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CASE STUDIES

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Mutual combination of selected principles and technologies of Industry 4.0 and quality management methods - case study

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ABSTRACT

In this paper the case study of the application of Failure Mode and Effects Analysis (FMEA) on the testbed "Smart Factory Line" has been described. The main goals of this study have been to verify feasibility and applicability of FMEA on such complex technical system and to show real possibilities of integration of Industry 4.0 principles and technologies with selected methods of quality management. The significant part of the paper is formed by extensive literature review of the related topics such as mass customization and individualization, Industry 4.0, Quality 4.0, fault management and their selected principles, methods and technologies, putting the stress on the team cooperation of experts of different specializations. The attention also has been put on the describing testbeds as platforms for the academy world and practice connection. This case of the practical integration of the smart factory testbed design and its products with the new FMEA approach based on the harmonized AIAG and VDA manual has brought new views on the practical realization of smart factories, on importance of building Quality 4.0 and on requirements for interdisciplinary education of the technicians and quality specialists for Industry 4.0.

KEYWORDS
Industry 4.0; fault management; FMEA; Quality 4.0; testbed

1. Introduction

Manufacturing has been and continues to be a cornerstone of the economy (Zhou et al. 2013; Hu 2013). During its evolution the manufacturing was several times influenced by unprecedent changes in societal needs, market forces and technological advances leading to the change in manufacturing paradigm.

The first paradigm called Craft production has been based on creating products straightly according to the customer requirements but at very high cost. Technological advances in a form of principle of interchangeability and moving assembly lines created the conditions for Mass production paradigm which has shown its efficiency for several decades producing low-cost products accompanied with large scale production. But the main limitations of this approach, i.e., very limited product variety and low flexibility, inhibiting innovation processes, impeded influence of great changes in consumer demands asking for high product variety and global competition for a long time.

Achieving new level in technological advances and the progress in the business models' theory led to the development of Mass customization paradigm in the late 1980s'. The aim of this paradigm is to offer a high diversity of customized products accompanied by the cost, quality and delivery efficiency, analogous to the mass production (Kristal, Huang, and Schroeder 2010). Applied concept, called "product family architecture", has enabled to explore economy of scale. The technological base of this manufacturing paradigm has been based on robots, flexible reconfigurable manufacturing systems, innovative enterprise systems (manufacturing executive system (MES), product life management (PLM), enterprise resource planning (ERP)), advanced quality management systems (QMS) and lean manufacturing approach (LM).

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These innovations brought desired high variety in products portfolio but also in their structure and functions which led to rising complexity of manufacturing systems and their control.

Such growing complexity, great acceleration of innovations in communication, information, computational and automation technologies, continual influence of the global competition and consumers' demand for more and more customized product, increasingly stronger pressure on resource-efficient circular economy needs (Sun 2018) and pressure of energetical crisis on the energetical efficiency have opened the door to industrial unprecedent development called Industry 4.0 or Smart manufacturing. Such new conditions are characterized by overlapped boundaries between the real and virtual words owing to the deep connection of physical equipment and information and communication technologies (Wang et al. 2017).

These trends are connected to the new manufacturing paradigm, Mass personalization production, which represents continual development from the mass customization with product family design to the conditions where customers will be incorporated into the design of products tailored to their individual demands and preferences (open architecture products) (see, e.g., (Jiao et al. 1998); (Berry, Wang, and Hu 2013) or (Hu 2013)).

These complex products and interconnected reconfigurable on-demand manufacturing systems must be highly reliable to be failure-proof with no unplanned stoppages resulting in financial losses. This goal can be reached applying tools of predictive maintenance (Zonta et al. 2020) and methods for failure analysis, identification, classification and risk assessment of these failures. This paper is devoted to the application of one of these methods in conditions of the smart manufacturing - Failure mode effects analysis (FMEA). It is an effective method used in quality planning and quality assurance (Rezaee et al. 2017; Oliveira et al. 2020; Webert et al. 2022).

To realize the highly innovative shift from automation to digitization, discussed above, and to switch it from the concept to reality, smart factory/Industry 4.0, testbeds were introduced (Puviyarasu and da Cunha 2021). They can help universities and industrial companies to do experiments with smart technologies in real-time (Abele et al. 2015). At present there is a deficiency in case studies about Industry 4.0 testbeds. In addition, every smart manufacturing system must have its quality management system and utilize various quality management methods which must be integrated with the rest of the manufacturing system. Studies relating to the testbeds mentioned above are focused only on the technological aspects.

The main goals of the study in this paper have been to verify feasibility and applicability of FMEA on such complex technical system and to show the real possibilities of integration of Industry 4.0 principles and technologies with selected methods of quality management on a case of the testbed "Smart Factory Line". To the best of authors' knowledge such application has not been found in the available literature sources.

Theoretical contribution of this paper lies in the compact analysis of the historical roots of smart manufacturing and description of some relations between technological, economic and social aspects of various manufacturing paradigms supported by quite wide literature review. It can help to practitioners, academicians and students of quality management study branch and other technical specializations to find the rationale for quality management systems in conditions of smart factories. This paper also offers comparison of the old approach to prioritization of actions needed for improvement of prevention or detection control based on Risk Priority Number (RPN) with the new approach based on Action Priority (AP) (AIAG (Automotive Industry Action Group) 2019) and brings discussion about benefits and some weaknesses of AP.

The structure of this paper is as follows: In the introductory section an analysis of the historical roots of Industry 4.0 and describing some main connections of technological, economic and social aspects of various manufacturing paradigms including Industry 4.0 has been made. The theoretical background and literature review in the second section are followed by more detailed delineation of selected methods and technologies applied in this case study (the third section). In the fourth section characterization of the testbed "Smart Factory Line" can be found. The application of FMEA to the products and processes of this testbed is described in the next section, followed by the discussion of the results and obtained knowledge with formulation of the future improvement (the sixth section).

2. Theoretical background and literature review

In this section a literature review relating to Industry 4.0, Quality 4.0, fault management and testbeds, topics forming the theoretical background of this case study, is presented.

2.1. Industry 4.0

Historically the way of the development of industry is characterized by four big waves, called industrial revolutions, going from steam to sensors. For each industrial revolution there are characteristic broadly applied new technologies and radical changes in practices coupled with new business logic (Lasi et al. 2014). The first industrial revolution was based on the mechanization in manufacturing and using water and steam power energy in production and later in transport. The second industrial revolution connected with new power sources (gas, oil and especially electric power), assembly lines and advanced communication tools like telephone and telegraph enabled wide development of the mass production. The third industrial revolution can be understood as the beginning of digitalization because of bringing programable logic controllers embedded into machines to automate selected processes and to collect and share data in some rate. But social, economic and market changes, continual rapid development of automation, communication and information technologies has brought the beginning of the fourth wave – Industry 4.0 that represents a shift in manufacturing paradigm from automated production to an intelligent manufacturing approach characterized by connectivity, flexible automation and intelligence and based on the deep combination of physical and virtual worlds, enabled by objects with sensors and actuators, as it is discussed in (Thoben et al. 2017). An idea that Industry 4.0 can be also understood as a technology framework for extending and integrating processes at intra-organizational and inter-organizational levels has been developed in (Xu et al. 2018).

A wide discussion based on very good broad literature review of Industry 4. can be found in (Qin, Liu, and Grosvenor 2016; Thoben et al. 2017; Moeuf et al. 2018; Oztemel and Gursev 2020). As most manufacturers are at the beginning of Industry 4.0 period and obviously they have little or no experience with it a discussion about real transition toward Industry 4.0 is very important. Ghobakhloo (2018) offers a holistic view of common steps that must be undertaken in transition of manufacturers toward the Industry 4.0. For implementation of Industry 4.0 there is also very important to be able to measure the performance of manufacturers with respect to the Industry 4.0 features, principles and methods. For this goal so called maturity models were created and discussed (see e.g. (Schumacher et al. 2016)).

