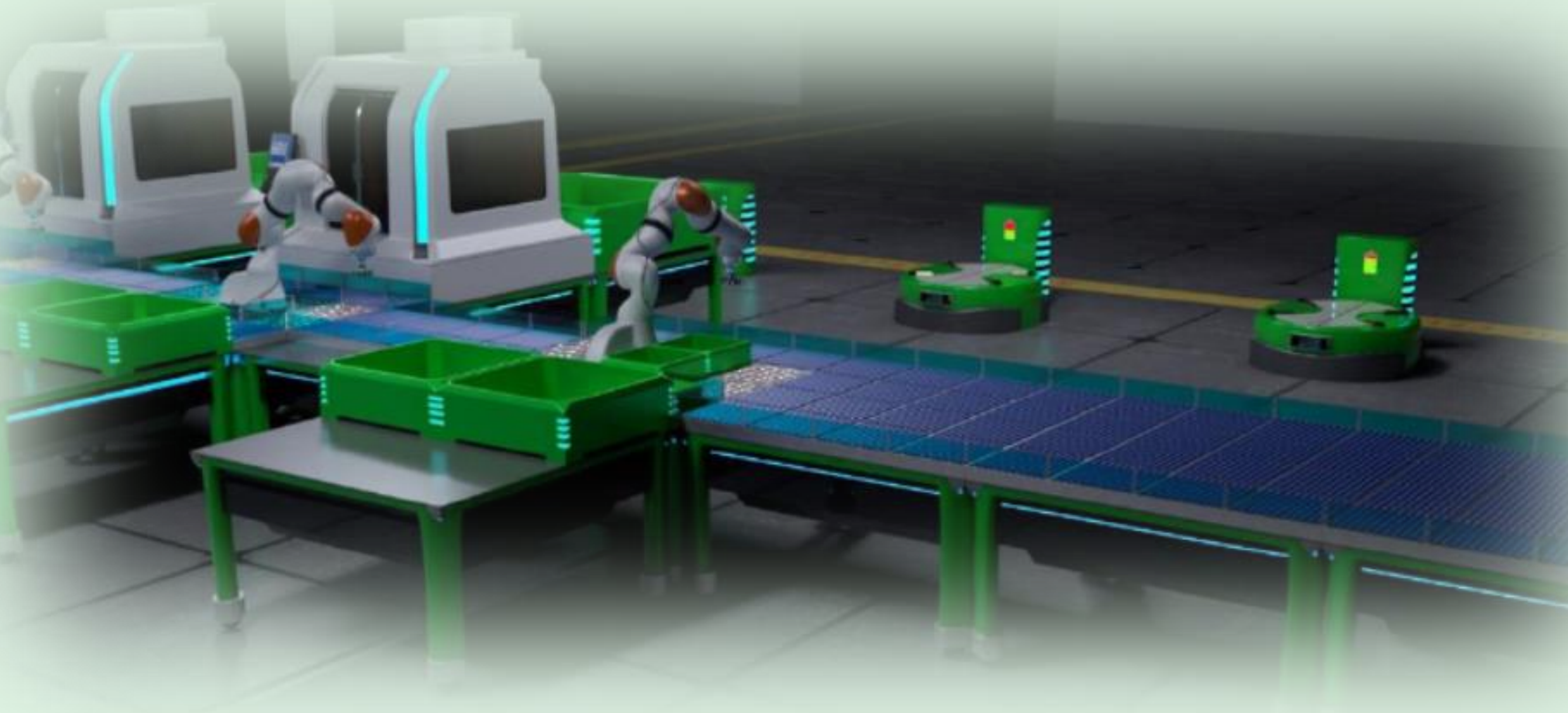

New Trends in the Development of Future Production Systems

Milan Gregor
Štefan Mozol
Patrik Grznár

Milan Gregor - Štefan Mozol - Patrik Grznár

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This publication is dedicated by its authors to the department of the Department of Industrial Engineering, which has been operating at the Faculty of Mechanical Engineering of the University of Žilina for more than 50 years and which trains specialists for Slovak and international organizations.

The Department of industrial engineering in Žilina has built a creative and motivating research environment, in cooperation with the public sector and industry has provided support resources for research, designed, and developed pragmatic mechanisms for the rapid application of emerging innovative proposals in practice. Thus, thanks to many years of effort of its staff, it was possible to realize a permanently functional, real connection of academic theories with the needs of practice.

As one of the executives of the Department of industrial engineering says: "*Our department is like an aircraft carrier. When the aircraft consumes fuel, it will use the aircraft carrier to replenish and restore the forces of the crew. Thus, the staff and graduates of our department are constantly replenishing the latest theoretical knowledge and renewing their own creative forces*"

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First edition.

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LIST OF ABBREVIATIONS

ABM	Agent-Based Manufacturing
ACO	Ants Colony Optimization
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AIE	Advanced Industrial Engineering
ANN	Artificial Neural Network
APM	Atomically Precise Manufacturing
CAS	Complex Adaptive System
CEIT	Central European Institute of Technology
CMOS	Complementary Metal-Oxid-Semiconductor
CPS	Cyber-Physical System
DF	Digital Factory
DSS	Decision Support System
ERP	Enterprise Resource Planning
ES	Expert Systems
FMU	Factory Mock Up
FoF	Factory of the Future
HMI	Human Machine Interface
HML	Human Machine Learning
HMS	Holonic Manufacturing System
HVACDE	Haptic-Visual-Auditory-Collaborative Design Environment
ICT	Information and Communications Technology
IMS	Intelligent Manufacturing System

IoT	Internet of Things
IIoT	Internet of Industrial Things
IoMT	Internet of Manufacturing Things
K-waves	Kondratjev waves
MAP	Mobile Automated Platform
MAS	Multi Agent System
MPS	Modular Production System
MRS	Mobile Robotic System
MTO	Make To Order
MWSN	Mobile Wireless Sensor Network
NGMS	New Generation of Manufacturing System
OEM	Original Equipment Manufacturer
PLC	Programmable Automation Controller
PSO	Particle Swarm Optimisation
RFID	Radio Frequency Identification
RMS	Reconfigurable Manufacturing System
RTLS	Real Time Locating System
SyNAPSE	System of Neuromorphic Adaptive Plastic Scalable Electronics
VDMS	Virtual Design of Manufacturing Systems
ZIMS	Zilina Intelligent Manufacturing System

PREFACE

Humanity is confronted with completely new paradigms that can simply be described as exponential and combinatorial changes. The use of new, advanced technologies and business model innovations result in disruptive changes. Many products and markets disappear in a very short time and are replaced by exponentially acting innovations.

In the classic business world, companies had plenty of time to adapt to changes. However, disruptive innovations bring such rapid and dynamic changes in the external environment that many companies are no longer able to fully adapt and are in danger of disappearing.

Industry 4.0 is based on the massive application of digital technologies. If businesses want to survive, they must find ways to adapt. Digitization requires the implementation of sensory systems, the Internet of Things, cloud computing and many other technologies. Advances in the field of Artificial Intelligence enable the application of intelligent algorithms directly in production processes. Their management can therefore use more prediction than statistics. The use of intelligent sensors, automatic data collection and analysis, and autonomous decision-making bring a paradigmatic change to the production environment. Manufacturing systems are becoming intelligent, and this type of manufacturing system has been referred to as - Intelligent Manufacturing Systems (IMS) or Smart Manufacturing.

Multi-agent control systems are increasingly being used for the management of production systems. Complicated production systems thus become complex, with all the consequences that complexity brings. Businesses must therefore look for new ways to respond to both external and internal changes.

The presented publication brings a set of knowledge about the changes that are gradually penetrating industrial enterprises, and which are often referred to as enterprises of the future Factory of the Future.

This publication is divided into eight chapters. In the first chapter, the authors indicated the long-term trends of economic development and the main factors that will influence the development. The second chapter contains an introduction to the issue of Factory of the Future. The third chapter evaluates the development of current production concepts. The fourth chapter contains information about the main technological changes affecting the organization of Factory of the Future.

The fifth chapter is dedicated to the Industry 4.0 phenomenon and provides brief information about the new environment for the future manufacturing concepts. In the sixth chapter, the authors discuss selected support tools for Factory of the Future. The seventh chapter contains information about the development of manufacturing paradigms over time.

In the eighth chapter, the authors discuss some new concepts of production systems. The final chapter summarizes the findings.

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The authors would like to thank Ing. Radovan Furmann, PhD. and Ing. Andrej Stefanik, PhD. from the company Asseco CEIT for allowing access to documents from the Asseco CEIT archive. The submitted publication presents part of the results of the research work from the Department of Industrial Engineering, Faculty of Mechanical Engineering, University of Žilina, students and PhD students of prof. Ing. Milan Gregor, PhD.

INTRODUCTION

Classic, static manufacturing lines still maintain their position in manufacturing. In many cases, their economic efficiency is more advantageous than that other, more flexible manufacturing concepts. However, the manufacturing environment is gradually changing. Static manufacturing concepts are expanded and often replaced by modular manufacturing concepts. The reason for this is the changed behaviour of customers.

Future manufacturing systems will differ significantly from todays. The changes will be caused not only by pressure from customers on variability of new products, but also by revolutionary changes due to technological innovations.

The most significant factor that influences the existing manufacturing environment is the customer. He wants to configure his future product in detail today and does so online. Therefore, manufacturers are forced to rapidly develop online digital configurators for their products. The digital model of the future product serves as an order. The manufacturer implements it in the method of manufacturing to order - Make To Order (MTO). Some customers want to be present at the "birth" of their product, they want to see with their own eyes how it is produced. Therefore, several manufacturers already today allow their customers such an experience through the concept of the so-called Glass Factory.

The manufacturing factory must be able to produce the desired product in the shortest possible time. Future manufacturing will produce products that will be adapted to the requirements of a particular customer, highly sophisticated, complex, capable of offering new functionalities and therefore require a completely new manufacturing environment.

The customization and personalization of products is a complex problem that researchers are already trying to solve today. On the one hand, they use the appropriate design of new products, also known as modular, ***reconfigurable products***. On the other hand, they are trying to increase the flexibility of the manufacturing system, which today we also refer to as ***reconfigurable manufacturing***. However, future manufacturing systems will use completely new principles in their operation.

The skyrocketing complexity of products and manufacturing systems has necessitated the development and use of completely new methods and approaches for product design and manufacturing. This was the reason why new technologies were created, referred to by the common name of Digital Factory or Virtual Factory.

The drivers of the development of Factories of the Future can be classified into two independent groups:

- *Emerging technologies* – technologies that are often overlooked at first and can later transform entire industries or service sectors. We also call these propulsion forces as ***push forces*** because changes occur under the influence of technological pressure.
- *Market changes*, changes in customer requirements – these changes can often be tracked as long-term trends. Customers ask for products (services) that better and more accurately satisfy their requirements, which manufacturers realize through the customization and personalization of products. Since customers make pull with their demand, we also call these changes ***pull-based forces***.

The aim of this book is to present the latest trends in the development of Factory of the Future and to present selected technologies that form the backbone of technological change and transformation that is gradually taking place in the industry. The book also presents the results of research carried out in cooperation among the Department of Industrial Engineering of the University of Žilina, the Institute of Competitiveness and Innovation of the University of Žilina and the Central European Institute of Technology - Asseco CEIT. The book is intended for specialists in the field of Factory of the Future and for management of production companies.

1 A VIBRANT ECONOMY – DRIVING CHANGE

In research, it become accustomed to referring to long-term cyclical changes in the economy as a ***vibrant economy***. The capitalist economy is cyclical, and its functioning resembles a pendulum. This term refers to the cyclical behaviour of the world economy, represented, for example, by a change in the development of gross domestic product (known long-term economic cycles, K-waves). The development phase of these cycles is always started by the discovery and use of new, revolutionary technologies, also referred to as emergent or breakthrough technologies. These technologies make it possible to kick-start a new economic cycle and serve as drivers of economic growth. Figure 1-1 shows the principle and mechanism of such long-term economic cycles, also known as K-waves. Realistically, if we were to use gross domestic product, for example, to follow the course of the wave, the whole curve would have an upward trend. Economists say that economic growth is a necessary condition for maintaining a viable economy (inflation, competition, etc.).

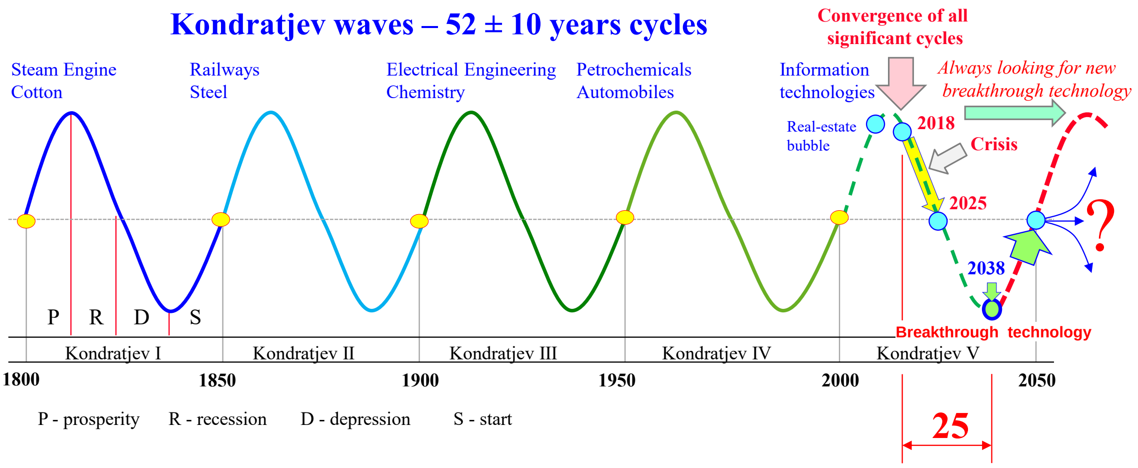


Figure 1-1 Kondratjev waves (K-waves)
Source: Gregor,M. (2014)

Thanks to the Austrian economist J.Schumpeter, K-waves (Kondratjev waves) became popular by using their principle as a mechanism in explaining innovative changes. Economic cycles are an objective reality, and here, too, the pendulum does not stop halfway.

