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Economic, Social Impacts and Operation of Smart Factories in Industry 4.0 Focusing on Simulation and Artificial Intelligence of Collaborating Robots

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Abstract: Smart Factory is a complex system that integrates the main elements of the Industry 4.0 concept (e.g., autonomous robots, Internet of Things, and Big data). In Smart Factories intelligent robots, tools, and smart workpieces communicate and collaborate with each other continuously, which results in self-organizing and self-optimizing production. The significance of Smart Factories is to make production more competitive, efficient, flexible and sustainable. The purpose of the study is not only the introduction of the concept and operation of the Smart Factories, but at the same time to show the application of Simulation and Artificial Intelligence (AI) methods in practice. The significance of the study is that the economic and social operational requirements and impacts of Smart Factories are summarized and the characteristics of the traditional factory and the Smart Factory are compared. The most significant added value of the research is that a real case study is introduced for Simulation of the operation of two collaborating robots applying AI. Quantitative research methods are used, such as numerical and graphical modeling and Simulation, 3D design, furthermore executing Tabu Search in the space of trajectories, but in some aspects the work included fundamental methods, like suggesting an original whip-lashing analog for designing robot trajectories. The conclusion of the case study is that—due to using Simulation and AI methods—the motion path of the robot arm is improved, resulting in more than five percent time-savings, which leads to a significant improvement in productivity. It can be concluded that the establishment of Smart Factories will be essential in the future and the application of Simulation and AI methods for collaborating robots are needed for efficient and optimal operation of production processes.

Keywords: industry 4.0; smart factories; economic and social impacts; collaborating robots; simulation; artificial intelligence

1. Introduction

Due to globalization, increasing market competition, and rapidly changing customers' demands there have already been many changes in production in the 21st century. The resources are limited; therefore, the current practices in the utilization of resources are not sustainable. Furthermore, the life-cycles of products are shorter and customers demand more complex and unique products in larger quantities. Based on the aforementioned changes, the production sector is going through a paradigm change (Ahuett-Garza and Kurfess 2018; Zhong et al. 2017).

Smart Factory is a complex system that integrates the main elements (e.g., autonomous robots, Internet of Things, Big data, Cloud Computing, Simulation, etc.) of the Industry 4.0 production philosophy (Gubán et al. 2017).

The significance of the research topic is that the Smart Factory concept has to be implemented in practice at manufacturing companies, because without the application of this concept the companies will be unable to maintain or increase their competitiveness in the future. The essence of the Smart Factory concept is that the traditional centrally controlled production processes will be changed by decentralized control, in which the intelligent smart machines, robots, tools, and intelligent smart workpieces communicate and collaborate with each other continuously by sensors (Kovács and Kot 2016). Smart Factories will result in production being more flexible, custom-oriented, sustainable and able to utilize resources more efficiently. Consequently, Smart Factories will be self-organizing, more competitive and optimize their own manufacturing activity (Jay et al. 2015; Stock and Seliger 2016).

The purpose of the study, beyond introducing the operation and concept of Smart Factories, also is to focus on application of collaborating autonomous robots, Simulation of the operation of robots and the Artificial Intelligence used by cooperating robots. The study is practice oriented, since the other aim of the research is to show Simulation of the operation of two collaborating robots in use in a real case study applying AI.

The methodology of the research was mostly analytical methods, due to the nature of the study, but descriptive methods were also used for the literature review and for description of the properties of Smart Factories. In the case study we mainly used quantitative research methods because of the computer-oriented topic, like numerical and graphical modeling and Simulation, 3D design, and results comparison. The methodology included applied research techniques like 3D modeling, using simulation tools, and executing Tabu Search (TS) in the space of trajectories, but in some aspects, the work included fundamental methods, like suggesting an original whip lashing analog for designing robot trajectories. From the point of view of the research design methodology types, the research used conclusive statements in connection with the Smart Factories scope and exploratory activities during the case study.

In the first part of the article the main elements and operation of a Smart Factory are introduced focusing on the Smart Devices of Industry 4.0, which are known as Multi-Agent Systems (MAS). These can be intelligent smart machines, collaborating robots, sensors, controllers, etc., which communicate with the production control system and the smart workpieces, so the machines coordinate, control, and optimize themselves and the whole production (Shrouf et al. 2014; Sunil and Sachin 2018; Wang et al. 2016a).

The significance of the first part of the study is that it summarizes the economic and social operational requirements and impacts of Smart Factories and compares characteristics of the traditional factory and a Smart Factory.

In the second part of the study the application of the collaborating robots, Simulation of the operation of robots and the AI used by cooperating robots are introduced and a real case study is presented. The essence of the case study is the efficiency improvement of the production processes—in which collaborating robots are applied—through the application of 3D design and Simulation software.

A normal operational scenario means when every smart device works correctly; robots collaborate together in order to achieve the targeted production tasks according to a production plan. An abnormal operational scenario is when a problem occurs in the production line that results in operational problems (e.g., malfunction, lost data, or defective product). In case of both normal and abnormal scenarios, there are two essential tools for task or problem solving.

One of these is Simulation, which can be applied effectively for modeling of future deterministic or unexpected stochastic events, and defining the optimal scenario for the future operation (Cservenák et al. 2014; Dudás 2010; Gubán et al. 2017; Straka et al. 2014).

The other important tool is the Artificial Intelligence of collaborating robots used for task or problem solving. AI is the ability of robots to learn and think logically and autonomously, not only depending on programs written by people (Dudás 2011; Wang et al. 2016b).

In the case study an assembly task is presented focusing mainly on the economic and efficiency characteristics of the modeled process. The case study involves two Mitsubishi robots in the same environment: The first is "RV-2AJ arm", which has five rotational joints, the second is "RV-2SD arm", which has six rotational joints. The RV-2AJ robot has to help the RV-2SD to reach the workpiece, which is far from its working space. The aim of the case study is to find the most profitable solution by the application of 3D modeling and simulation of plausible variations.

The primary added value of the research is that a real case study is introduced for Simulation of the operation of two collaborating robots applying AI. The Simulation and AI methods presented an improved solution for the motion path of the robot arm, resulting in a time-savings of five percent, which brings about a significant improvement in productivity.

In summary, the establishment of the Smart Factories and the application of collaborating robots will be needed in the future to realize more competitive, flexible, and sustainable production. Furthermore, it can also be concluded that the application of Simulation and AI methods for collaborating robots are essential tools for the efficient and optimal operation of production processes.