To be able to create smart factory (Thoben et al. 2017), based on ideas, principles and technologies of Industry 4.0, challenges, risks and barriers (e.g., defining appropriate infrastructures and standards, educating employees, solving data security problems) must be recognized and studied (Hofmann and Rüsch 2017).

Industry 4.0 is based on real-time collected data driven manufacturing systems, vertically and horizontally integrated processes of great flexibility enabling production of highly customized products. Product variants can be self-determined by parts with their own memory - items delivering their own production data to intelligent automated machines, which can share and exchange information to control processes in production and logistics by themselves. To support self-control and self-decision-making, data in a large amount (Big data) must be collected in a real-time mode from all processes of the life-cycle. It will enable production of small lot sizes of requested individually customized products quickly, flexibly and effectively with required quality level. Such production systems are called Cyber-physical systems (CPS) and represent the new way of human-machine interaction enabling to reduce risk of errors and make faster and better decisions. These ideas are discussed in more detail for instance in (Sanislav and Miclea 2012; Shirase and Nakamoto 2013; Ivezic, Kulvatunyou, and Srinivasan 2014; Albers et al. 2016; Sipsas et al. 2016; Longo, Nicoletti, and Padovano 2017; Thoben et al. 2017; Kamble, Gunasekaran, and Gawankar 2018; Kong et al. 2019).

The main technologies and tools driving Industry 4.0 are as follows: Internet of things, Internet of services, Cloud computing, Radio frequency identification, Big data predictive analytics, Data mining and methods for decision making in real time, Digital twins, Virtual reality, Augmented reality, Autonomous robots, Cyber-physical systems, Machine to Machine M2M communication. Detailed information about these instruments can be found e.g., in (Wang 2013; Wang 2014; Thoben et al. 2017; Moeuf et al. 2018; Riahi and Riahi 2018; Shahrubudin et al. 2019; Jones et al. 2020; Sheth et al. 2021; Vasarainen et al. 2021; Habib and Chukwuemeka 2022; Zhao et al. 2022). Some of these technologies and tools will be described in detail in the third section.

2.2. Quality 4.0

Hand in hand with technological changes and changes of business models the quality and performance concepts have changed, too. Digital transformation, the core of Industry 4.0, has disruptive effect on the quality management never seen before (see e.g. (Dias, Carvalho, and Sampaio 2022); (Popkova, Ragulina, and Bogoviz 2019)). With coming mass production in the past, the inspection has become a vital process to achieve the product quality. The need for the pure inspection was then minimized by the application of statistical methods and data analysis which continuously led to the quality management systems based on prevention. Such quality management systems has have been successful in planning, controlling, assurance and improving productivity and competitiveness in organizations for many decades (Dias, Carvalho, and Sampaio 2022). But the quality management relating to Industry 4.0, called Quality 4.0, starts to be a key for solving challenges in new production systems where every action and process should be monitored, recorded and evaluated in real-time (see e.g., (Gray-Hawkins et al. 2019)). Quality 4.0 matches the concept of Industry 4.0 for achievement of quality and performance excellence objectives (Radziwill 2020; Dias, Carvalho, and Sampaio 2022). Quality 4.0 can be viewed as a new approach by which digital tools can be used to manage improvements across the whole value chain. It shifts quality from the production to the system design and really integrates quality with the business environment. In addition, due to the movement from a customer-centric view to co-creating products with customers quality management becomes a vital part of organizational innovation where disruptive and radical innovations open the door to the big changes in the approach to quality (Lee, Bagheri, and Kao 2015; Sony et al. 2020).

It means that technology itself is considered as a key topic of Quality 4.0, but it is not the only component of the transformation toward Quality 4.0 (Dias, Carvalho, and Sampaio 2022). Quality 4.0 should be considered as large-scale transformation with effects on culture, leadership, collaboration and compliance and maximization of value for the organization. It can be concluded that integrated with traditional quality management practices the new technology brings the change for the performance improvement. Progress in human capabilities and the development of human-machine mutual communication start the way of transition toward agile Quality 4.0 as discussed in (Radziwill 2018; Yadav et al. 2020; Dias, Carvalho, and Sampaio 2022).

There were defined four main streams in Quality 4.0 development: 1. digital quality management (application of digital technologies to quality management itself, to its methods, tools, its human aspects); 2. quality of digital products and services (quality of cyber-physical systems, Internet of things, services; quality of big data and their security); 3. quality management for increasingly digital product design and development of production processes (further integration of systems engineering and quality, closed-loop manufacturing, increased collaboration and co-creation of manufacturers with customers); 4. risk management (as a part of the whole life-cycle with higher stress on the earlier phases of the product and process development). These aspects of Quality 4.0 are very well discussed in Dias, Carvalho, and Sampaio (2022). The new aspect of quality management in the era of digital transformation is the supply chain quality integration (Huo et al. 2019).

2.3. Fault management

As the smart manufacturing systems are very complex, there could be a high risk of faults that evocate unwanted downtimes and increased production costs. For this reason effective predictive fault handling, as a part of quality management, is necessary. Fault management consists of the following steps: data collection, data pre-processing, feature selection, fault prioritization and fault amendment. For every step there are various traditional or new methods available (for more information see e.g. (Wedel et al. 2016); (Webert et al. 2022)).

FMEA is very effective method for the prioritization phase belonging to the traditional quality management tools with a large potential to be integrated with digital transformation technologies and to become an effective tool in the frame of the Quality 4.0 environment. A comprehensive review of various approaches and applications of FMEA can be found in (Sharma and Srivastava 2018). Another rich literature review of FMEA containing its critical analysis and description of its perspectives in the frame of the future intelligent manufacturing systems can be found in Wu et al. (2021).

2.4. Testbed

A testbed can be defined as a platform for experimentation of large development projects. It allows for rigorous, transparent, and replicable testing of scientific theories, computational tools, and new technologies. Generally, the term is used to describe a development environment that is protected from the hazards of testing in a live or production real conditions. In connection with Industry 4.0 and smart factories many Industry 4.0 testbeds have been created. Industry 4.0 testbeds in general are meant for testing. validation, benchmark and verification new technologies and architectures related to the industrial internet of things in the laboratory to validate scientific theories, algorithms and tools before using them in actual industrial applications. These testbeds have three common functions: 1. Smart factory prototype function - they show how new applications, new technologies and processes, new products and services and also new security means operate together on the base of the Industry 4.0 platform; 2. Innovation platform function – Industry 4.0 testbeds integrate platforms for research a development, education and skills development relating to Industry 4.0; 3. Catalyst of digital transformation using elements such as workforce transformation, value creation, regulation, industry networks (Gallagher 2017).

Various Industry 4.0 testbeds with individual properties were created at the universities' research centers or in the companies round the word (for instance SAAB Industrial IoT testbed consisting of industry ready IT/OT technologies and integrating data gaining, analytics and software technology platforms; Swinburne Industry 4.0 Test-lab for the composite product automation in Australia; the Czech Technical University Prague testbed representing unique concept of the manufacturing line that thanks to variability of machines, robots and software tools including augmented and virtual reality enables to test Industry 4.0 technologies; Swedish-German testbed for Smart production at KTH campus serving as a unique test and validation platform for cross-location developments in Industry 4.0, predominantly for small and medium sized companies; Fraunhofer IIS 5 G Bavaria Industry 4.0 Test Bed, suitable for testing wireless applications with 5 G).

3. Description of selected applied methods and technologies

In this section methods and technologies applied to the testbed "Smart Factory Line" will be delineated.

3.1. Used methods and technologies of Industry 4.0

3.1.1. Cyber-physical production systems

Cyber-physical production systems (CPPS) are the essential components of Industry 4.0 applications (Francalanza, Mercieca, and Fenech 2018; Oztemel and Gursev 2020). CPPS integrate in manufacturing virtual and physical dimensions to form a truly networked world in which intelligent objects can communicate and interact with each other.