Economic growth is a philosophical question. It reflects our attitude to life. Growth at all costs is meaningless, albeit economically justified. Mass psychosis, we can also call it growth disability, forces people, individuals to adapt. Although not all of us are comfortable with this approach, the mass of people forces us to take steps that promote steady economic growth. Why do this mass of people? Are they aware of their behaviour or do they do it for the same reasons as I do? Because the majority, do it? It is mysterious and nonsensical at the same time, and in the literature, it is called the "Abigen Paradox".

What is less considered when studying K-waves is the fact that not only the economy behaves cyclically, but also changes in the social sphere are closely tied to cyclical economic changes. In practice, this then means that technological change will kick-start economic growth, which also requires rapid changes in the social sphere. At this stage of development, usually rapid technological growth is not reflected in rapid growth in the social sphere. Preparing people for the use of new technologies is lagging, which creates contradictions and gradually creates a brake on technical progress (Figure 1-2).

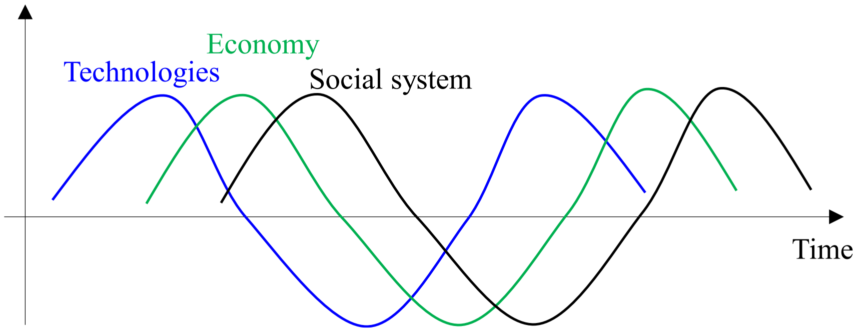


Figure 1-2 The relationship - technology, economy, and a social system
Source: Gregor,M. (2015)

On the other hand, in the shorter term, we are witnessing changes in industry that highlight the importance of selected factors for economic growth. Over the past fifty years, the meaning that is attributed to people and the technique that we tend to call the pulsating mechanism has changed cyclically (Figure 1-3).

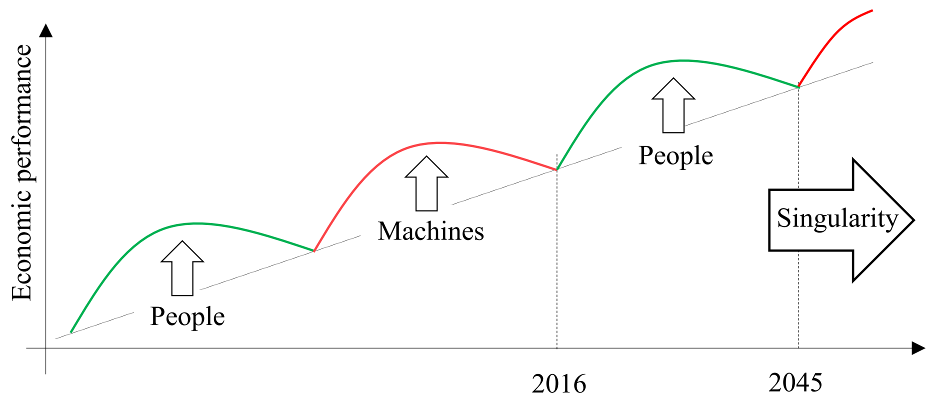


Figure 1-3 Moving towards a singularity
Source: Gregor,M. (2015)

Scientists define the decisive directions of technological progress as follows:

- *Artificial intelligence*, whose algorithms enable the intelligent behaviour of technical systems and whose research is directed towards the development of the digital brain.
- *Robotics*, where research runs in a variety from nanorobots (nanobots) to mobile humanoid robots (humanoids).
- *Nanotechnologies*, for which research began in the field of nanomaterials and currently the main challenge has become the development of a molecular assembler. Although it exists in nature in living biological systems, its implementation in dead technical systems is still a dream of the future.
- *Genetics*, where, after the decoding of human DNA, there are the greatest expectations of changes in health, longevity, and quality of life.

The future is stochastic, not deterministic. Therefore, it is difficult to believe the predictions made by various reputable companies. The butterfly wings effect says that everything in the world can change with one movement of butterfly wings, and the only certainty is change.

1.1 GLOBALIZATION AND MEGATRENDS

Globalisation is, by its very nature, the elimination of regional disparities for the purpose of creating common markets and the penetration of new technologies or ideas in a global format. Globalization can advance societies as well as destroy them. However, when properly implemented, it represents an environment that, in terms of innovation, forces companies to respond to changes in the global perspective with their product base. Competition in global markets represents an engine for the development of knowledge in various industrial areas. Companies strive to apply new technological advances in such a way as to reduce the cost of manufacturing a product and thus increase their profit or be more competitively successful in the market with the price of their products. As positive as it is, it also has a downside. So, for example, countries with a small, developed industry are not able to protect themselves against the influx of products that, due to technological maturity, are many times cheaper than domestic ones. This puts many companies in a boom or bankruptcy, where investment in innovation and development is not possible. Many states therefore protect businesses against the influence of globalism and large multinationals. The waves of globalization can be divided into 2 stages. First, economic experts call *Globalization 1.0*. This first wave resulted in the emergence of a middle class in developing countries and China, and the disappearance of a strong middle class in developed countries. The new second wave of globalization is referred to as *Globalization 2.0*. This will affect the middle class in developed countries, automate all work and strengthen the importance of fast-growing economies, also referred to as BRICS countries. As such, the concept of globalization was launched in the USA, where lobbying companies sought to have one country set the rules. This has forced many countries to reconsider their relationship with globalisation. Therefore, *Glocalization* becomes a new term, which means that each country builds its own, local relations, that is, what suits its interests. Globalisation is turning into Glocalization, that is, a unipolar world is turning into a multipolar one, and local and regional interests and themes are growing stronger. Globalization was started by the USA. The goal was to fulfil the intention that one country would determine the rules to which the whole world had to adapt. It suited the interests of this country. However, globalization is ending, and the country that most contributed to its creation, the USA, is also helping to end it. Capitalism, as we have seen and known it until now, is also coming to an end. The era of post-capitalism is coming, which is referred to as "digitalization". Digitalization creates ideal conditions for centralization and total control of all processes. So, is it a return to communism? It is not! It will not be the people who will control and govern, but a narrow group, known as the "Global Predictor".

The world is constantly confronted with a change in people's thinking, which is influenced by technological development, as well as the development of human potential made possible by automation. Depending on his discretion, a person chooses a certain trend of his preferences. However, his preferences can be considered for a wider group of people because, whether a person realizes it or not, he is programmed by the media, social networks as well as social relationships with others. Therefore, if a certain group of the population prefers a certain direction and we identify it, our product is marketable to a wider group of potential customers. He was the first to specify the concept of megatrends (Naisbitt,J. 1982). In his book, he describes the future with which humanity will be confronted at the turn of the millennium. He defined megatrends as the direction of long-term political, economic, and cultural changes in society that occur when transforming the industrial period into the post-industrial period.

Currently, according to Gregor,M., Magvaši,P. (2014), the following megatrends are identified as the main ones: demographic change, individualism, social and cultural disparity, health and growing life expectancy, gender role change, new mobility patterns, digital culture, learning from nature, artificial intelligence, technology convergence, Globalization 2.0, knowledge economy, entrepreneurial ecosystems, changing the world of work, new patterns of consumption, lack of energy and resources, climate change and environmental pollution, urbanization, a new political order of the world, and a global security risk.

Megatrends represent significant growth potential. A correct understanding of megatrends and the preparation of future manufacturing systems in their spirit helps to increase the competitiveness of the factory compared to others. Ultimately, however, megatrends spur the emergence of innovations, without which the factory will not be able to assert itself. As a result, pressure is exerted on changes in products, production and assembly manufacturing systems.

2 FACTORY OF THE FUTURE

The latest trends in supporting productivity growth in the 21st century, in which Europe has a leading position, are oriented towards further automation, informatization, digitization, digital enterprise and intelligent industrial solutions. Digitization, computerization and even system solutions are becoming the main source of productivity growth. Innovative solutions are developed as plug and play, plug, and produce to minimize downtime. Montorio,M.,Taisch,M. (2007a) and Montorio,M., Taisch,M. (2007b) have developed a forecast of further technological development, based on pull and push factors, as shown in Figure 2-1.

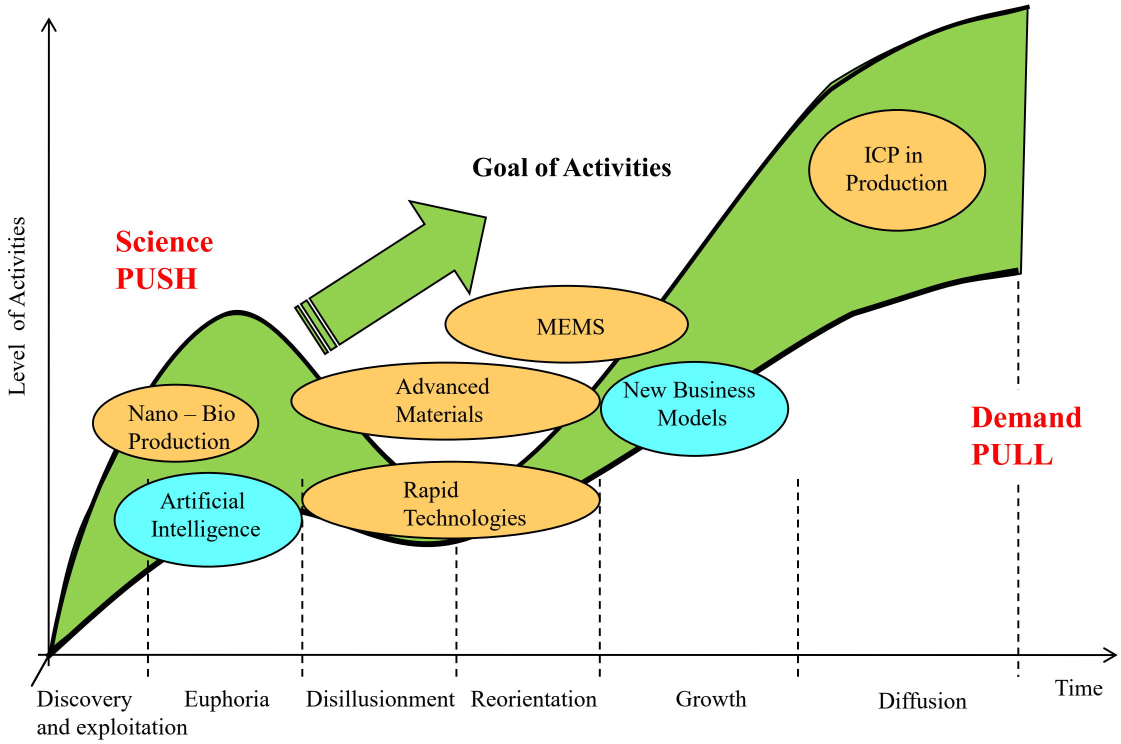


Figure 2-1 Technologica Growth – Pull/Push
Source: Montorio,M.,Taisch,M. (2007a)

Prof. E.Westkämper, from the Fraunhofer Society (Germany) developed strategic development trends within the activities of the ManuFuture - EU European Technology Platform, which he labelled as **Advanced Industrial Engineering (AIE)** and which include three dominant areas: *adaptive manufacturing, business networks and digital engineering*. The development of them is illustrated in Figure 2-2.