In the first part of the study the concept, main elements and operation of a Smart Factory are introduced. Furthermore, the economic and social operational requirements and the economic and social impacts of Smart Factories are summarized. The characteristics of the traditional factory and the Smart Factory are also compared. In the second part of the study, the application of the collaborating robots, Simulation of the operation of robots, and an AI method used by cooperating robots are introduced in a case study.

2. Literature Review

The Industry 4.0 production philosophy, as a whole complex concept—known as the Industry of the Future—was created in Germany at the Hannover Fair in 2011. This concept has prevailed worldwide due to its strategy, which is based on a new way of organizing operations at the industrial level using new technologies (Nasser 2014) and represents the upcoming 4th industrial revolution. According to the concept, the 1st industrial revolution was the age of mechanization, the application of the steam engine. The 2nd industrial revolution was the age of mass production and electricity, while the 3rd industrial revolution was the age of automated production through the application of electronic and informatics (IT) systems (Figure 1).

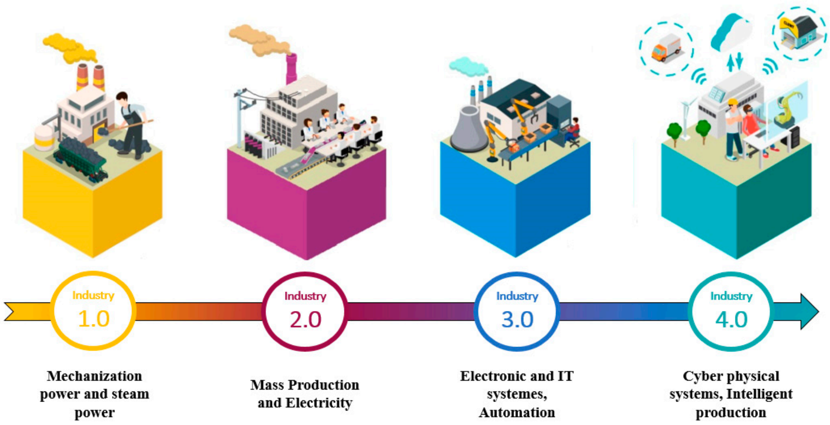

Figure 1. The four industrial revolutions.

The technologies applied in the recent Industry 4.0 concept to create a Smart Factory are more interconnected, more communicative and more intelligent than traditional manufacturing (Hu et al. 2018). Instead of traditional supply chains, a digital global supply chain network is needed in the Industry 4.0 concept, one that can adapt flexibly to the changing unique customers' demands, to the activity of the supply chain members and to the changing market environment.

Industry 4.0 can be defined as a digital transformation making autonomous decentralized decisions in all cyber physical systems where each element works in interaction. Products and machines communicate with each other, and the transfer of information is implemented by sensors, linked in a global network, which is itself connected to the whole supply chain that guarantees the individual needs of customers (Sung 2017).

Pillars of Industry 4.0

Interoperability, virtualization, decentralization, real-time capability and modularity must be present in the production systems in the Future Industry. These features are based on nine pillars, according to the Boston Consulting Group, and these are the newest technologies known all over the world (Rüsmann et al. 2015). Figure 2 describes these nine main pillars of the Industry 4.0 concept (Noha et al. 2019; Shrouf et al. 2014; Smit et al. 2016; Vaidya et al. 2018).

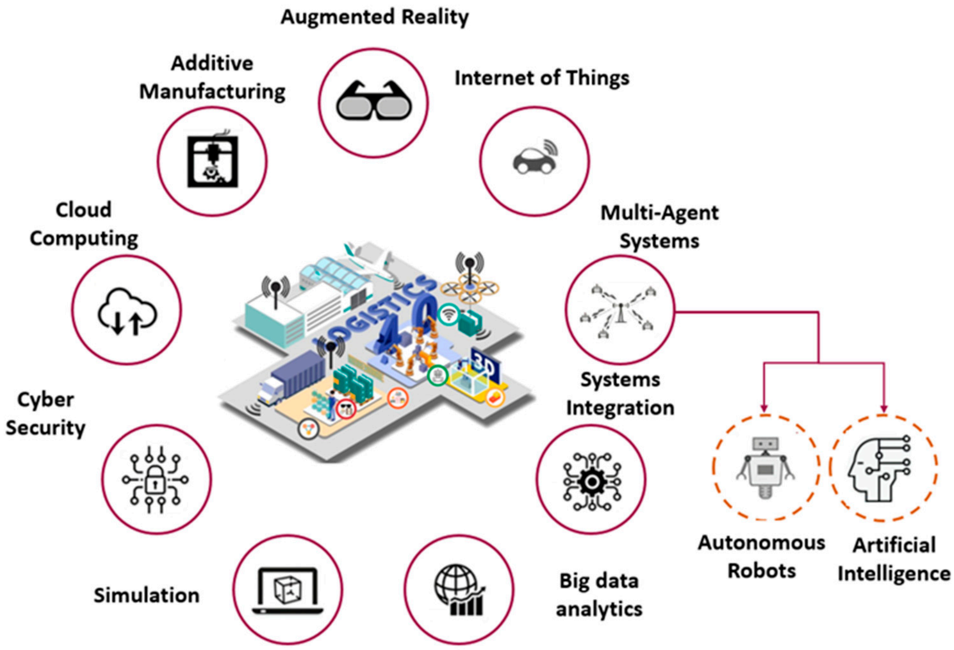

Figure 2. Main pillars of Industry 4.0 concept.

1. **Multi-Agent Systems** (MAS) can be intelligent smart machines, collaborating robots, sensors, controllers, etc., that are communicating with the production control system and the smart workpieces, so that machines coordinate, control, and optimize themselves and the whole production process.

    - **Autonomous Robots** are intelligent industrial robots that can cooperate and collaborate with each other during manufacturing in order to perform more complex tasks with higher efficiency.
    - **Artificial Intelligence** is the ability of robots to learn and think logically and autonomously, not only depending on programs written by people.

2. **System Integration** means the optimal reconfiguration of the connecting Cyber Physical Systems, which can be sensors, actuators, etc. (vertical integration); and the optimal operation of the whole supply chain including suppliers, manufacturers, service providers, etc. (horizontal integration).
3. **Big data** means the huge amount of information required for the optimal operation of the intelligent network-like systems. The collection, analysis and evaluation of this data set are essential for real-time decision making.
4. **Simulation** tools are used for optimization of production processes and maximal utilization of resources. Simulation is an efficient method for modeling deterministic and stochastic processes and supporting decision making.