Generally, CPPS can be described as follows: CPSS "consist of embedded systems with the ability to communicate, preferably via internet technologies. Those special types of embedded systems, based on powerful software systems, enable the integration in digital networks and create completely new system functionalities. Moreover, these systems are part of the cyberspace because of their digital representation. They are more than just an interface due to their ability to represent relevant knowledge about the physical reality and autonomous computing capacity for analysis and interpretation of the data." (Berger et al. (2016), 639). In connection with CPPS, information security is inseparable topic (see for instance (Ning and Liu 2012); (Dagli 2016); (García-Valls et al. 2017)). Another important aspect of the CPPS effective operation is the problem of the predictive maintenance (see e.g., (Sahli et al. 2021)).

Commonly CPPS have five levels: configuration level, cognition level, cyber level, data to information level and smart connection level (for more detail see (Lee, Bagheri, and Kao 2015)).

3.1.2. Internet of things

The main purpose of Internet of things (IoT) is to put together and coordinate information from all diverse sources through a common language for devices and applications. Connection of all these objects enables sharing their data and supporting their communication leading to a better understanding how they work and co-work to make self-decision possible. It means that through IoT machines and products communicate with each other cooperatively as everything is interconnected wirelessly (see e.g., (Gallagher 2017); (Leloglu 2017)).

3.1.3. Digital twin

At present the digital twin (DT) is predominantly considered as digital representation of real objects (production and transport equipment, processes, systems, workers or the complete environment). But DT is not only virtual model of its real counterpart. It is also a dynamic carrier of data and status information, obtained through various sensors linked up with IoT. DT serves as a tool for monitoring physical objects, technologies and processes in real time and space as this technology enables to create very detailed digital model using actual data. Using DT as a part of complex simulation models accelerates and makes easier the decision-making processes as it facilitates direct identification of possible effects of considered changes and enables to detect weaknesses. Complex literature review of the DT topic can be found in Jones et al. (2020).

3.1.4. Virtual and augmented reality

Virtual reality (VR) and augmented reality (AR) technologies give manufacturers, building new digital manufacturing, great opportunities to avoid mistakes and to simulate products and processes in advance during the design phases (Vasarainen et al. 2021). In AR, user uses additional features supplemented to the real world with the help of a computer system. On the other hand, in VR the user is isolated from the real world and the system immerses him in a separate virtual, computer generated world. DT integrated with VR interface can be used as a virtual testbed before the physical implementation (see e.g. (Pérez et al. 2020)).

3.1.5. Cloud technology

Cloud systems are the simplest online storage service and good means for handling Big data (Berisha, Mëziu, and Shabani 2022; Chen 2017). In (Stergiou et al. 2018) authors solved new security techniques in clouds.

3.2. FMEA

FMEA is a team based, structured improvement method for the potential failure modes' analysis, their identification and classification, analysis of failure mode causes and effects as well as for their risk evaluation and prioritization of actions needed to reduce this risk (Oliveira et al. 2020). FMEA is used during the design phase with the aim to avoid potential future failures and continues through the life of the product or service. The outputs of the FMEA are solutions to prevent or reduce the severity or the probability of failures, starting with failure-modes with the highest priority. The priorities are set on the base of evaluation of every failure mode severity (S), occurrence (O) and detection (D) (Sharma and Srivastava 2018).

FMEA approach applied to the design of the testbed "Smart Factory Line" processes and products corresponds to the methodology covered by the new FMEA handbook (AIAG 2019). This handbook represents the first international guide on FMEA, harmonizing previous AIAG (Automotive Industry Action Group) and VDA (German Practices Association of the Automotive Industry) manuals on the base of their best practices. The new FMEA handbook is focused on the Design FMEA (DFMEA), Process FMEA (PFMEA) and supplemental FMEA-MSR for monitoring and systems response with the new, very detailed 7-steps methodology. These steps are as follows: planning and preparation; structure analysis; function analysis; failure analysis; risk analysis; optimization and results documentation. For each structure part and element of the product or process and their functions must be defined failure mode and its failure cause and failure effect, three elements of the failure chain. Then each chain must be evaluated using three above mentioned rating criteria: S, O and D. Criterion S is a measure based on the size of the potential impact of the failure on the smooth functioning of the machine or the safety of the operators. Criterion O is connected to the rate of possibility of the potential root cause of a failure arising and criterion D references the rate of possibility the failure mode to be early-detected. Each of these criteria has a rating of 1 to 10 points (10 points represent the most severe, the most frequent and the most undetectable failures). After evaluation of these three criteria, prioritization of actions reducing the failure risks must be realized. In the new FMEA handbook the prioritization based on RPN were replaced by the rating method based on AP (AP defines the actual need of action to reduce risk and so represents its priority). RPN is constructed as a multiple of criteria S x O x D. It means that all criteria have the same weight and for various combinations of them there can be the same value of RPN. It could lead to the problems with prioritization of actions to reduce the risk. In addition, there was not any recommended limit for RPN saying when to take some action or not. It has led to the subjective setting of this limit in companies. The AP approach reduces these problems. It gives more weight to criterion S, then O and finally D (see AP matrices in (AIAG 2019, 70)). In addition, AP has been divided into three categories (low L, medium M and high H). Priority H means that actions to improve prevention and/or detection controls must be defined, priority M means that such actions should be defined, priority L means that appropriate actions can be defined. Above mentioned AP matrices are constructed in a such way that failure modes with high values of S definitely lead to AP H or M but also in a case of smaller values of S and higher values of O or D the methodology leads to H or M. This provides companies with the unified and clear rules for decision about necessity of the action and results in the simplified decision-making process. The prioritization process can be then simply automated.

4. Description of testbed "smart factory line"

In this section the facilities, virtual elements, products and processes of "Smart Factory Line" will be described.

4.1. Description of facilities and virtual elements

The FMEA analysis was applied to the testbed "Smart Factory Line". This testbed is a platform for teaching, demonstration, testing and research of automatic control, industrial and mobile robots using approaches of digitalization and virtualization of systems and processes including predictive maintenance. "Smart Factory Line" includes an automated production line containing a digitized production process with Industry 4.0 elements. The production line produces two types of products. The line enables product assembly using a fully automated process, product testing, product inspection and product layout, too.

This platform is also intended to provide the basis for further development of these systems. At the same time, it has been designed to enable the integration of systems based on 5 G networks into industrial applications, for big data collection and processing, for interconnection within the IoT and for the application of selected principles and methods of Quality 4.0.

The production line and its facilities can be depicted using 3D model (Figure 1).

The core of the assembly line is formed by four Kuka robotic arms (numbers 1 – 4 in Figure 1) that perform all robotic operations of automatic assembly. The production line also includes three manual workstations (numbers 5 – 7 in Figure 1) which are used for loading of parts, manual assembly and collection of finished products. There is also an automated warehouse (number 8 in Figure 1) of individual production parts and an electronic tester (number 9 in Figure 1). The individual production parts and manufactured products are then moved within the line on pallets along a conveyor belt - Bosch Rexroth conveyor, that is interconnected in a circular fashion (number 10 in Figure 1).

The entire line is equipped with a huge of sensors, such as vibration sensors for diagnostic and predictive maintenance purposes. The line also includes number of surveillance cameras as well as a camera for optical inspection purposes. The images from the surveillance cameras are then digitally transmitted to a set of monitors being in the vicinity with the line for the inspection and demonstration of the operations being carried out.

The control system of the line is based on Siemens Simatic S7 1500/1200 PLC. The individual visualization and operator panels use the Siemens WinCC and Simatic HMI platform. The control system and operator systems are overlaid by an MES system on the Siemens Opcenter Execution Discrete platform, which is primarily designed for data collection, inventory management and production order entry. The safety of the entire system is ensured by Leuze products. It is also important to mention that the robotic line also uses mobile AGV robots, which are primarily used for the removal of already manufactured products. Once the product assembly is completed, the mobile robot drives autonomously to the line area where the individual products are placed on the prepared robot platform by means of the robotic arm. The robot then drives out of the production line to a predefined position within the building, where the manufactured items can be conveniently picked up.