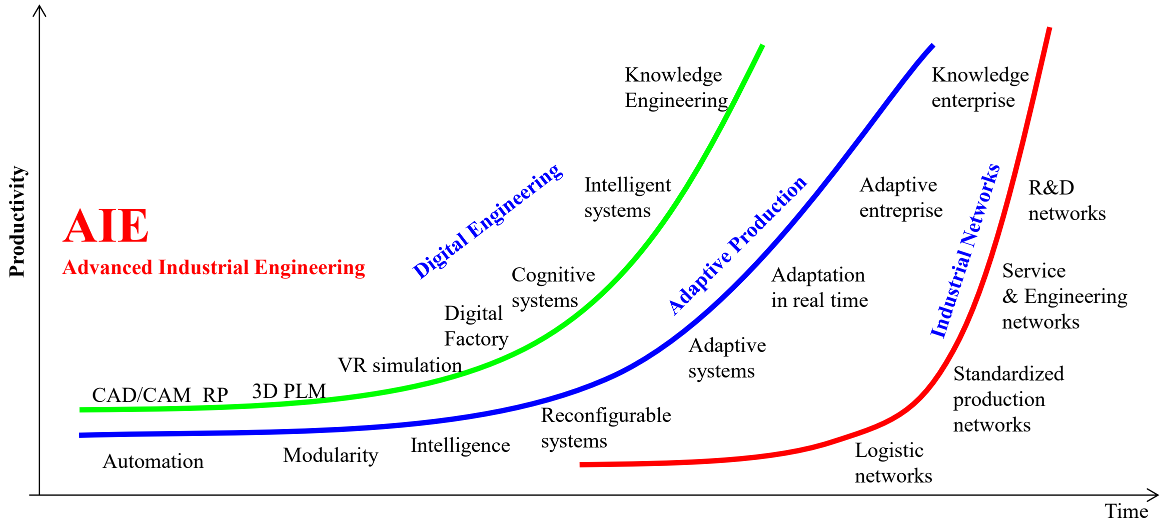


Figure 2-2 Future development trends
Source: Jovane, F., Westerkämper, E., Williams, D. (2009)

The demand for adaptability of production systems, i.e. the ability to quickly adapt (adapt) to external and internal changes, has become dominant in production systems. Production systems that meet the requirement of adaptability are called *Adaptive Production Systems.*

Adaptive production is a concept that consists of the following main elements (Gregor,M., Gregor,T. 2015):

- Holonic system of autonomous production management in real time.
- Modular structure supporting reconfigurability (plug and produce).
- Mechatronic systems.
- Sensors and device actuators (systems for internal actions).
- Sensors for the environment of the production system (systems for external actions).
- Simulation - emulation systems for decision support.
- Standardized interfaces (mechanical, electronic, software, network, ...).
- Learning system (before action, in action, after action).
- Knowledge base, best practices database.

The concept of adaptive manufacturing is shown in the Figure 2-3.

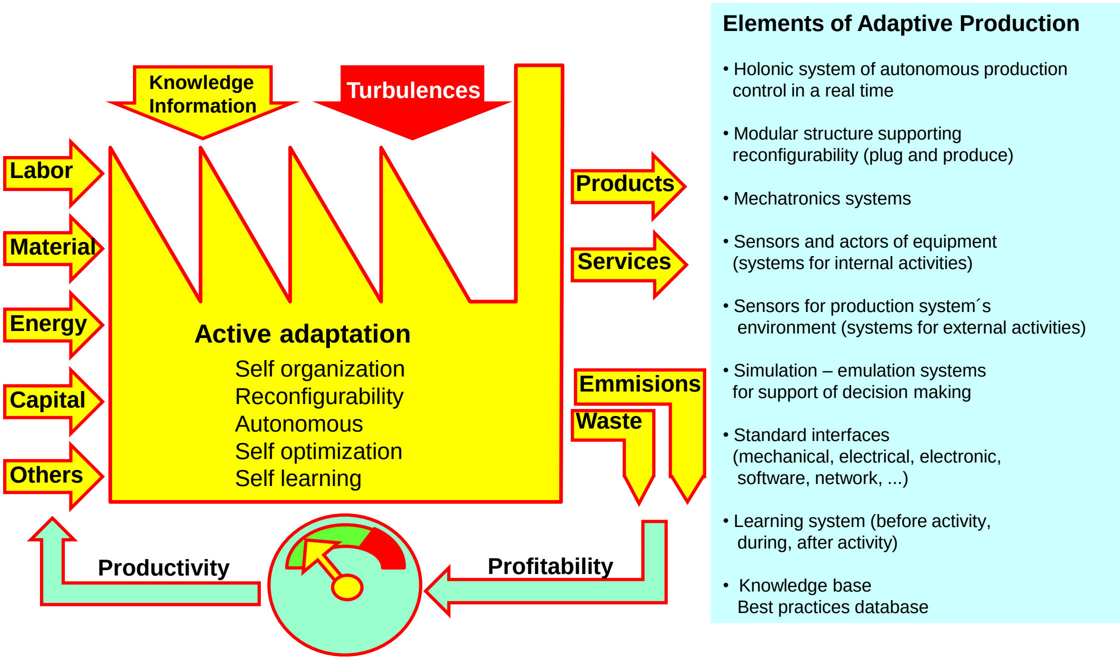


Figure 2-3 Adaptive Production
Source: Gregor,M.,Gregor,T.(2015)

Network production is a concept that is supposed to guarantee the co-operation of individual elements of the entire logistics chain and its functional optimization. Such network production concepts are sometimes concepts are mislabelled as virtual enterprises (Virtual Factory).

Digital production - enables the entire development of the production system to be implemented in a digital environment (digital enterprise model). When such a model is completed, verified, and validated, it is simply transferred to the control system of a real factory. Production is carried out based on designed digital models of products, on real production equipment. Therefore, the digital enterprise model must integrate buildings, people, technology, transport, management, energy and energy system, maintenance, etc. Coping with such demanding tasks is only possible with the support of hierarchical data models (for example Standard IEC 62264). The digital production model represents a parallel, virtual, simplified image of the production system. This approach makes it possible to simulate in advance the future behaviour of the production system under changing input conditions (representing endogenous and exogenous events). The principle of this concept is shown in the Figure 2-4.

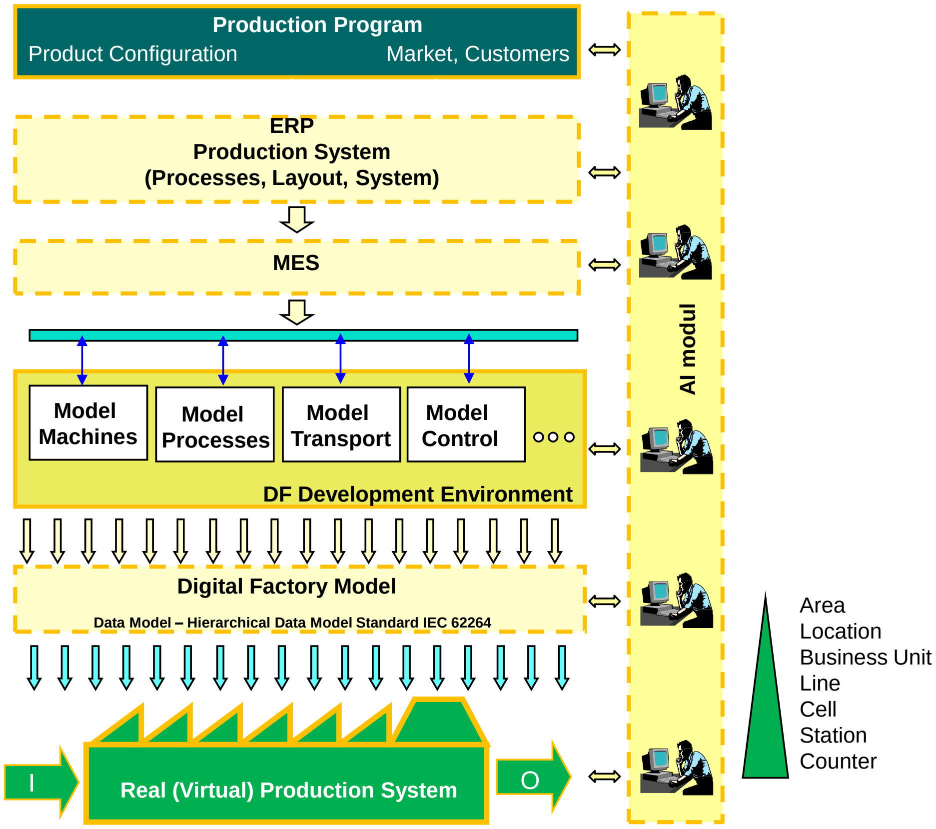


Figure 2-4 The principle of applying virtual business models to real businesses
Source: Gregor,M. et al. (2011)

A new source of productivity growth in the following stages of development will certainly be intelligence (artificial intelligence), the application of knowledge systems and intelligent holonic solutions. The main product sold will be knowledge. Today, behind the closed doors of research laboratories, there is a stormy and secret research in the field of humanoid robots that will take over the entire service area in factories. Already in the 18th century, Elli Whitney proposed the principle of modular construction of products. Modularity was gradually transferred to the area of tools, machines, production lines and production systems. Currently, modular enterprises are being developed. It is the tools and technologies of the digital enterprise that provide support for the design of modular enterprises that entrepreneurs integrate in the global space in a plug and work manner. Such complicated and sophisticated systems require completely new approaches to their design and testing.

Current research in this area is focused on the modularity of the entire value chain, which works as an autonomous and cooperating network. Such systems can only be designed using computer simulation. Virtual networks, created ad hoc when changing customer requirements and fundamental market changes, require immediate reconfiguration of the entire system. Changing the configuration of such complex systems can only be studied and optimized using simulation. All the above only documents the efforts of entrepreneurs in search of permanent competitive advantage and intensification of productivity growth.

2.1 HOLISTIC OR REDUCTIONISM?

What has been happening in the last 20 years in the field of manufacturing and new technologies can simply be called '*reductionism*'. Many scientists reduce the problem of the whole to their discipline, an isolated area, declaring it the only correct one. Instead of holism, we are increasingly immersed in reductionism. Emergence (the emergence of new entities) has its opposite in synergy (synergy of existing entities).

Manufacturing systems are intricately interconnected socio-economic systems. New technologies such as the digital twin, 3D printing, digitization, artificial intelligence, etc. are just elements, tools of something bigger, of the whole.

We can ask ourselves: What is all this supposed to serve for? Who is it supposed to serve? Who benefits from all this?

Advanced manufacturing systems are strongly interconnected systems where man, machine, technology, material, and environment work together. We refer to complexly interconnected technical systems as cyber-physical systems (CPS). It should be added that in the coming decades it is more correct to talk about socio-cyber-physical systems, since man is and will remain part of them for a long time.

Systems interconnected in this way have a goal-oriented behaviour. Ensuring goal-oriented behaviour requires, first, the setting of goals and a decision on how (by road) these goals will be met. The formulation of objectives and the strategy for their achievement is based on the acquisition and use of knowledge. The fulfilment of the objectives is ensured by the control system. The latter uses a set of controlled factors, the change of which achieves the optimal behaviour of the controlled system or, in other words, the target values of the parameters of the controlled system. Automatic setting of optimal values of significant factors requires the use of artificial intelligence technologies (neural networks). The latter cannot work in isolation, but in synergy with its surroundings. Such behaviour is directed towards a holistic system.

The control system must function similarly to a person's immune system. The latter consists of two differently functioning parts. The first is called non-specific, and the second is a specific part of the immune system. Non-specific defence protects a person from any threat coming from the outside. It is the first line of defence. If it is not quite effective, and some enemies penetrate it, a second line comes into play - a specific defence. The latter represents a higher form of defence which creates special soldiers (antibodies) against each enemy. These antibodies have a very long memory and can recognize a specific enemy even after years and effectively fight it. Businesses also need to create their own immune systems to protect them from threats from outside and inside. Having mastered the "enemy", the factory must encode the procedures by which it solved the problem into the immunity system of the factory, so that they become an automatic mechanism of its defence.

2.2 EVOLUTION OF FACTORY OF THE FUTURE

The development of Factory of the Future is influenced by two main drivers:

- *Technological developments* that include elements of exponential growth, achieved mainly through digitalisation. *Exponential economic growth & exponential decrease in costs (Moore's law).*
- *Globalization* – offshoring & reshoring, rich versus poor.

  Changing customer behaviour – local versus global turbulence.

The most influential technologies for Factory of the Future can be divided into two groups and summarized in a short overview (Gregor,M., Gregor,T., Patka,J. 2016).

The first group is formed by "*tangible*" technologies which include:

- *Robotics* – industrial, service, cobots.
- *Mobile robotics* – collective robotics, swarm robotics.
- *Additive technologies* – mass manufacturing of final products.
- *Nanotechnology* – change in the very principles of manufacturing molecular assembler.
- *Factory Twin* – the digital twin of the factory – an integrated hybrid world.

The second group consists of "*intangible*" technologies like:

- *Digitization* – dematerialization & demonetization.
- *ICT* – IoT, IIoT, IoMT, Cloud, sensory, identification – RFID, ...
- *Telefacturing* – household-controlled manufacturing, transition period to the Unmanned Factory.
- *Artificial intelligence* – intelligent everything (machines, tools, fixtures, pallets, conveyors, MRS, ...).
- *Virtual reality* – holography, immersion, holo-video, holo-simulation, ...
- *Manufacturing planning and control* – approximate control (metamodels).
- *Multi-agent systems* – complex socio-economic systems, behavioural prediction.
- *Knowledge Systems & Brain Computer Interface.*
- *Big Data* – analytics, correlations, prediction.