5. **Cyber Security** includes technologies that are developed to protect systems, networks and data from cyber-attacks.
6. **Cloud Computing** provides unlimited computing power to transfer, store and analyze the huge amount of data required for the optimal operation of systems.
7. **Additive Manufacturing** is an innovative technology to build three-dimensional objects by adding layer upon layer of a given material. This 3D printing technology provides the possibility of manufacturing more complex and unique components and products, which is needed for more flexible and unique production.
8. **Augmented Reality** provides the possibility of visualization of manufacturing processes by transforming the real environment to a virtual environment.
9. **Internet of Things** (IoT) technology allows objects (e.g., machines, vehicles, products or other devices) to communicate and interact with each other. IoT provides the network connection and data exchange of objects.

Smart Factory is a complex system that integrates these main elements (e.g., autonomous robots, IoT, Big data, Cloud Computing, and simulation) of the Industry 4.0 production philosophy. The essence of the Smart Factory concept is that the traditional centrally controlled production processes will be replaced by decentralized control, in which the intelligent machines, robots, tools, and intelligent workpieces communicate and collaborate with each other continuously. Smart Factories are self-organizing, self-optimizing, and more competitive. Factories can self-optimize their own performance, self-adapting to new situations and conditions.

3. Concept of Smart Factory

At present, due to globalization and the continuous changing market competition according to the customers' demands, the Industry 4.0 production philosophy can be applied to provide the required quantity and quality of the final products. Science and politics have to work together to establish the Industry 4.0 concept in practice. That means that in the production sector a complete restructuring of production processes is needed and the current analog, centralized workflow has to be transformed into digital, decentralized production processes. At the same time the Industry 4.0 concept offers new business models, new products and new services. All of these transformations are based on internet-driven self-controlling and sensor-aided production systems, thanks to increased programmability, connectivity using IoT, memory storage capacity for Big data, and sensor-based capabilities.

These radical changes in the industry will lead to the creation of Smart Factories and will make the production and logistics sectors more efficient, more flexible, and more customer-oriented. This economic paradigm change means saving costs, reducing lead times, and improving the quality of final products (Kostál et al. 2011; Stock and Seliger 2016). The Smart Factory has a key role in the Industry 4.0 concept—it is a factory that is context-aware and assists people and machines in execution of their tasks autonomously. It includes vertical integration technology and networks of manufacturing systems in order to achieve intelligent and highly flexible production systems using the IoT as tool of communication. The Smart Factory is self-organizing, auto-adapting and learns new conditions and demands in real time (or near real-time). The Smart Factory combines many technologies in order to satisfy customers' demands, starting from smart products and services connected to the internet to collecting and analyzing data using smart applications. IoT technology enables the customers to be more involved in the production design process (Wang et al. 2016a).

3.1. Economic and Social Operational Requirements of Smart Factories

During the implementation of Industry 4.0 in existing manufacturing companies many challenges arise, and thus the following requirements have to be fulfilled (Kovács and Kot 2016; Sunil and Sachin 2018; Sung 2017; Shrouf et al. 2014)

3.1.1. Economic Requirements from Aspects of Smart Production, Services, Customers and Government Economic Policy

- Smart Factories can be established where governments support the establishment and operation of factories applying Industry 4.0 technology by advantageous fiscal and economic policies (tax allowances, other financial support, etc.).
- A requirement of the operation of Smart Factories is the establishment of an essential and adequate infrastructural background, especially focusing on multimodal transport possibilities (road, rail, water, air) and further joining services.
- Smart Factories have to establish the essential and adequate logistical services related to production (transportation, warehousing, other value adding services, etc.).
- In Smart Factories the traditional centrally controlled production processes have to be changed to decentralized control, in which the intelligent machines, robots, tools and intelligent workpieces communicate and collaborate with each other continuously by sensors.
- Stability and reliability have to be provided in the communication between machines and between machines and workers using IoT.
- Cyber security has to be ensured, which includes technologies to protect systems, networks and data from cyber-attacks.
- All physical assets of the production have to be digitized and automatized, providing the integrity of production processes.
- Digital Supply Chains have to be created using IoT.
- Factories have to become self-organizing, self-regulating and self-adapting in order to optimize their own operations. Factories have to control and optimize their own decisions by analyzing processes and finding optimal solutions.
- Interoperability, virtualization, decentralization, real-time capability, and modularity have to be created in the production systems and processes.
- Productivity, flexibility, resource utilization and sustainability have to be improved in order to improve competitiveness and achieve intelligent production providing the required product quality, minimal production cost, and minimal lead-time.
- The production has to be more customer-oriented, because the customers require more complex and unique products in larger quantities in shorter lead times.

3.1.2. Social Requirements from the Aspects of Employment Market, Safety and Labor Law of Workers

- A highly skilled labor force will be needed for the programming and operation of the intelligent devices in Smart Factories. The number of those workers will be reduced, replaced by intelligent devices.
- An adequate number of specialized and well-trained workers have to be employed for all of tasks in order to maintain jobs and create new jobs.
- Workplace safety and labor law protection have to be provided for the workers:
    - Workplaces and manufacturing technologies have to be safe for employees and for the environment. Risks that could affect workers have to be reduced and chemicals and physical hazards have to be eliminated.
    - Human rights, labor laws and safety-at-work rules have to be in compliance.
    - Workers have to be trained for the concept of Industry 4.0 to find optimal solutions in normal and abnormal production situations.
    - More attractive levels of income and additional allowances have to be provided for the workers.

- ◦ Workers have to be motivated to improve their efficiency and creativity by several means (e.g., providing opportunities for training and for advancement; additional allowances; improving job satisfaction of workers).
- ◦ Efficient cooperation has to be created between the management and the Trade Unions of employees.

3.2. Economic and Social Impacts of Smart Factories

Figure 3 shows the main elements of the positive impacts of Smart Factories. Numerous economic and social impacts of Smart Factories are found in the literature (Kostál et al. 2011; Kot 2018; Kovács and Kot 2017; Romenda et al. 2018; Urbański et al. 2019; Virág and Szirbik 2012).

Figure 3. Positive impacts of Smart Factory.