As to the virtual elements the testbed "Smart Factory Line" includes a true-to-life 3D virtual model (Figure 2) of the production line and the surrounding environment inside the building. The visualization was realized using Unreal Engine 4.25 and the model was created using the open source tool Blender. The resulting model is interactive and can be used in VR. The model will be further used in various areas, including the possibility of planning future modifications of the line, training staff and students in familiarizing themselves with the line and its parts, virtual tours, marketing and advertising purposes and application of FMEA.

DT, a complex virtual image of the production line and its products, was also created (example is in Figure 3).

The aim is to demonstrate the use of DT and virtualization technologies throughout the entire product introduction process, covering:

- product prototype design and implementation;
- design and implementation of a production system;
- design and implementation of production system management, system testing,
- operation of the system;
- service and maintenance.

For the design of DT of the product and DT of the process the software tools 3DEXPERIENCE, the PLM

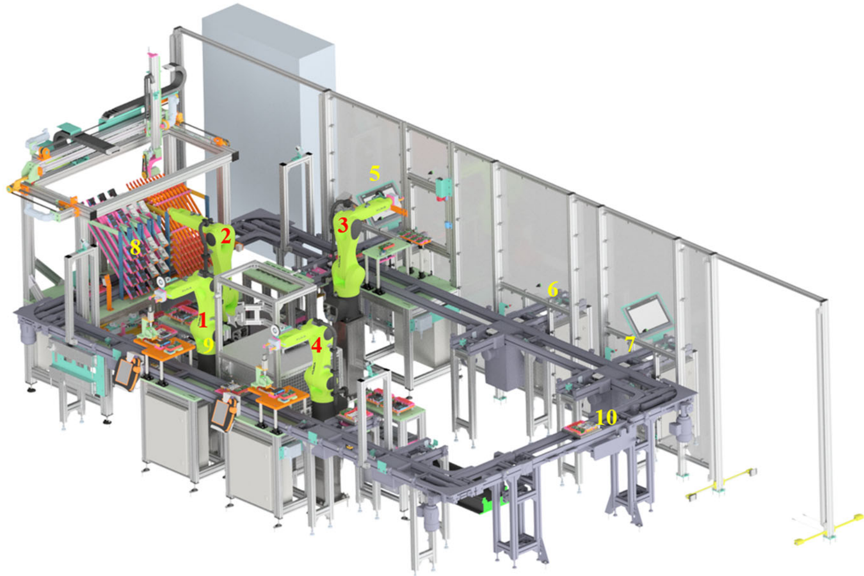

Figure 1. “Smart Factory Line” and its facilities.

Figure 2. “Smart Factory Line” visualization.

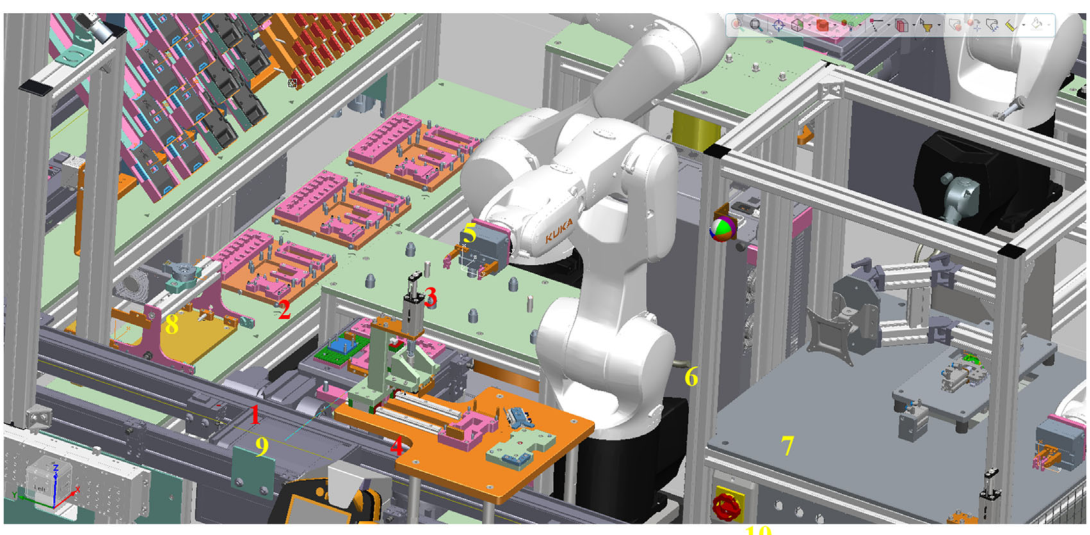

Figure 3. “Smart Factory Line” digital twin in Technomatic SW.

Figure 4. Vizualization of three variants of the main product.

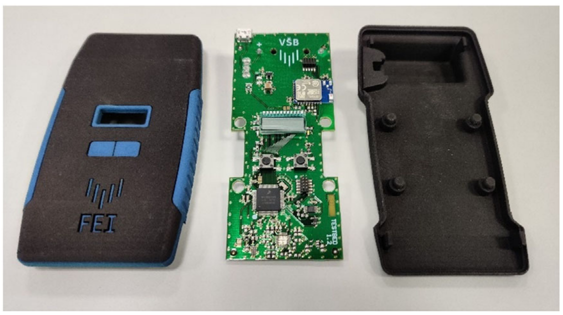

Figure 5. Product design.

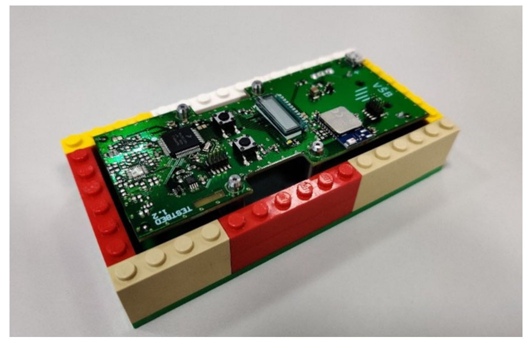

Figure 6. LEGO product.

software tool Siemens Technomatix, and NX MCD were advantageously used.

4.2. Description of products

The testbed "Smart Factory Line" is intended for production of a design promotional item. This product is produced in three basic variants, namely as thermometer, pedometer and heart rate monitor (Figure 4). In addition to this design promotional item, the production line enables assembly of a product that is composed of LEGO bricks, whereby any color combination of bricks and type of product can be selected before the start of production. In this case, the process involves both assembly and disassembly. This wide product variability underlines the essence of the testbed "Smart Factory Line" concept, the importance of implementing Industry 4.0 methods and approaches to support at present prevailing mass customization and individualization manufacturing paradigm.

The design product (Figure 5) consists of three main components. The middle component (electronic circuit board), differing according to the final product intended use as pedometer, thermometer or heart rate monitor, is inserted between a pair of design parts. After assembly the product is taken over by the customer who ordered the product and the product is not again decomposed.

The second product is the LEGO product (Figure 6), which offers more options for individual selection. As with the design product, customer can choose what type of electronics the product will contain (pedometer, thermometer, heart rate monitor). Next, the customer can choose the color of eight cubes that will be placed on the product. After mounting the cubes on the base plate, the electronics are inserted into the resulting frame. The finished product is presented on the premises of "Smart Factory Line" and is then returned to the line, where the product is broken down into individual components, which are again stored in the warehouse.

4.3. Process description

The request to start the production is entered via visualization from the control workplace. When ordering a product, it is possible to choose the type of product (Design or LEGO) and the electronics that the product will contain. In the case of a LEGO product, the color of the cubes, that will be placed on the product, must be chosen (Figure 7).

After scanning the QR code of each component for the control, the robot with a linear drive takes away components from the warehouse and inserts them into the supply container (Figure 8) according to the specified product. After inserting all required components to the container, the robot puts it to the place by the assembly workplace. At the same time the robot removes the empty container from the previous assembly operation and transports it back to the warehouse.