3 EVOLUTION IN THE DEVELOPMENT OF TODAY'S FACTORIES

Historically, several decisive factory concepts have been created. (Wiendahl.H., Reichardt,J., Nyhuis,P. 2015) state the division of factories based on the dominant organizational principle as follows:

- *Functional Factory* – functional areas (units) with the same technology are created, through which products flow. Examples of such units are mechanical processing, heat treatment, surface treatments, assembly, etc.
- *Segmented Factories* - they are more flexible and can better respond to changes than functional factories. They are made up of small production units, clearly oriented towards the product and the market, and tend to be responsible for financial results.
- *Network Factories* – have multi-level supply systems (Tier 1, Tier 2, …). These suppliers supply material, components, modules, or entire subsystems.
- *Virtual Factory* – is created by connecting several factories for the realization of a certain product, while they use their processes and resources according to needs. If the company that has direct contact with the customer is not a manufacturing company, we call such a grouping a virtual factory. Typically, firms create a virtual pool where the assets remain owned by the network participants. One of the forms of such cooperation is a Joint Venture, in which the partners create a new entity for joint business, in which they also invest part of their property (assets).

The decisive development concepts of production systems can be summarized as follows:

- **Lean Production** – it is oriented towards the elimination of all wastage and losses, continuous quality improvement aimed at cost reduction with the main goal of shortening product lead times. As a response to strong competitive pressure and limited resources, it offers a set of operational techniques, approaches and tools that enable the productive use of limited resources.

- **Flexible Manufacturing Systems** – they are oriented towards the production of a wide range of product families in one production system (by product). They usually have a fixed capacity and fixed functionality in the projected time frame. They are a reaction to known (predictable changes).

- **Agile Production** – represents a business strategy focused on company reactions in a difficult to predict business environment. Its main goal is the rapid response of the manufacturing company to constant changes in customer requirements, the result of which is the growing complexity of products. They relate to changes in the entire company, not just production.
- **Reconfigurable Manufacturing Systems** – by changing the structure or replacing components (plug and produce), they enable a quick change in the functionality and capacity of the production system depending on the immediate production conditions (for example, a change in production quantities, a change in the type of products, a change in the configuration of processes, the integration of new technologies, etc.). They typically use a reconfigurable, modular concept of hardware devices and an open software architecture.
- **Fractal Enterprise -** this concept is the subject of intensive research in Germany. Its author (Warnecke,H.J. 1992). The goal of the project is to change the existing organizational structures into flexibly changing and adapting units (fractals) to external circumstances. The concept of fractal enterprise can be thematically assigned to the field of Bionic Production Systems (Warnecke,H.J., Košturiak,J., Debnár,R., Gregor,M., Mičieta,B. 2000).
- **Digital Factory -** a new concept, dynamically developing, based on the application of digital models, modelling, and simulation, with a huge potential for fast, highly efficient, final solutions of products and production systems.
- **New Generation Manufacturing Systems -** the latest development concepts of manufacturing systems of the future, including all the above-mentioned development trends, are usually referred to as Next Generation Manufacturing Systems (NGMS) – so manufacturing systems of the new generation.
- **Holonic Production Systems** – represent concepts of production systems where the system-wide (holistic) effect is achieved by the cooperation of autonomous individual holons. Holon is represented as an individual, unique part of the system

(subsystem), consisting of a set of cooperating elements of a lower level, which ensure the complex fulfilment of defined tasks (production, storage, transport, monitoring, transportation, etc.).

- **Bionic Production Systems** – to solve complex and unpredictable changes in the business environment, they use as inspiration the principles observed in living nature (adaptation, self-organization, learning, evolution, competition, genetics, natural selection, cooperation, etc.). Like living organisms, the target, global behaviour of a production system is achieved through the competitive interaction of many entities of the system. They can solve problems even in cases where these are insufficiently defined and described (decision-making under uncertainty), there is not enough data about events (predictive models) and so on. Current research is focused on the behaviour of living organisms and the application of acquired knowledge in the management of production systems.
- **Intelligent Manufacturing Systems** – are production systems that have capabilities like human intelligence (artificial intelligence, decision-making models, self-management, etc.). Currently, they are most often conceived as so-called agent systems (systems with distributed intelligence). Artificial intelligence methods (expert systems, neural networks, genetic algorithms, etc.) are used to optimize the behaviour of the production system.

The development of production systems is illustrated in the Figure 3-1.

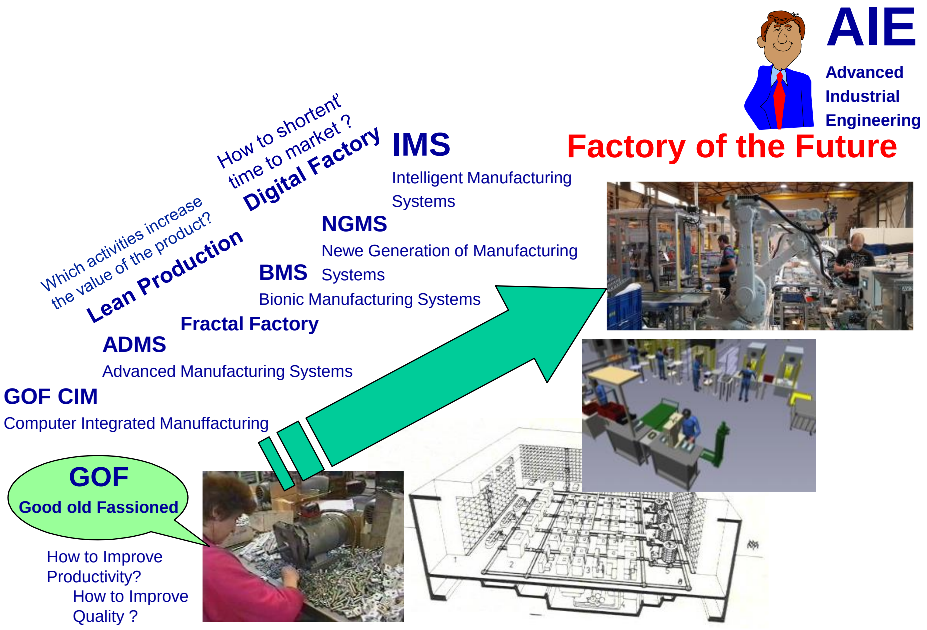


Figure 3-1 The Development of Production Systems

The evolution of different types of manufacturing systems is shown in the Figure 3-2.

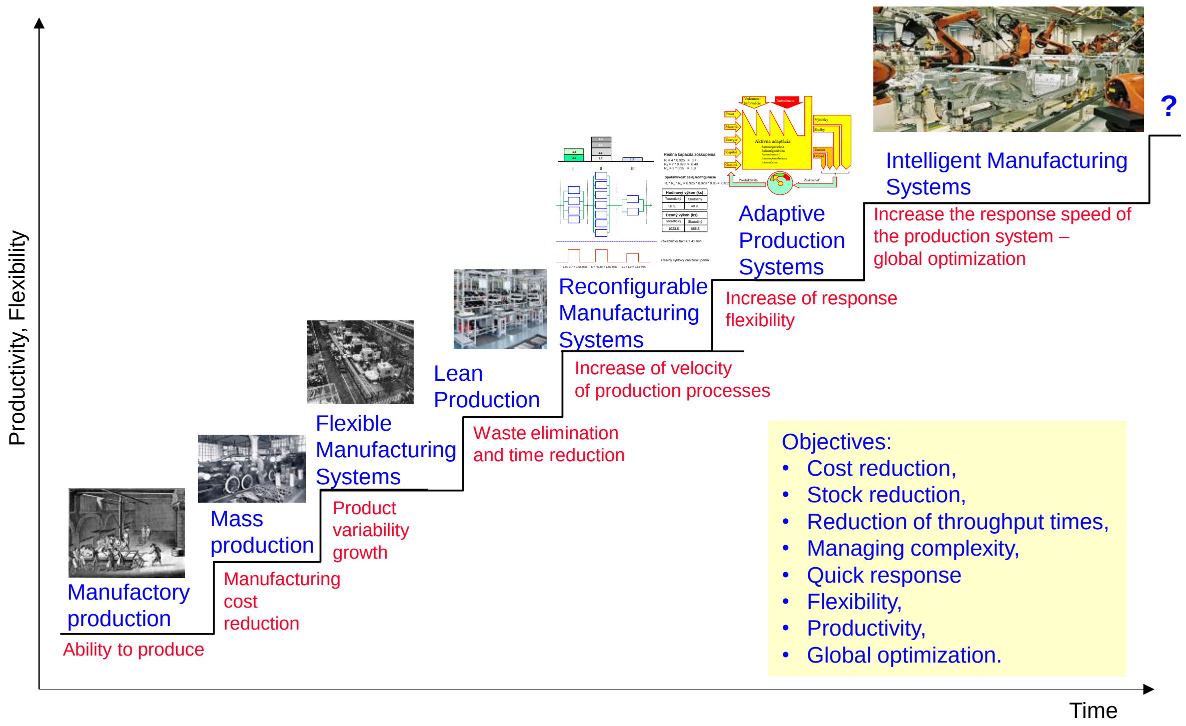


Figure 3-2 The Evolution of Manufacturing Systems

As Figure 3-3 shows, evolutionary changes are carried out in three main ways in today's factories:

1. *Revitalization*, the task of which is to "revive" and restore the declining functions of the factory.
2. *Reconfiguration*, which results in a complex change in the functions and structures of the factory.
3. *Restructuring*, which has the task of comprehensively changing the existing structures of the factory.

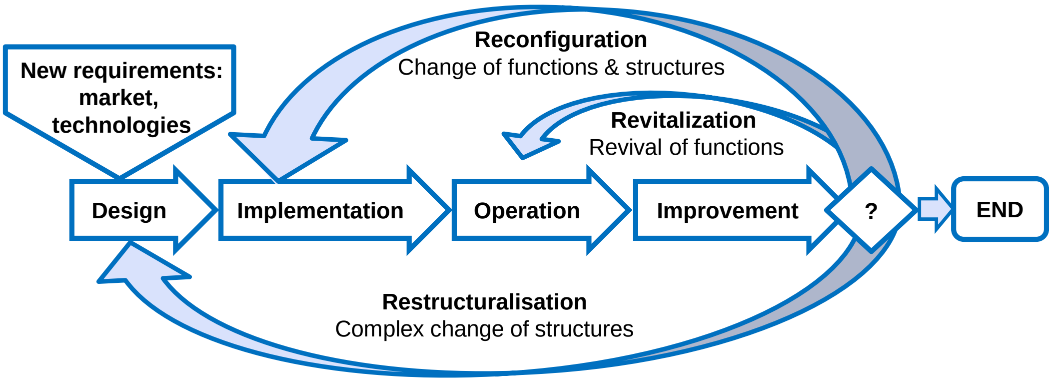


Figure 3-3 Evolution in the development of today's factories
Source: Gregor,M. at al. (2017)

Factory of the Future will use advanced technologies that will revolutionize the existing manufacturing base in a revolutionary way. In addition to advanced technologies, two new concepts will play a decisive role in this development: the Digital Factory and the Virtual Factory.

4 MAIN TECHNOLOGICAL CHANGES AFFECTING THE ORGANIZATION OF FACTORY OF THE FUTURE

4.1 ROBOTICS

The topic of robotization is currently one of society-wide topics, and many experts have a different opinion on it. There will not be many people working in the factories of the future, but still some people will work in it. Therefore, today's developers must design devices for manufacturing systems in such a way that they are able not only to communicate with people but also to cooperate safely (Gregor,M. at al. 2017). The world development of machines, robots is much faster than the ability and capacity of a person to absorb all new knowledge. Machines can use artificial intelligence and draw new knowledge through the internet. The algorithms that allow them to do so can now be improved and optimized autonomously. Machines, robots have access to cloud-based knowledge databases, interconnected by a virtual worldwide network, which allows them almost unlimited possibilities to obtain new information and learn (Gregor,M. et al. 2015). Already today, it is possible to meet in almost any manufacturing company with a robot, where they replace dangerous and routine activities for humans. Currently, the most promising are:

- Industrial robots.
- Cooperative robots.
- Mobile robotics.
- Service robotics.
- Humanoid robots.

Forecasts of the further development of robotics are based on the latest research and development results. They clearly indicate future trends and the direction of use of future robotics.

In a clear form, the estimate of the future development of industrial robotics to 2027 is for individual periods shown in Figure 4-1.

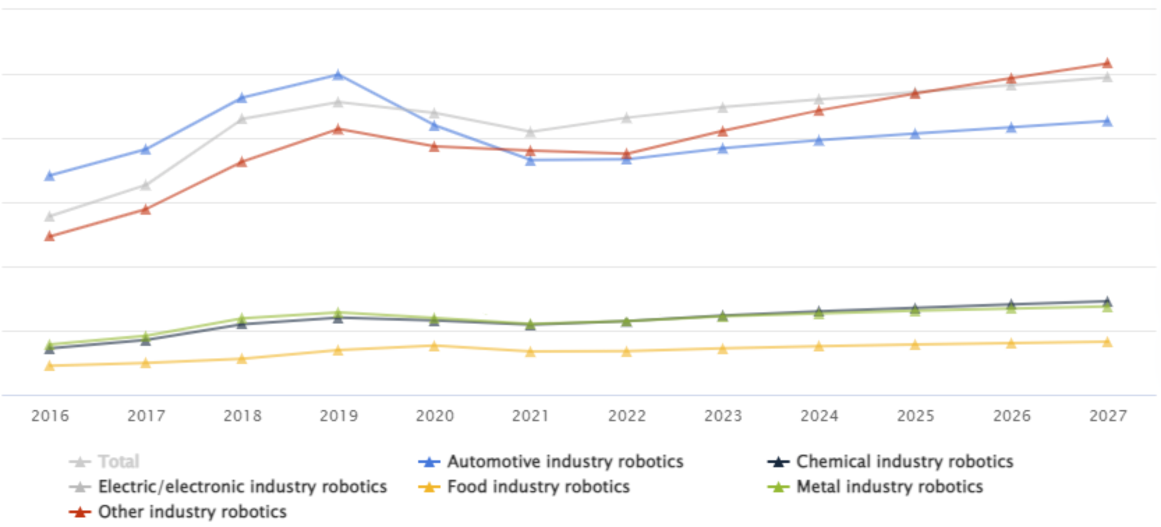


Figure 4-1 Revenue in the Industrial Robotics segment to 2027
Source: Statista (2023)

Significant growth in the deployment of robotics is expected mainly in the field of service robotics, robotics in medicine and healthcare, household services, which is shown on Figure 4-2.