3.2.1. Economic Impacts of Smart Factories on Production, Services, Final Products, Customers and Government Economic Policy

- In Smart Factories the traditional centrally controlled production processes will be changed to decentralized control, in which the intelligent machines, robots and intelligent workpieces communicate and collaborate with each other continuously.
- Factories will be self-organizing, self-regulating and self-adapting, thereby their operations can be optimized.
- Smart Factories will be more productive, flexible, sustainable and competitive.
- Utilization of machine and human resources will be higher.
- Production and joining services will be more flexible and customer-oriented in order to adapt to more unique and rapidly changing customers' demands, because the customers require more complex and more unique final products.
- Due to the intelligent production, which will result in high quality unique final products, custom-designed product/service portfolios, short production lead time, and delivery time, the satisfaction of customers will increase.
- Final products will be cost-efficient, durable; produced by innovative manufacturing technologies, business processes that use energy and material resources efficiently.
- Continuous performance measurement and evaluation of production processes will result in efficiency improvement and the reduction of operational costs.
- Companies will gain higher income and profit, which provide the possibility of investment in new high-tech and environmental-friendly technologies and continuous development of the infrastructure and joining services (transportation, warehousing, other value adding services).
- The operation of Smart Factories will result in the continuous development of the infrastructure, which will be advantageous not only for the companies, but at the same time for the entire region.
- Final products will be environmentally friendly, renewable resources will be used during the manufacturing. Recycling of wastes can be provided.
- Smart Factories will provide sustainable production in the long term from economic, environmental and social aspects.
- Due to the operation of Smart Factories, tax revenue for governments will increase. Thereby the governments can support the factories by more tax allowances and other financial support in

order to encourage the use of more high-tech and environmental-friendly technologies, to create more new jobs and to realize higher profit.

3.2.2. Social Impacts of Smart Factories on the Employment Market, Safety and Labor Law of Workers and Educational System

- Due to factories becoming automatized and self-organized, self-regulated and self-adapted, the employment market will be transformed. On the one hand, some workers can be replaced by intelligent devices, so the number of less skilled workers will be reduced. On the other hand, a highly skilled labor force will be needed for the programming and operation of the intelligent devices, because Smart Factories require well-trained workers.
- Based on the before mentioned facts, specialized and well trained workers have to be employed for all tasks, which may maintain jobs and create new jobs, which may result in the reduction of the unemployment rate.
- Workers will be more motivated because they can get higher incomes and additional allowances; furthermore, they have opportunities for training and for advancement. Therefore, their job satisfaction will be increased.
- Well-trained workers will find optimal solutions in both normal and abnormal production situations.
- Efficient cooperation will be created between the management of Smart Factories and the Trade Unions of employees, which will also improve the satisfaction of the workers.
- Smart Factories will provide sustainable production also from social aspects:
    - Safety for workers will be provided: compliance with human rights, labor laws and safety-at-work rules. Workplaces and technologies will be safer for the environment, eliminate or minimize chemicals and physical hazards, and reduce the risks of workers.
    - Workers will be provided the possibility to improve their efficiency and creativity and participate in operational decision making, while opportunities for training and advancement will be also provided.
- Educational system will be reorganized to train a specialized, highly skilled labor force according to the requirements of Smart Factories (Hariharasudan and Kot 2018). IT knowledge will become more important in the future; therefore, the IT competencies of future employees have to be developed from the beginning of elementary school (establishment of digital schools).

3.3. Comparison of Characteristics of the Traditional Factory and Smart Factory

There are significant differences between traditional factories and Smart Factories. A comparison of the characteristics of traditional plants and Smart Factories are summarized in Table 1 (Wang et al. 2016b).

Table 1. Comparison of the traditional factory and Smart Factory.

Traditional Factory	Smart Factory
• Centrally controlled and monitored production processes in which traditional manufacturing devices (machines, tools, etc.) are applied.	• De-centrally controlled and monitored production processes in which intelligent machines, robots, tools and intelligent workpieces are applied.
• There is no continuous communication between humans, machines, tools and workpieces.	• Humans, smart devices and smart workpieces communicate and collaborate with each other continuously.
• Lower machine and human resource utilization due to centrally controlled operation.	• Higher resource utilization, due to self-organizing, self-regulating and self-adapting operation.

Table 1. *Cont.*

Traditional Factory	Smart Factory
• The resources are limited, therefore the current practices in the utilization of resources are not sustainable.	• Sustainable production can be provided in the long term due to more efficient resource utilization.
• Limited and predetermined resources are available during the manufacturing; fixed production lines which are non-reconfigurable.	• Application of more flexible production and logistical systems and processes results in more unique and custom designed production.
• Electronics and information technologies (IT) are used, but devices (e.g., machines, vehicles, products, etc.) do not interact with each other.	• IoT technology allows devices to communicate and interact with each other through a network connection and data exchange of devices.
• Lower productivity, flexibility, sustainability and less efficient resource utilization result in lower competitiveness of enterprises.	• Higher productivity, flexibility, sustainability, and efficiency of resource utilization result in more competitive enterprises.
• Traditional production provides the required product volume and quality at higher production cost and longer lead time.	• Intelligent production provides—provides the required product volume and quality with minimal production cost and minimal lead time.
• Production of traditional basic commodities. Low product variety, high volume. Relatively long product life cycle of final products.	• Production of more innovative, more unique and custom designed final products. Higher product variety, lower in volume. Short product life cycle.
• Frequent errors in the production process result in wastes, extra costs and long lead times.	• Stochastic events and errors can be minimized, thus wastes, total costs and lead times can be reduced.
• A larger workforce has to be applied, therefore higher labor costs for the enterprises. Most of the workers are unskilled operators.	• Part of the workforce can be reduced and replaced by intelligent devices. A highly skilled workforce is needed for the programming and operation of the intelligent devices.

3.4. Main Elements of a Smart Factory

The Smart Factory is the integration of Smart Devices, humans (employees and customers) and Smart Products. The Smart Factory uses Smart Devices in order to satisfy customer demands, starting from Smart Products and Smart Services connected to the Internet. Then the Smart Factory collects and analyzes data using Smart Applications. Workers of Smart Factories have to possess high IT, production and logistical knowledge. IoT technology enables the customers to be involved in the production design process of Smart Products (Shrouf et al. 2014).

- The first part of the Smart Factory is made up of Smart Devices, i.e., Multi-Agent Systems (MAS) which can be formed by intelligent industrial robots, sensors, controllers, and CNC machines cooperating together to create flexible and competitive production processes and the joining logistical services.
- The second part of the Smart Factory is the humans. One group is the workers who create and apply the elements of Industry 4.0 concept (e.g., Smart Devices and communication network), which requires high IT, production and logistical knowledge. The second group is the customers, who can define the specification of their Smart Products to be produced due to the application of IoT technology. Thereby, customers can participate in the production design processes.
- The third part of the Smart Factory is the Smart Products (workpieces and final products), which sense the production environment with internal sensors and control and monitor their own production processes by communicating with Smart Devices.

Figure 4 shows the most important elements and areas of activity of a Smart Factory.