The small transport pallets moving on the production line, are parked in the assembly space or in other parking slots. The used pallet is every time put back to the park place. During the preparation of production this pallet is moved to the assembly workplace

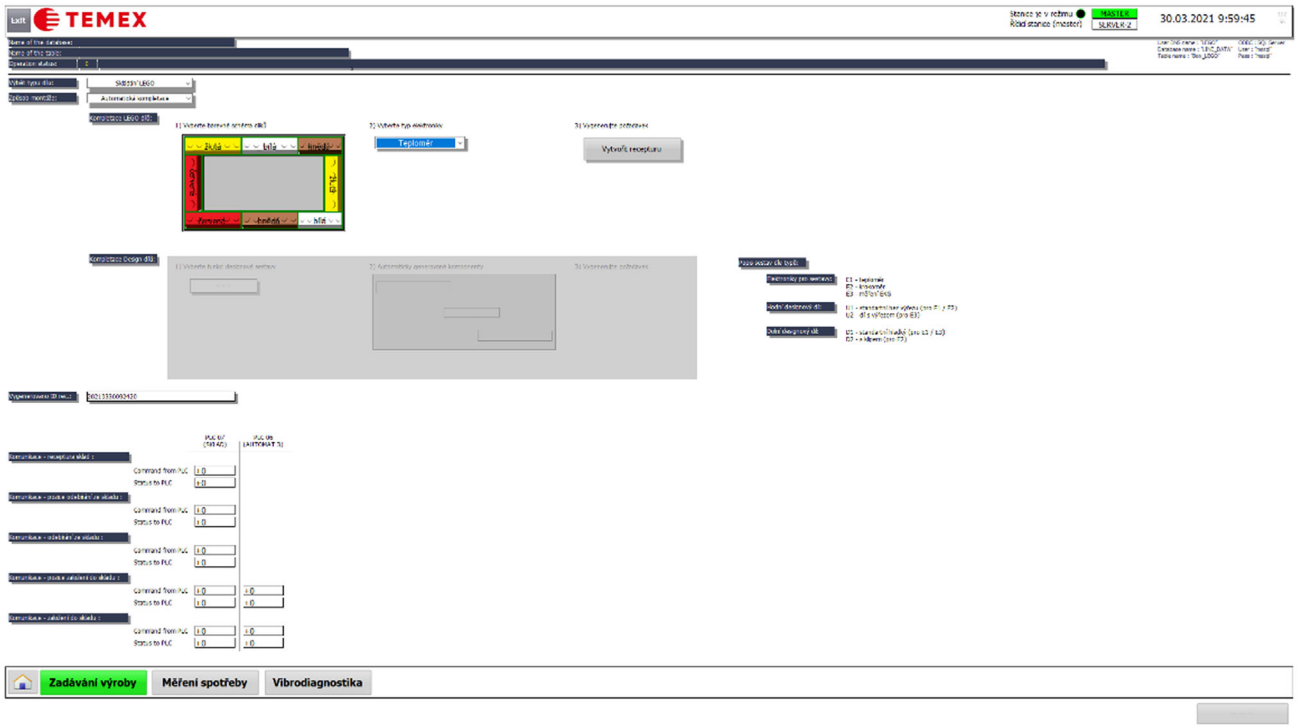

Figure 7. Visualization for product ordering.

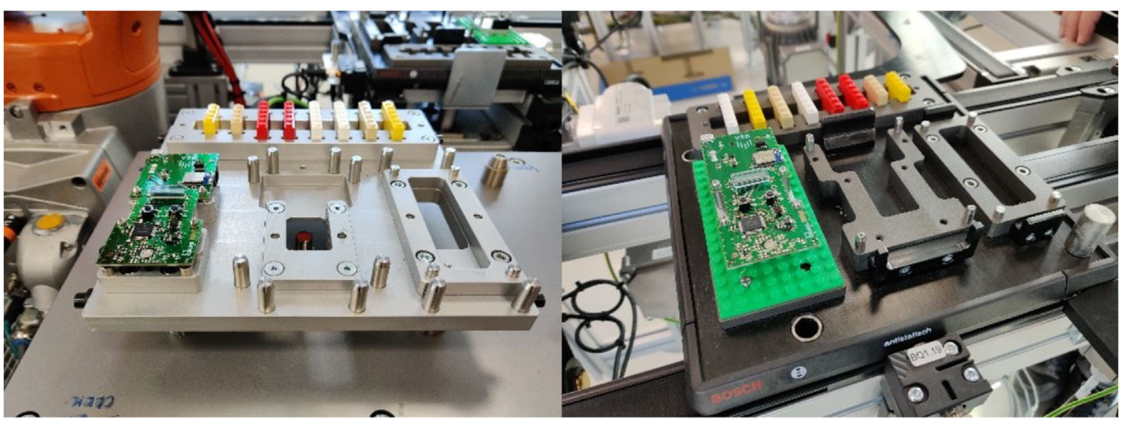

Figure 8. Containers for transporting components.

where components of the product are assembled. The production line contains a pair of stations for automatic assembly and a pair of stations for manual assembly. The automatic assembly station is used to assemble products from individual components. The manual assembly station is used to assemble products manually and includes a panel that shows how the product is to be assembled (digital working instructions).

As to the robotic assembly, for the first time the robot moves the printed circuit board to the tester and starts the testing. At the same time the assembly operation is running (the robot takes out the components from the disposed container and the assembly is realized in the assembly jig). During the assembly operation the tested electronic part is put into the product. When the test has failed the electronic part is put back to the container and the requirement for delivering a new electronic part is dispatched. After the assembly operation the optical inspection is realized using cameras located on the robotic arms. Then the finished product is located to the transport pallet and goes to the place where it is moved to the mobile robot for the delivering. When the LEGO product was produced the mobile robot comes back to the handover place and the robot with a linear drive puts the product back to the transport pallet. Then the pallet goes to the disassembly working place where the robot for disassembly will execute disassembly using the disassembly jig. The components of the disassembled product are put to the transport pallet in the pre-defined positions and the pallet is moved to the warehouse where are partial components again stored. The printed circuit board is put back to the warehouse for electronic parts. The empty transport pallet goes back to the assembly workplace.

Automatic inspection processes can run parallel and independently. When the defect has been detected it must be defined the cause and based on the type of the defect the production line starts to run activities according to pre-defined rules.

5. Application of FMEA

In this section the application of FMEA on the testbed "Smart Factory Line" will be described.

The main goals of this primary study were to verify feasibility and applicability of FMEA on such complex technical system and to show real possibilities of integration of Industry 4.0 principles and technologies with selected methods of quality management. During realization of this study a big stress was put on a broad exploitation of knowledge and skills of employees of all joined workplaces to verify possibilities of synergic utilization of knowledge in quality planning, injection of plastics, electrotechnics, cybernetics and robotics. It was enabled by co-operation of employees of Department of quality management and Department of cybernetics and biomedical engineering with employees of IdeaHub, z.s. company and the workplace "Smart Factory Line".

Application of FMEA was realized in the following steps:

1. initial phase and definition of the time schedule and contents of the individual steps;
2. realization of DFMEA;
3. realization of PFMEA;
4. elaboration of the final report;
5. evaluation of obtained results.

5.1. Initial phase

First it was decided to apply FMEA to the testbed "Smart Factory Line" – DFMEA to its products and PFMEA to the process of assembly. Then the FMEA realization team was set up, consisting of 5 members (1 employee from Department of cybernetics and biomedical engineering, 2 employees from organization IdeaHub, z.s. company and 2 employees from Department of quality management, that also assumed a role of team coordinators and facilitators). Then it was decided to realize the FMEA application in the frame of the new harmonized version of handbook for FMEA (AIAG 2019). Creation of the time schedule of the application of FMEA and defining contents of the planned meetings was very important part of the initial phase. Except setting the logic succession of DFMEA and PFMEA four meetings for the core realization of the both FMEA analyses were planned (useful instruments for these activities are for instance JIRA or MS Project). Realization of the DFMEA and PFMEA was divided into 7 steps as recommended in the handbook (AIAG 2019).