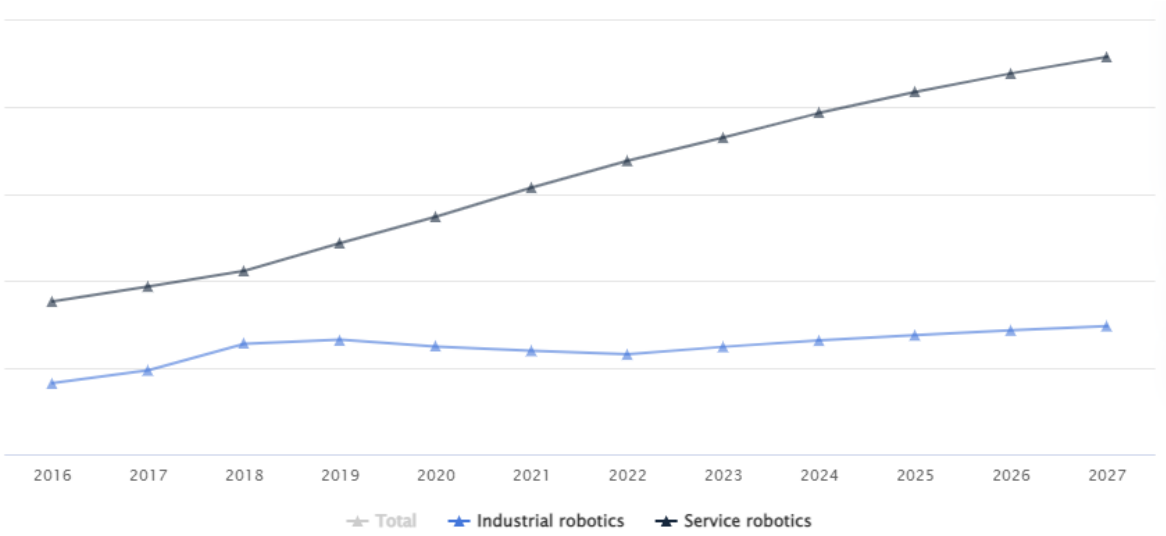


Figure 4-2 Deployment growth for Industrial and Service robotics to 2027
Source: Statista (2023)

4.1.1 Industrial robots

Research, development, and deployment of industrial robots are constantly on the rise. The result of the development of the technical base of components, modularity, sensorics and support of artificial intelligence is an unprecedented growth in the number of robot implementations in industry.

4.1.2 Cooperative robots

Cooperative robots (cobots) are robotic systems, capable of performing selected operations and safely cooperating with humans in their implementation (Gregor,M., Gregor,T., Marčan,P. 2016). Cobots are another revolutionary change in robotics. Although their development is still ongoing, today all major robot manufacturers also have cobot versions in their offer, and their number is growing dynamically. Cooperative robots are a solution that will fundamentally speed up robot applications in areas where it has been difficult or impossible to use robots (Marčan,P. 2015).

Analyses of the deployment of these robots show that even at this early stage, when the mass deployment of cobots and thus the reduction of the cost of their manufacturing have not yet taken place, they are able to achieve high efficiency and bring significant cost savings to manufacturers. The estimated hourly cost of a cobot's work today is approx. $4, with the hourly price of comparable human labour hovering around $22 to $50 in developed countries. Multiple industry analyses have confirmed that when deploying a cobot, a business can save up to $3.5 million over its lifetime.

There is a clear trend in manufacturing, conditioned by a reduction in the relative unit costs of operations, as the volume of manufacturing increases (Figure 4-3). As can be seen, co-worker robots (cobots), robots capable of cooperating with humans, have a significant place in robotic applications in industry.

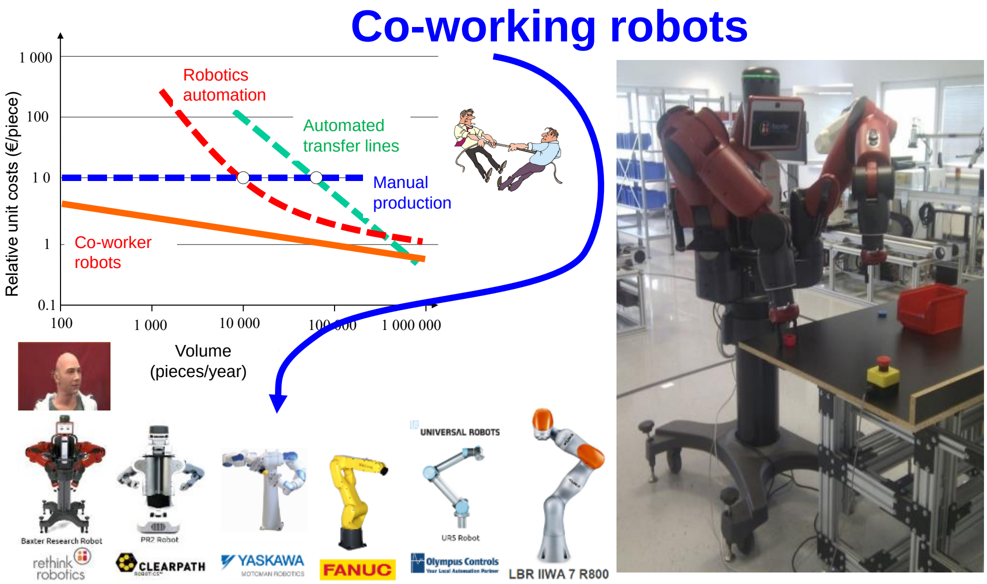


Figure 4-3 Relative unit costs of the operation for different manufacturing volumes
Source: Gregor,M., Medvecký,Š. (2015)

Cobots represent a strong growth trend with a gradual transition from simple cobots applications to more sophisticated solutions, leveraging the results of research in the field of artificial intelligence and knowledge systems.

Figure 4-4 shows the change of size of the collaborative robot (cobot) market worldwide in 2020 and 2021, with a forecast for 2023 to 2030 in U.S. Dollars

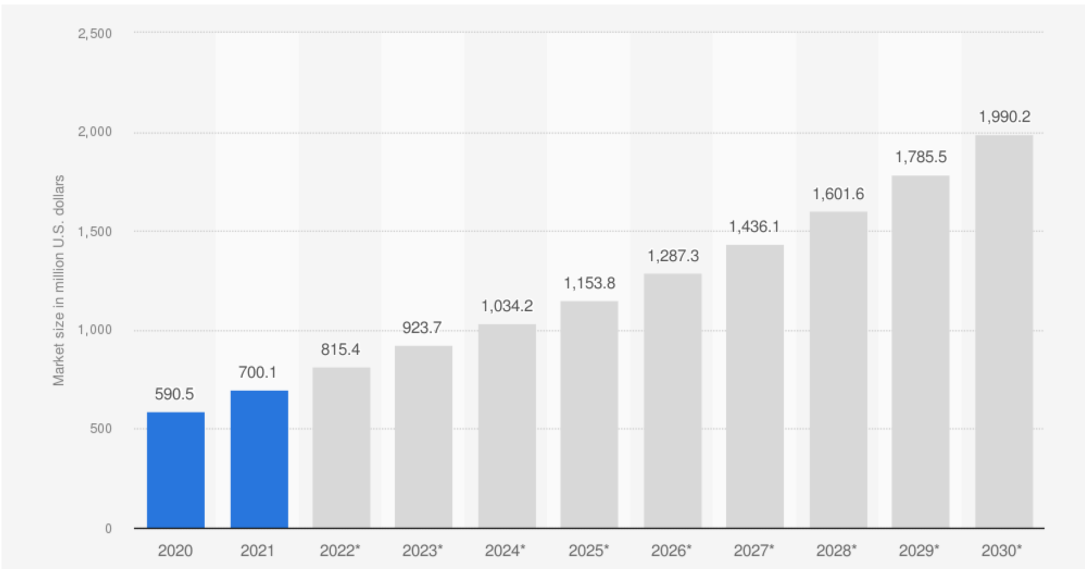


Figure 4-4 Forecast for cobot markets growth
Source: Statista (2023)

4.1.3 Mobile robotics

Another area that is undergoing revolutionary changes is mobile robotics. This has moved from solutions introduced in the industry in the eighties to a whole new level of quality. Today's mobile robots are intelligent, equipped with state-of-the-art visual localization and navigation systems, extensive sensors, and can autonomously make and execute complex decisions. Internal business logistics has become the main area of deployment of mobile robots in industry. Well-known solutions of mobile robotic systems - Automated Guided Vehicles (AGV) have already become standard in the automotive industry and are gradually penetrating other areas (electrical engineering, paper industry, healthcare, airports, etc.). Examples of the deployment of AGVs of Asseco CEIT company in Skoda Auto and VW Slovakia are shown in Figure 4-5 and Figure 4-6.

Figure 4-5 CEIT mobile robotic systems in Škoda Auto
Source: Asseco CEIT (2023)

Figure 4-6 CEIT mobile robotic systems at VW Slovakia
Source: Asseco CEIT (2023)

The development is moving towards - MAP (Mobile Automated Platforms) and the use of an open operating system for robotics in the field of manufacturing (http://ros.industrial.org), working on the basis of HTTP-RPC technologies, with easy connection to various types of industrial networks and easy connection to the web (see also http://ric-eu.rosindustrial.org).

The development of this area is based both on the industry's growing needs for robotic assistant solutions and on the rapid development of cooperative robots (cobots), capable of safely cooperating with humans and other equipment in manufacturing.

An example of a MAP developed in cooperation between Asseco CEIT and the University of Žilina is given in Figure 4-7.

Figure 4-7 Asseco CEIT Mobile Robotics Platform
Source: Asseco CEIT (2023)

4.1.4 Flying Robotic Systems - Drones

In the last decade, applications of aerial (flying) mobile robots, so-called drones, were growing. Audi was one of the first to experiment with their application in industrial production in 2013. This type of mobile robot can perform a range of tasks in production, such as: delivering material and spare parts, measuring dimensions, inventorying warehouses, monitoring space security, etc. The integration of drones, equipped with special sensors, and other sensory systems in production creates an integrated sensory environment, also known as *Ambient Intelligence*. An example of the use of a drone in the assembly of Audi is shown in the Figure 4-8.

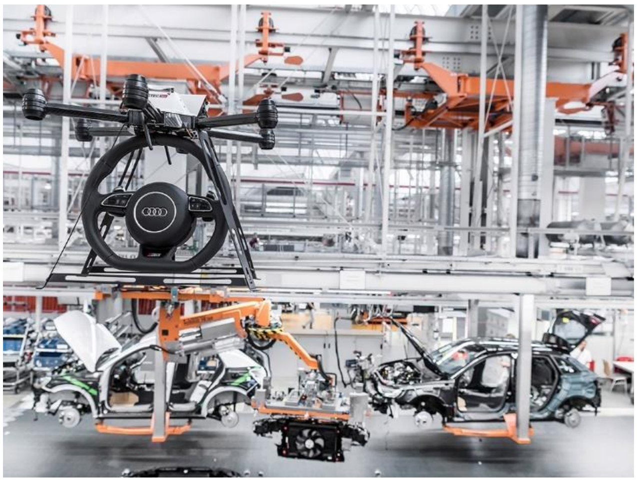


Figure 4-8 Drone in a car assembly
Source: Allaboutlean. (2023)

In addition to drones, cheap miniature flying robots are also being developed, fully equipped with sensors and in industry mainly intended for monitoring the safety of factory spaces. They are deployed similarly to sensors and can form so-called robotic dust, which refers to the massive deployment of such robots in production facilities. An example of this type of robot, developed mainly at the Massachusetts Institute of Technology (MIT), is shown in the Figure 4-9.

Figure 4-9 Miniature, flying robotic systems

4.1.5 Swarm intelligence in mobile robotic system solutions

When simulating the behaviour of social systems, such as shoals of fish or flocks of birds, scientists developed an optimization method that they named Particle Swarm Optimization (PSO). This method is based on the use of virtual particles that can move in virtual space. The movement of individual particles is modelled by changing their coordinates. The algorithm calculates the new coordinates of each particle based on the direction and speed of its movement. According to (Budinská,I. 2015), the speed and direction of movement of particles are determined by three components:

- *The moment* that forces the particle to continue in the direction of its current movement.
- *The cognitive component*, which attracts the particle to the place it has evaluated as the most suitable for its next movement. The cognitive component is related to the knowledge of the particle itself.
- *The social component*, which is related to the knowledge of the whole group (swarm). In each step of the algorithm, it attracts an individual particle to the area most suitable from the point of view and evaluation of all particles of the swarm.