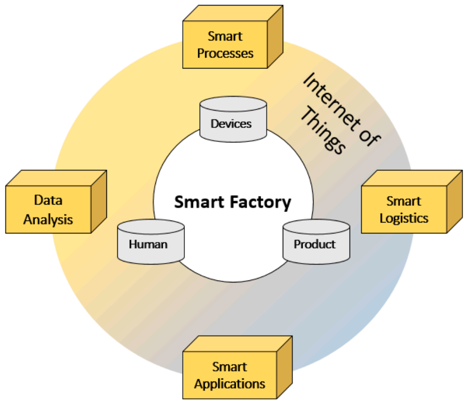

Figure 4. The main elements of a Smart Factory.

4. Multi-Agent Systems in the Smart Factory

Generally, the Multi-Agent System is a set of many Agents that represent real or virtual entities, operate in the same environment and are capable of perceiving and acting on the environment and communicating together, resulting in autonomous behavior in order to achieve interactions (Kaddoum 2008). Usually, an Agent is characterized by reactivity, proactivity, sociability, and autonomy (Sekala et al. 2018). In Smart Factories the Multi-Agent Systems present an essential core forming a self-organized and autonomous manufacturing system based on an industrial network and intelligent mechanism to achieve the sequence of operations required for production.

The concept of the Smart Factory is based on improved production processes due to more efficient utilization of physical resources, taking into consideration predefined constraints (delivery time, product quality, product type, etc.), in order to achieve the goal of production in case of unpredictable disruptions and problems when a certain number of Agents have to be activated in the same environment (Hernández et al. 2013).

Agents can be classified into four groups regarding to their activities (Wang et al. 2016a):

- Machining Agents (MA) perform a manufacturing or testing operations, e.g., a CNC machine, 3D printer or robots,
- Transport Agents (TA) are responsible for transportation of products, such as conveyors, AGVs, etc.,
- Product Agents (PA): Smart Products that are produced by intelligent manufacturing systems and are able to communicate with the machining and t transport Agents,
- Supplementary Agents (SA): e.g., buffers that temporarily store Product Agents.

4.1. *Collaborating Robots in Smart Factory*

Multi-Agent Systems include the collaborating robots using AI, which is an essential element of Industry 4.0 concept. Collaborating robots are autonomous robots that become more autonomous and cooperative. Intelligent robots can interact with people, machines, equipment, products and other robots in order to improve productivity and product quality. These robots can perform more complex tasks and manage unexpected problems.

The term machine-to-machine (M2M) communication is the association of information and communication technologies (ICT) with intelligent devices in order to interact together without human intervention. This M2M communication technology is used by collaborating robots (Amodu and Othman 2018).

A collaborating robot is able to interact with another robot in order to solve a problem in a complex situation. Application of the Industry 4.0 concept creates Smart Factories based on physical smart devices, thereby generally minimizing the number of workers in the workplace. However, a highly skilled labor force is needed for the programming and operation of the intelligent devices.

4.2. Operational Strategies in a Smart Factory with Collaborating Robots

There are many strategies and technologies in order to operate and control a manufacturing process in the Industry 4.0 depends on the production situations. We can define basically two scenarios in the Industry 4.0 concept:

1. **Normal Scenario:** When all of the manufacturing elements work correctly, agents (e.g., robots) collaborate and communicate together to achieve tasks according to a production plan. In this scenario each agent controls its own activity.
2. **Abnormal Scenario:** When a problem occurs in a production line which is caused by any of agents, this results in an operational problem in the manufacturing system i.e., malfunction, lost data or defective products. This abnormal situation can create many further economic problems.

    - Simulation: Simulation is an efficient tool of Industry 4.0, which provides the modeling and visualization of the manufacturing processes of the Smart Factory in order to avoid problems and achieve more flexible and more efficient production.
    - Artificial Intelligence: AI is the ability of robots to learn and think logically and autonomously, not only depending on programs written by people, but also independently. AI helps to create smart manufacturing environment where agents adapt to critical situations faster and make optimal decisions.

5. Role of Simulation Tools and AI in Improving Efficiency of Smart Factory

5.1. Simulation

3D Simulation in the Smart Factory describes the modeling and visualization of real process functioning or system behavior over time in order to predict, evaluate and validate the performance of complex stochastic systems, processes and production tasks. Thanks to the exponential growth of computing power, industrial simulation tools have been widely used in order to optimize the design and operation of the systems. The essential point of the simulation tool in the future industry is its ability to transform the basic concepts of the smart factory into reality owing to the exact structural and dynamic representation of production lines. This makes it possible to find the optimal behavior and control of the manufacturing units and identify cost reduction opportunities such as optimizing the direct and indirect workforce (Xu et al. 2016).

5.2. Artificial Intelligence

AI is recognized as a computer discipline that aims to model or simulate so-called intelligent human behaviors such as perception, decision-making, comprehension, learning, etc. (Lee et al. 2018). It is concerned with the development of computer programs capable of performing complex tasks. The concept of AI represents the digital brain of Industry 4.0 and is its driving force. It consists of the use of machine learning that allows machines to predict their future operations and allows them to learn from the experience independently. It also allows communication between the machines and the interfaces using distributed AI in the concept of multi-agent systems. Thanks to the sensors installed in the production systems, AI makes it possible to capture the energy consumption of individual machines, to analyze the maintenance cycles and then to optimize them during the next step. It can also indicate when operating data are faulty. As the amount of data increases, the system optimizes its efficiency and allows more accurate predictions. Using AI techniques, Industry 4.0 intelligent systems can, for instance, identify objects on conveyor chains with image recognition, sort them automatically, and identify product defects in terms of precision and quality.

- AI is a diverse field of scientific methods and includes several main technologies and techniques (Table 2).

Table 2. AI methods and their possible use in Industry 4.0.

AI Methods	Role Specification
Artificial Neural Networks	Generally used to carry out real-time flexible pattern recognition in industry using a variety of sensors. ANN can analyze very large amounts of data in real time and offer concrete answers to problems that may arise from the production process. Generalization and self-learning capabilities are used in handling modified conditions and scenarios.
Machine Learning	The ability of robots to learn from experience, to improve their performance and to adapt their behavior to new and changing environment.
Logic-Based AI	Knowledge representation and inference in all tasks and decision situations treated by the AI where binary logic is sufficient, like making a decision on starting an investment.
Fuzzy Logic	Imitation of the way of decision making in humans that involves all intermediate possibilities between the extreme values YES and NO. Mainly used in process control to make it more flexible.
Evolutionary and Genetic Algorithm	Very robust methods that can be used almost everywhere in quasi-optimum searching when time is not critical and model formulation is problematic
Methods inspired by living creatures, like Swarm Intelligence	Creation of multi-agent systems and complex structures characterized by self-reorganization and collective behavior planning and decision making capability

These soft-computing methods are integrated naturally with the classic optimization methods of mathematics and operation research to create a strong foundation for the design and operation of very complex production systems comprise of industrial, economic, and human aspects alike.