5.2. Realization of DFMEA

Defining the rate of detail of the products' description (analysis of the product structure) was very important step of this analysis. Especially it was a problem of the printed circuit board with a huge number of components that was necessary to combine into several functional units. These functional parts were then considered to be the smallest indivisible units of the analyzed product during the whole DFMEA analysis. The product was divided into 8 individual parts (6 of them belonged to the electronical part of the product) – see Figure 9.

During the meetings of the FMEA team the rest of steps of DFMEA analysis were done using brainstorming. The analyses were led by the member of the Department of quality management. At first the analysis of functions of the testbed "Smart Factory Line" and their decomposition into subsystems' and partial components' functions were made. The team defined 5 functions of the whole product that were decomposed into 9 functions of subsystems and 14 functions of partial components (Figure 10).

In the frame of the failure analysis, the potential failure modes, their effects and causes for every component function that could occur during the whole product life cycle were defined. In total 20 potential failure modes of the product were defined. As an example, the failure analysis for the system element called "bottom part" is presented (Figure 11).

The failure analysis was followed by the risk analysis where quantification of criteria S, O and D of all defined potential failure modes was done. To be able to quantify these parameters at first it was necessary to define for every potential failure mode, resp. its cause, actual/designed controls reducing the risk of the occurrence of the given failure mode. Then it was necessary to describe ways of the failure mode detection that evaluates the efficiency of actual/designed control mechanisms. The quantification of S was realized using 10 points-scale where 1 point represents

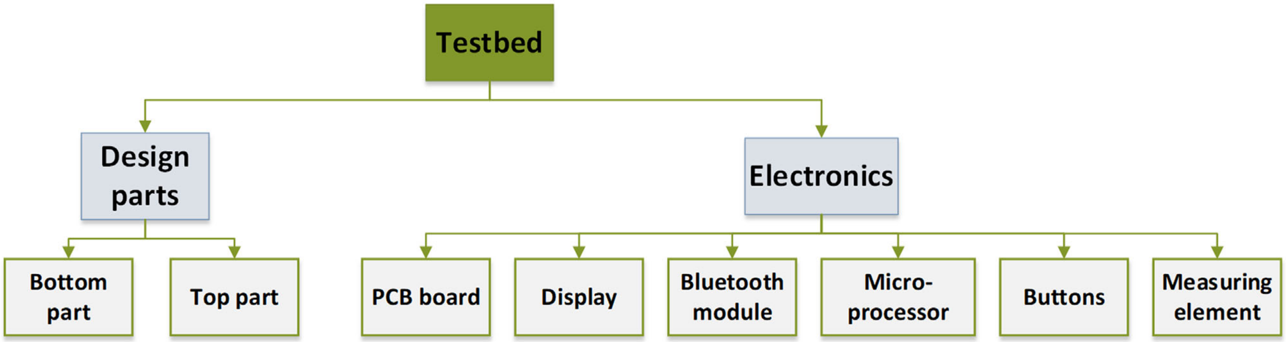

Figure 9. Structure of the product.

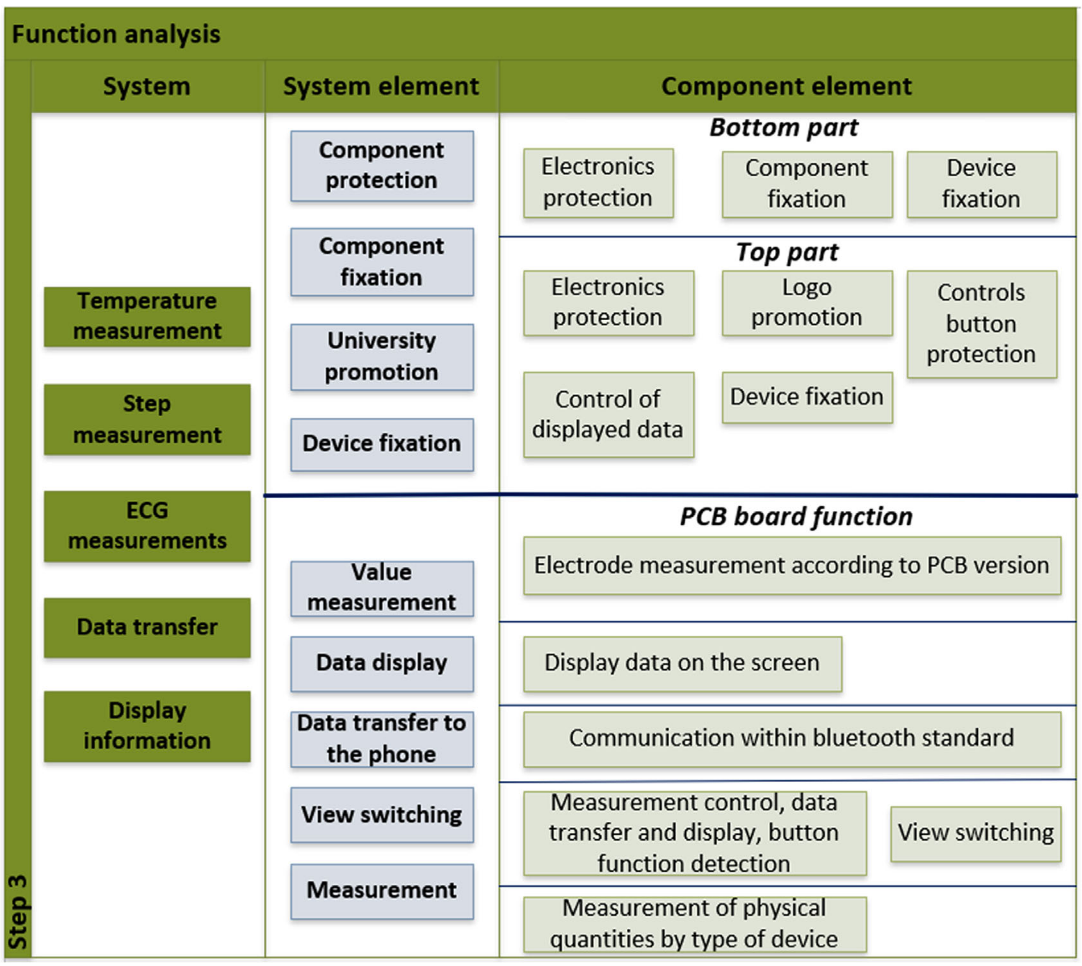

Figure 10. Function analysis.

zero or wholly insignificant effect of the failure mode. On the contrary 10 points represent danger for health, life or possession. The criteria O and D were quantified using again the scale of 1 – 10 points where 10 points represent the highest probability of the failure occurrence, resp. the smallest probability of its detection. Based on the values of the criteria S, O and D, the action priority (AP) was found in the rating matrices (AIAG 2019, 70). In the frame of DFMEA for “Smart Factory Line” in the whole 25 AP were defined (11 with the lowest priority L and 14 with priority M). In Figure 12 the results of the risk analysis for the system element “bottom part” can be seen.

In the following optimization step of DFMEA two preventive actions with the aim to reduce probability of the occurrence of the potential failure modes were defined for all failure modes with M priority level. An example of optimization is presented by Figure 13.

Repeated evaluation of the criteria S, O and D proved efficiency of the proposed actions. For 8 AP

Failure analysis (Step 4)

System element	Function	Failure effect	Severity	Potential failure mode	Failure cause
Bottom part	Electronics protection	Decay of design part - limitation/design degradation	8	Destruction of the bottom part	External destructive force effect
	Component fixation	Buckling and possible damage to the board - main function lost	8	Damage of fixators	External destructive force effect
		Degraded visual qualities	3	Colour fading Surface damage	External destructive force effect
	Device fixation	Unable to fix the device - reduced comfort of usage	3	Clip breaking	External destructive force effect

Figure 11. Failure analysis of the "bottom part".