By changing and adjusting the input constants, which determine the weight that individual components exert on the particle's movement, it is possible to influence the behaviour of the entire swarm.

For the management of a large group of autonomous entities, new management principles are used, based on nature, and based on the algorithms of intelligent swarms (swarms intelligence). A swarm or flock, as a group of individuals, usually exhibits collective behaviour in nature. Such a swarm, even if it is composed of relatively simple entities, can exhibit very complex and intelligent behaviour. The group manifests itself in a new type of behaviour that is not found in the individuals forming the group. Such a phenomenon is also called emergent behaviour (Budinská,I. 2015).

Even if we currently view the intelligence of swarms as something artificial, theoretical, and unnecessary, the short future will surely bring many surprises.

Solving some situations in complex systems often requires the coordinated cooperation of several entities that must communicate together and act as one group, fulfilling a defined goal. Such joint action of several robots is today referred to as swarm robotics.

For ants, bees, birds, fish and other flocks of living organisms, certain, simple rules of swarm behaviour apply in nature, which ensure the fulfilment of a common goal. Likewise, individual production entities will be integrated into swarms, which will be managed about the fulfilment of the global goal. An example that is currently the subject of research and applications in the production environment are the so-called robotic assistants (for more details, see (Gregor,M. et al. 2018a).

The use of swarm intelligence (ant colonies) and the evolutionary algorithm Ants Colony Optimization (ACO) for balancing assembly lines was investigated by (Štollman,V. 2009). The application of the sheep algorithm was applied in the scheduling of workshop operations by (Figa,Š. 2010).

4.1.6 Collective Robotics

In order for robots to be able to carry out demanding tasks, often times in an unfamiliar environment, they must have autonomous abilities, i.e. the ability to adapt to their environment, adapt to changing environmental conditions, be able to collect and evaluate information about their internal state and the state of the environment (perception), predict future situations, make the necessary decisions and of course learn from the situations they solve. Such tasks can already be solved today by individual, advanced robotic systems.

Future production will require the deployment of many autonomous robots. Such a group of robots must cooperate with each other when completing tasks, which is why we refer to the cooperation of such robots as cooperative behaviour of robots or, for short, as *collective robots.* Targeted behaviour of a group of cooperative robots requires new ways of control and optimization. Collective robots will become the most important in the industry of the future.

It seems that the easiest way to "grasp" the issue of collective robots is to use knowledge from the collective behaviour of living organisms. They can quickly adapt to a changing environment. The meaning of the entire adaptive process in living organisms is the survival, preservation, and development of the given biological species. To do this, living organisms must work together. In a long stage of their evolutionary development, living organisms have found optimal ways to organize and perform all tasks so that the whole organism survives. The individual members of these complex, living organisms have developed the necessary forms of division of labour and mechanisms of mutual coordination of their activities. The fulfilment of tasks that benefit the whole organism has become important.

The behaviour of future collective robots must resemble the behaviour of living organisms. From this point of view, we must distinguish the concepts of swarm robotics and collective robotics (Gregor,M. et al. 2018a).

Robotic swarms include a set of relatively simple, homogeneous robots. The behaviours of such robots imitate the behaviours of simple living organisms (we refer to them as swarms, flocks), such as bees, ants, or flying birds. Relatively simple rules apply to the collective behaviours of such a swarm. Each individual member of the swarm has a precisely specified range of activities that he performs for the benefit of the entire swarm.

Collective robotics usually includes many, often very heterogeneous robots. Heterogeneous robots can include a whole set of autonomous robots that do not require human service, from mobile, road, flying (drones) to floating robots. These robots have strong autonomous functions, intelligence, and mobility capabilities. Such robots cooperate with intelligent sensor networks and computer systems, organized into cloud solutions. In the case of complex control of collective robots, it is no longer possible to use classic, centralized control. The results of research so far have shown that the control of collective robots will require a "custom" operating system.

The cooperation of collective robots differs significantly from the cooperation of simple swarm robots. When performing complex tasks, in a demanding and unknown environment, collective robots must use distributed control mechanisms that can combine the behaviour of individual, autonomous robots into the complex behaviour of the entire group of robots. We refer to such behaviour as ***holonic***. It is typical to use an agent approach and multi-agent systems (MAS) for the management of holonic systems.

In the process of co-operation of a group of individual, autonomous robots, a higher level of collective intelligence arises, which is known as ***emergency***.

4.1.7 Service Robotics

A more detailed analysis of the historical development of recent decades documents the dynamic growth of robotic applications in the field of service robotics. Service robots represent the main challenge of the future (Figure 4-10).

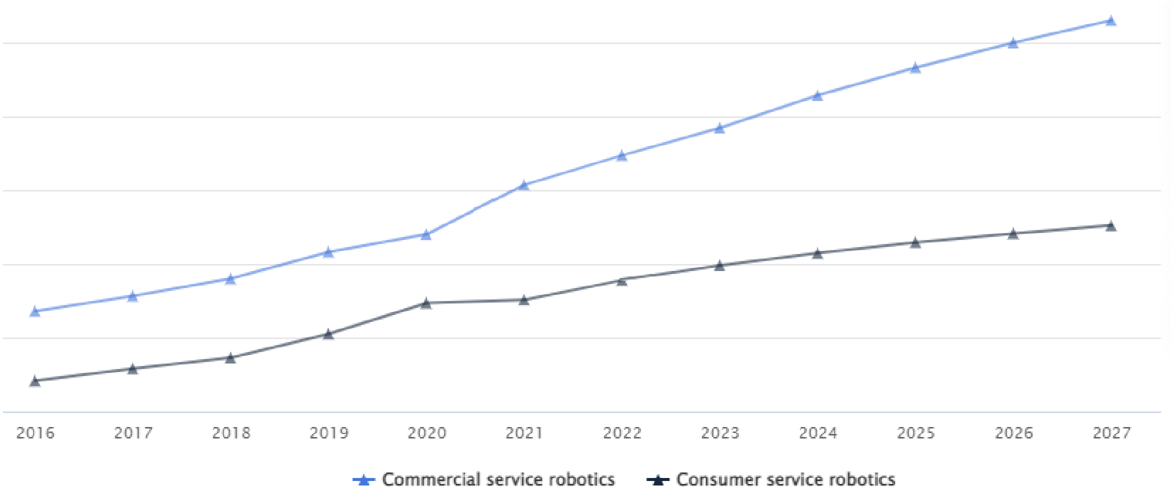


Figure 4-10 Evolution of the global market size for robotics by 2027
Source: Statista (2023)

Service robotics will significantly change manufacturing factories in the short future. Advances in artificial intelligence allow robots to be used even in situations that have been the domain of humans in the past. Just as robotics and mobile robots have gradually penetrated logistics, service robots are also penetrating administration, technical preparation of manufacturing, development, and other areas.

In the past, this area was dominated by Japanese and now also Korean developers. Although humanoid robots are far from being able to cope with humans, it is only a matter of time before they can replace him in many manual and later cognitive activities.

Mobile Automated Platforms (MAP) represent a class of humanoid robots, specially developed for the needs of assistance in manufacturing activities. In Germany, the solution developed on IPA FhG, referred to as rob@work 3 (Figure 4-11), which represents a new development platform, is becoming standard in the automotive industry. It is based on the IPA-Care-O-bot 3 concept, developed originally for the field of service and home services.


Figure 4-11 O-Bot 3 and rob@work from the development of IPA FhG
Source: Care-o-bot (2023)

It is estimated that within 20 years androids will be quite commonly deployed in industry and households (Gregor,M., Medvecký,Š. 2015). Mobile manufacturing assistants support workers in manufacturing, communicate with people, therefore require a suitable interface for communication with humans - Human Machine Interface (HMI), such as Automatic Manufacturing Assistant (APAS) of the German company Bosch, developed within the framework of the PRACE project (http://www.prace-ri.eu/) or plug &produce solutions developed within the PAN-Robots project (http://www.pan-robots.eu/).

4.1.8 Humanoid Robots

From J. Čapek's first ideas, robots were designed to resemble humans. This property (similarity), i.e., the application of human characteristics and peculiarities to inanimate objects is called *anthropomorphism.* It mainly concerns humanoid robots - humanoids. This type of robots is undergoing a turbulent development, in which Japan and South Korea have a leading position. This group of robots represents service robots that will replace humans in the performance of many activities in the future.

In 1970, Masahiro Mori published his theory about how people react to the presence of robots that are very similar to humans and react or perform activities like humans. He investigated the dependence of two factors (Figure 4-12): emotional response of people and degree of similarity between robot and human.

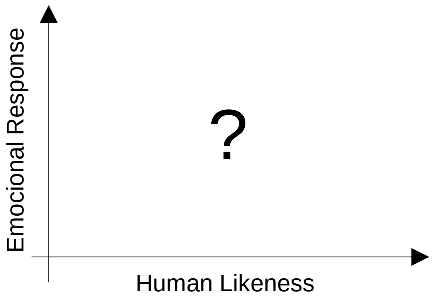


Figure 4-12 The dependence of a person's emotional response on the robot's appearance and behaviour

Mori called this emotional reaction of people to the appearance and behaviour of robots the phrase "Uncanny Valley". Uncanny means strange, disturbing, suspicious. Uncanny Valley is therefore the area of negative emotional reactions of people towards robots, which are very similar to people (see: https://sk.wikipedia.org/wiki/Uncanny_valley).

The uncanny valley is mainly about humanoid robots and their interactions with humans. Humanoids can be designed in such a way that their external form can resemble the appearance of a human. An example of continuous morph change is shown in Figure 4-13 (http://www.livescience.com/47767-how-lonely-people-view-uncanny-valley.html).

Figure 4-13 Example of continuous morph change

Mori's research showed that if the appearance of the robot approaches the appearance of a person, to a certain degree of similarity, the person first reacts neutrally, and gradually his emotional reactions grow positively. This is true up to a certain level in which the robot already looks very much like a human and reacts like a human. From this threshold level, a person emotionally perceives a robot as a foreign or repulsive entity. It is this area that creates a chasm on a relatively narrow strip, labelled as a *bizarre valley*. If the likeness of the robot with the human continues to grow to a very high degree of agreement, the human perceives the robot positively again. Mori depicted this dependence in the form of a graph (Figure 4-14). The drawn emotional reaction of people towards the anthropomorphism of robots agrees with the results of Mori's research.

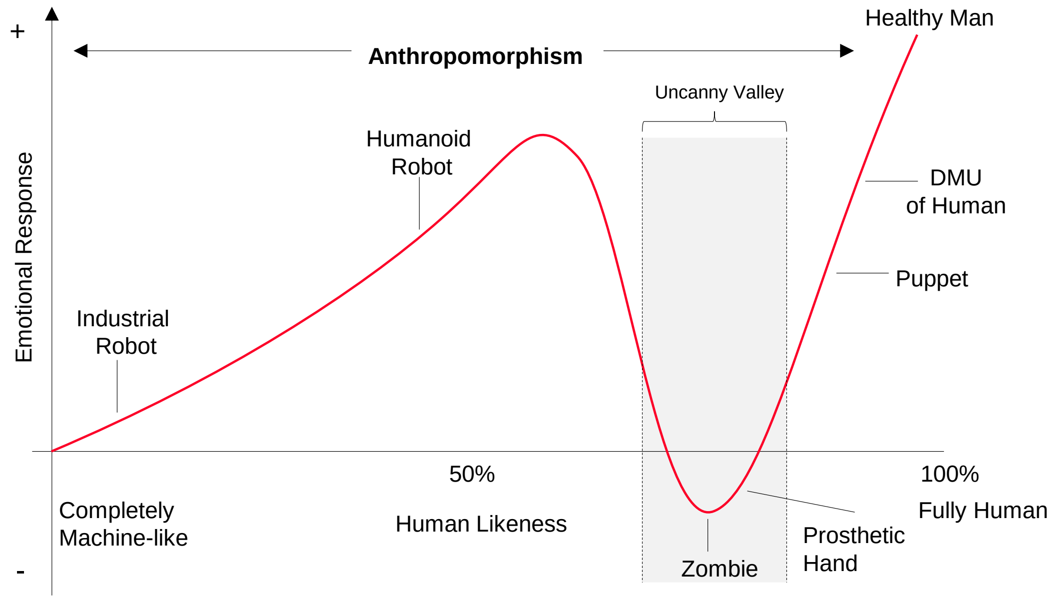


Figure 4-14 Uncanny Valley

Therefore, research into the emotional reactions of people to robots continues. The term *Second Uncanny Valley* has also appeared. The latter represents research into the uncanny valley problem in a post humane society (Figure 4-15).

