be formed which is sufficient to complete technological route of item manufacturing.

![Figure 3. The Industry 4.0 cyber and physical production cluster structure.](image)

Each cluster is an independent technological section of a cyber and physical production. Failure of one of those CPSs of any section leads to the necessity to engage an analog CPS form another technological section. In this case, the robotized transport system has to transport materials and components among the sections, which creates some delays for both sets of CPSs (clusters). Also the completion of production tasks from another section could be achieved only after technological operation completion in a working CPS which is the reason of additional delays of the company equipment functionality.

The CPS reserving cluster way is a way of cyber and physical production components duplication in the level of technological sections and can be applied to manufacture the items in an exceptional case in the level of CPSs being duplicated. A duplicating CPS is engaged to complete a functional task of the neighbor section for the time which is necessary to repair a failed CPS.

The CPS cluster reserving has the average values of CPS failure and the consequences of this failure for the production efficiency.

5. **Conclusion**

Functional safety of cyber and physical production is an important property of the Industry 4.0 smart factory. Production functional safety is provided by the reserving of low reliable components, which first include cyber and physical systems, which are realized with a software and in the physical level.

Highly reliable cyber and physical productions projection with the increased functional safety is done by calculations based on mathematical analysis of the real CPSs exploitation statistical data and their specifications. CPS specifications show the points of CPS probable failure in time, which enables to create equivalent schemes (models) of cyber and physical production technological lines reliability. The reliability equivalent schemes calculation of different topology CPSs helps to detect the low
reliable section and components, which must be duplicated in reality.

Real production exploitation statistical data helps to make sure the evaluation of technological lines reliability, which were calculated to increase the CPS reliability mathematical models adequacy and to increase the functional safety of the Industry 4.0 smart factory.

References
[1] Zhao H, Zheng C, Dzapo H, Liu S, Guo Y, Gao X and Wu T 2019 Energy procedia 158 6139-44
[2] Bogatyrev V A, Parshutina S A, Poptcova N A and Bogatyrev A V 2016 Communications in computer and information science 678 337-348
[3] Tikka V, Lana A, Belonogova N, Honkapuro S, Lassila J and Partanen J 2019 Energy procedia 158 6664-71
[4] Jin M, Jia R, Das H P, Feng W and Spanos C 2019 Energy procedia 158 6152-57
[5] Zhu L, Wang P 2019 Energy procedia 158 3853-58
[6] Trianni A, Cagno E, Accordini D 2019 Energy procedia 158 3346-51
[7] Wang Y H, Li Z X 2019 Procedia computer science 154 416-423
[8] Gurjanov A V, Zakoldaev D A, Shukalov A V and Zharinov I O 2018 IOP Conference Series: Materials Science and Engineering 327 022110
[9] Zakoldaev D A, Shukalov A V, Zharinov I O and Zharinov O O 2018 Journal of Physics: Conference Series 1015 052033
[10] Prinz F, Schoeffler M, Lechler A and Verl A 2018 Procedia CIRP 72 910-915
[11] Mourtzis D, Milas N, Athinaios N 2018 Procedia CIRP 78 301-306
[12] Zhang C, Xu W, Liu J, Liu Z, Zhou Z and Pham D T 2019 Procedia CIRP 83 118-125
[13] Dukalski R, Cencen A, Aschenbrenner D and Verlinden J 2017 Procedia manufacturing 11 185-197
[14] Vieler H, Lechler A, Riedel O 2017 Procedia manufacturing 11 2077-82