Risk analysis (Step 5)

System element	Failure effect	Potential failure mode	Prevention controls	Occurrence	Detection controls	Detection	AP
Bottom part	Decay of design part - limitation/loss of product functions - design degradation	Destruction of the bottom part	X	3	Visual inspection	6	M
	Buckling and possible damage to the board - main function lost	Damage of fixators	X	3	Visual inspection	6	M
	Degraded visual qualities	Colour fading	X	3	Visual inspection	5	L
		Surface damage	X	3	Visual inspection	5	L
	Unable to fix the device - reduced comfort of usage	Clip breaking	X	3	X	6	L

Figure 12. Risk analysis for the system element "bottom part".

with the priority level M this level was changed to the level L. It had led to the significant improvement of "Smart Factory Line" design and the design of its products, creating very good base for the following application of the PFMEA analysis.

5.3. Realization of PFMEA

PFMEA analysis was realized in the frame of two meetings of the FMEA team. The first meeting was devoted to the preparation of the proper PFMEA analysis.

To be able to realize PFMEA the solving team had to get acquainted with the process of assembly. Based on defining all steps of the assembly process the flow chart was created. As it can be seen (Figure 14) the designed assembly process consists of 5 operations (storage, assignment order for assembly, uploading from storage, assembly and transport of the finished product to the customer) divided into 17 individual steps.

The analysis of the functions in the frame of PFMEA was focused on the definition of the functions of the individual operations. 17 individual functions were defined, based on the individual steps of the analyzed assembly process. As compared to DFMEA, the failure analysis in the frame of PFMEA was focused on discovering of failure modes, their causes and effects concerning the assembly process. The potential failure in this case can lead for instance to

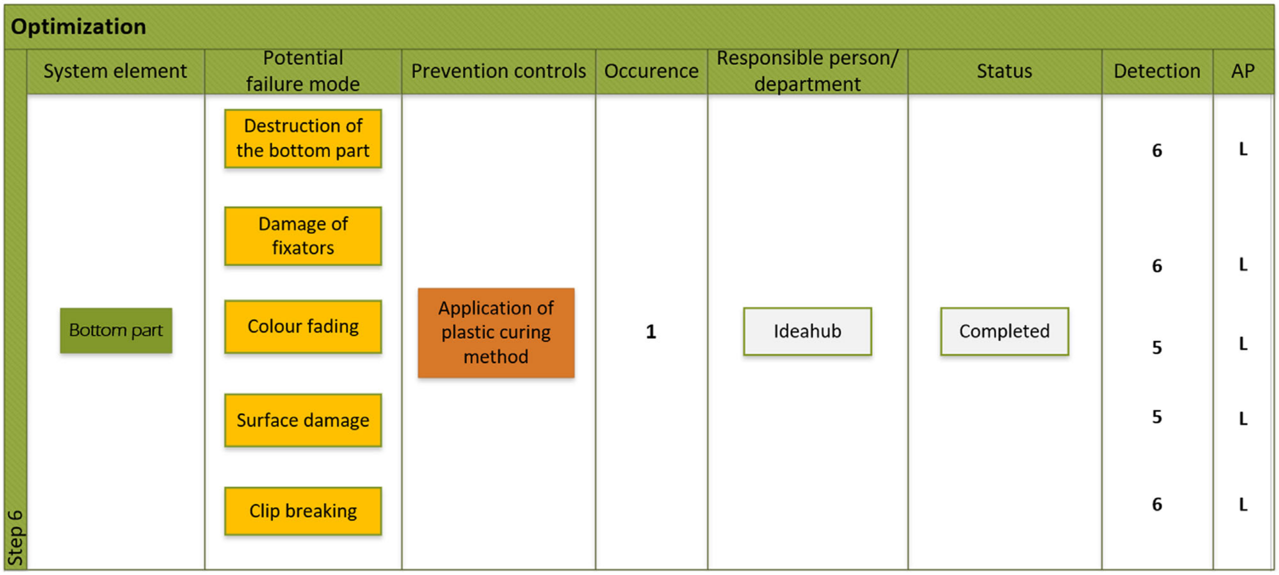

Figure 13. An example of the optimization phase.

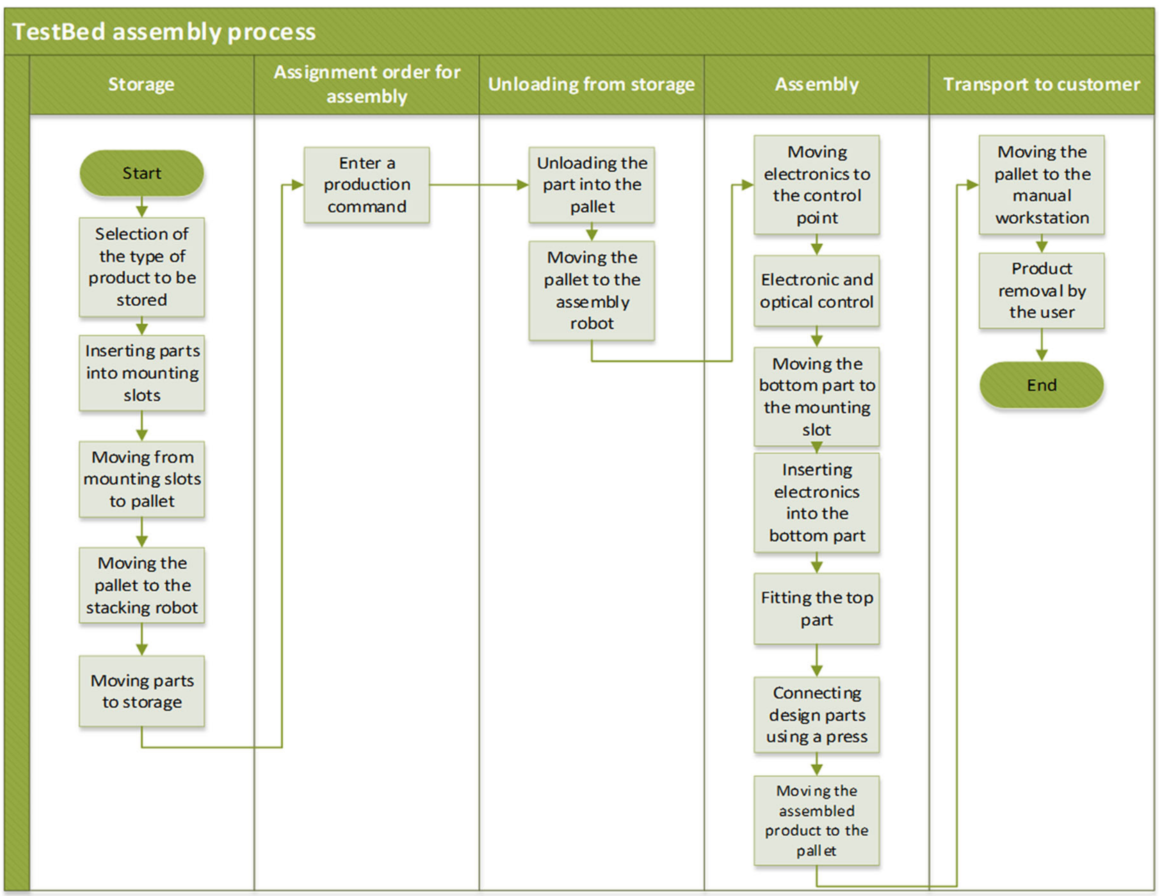

Figure 14. Flow chart of the assembly process.

impossibility or incorrect execution of the consequent operations. The FMEA team revealed 18 potential failure modes evocated by 12 causes.

During the following risk analysis 3 AP with the highest priority H were set (i.e., imprecise inserting the component into the slot, inserting into incorrect slot and entering the inserted component under the rest of the stored components) and 6 AP with the medium priority M. The team solved 3 failures with AP on the highest H level. Installing the pneumatic plugs was proposed as the solution. After realization of this action and observing its practical effect the AP level was reduced to the level L. The proposed solution was evaluated as highly efficient.