6. Case Study

This section presents a case study to emphasize the importance of robot cooperation, simulation and AI methods in the realization of the advanced technologies in Smart Factories. The first subsection defines a robot cooperation task. The second focuses on geometric modeling of the robots using CAD software and the documentation of features such as joint oriented properties and characteristics used in dynamic modeling. The URDF file for storing these data and the synchronization link to connect the design tools with the simulation software are also mentioned. The third subsection discussed the approach taken to solve one step in a robot cooperation situation, introducing an original cycle time optimization method that uses a whip lashing motion analog and utilizes the resources of the MATLAB R2018a Robotics System Toolbox. As an extension of the model, the determination of the trajectory having quasi-optimal cycle time is described with the integrated TS optimum searching method.

The cooperation of intelligent robots is a possibility and a need at the same time in modern Smart Factories. The intelligence of the robots essentially originates from the AI techniques (see Ballagi and Kóczy 2008; Dorigo and Sahin 2004; Momen and Sharkey 2009). Both robot-robot and human-robot cooperation will be a source of productivity improvement in unmanned Smart Factories in the close future (Ballagi et al. 2014; Ballagi and Kóczy 2010; Corke et al. 2005; Faber et al. 2015; Kóczy and Ballagi 2009; O'Hara and Balch 2004). In addition to kinematic modeling and trajectory planning, the solving of dynamic tasks of industrial robot arms has become an intensively researched area in the last decade (Al-Mashhadany 2010; Chen et al. 2014; Yaskevich 2014). The torque control of dynamically handled robot arms is studied along with the kinematics oriented design of trajectories (Chen et al. 2012; Peng et al. 2009; Sciavicco and Siciliano 2000). Our research uses the torque control capabilities of the MATLAB Robotics System Toolbox, similarly to the studies of Maged et al. (2015) and Piltan et al. (2012). However, the difference is that our research targets the determination of the minimal cycle time based on a new whip lashing motion analog in the first case study and with integration of TS in the second introduced study. The main question is, what are the efficiency gains of these proposed methods by reducing cycle times?

6.1. The Task

In this section we will present an example of a simple task, focusing mainly on the economical or efficiency characteristics of the modeled process. To find the most profitable solution, the research uses 3D modeling and simulation of plausible variations.

The task is the following: In the same environment there are two Mitsubishi robots, the first one on the left side of Figure 5 is a "RV-2AJ arm", which has 5 rotational joints, while the other is a "RV-2SD arm", which has 6 rotational joints. The RV-2AJ robot needs to help the RV-2SD reach the workpiece, which is far from its working space. The applied RV-2AJ robot is a favorite for such investigations and developments owing to its small size and plentiful capabilities (Ayob et al. 2014; Ayob et al. 2015a; Ayob et al. 2015b; Coman et al. 2009; Šljivo and Čabaravdić 2013).

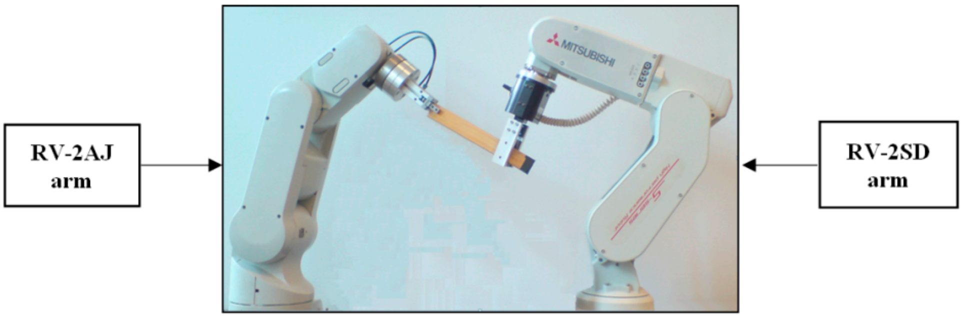

Figure 5. RV-2AJ robot aids the RV-2SD robot to get the necessary workpiece.

6.2. Robot Modeling

For the computational modeling and simulation, the first step is to provide the geometric and kinematic model of the robots. For this the 3D Computer Aided Design (CAD) software SolidWorks was used. The models of the two robots are shown in Figure 6.

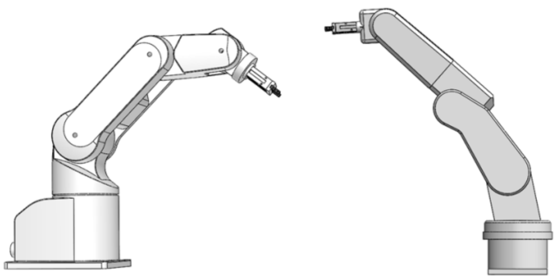

Figure 6. RV-2AJ and RV-2SD robot arms in SolidWorks.

The study of this scenario is based on trajectory planning and the methodology for modeling it in a virtual environment, starting from an acceptable trajectory and ending with a more economical optimal trajectory that needs less working cycle time. The workpiece location (the starting point of the trajectory) and the transfer point for the RV-2SD robot arm (the endpoint of the trajectory) were given, and the task was the determination of the trajectory of the motion between the two points needing minimal cycle time. For solving this task, not only the geometric parameters of the motion are important, but the dynamic properties of the full system. Because of this, the optimization process considers the trajectory geometry and the forces and joint torques that arise from dynamic behavior of the system, so the accelerations and masses of the robot arm parts also taken into account.

In the first phase of the analysis presented here the motion of the RV-2AJ robot arm is developed, where the starting point and the end point of the motion were given as the sender location of the conveyor belt and the transfer location to the RV-2SD robot arm.

SolidWorks allows us to export our models into other platforms that provide a flexible environment and perform closed loop control design while the simulation applications carry out our dynamic analysis of robots. This communication process is executed using two methods:

- **Simscape Multibody link:** This module allows synchronization between SolidWorks and MATLAB Simulink. Using this MATLAB add-on to convert RV-2AJ 3D model file to a Simscape model is automatic in XML format (Figure 7), so all the modules and robot parameters are presented in the MATLAB Simulink. Simscape is part of the toolbox of Simulink that is intended for modeling different engineering processes; the Mechanical and Multibody modules are suitable for our goals.
- **Creating URDF file:** In SolidWorks we can also create an URDF file as shown in Figure 8. This type of file regroups all the parameters of the robot (Links-Joints-Type of Joints-Coordinate systems-Inertia matrix-Joints limits). A URDF file can be executed in MATLAB software and also in many other simulation software.