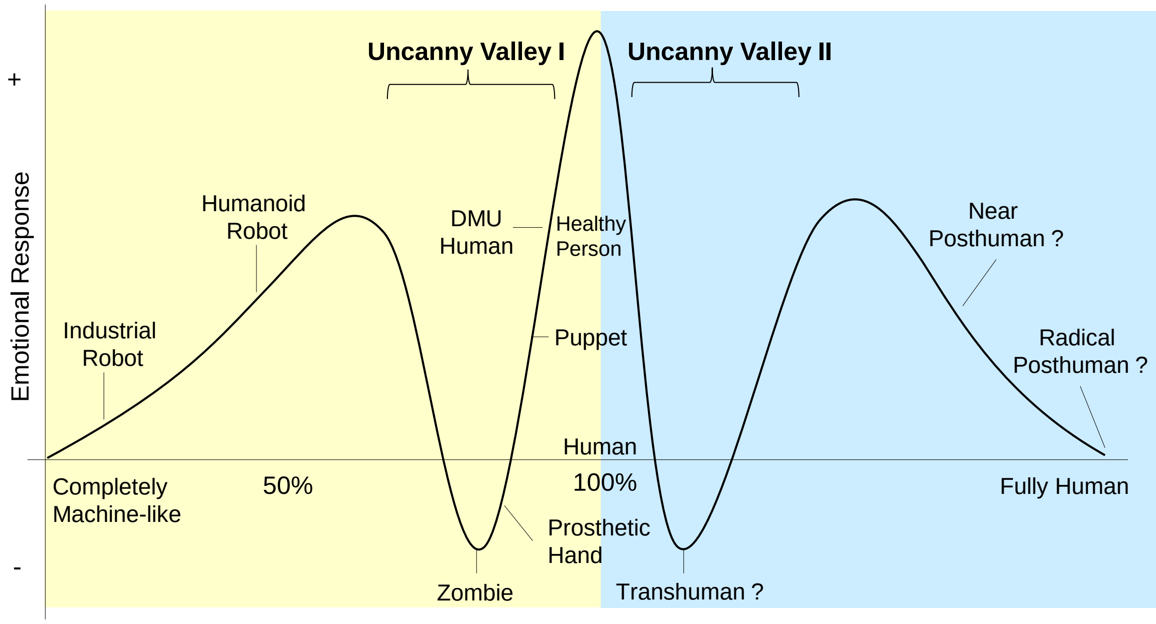


Figure 4-15 Second Uncanny Valley

Examples of humanoid robots or androids and their similarity to humans are shown in Figure 4-16, Figure 4-17, Figure 4-18. More detailed information can be found on the Internet, for example (BBC, 2023).

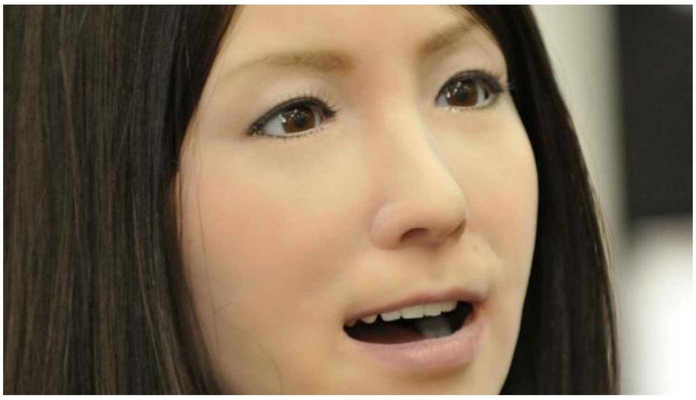


Figure 4-16 Female Humanoid
Source: Getty Images (2023)

Figure 4-17 A female humanoid together with the author
Source: Getty Images (2023)

Figure 4-18 A male humanoid together with the author
Source: Getty Images (2023)

A humanoid child is shown in Figure 4-19.

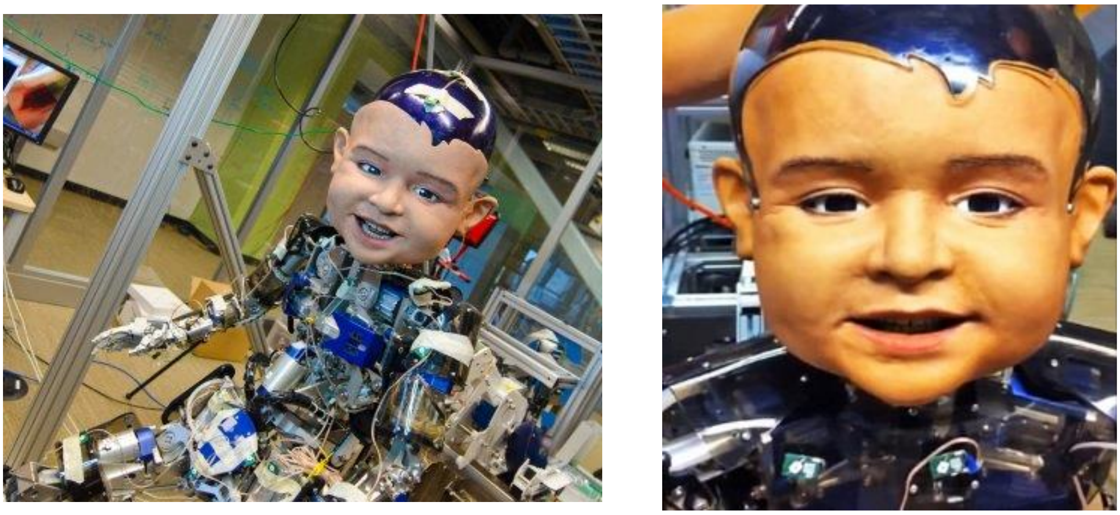


Figure 4-19 Humanoid child
Source: Ibtimes (2023)

4.1.9 Real Time Locating System (RTLS)

RTLS technology is a new technology that allows tracking the movement of all objects in production. An example is Sewio's RTLS technology. This technology uses broadband networks (Figure 4-20) and a whole range of other hardware elements.

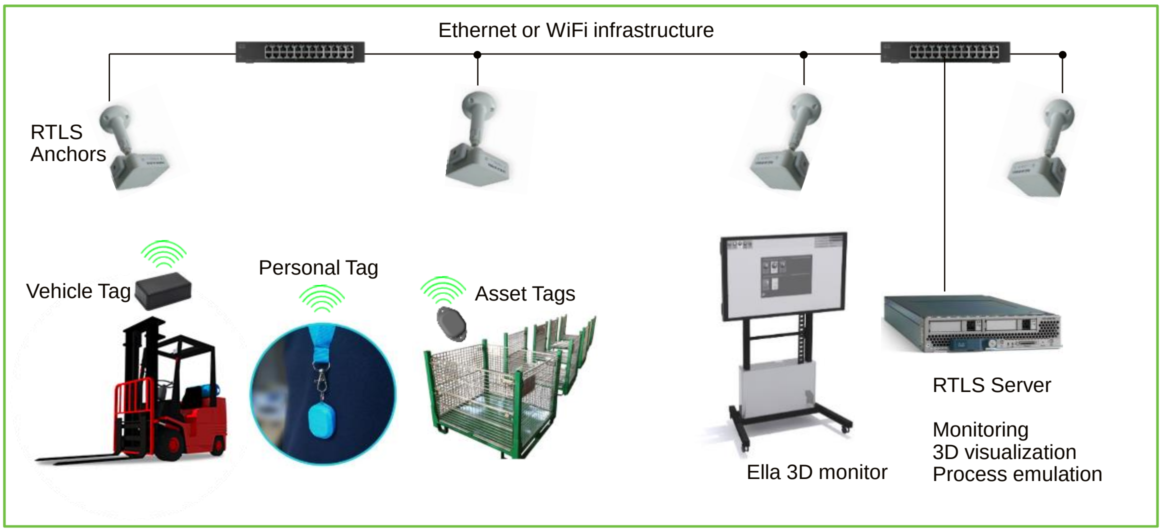


Figure 4-20 RTLS Network Architecture
Source: Gregor,T.(2018b)

Figure 4-21 shows an example of the real application of RTLS technology in the monitoring and management of the production system.

Figure 4-21 RTLS of the Asseco CEIT company
Source: Gregor,T. (2018b)

5 NEW ENVIRONMENT FOR THE FUTURE MANUFACTURING CONCEPTS

The new manufacturing environment will require unconventional communication systems and next generation means of communication. The efficient operation of adaptive manufacturing and logistics systems requires the application of the latest information and communication technologies: the Internet of Things and cloud computing. Adaptive logistics uses the services of many systems to ensure its own communication, such as: intelligent sensors, sensor systems, mobile sensor networks, agent control system, etc.

Static sensors have been replaced by "wireless" sensors that can now be placed on mobile objects, which has enabled the emergence of Mobile Wireless Sensor Networks (MWSNs). Gradually, various classes of sensor networks and entire generations of sensors have been developed, and the development continues very quickly. Its goal of development in manufacturing and logistics is to replace the senses of man with "digital senses", with which autonomous control systems can already work (Gregor,M. 2016).

5.1 INDUSTRY 4.0

For the fourth industrial revolution, the designation Industry 4.0 is used in Europe, in the USA it is known as Smart Industry. Industry 4.0 represents a long-term development process; we can say that it represents a revolutionary movement in industry. As in other cases, also in the case of Industry 4.0, this movement has its supporters and opponents. The fourth industrial revolution is a real revolution, it is a controlled process. Digitization is the driving force behind this revolution, and Cyber-Physical Systems (CPS) are the tools for implementing change. During it, several basic paradigms change. Changes take on an exponential character, which is why, for example, in the automotive industry expects that the changes of the next 5 years will be greater than those of the last 50 years. The cornerstones of the fourth industrial revolution are digitization, virtualization, and Cyber-Physical Systems, supported by advanced technologies, which include Artificial Intelligence, or Industrial Internet of Things (IIoT). Schematically, the structure of Industry 4.0 is shown in the Figure 5-1.

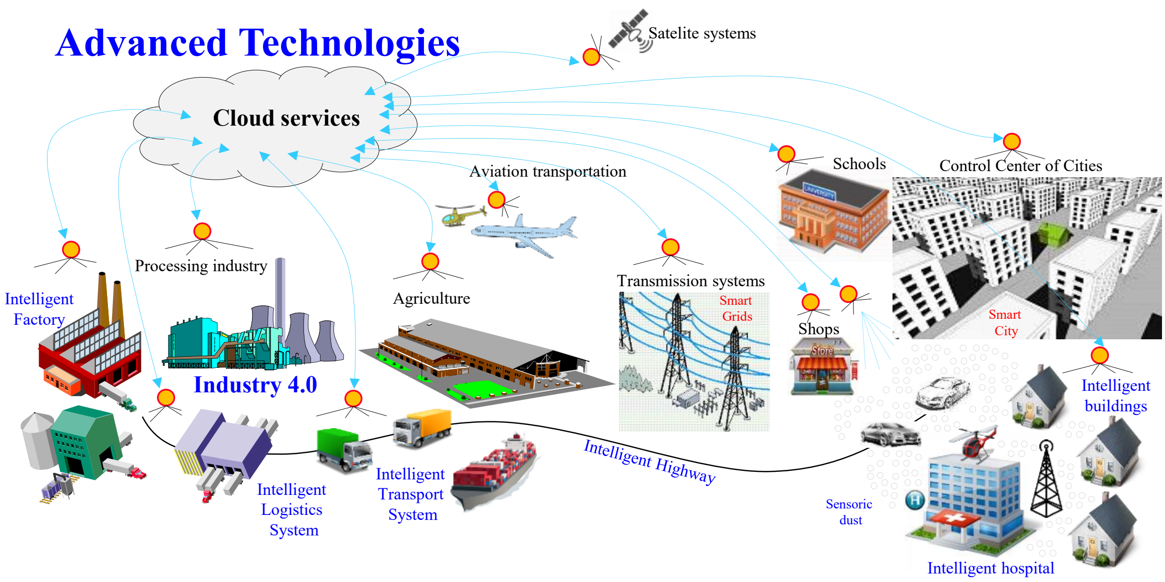


Figure 5-1 Industry 4.0
Source: Gregor,M., Gregor,T. (2016)

Prof. H.J. Warnecke from FhG (Warnecke,H.J. 1992) suggested decentralized structures (fractals), for a new production environment, which provoked thoughts about Cybernetic-Physical Systems in Germany.

Author Bauernhansl, T. (2017) presents the estimated cost savings when introducing the elements of Industry 4.0, their summary is given in the Tab. 5-1.

Tab. 5-1 Estimated cost savings when introducing the elements of Industry 4.0

Costs	Effects	Savings Potential (%)
Storage Costs	Reduction of safety stocks	30 to 40
	Avoiding the effect of BULLWHIP and BURBIDGE	
Construction Costs	Growth of OEE	10 to 20
	Process loops	
	Improvement of staff flexibility	
Logistics Costs	Increasing the degree of automation	10 to 20
Total Costs	Expanding the range of management powers	60 to 70
	Reduction of tears	
Quality Costs	Quality in real time processes	10 to 20
Maintenance Costs	Spare parts optimization	20 to 30
	Current state identification (process and measured data)	
	Dynamic prioritization	

Some manufacturers report a reduction in complexity costs of up to 70%, which has been achieved mainly through a new approach to managing manufacturing operations.

Each company must define its own way of migrating its technologies and systems to Industry 4.0 standards. The structure of the reference model of the Industry 4.0 architecture is shown in the Figure 5-2.