5.4. Elaboration of the final report

Running analyses and the results of DFMEA and PFMEA were described in the final report that complements tables of DFMEA and PFMEA. These tables are attached to this paper in the file with the supplementary material. The results were discussed with all members of the FMEA team and can be shared with FMEA teams for new FMEA applications and for training and education.

6. Discussion

The realization of the described application of FMEA has brought not only possibilities for improvement of the design of "Smart Factory Line" and planned products but it has revealed various more general aspects. It has proved very important role of the preparation phase. Very important factor influencing quality and efficiency of realization of the FMEA analysis on "Smart Factory Line" was composition of the FMEA team. The team was exclusively consisted of skilled workers from the concerned university workplaces and private organization. The roles of facilitators, coordinators and guarantors of quality management issues were taken by the members of the Department of quality management. The high quality of the expert knowledge and skills of every team member in condition of the smart manufacturing is one of the basic preconditions for application of FMEA and other preventive quality management tools because the object of these applications is very complex and expensive production system where reliability must be ensured as early as possible. Further, the efficiency of results and recommendations arising from the application of FMEA and other quality management tools and methods inevitably depends on the quality and precision of the exploited data and "smartness" of information transformed from these data. It is also strongly related to the team composition and expert quality of every team member.

The cooperation of the members of this expert team also has brought mutual enrichment in the expert fields which individual members are not objectively familiar with. In addition, the realization of the FMEA analyses prepared these workers to be well skilled mentors for training in applications of FMEA and other quality management methods in conditions of the smart manufacturing in the frame of the future education of students and workers from various firms.

Further findings relating to the preparatory phase have concerned the quality of planning activities. It was proved that well elaborated time schedules of meetings and their contents are inevitable precondition for the effective realization of FMEA and other team-based methods and it is effective prevention against a time waste. Very interesting finding has related to the phases of the own FMEA analyses where brainstorming is the basic method. It has shown that even in conditions of the smart manufacturing the personal meetings have its irreplaceable position in the application of such method for ideas generation. On the other hand, the experience of the FMEA team has shown that in un-predicable conditions, such Covid-19 epidemy, various other methods without personal contact of the team members can substitute classical brainstorming (mails, application of MS Team and other similar applications) to some extent.

Wholly new experience was brought applying the AP approach to prioritization of actions to reduce risks. As companies use predominantly the RPN approach so far, it was very valuable to verify the new AP approach. It has shown that the new approach brought anticipated convenient and quick decision-making on actions for the risk reduction. But it must be carefully perceived that benefits of the prioritization process based on AP criterion can be devastated when quantification of criteria S, O and D, the domain of human factor, is done subjectively and unprofessionally. In addition, the AP approach is not robust enough against possible attempt to intentionally under-evaluate risks with the goal to reduce necessity of taking actions. For this reason, setting values of S, O and D is really critical process of the FMEA analysis and it must be sufficiently subsidized with skilled people, money and time.

Above mentioned experience, obtained during the realization of FMEA in the frame of the described case study, can be utilized during education and training of students of quality management study branch and other study branches and during training employees from various companies, too. These future trainings could be supported by virtual reality technology that is already a part of "Smart Factory Line".

Application of FMEA on "Smart Factory Line" was influenced by a huge number of other factors. They were defined using SWOT analysis describing not only strengths of this application but also weaknesses and resulting opportunities and threats (Table 1).

Table 1. SWOT analysis.

S	INTERNAL STRENGTHS	W	INTERNAL WEAKNESSSES
1	Synergetic application and development of Hard, Soft and IT skills	1	High time and organizational requirements
2	Better student preparation for practice	2	Dependence on other departments and the private sector
3	Cooperation with private subjects	3	The need of a proactive approach and student motivation
4	Increased student satisfaction and engagement	4	Difficulty of implementation in case of stricter epidemiological measures
5	Involvement of a wide range of fields of study and departments		
O	EXTERNAL OPPORTUNITIES	T	EXTERNAL THREATS
1	Change of mindset and attitude of academic staff	1	Lack of willingness to share know-how of the involved subjects
2	Involvement of experts from practice in teaching	2	More possibility of "cheating" by students
3	Availability of advanced SW and HW	3	Unwillingness to change on the part of university staff and management
4	Increasing the prestige of the field study and the university	4	High workload of involved staff (mentors)
5	Faster implementation of the latest knowledge from practice into teaching		

SWOT analysis and the deep literature review have revealed that applying FMEA in practice will need to focus the future research on three main directions having an influence on the effectiveness and efficiency of FMEA applications in conditions of smart factories including Industry 4.0 testbeds:

1. to ensure that potential failure modes are precisely and quickly identified;
2. to ensure that the risk level of these failure modes is precisely evaluated to support decision making process, relating to realization of effective and efficient solutions for failures prevention;
3. to support creating proposals of effective and efficient solutions to prevent failures.

All goals correspond to the fact that new manufacturing conditions are more and more based on very complex manufacturing systems consisting of various networked software and physical systems, connected through the real-time data collection, processing and monitoring. Such deep connectivity of these manufacturing systems brings new potential hardware and software failure modes having effect on each other. These conditions also lead to necessity to create and manage the multi-specialists fault handling team and to ensure for this team precise information about processes and products in satisfactory quality, quantity, on time. Another problem of such multi-specialists' team relates to the fact that the opinion of each member can be influenced by his/her specialization, position, function or knowledge which can lead to biased evaluation. For this reason, possibility to share information and consult related issues must be guaranteed. Such changes call for adaption of the traditional FMEA approach. The main directions for this adaption can be as follows:

- creation of the shared knowledge base for FMEA teams covering all phases of product life cycle incorporating also outputs of other quality management methods, such as fault tree analysis, design of experiments, design verification plan and report;
- using virtual reality and digital twining for visual presentation of the designed product or process to all specialists from FMEA teams;
- searching and application of decision-making techniques to ensure that decision-making is based on more objective information (multi-criteria decision-making techniques or techniques enabling to achieve consensus of experts' opinion).

One of very important outputs of the FMEA application to "Smart Factory Line" processes and products has been creation of innovative form of education for technical experts including quality engineers.

7. Conclusion

In this paper the case study of application of FMEA on the testbed "Smart Factory Line" was described. The main goals of this study were to verify feasibility and applicability of FMEA on such complex technical system and to show real possibilities of integration of Industry 4.0 principles and technologies with selected methods of quality management. The case study has shown necessity of building smart factory testbeds that must be based on a high-quality interdisciplinary team including also specialists for quality issues, which enables to really build up Quality 4.0 approach. Case study also revealed the necessity and meaningfulness of tight co-operation between practice and academic word.

Applying one of the most important principles of quality management, i.e., continual improvement, after realization of FMEA on processes and products of "Smart Factory Line" SWOT analysis was made and several goals to improve FMEA applications were defined:

- creation of the shared knowledge base for FMEA teams covering all phases of product life cycle

incorporating also outputs of other quality management methods;
- using virtual reality and digital twining for visual presentation of the designed product or process to all specialists from FMEA teams;
- searching and application of decision-making techniques to ensure that decision-making is based on objective information.

These recommendations and directions of the future research can be exploited for other applications of FMEA and other quality management tools and methods not only in the frame of the testbed "Smart Factory Line" but at other universities or in factories trying to go ahead with the trend of Industry 4.0 and Quality 4.0.

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David Vykydal holds a Ph.D. in Industrial Systems Management. Currently he has been working as an assistant professor at the Department of Quality Management at the Faculty of Materials Science and Technology of VŠB-Technical University of Ostrava in the Czech Republic and also holds the position of quality manager of this university. His teaching and research activities are focused on the issue of quality management, the development and practical use of methods and tools for planning and quality improvement, and the application of computer support in this area. He was a manager or co-researcher of various national or international projects. In the field of quality management, he is the coauthor of three book publications and number of scientific papers published in international journals and proceedings of conferences. Some of the diploma theses of the students, where he was a supervisor, won the national competition for the “František Egermayer Award”, organized by the Czech Society for Quality. During his professional career he co-operated with a number of industrial enterprises as well as organizations from the public sector.

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