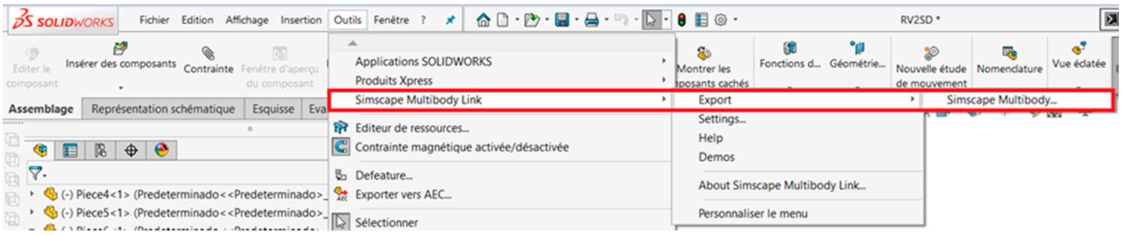

Figure 7. Simscape Multibody Link in SolidWorks.

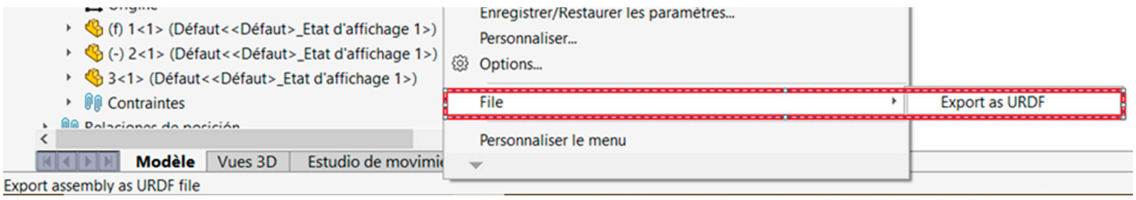

Figure 8. Generating a URDF file in SolidWorks.

Using these operations, we created XML and URDF files for RV2-AJ and RV2-SD robots in order to present them in Matlab Simulink software.

Different methods can be used for determining the optimal trajectory: an analytical method using derivatives of motion properties to find time minimum, a simulation based method integrated with a systematic search using AI in the space of trajectory variants, and a genetic algorithm based solution are also possible. Hereinafter the second variant, using AI search method and 3D simulation, is selected and the SolidWorks and Matlab Simulink integration was used for determining the time values for comparing different trajectories.

6.3. Simulation via MATLAB

Using the XML and URDF file of RV-2AJ robot arm the analysis and comparison of trajectories efficiency was carried out in MATLAB Simulink. In the first phase a trivial motion path and a more sophisticated motion path were generated and analyzed. The second phase of the research will involve the use of randomly generated set of possible paths considering the limitations of the robot and the workspace and the AI method TS for determination of the quasi-optimal trajectory among the potential paths.

The trivial trajectory is determined by calculating an angle step dividing the (end angle)—(start angle) difference with a constant for a given joint and the discrete positions of the joint are generated using joint coordinates incremented with the angle step. The method was repeated for each joint with the same divisor constant. With this method, every joint needs the same time to reach the end position from the start point, but the constant angle velocity will be different from joint to joint.

The sophisticated trajectory uses a whip lashing motion analog suggested by us to decrease the cycle time of the robot. In the whip lashing motion, the weightier parts of the whip that are close to the hand start to move first, followed by the end of the whip, as the deceleration energy of the larger connecting parts provides an accelerating motion and the whip end catches up on its arrears of motion. The robot acts as a whip, in the starting period the smaller ending parts fall behind the larger parts that are closer to the base and move closer to the larger parts, thus decreasing the rotational inertia of the full robot arm, but at the end of the motion they take the deceleration energy of the larger parts and catch up on the arrears of angles. In this model the deceleration energy of the larger parts of the robot arm accelerates the rotation of the smaller arm parts and is not absorbed by the base of the robot. The method results in smaller torque at the larger joints at the same time as the trivial method, where the rotational inertia of the arm is larger.

The modeling of the two methods can be followed in Figure 9, where the three views of the united starting and ending position of the robot body are shown with the paths of the moving workpiece point. The lighter blue trajectory depicts the motion produced by the sophisticated method and the darker brown represents the trivial method's path.

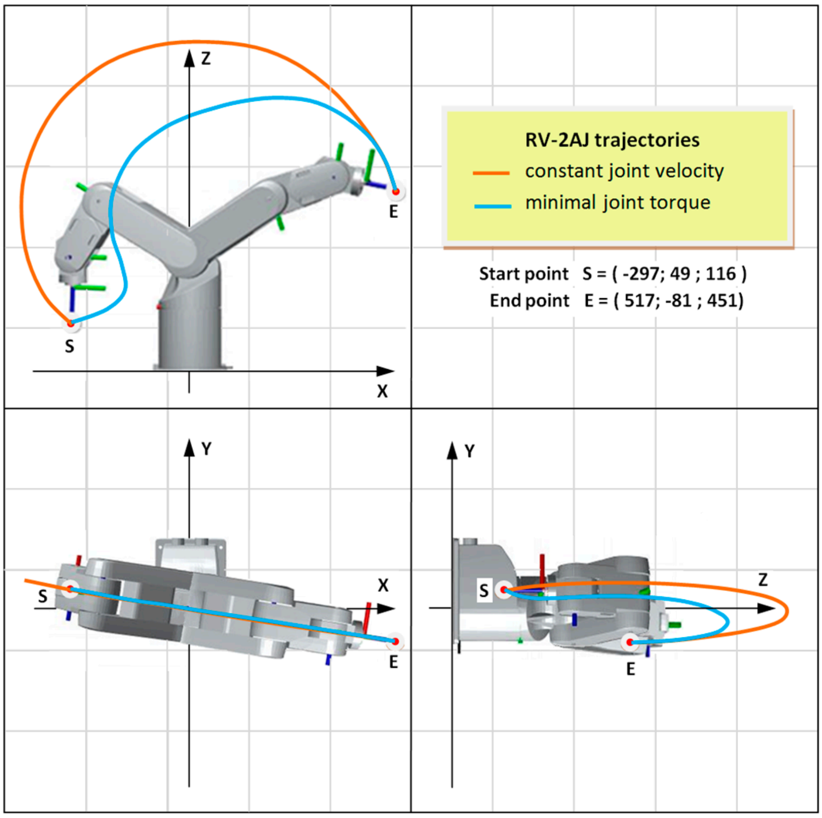

Figure 9. Trajectories between the S start point and E end point.

To determine the smallest possible cycle time, which is limited by the allowed torques of the robot joint drives, a successive approximation algorithm was used. This algorithm starts with a cycle time that is large enough for travelling the trajectory with joint torques under torque limits, then decreasing the expected cycle time the algorithm returns until a final cycle time is yielded with a torque maximum that is close to the corresponding torque limit.

For this we can use the RigidBodyTree Object of the robot from URDF file, which defines the robot parts and joints parameters, and the *inverseDynamics* MATLAB Robotics System Toolbox function, which can calculate the torque function for every joint while providing a previously set expected cycle time for travelling the trajectory. The torque function gives the joint torques for the joints for every time point of the motion along the trajectory. These torques move the robot hand along the trajectory throughout the set expected cycle time.

The pseudocode of the time minimization is shown in the following for a given trajectory, see Cycle Time Minimization Algorithm (Algorithm 1).

Algorithm 1. Cycle Time Minimization Algorithm.

algorithm *Cycle-time determination* is

input: RigidBodyTree Object *RBT*,
starting pose of the robot *sp*,
trajectory definition data *td*,
starting cycle time *sct*,
starting time step *sts*,
ending time step *ets*

output: Expected cycle time *ct* such that time step *ts* ≤ ending time step *ets* and the joints torque maximums *mt*[*j*] ≤ allow torques *at*[*j*] for every joint *j*.

```
ts ← sts
ct ← sct + ts
do
    torque overload flag tof ← No
    ct ← ct - ts
    for each joint j in Joints do
        for every time point i in TimePoints do
            calculate torque[j][i]
        mt[j] ← max_i torque[j][i]
        if mt[j] > at[j]
            tof ← Yes
    if tof = Yes
        ct ← ct + ts
        ts ← ts/2
while ts > ets or tof = Yes
return ct
```

The simulation proved that the sophisticated motion path results in a time savings of more than five percent compared to the cycle time of the trivial method at the same limiting maximum torques at the joints. The exact value depends on the weight of the moved workpiece.

In the second phase of the research the use of TS AI method is intended. In opposite to the task of the first phase, where only two different trajectories were given and compared by cycle times minimized based on maximal joint torque utilization, this improved phase of the research will focus on determining the quasi-optimal trajectory form that has the minimal cycle time among the possible many trajectories between the given start point and end point. The space of the search is broader, so the many checked trajectories will be generated randomly. TS is a locally informed search method, which means that neighboring trajectories are considered in one step of the algorithm. Neighboring means that the differences between the 3D space coordinates of the holder points of the two trajectories are below a given limit. Consequently, the middle parts of the neighboring curves are not far from each other. For generation such trajectories the Trajectory Generation functions of the Manipulator Algorithms in the Robotics System Toolbox can be used. The polynomial trajectory generation results in spline curves going through waypoints. Neighboring trajectories can be generated by changing the coordinates of a randomly selected waypoint. Starting from a trivial trajectory applying such local modifications of the trajectory spline the TS algorithm can move from trajectory to trajectory to reach trajectories that need less cycle time.

The method is similar to an inverse hill climbing algorithm but the essence of the TS is that it can get out from the set of neighboring trajectories that have locally small cycle time, disabling the checked curves in this set and looking for neighbors among the trajectories further away, even if these have larger cycle time. In such a manner the TS algorithm can discover new regions for the waypoints—new trajectories—and after a short discovery period, it can find trajectories with a smaller cycle time than the previous local minimum. It can be imagined in 3D space as if the spline of the starting trajectory changes its shape with local modifications and reaches a final form that has the least cycle time among the checked ones. Generally, in this modification process, the value of the cycle time fluctuates, but the deepest local minimum value and the corresponding curve are always stored and at the end of the search, it gives the cycle time of the quasi-optimal trajectory.

7. Conclusions

The Smart Factory concept integrates the main elements (autonomous robots, IoT, Big data, etc.) of the Industry 4.0 production philosophy in which each element (intelligent machines, tools, intelligent workpieces, and humans) of the network-linked intelligent system communicate with one another in order to realize self-organizing, self-optimizing, and more competitive production.

In the first part of the study the concept, main elements and operation of a Smart Factory were introduced. The significance of the first part of the study was that the economic and social operational requirements; furthermore, the economic and social impacts of Smart Factories in the practice were summarized (Sections 3.1 and 3.2) and the characteristics of the traditional factory and the Smart Factory were also compared (Table 1).

In the second part of the study the application of the collaborating robots, Simulation of the operation of robots and the AI used by cooperating robots were introduced. Furthermore, the study is also practice oriented, because the efficiency improvement of the production processes—in which collaborating robots are applied—was introduced by the application of a 3D design and a Simulation software.

In the case study an assembly task was presented, focusing mainly on the economical and efficiency characteristics of the modeled process. Its aim was to find the most profitable solution by the application of 3D modeling and simulation of plausible variations. In the case study there are two Mitsubishi robots in the same environment: "RV-2AJ arm" with five rotational joints and "RV-2SD arm" with six rotational joints. The role of the RV-2AJ robot is to pass a workpiece to RV-2SD.

The main significant added value of the research is that a real case study is introduced for simulation of the trajectory of a five-degree-of-freedom robot arm introducing an original whip-lashing analog in the robot operation. The conclusion of the case study was that the simulation proved the sophisticated motion path resulted in more than five percent time savings compared to the cycle time of the trivial method at the same limiting maximum torques at the joints. The method will be used for the RV-2SD robot in a second phase and for the two cooperating robots as an integrated collaborating system in the third phase of the research. In the future, robots will be able to perform these calculations for themselves, as collaborating and intelligent robots.

The time saving advances using the original whip-lashing analog can be achieved mainly in the case of motions that span a larger region of the 3D space of the robot. The use of TS integrated with the introduced cycle time minimization method based on maximal utilization of joint torque possibilities can be used for every robot motion planning where there is no object in the determined path. This trajectory optimization method also needs powerful computational hardware for considering many waypoints because of its iterative property and the embedded inverse Dynamics MATLAB toolbox function.

It can be concluded that the establishment of the Smart Factories and application of Smart Devices (collaborating robots, machines, sensors, etc.) and Smart Workpieces will be essential in the future to realize more competitive, flexible, sustainable, and custom-oriented production. It can be also summarized that the application of Simulation and AI methods for collaborating robots are essential tools for efficient and optimal operation of production processes.

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