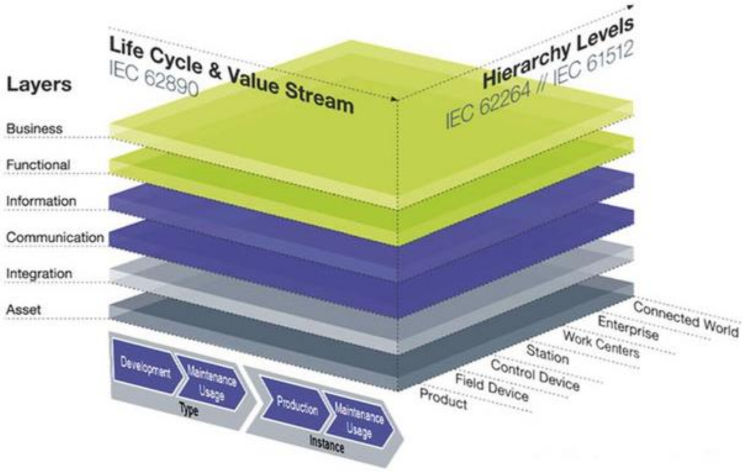


Figure 5-2 INDUSTRY 4 .0 Architecture Reference Model - RAMI 4.0
Source: RAMI (2023)

Such a reference model shows that it is a data-centric industry, the management of which is based on data processing using appropriate technologies such as Big Data or Advanced Data Analytics. The solution based on Big Data enables the detection of irregularities, losses and inefficiencies in production, the prediction of the future behaviour of production systems using simulation and prediction models, or the prediction of malfunctions and unexpected situations in production. All this forms the basis for the emergence of intelligent processes that are fully automated, flexible, self-organized, reconfigurable, and self-learning.

5.2 INTERNET OF THINGS IN MANUFACTURING AND LOGISTICS

The Internet of Things, and especially its variant for manufacturing, also called the Internet of Manufacturing Things (IoMT), is beginning to successfully assert itself in manufacturing.

Internal logistics, as part of the manufacturing process, uses IoT services to provide for its communication needs.

5.3 IDENTIFICATION OF OBJECTS IN LOGISTICS

Adaptive logistics systems will require unambiguous identification of all objects, static and dynamic, located in the logistics system. Every logistics object must be clearly identified at every time and in every place. This requirement is necessary especially for solutions in which logistics activities will be controlled by the processed product. In such a dynamic environment, there will be many coincidences and the need to solve alternative transport or handling strategies, which will require permanent replanning of logistics routes or available logistics resources.

Radio Frequency Identification (RFID) technologies are most often used for unambiguous identification of objects.

5.4 VIRTUAL REALITY AND AUGMENTED REALITY IN THE DESIGN OF LOGISTICS SYSTEMS

A good example of a modern approach to the design and testing of logistics systems with the support of virtual reality and simulation is the solution developed by the company Asseco CEIT, with the trade name CEIT Table (Figure 5-3). It was described in more detail in Gregor,M., Medvecký,Š., Štefánik,A., Furmann,R., Mačúš,P. (2016).

Figure 5-3 CEIT Table
Source: Asseco CEIT Archive (2023)

Another example from the CEIT workshop, using virtual and augmented reality technologies, is the system for training workers of complex robotic workplaces, referred to as the CEIT Trainer (Figure 5-4). The solution was developed by Asseco CEIT in cooperation with VW Slovakia and is currently being expanded in the automotive industry.

Figure 5-4 CEIT Trainer
Source: Asseco CEIT Archive (2023)

5.5 HVACDE

Another area of co-operation in research and development is the virtual development environment (Cave). The customer can try out the operation of his future solution in a virtual reality environment (Figure 5-5), which is being developed in cooperation between the University of Žilina and the Asseco CEIT company and has received the label Haptic-Visual-Auditory Collaborative Design Environment (HVACDE).

Figure 5-5 HVACDE – Virtual Design Environment

5.6 CLOUD COMPUTING

Cloud computing represents a new technology that replaces classic software solutions with a new approach that provides software as a service. This approach gradually relieves the client of providing routine activities, maintaining the necessary computing power, storage memory space and the need to monitor the latest developments in this area.

Figure 5-6 shows a gradual change in the provision of the service, when the client solves his technological tasks and the entire system of communication and its renewal is taken care of by the cloud service provider.

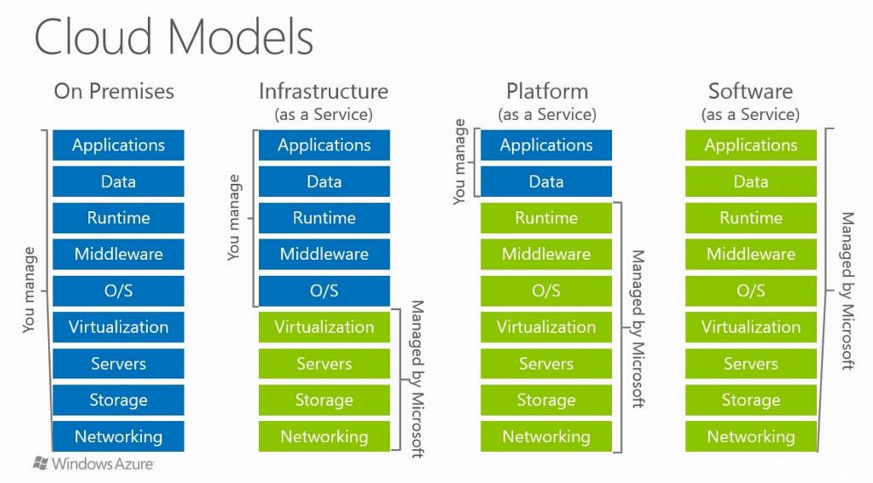


Figure 5-6 The concept of Software as a Service (SaS)
Source: Quora (2023)

The Internet of Things connects manufacturing and logistics to a cloud-based solution so that all system information is stored and accessed online in the cloud, and operational interventions can be done by connecting to the internet from anywhere in the world. When using such a solution, the factory will no longer need its own IT solutions, servers, and data storage, but will use cloud and Direct Memory Access Databases, which will enable a huge acceleration of IT communication in the industry.

5.7 COMPUTATIONAL SYSTEMS FOR FUTURE MANUFACTURING ENVIRONMENTS

Since the 70s of the last century, the computational speed of computers has been achieved mainly by increasing the density of transistors on integrated circuits. Today's microprocessors are designed as single-dimensional layers of silicon, into which integrated circuits are steamed. The dependence of the number of transistors on the integrated circuit and the price of the processor is known today as Moore's Law. It says that about every two years, new technologies are developed that make it possible to double the computing or memory capacity of chips.

The density of transistors on the integrated circuit is currently approaching its physical limits, and further major speed increases in this way will no longer be possible. The new possibilities for future growth of computational speed use two main strategies. The first is a combination of higher computing power and other resources on the computer (scaling up). The second uses the concatenation of many servers to form a single virtual computing system (scaling out).

One of the promising directions for increasing computing power is also the application of computational principles, which are used by the human brain. Although his memory works sequentially (we are not able to quickly repeat memorized words from behind), but he realizes the processing of the information obtained through massive parallel calculations. Thus, in the evolutionary process, nature has developed a much more effective solution than the previous technical solutions developed by humans.

IBM also came up with the idea of computing systems, built on centralized data processing Data Centric Deep Computing - (DC), which should speed up computing. The latest directions in the development of new computational systems are oriented towards quantum, neurosynaptic and cognitive computational systems.

The greatest promise in this area is neurosynaptic and cognitive computing systems. Transistors used in conventional chips have only limited use. They use Complementary Metal-Oxid-Semiconductor - (CMOS) technology. Such transistors can simultaneously communicate with no more than four other transistors. Neurosynaptic chips, developed at the IBM Research Centre, try to mimic neuronal behaviour. In neurosynaptic calculations, each electronic element must be able to communicate with thousands of other elements, like what the neurons of the human brain do (these have up to 10 thousand such connections). In 2008, IBM launched the SyNAPSE (System of Neuromorphic Adaptive Plastic Scalable Electronics) research project. The latest chip with 256 million synapses only needs about 0.1 Watt to power. IBM scientists predict that by about 2038, a chip with a computational capacity comparable to the human brain will be developed.

Cognitive Computing represents a new developmental stage in the evolution of computing technologies. Cognitive systems can learn, search for (mine) data from a mountain of data and recognize new "patterns" (cross correlations) in them, communicate naturally with people and thus penetrate the complexity of the analysed systems. This allows for a holistic view of the analysed systems and their behaviour.

The concept of cognitive systems is a multilayer architecture, in which the uppermost layer is formed by the learning system. It is followed by a layer of organization and interpretation of data, supported by new database systems. The following layer is devoted to architecture and system design (data centric architecture). The core of the architecture of cognitive computing systems is based on the use of nanotechnologies, which make it possible to create the nuclear elements of a cognitive computer by manipulating matter at the level of molecules and atoms.

5.8 ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

The development of computers accelerated the development of a scientific discipline called Artificial Intelligence (AI). Its goal is to "learn" how to program computers so that they can imitate human intelligence, or even report more intelligent behaviour than a person has. Artificial Intelligence itself covers a wide range of areas, from pattern recognition and special Image recognition, to speech recognition, to machine learning (Gregor,M., Nemec,D., Hruboš,M, Spalek,J. 2017).

Artificial Intelligence forms the basis of intelligent computer programs that have enabled the emergence of intelligent products, intelligent machines and devices, intelligent manufacturing systems and the entire, artificial intelligent world.

The main tasks solved by artificial intelligence include, for example: recognition, interpretation, decision-making, machine learning, planning and prediction, feedback, self-monitoring.

The main methods of Artificial Intelligence include Artificial Neural Networks (ANN), fuzzy systems, fuzzy logic, evolutionary algorithms, artificial life, knowledge systems (representation, collection, storage, and use of knowledge), image, sound, speech recognition, etc., expert systems (ES) and decision support systems (DSS).

Pattern recognition covers a wide range of applications, from image analysis, character recognition, speech analysis, man and machine diagnostics, person identification, industrial inspection, etc.

In the field of pattern recognition, a range of new approaches and methods have been developed, such as: discriminatory analysis, feature extraction, error estimation, cluster analysis, sometimes collectively referred to as statistical pattern recognition. Other methods include grammatical inference and parsing (also referred to as syntactic pattern recognition).

Research in this area is mainly focused on new, innovative pattern recognition methodologies and special tools for manufacturing engineering purposes (Gregor,M.,Gregor,M. 2014):

- Development of methods for pattern recognition and tools for 3D activities. An example of an application is the instant recognition of the orientation of parts in a machine or preparation, which will make it possible to simplify the identification of operations that need to be performed on the product and automatically perform such operations.
- Development of an integrated approach, based on pattern recognition, usable for the design of manufacturing systems with the application of well-known techniques for machine deployment, which will allow the design or automatic selection of multifunctional Machining Centres. Such systems are developed as an integrated collaborative environment, integrating the design of manufacturing layout and flexible automation, with the aim of reducing the costs of in-process handling and transport.

From the algorithm point of view, we can divide all tasks into two boundary classes, into tasks easily algorithmizable (they use familiar rules, examples are arithmetic operations) and tasks that cannot be simplified so that we can represent them by rules or algorithms (recognition of complex patterns, creativity, thinking, examples are cognitive activities).

The first class presents activities that will be or are already carried out by computers today. Computers can solve such tasks much better, faster, and therefore more efficiently.

The second class, represented by cognitive activities, is the subject of worldwide research, especially in recent decades. In this area, the human brain works several orders of magnitude more efficiently (both in terms of performance and energy) than computers, and it is estimated that this will take some time.

5.9 MACHINE LEARNING AND COGNITIVE SYSTEMS

Several new directions of research and applications are emerging in the field of machine learning, such as Deep Learning and Wise Learning. Wise Learning represents a way of learning, also referred to as Human Machine Learning - (HML), in which an Artificial Intelligence system learns by observing human behaviour in decision-making situations (for example, driving a car, making decisions in logistics, etc.).

Another area where machine learning systems can be used is dealing with critical situations. In conventional approaches, statistical methods are used to analyse the level of risk, realized on historical data. To exclude the occurrence of critical states, fuzzy cognitive methods are used in the new approaches, which combine statistics with fuzzy logic and use it to predict events. A promising direction of research is the so-called Fuzzy Cognitive Maps.

Scientists are currently working on two different approaches to learning systems. It is believed that when simulating them, it will be possible to use an already created digital brain (Kurzweil,R. 2013), (Gregor,M.,Gregor,M. 2015). The first of the ways is based on the use of an analogous learning approach to that used by the human brain. This learning begins with an "empty" brain, which is learned gradually, like a small child. It is estimated that such learning will last if it does in humans, which several scientists reject. Therefore, another way was sought. The second way of learning assumes that we will be able to scan the contents of the brain. In this case, the brain contents of an adult (several people) who already have enough knowledge are taken, and his patterns stored in the neocortex are copied into the digital brain. Scientists estimate that the development of the necessary brain scanning technology will only be real around 2040.

Data processing using advanced data analysis methods enables the next evolutionary step (Figure 5-7). Historically, in past centuries, mathematical models were used for modelling and analysis. Computer simulation enabled dynamic analysis of systems. The theory of optimization extended the simulation and enabled the on-line search for optimal solutions. Emulation was used to speed up the design and development of control algorithms and systems. All the approaches described above were mainly used in ex post analyses.

Prediction models are a new direction of development based on data processing and analysis. These enable ex ante analysis and detailed prediction of the future behaviours of the investigated systems.

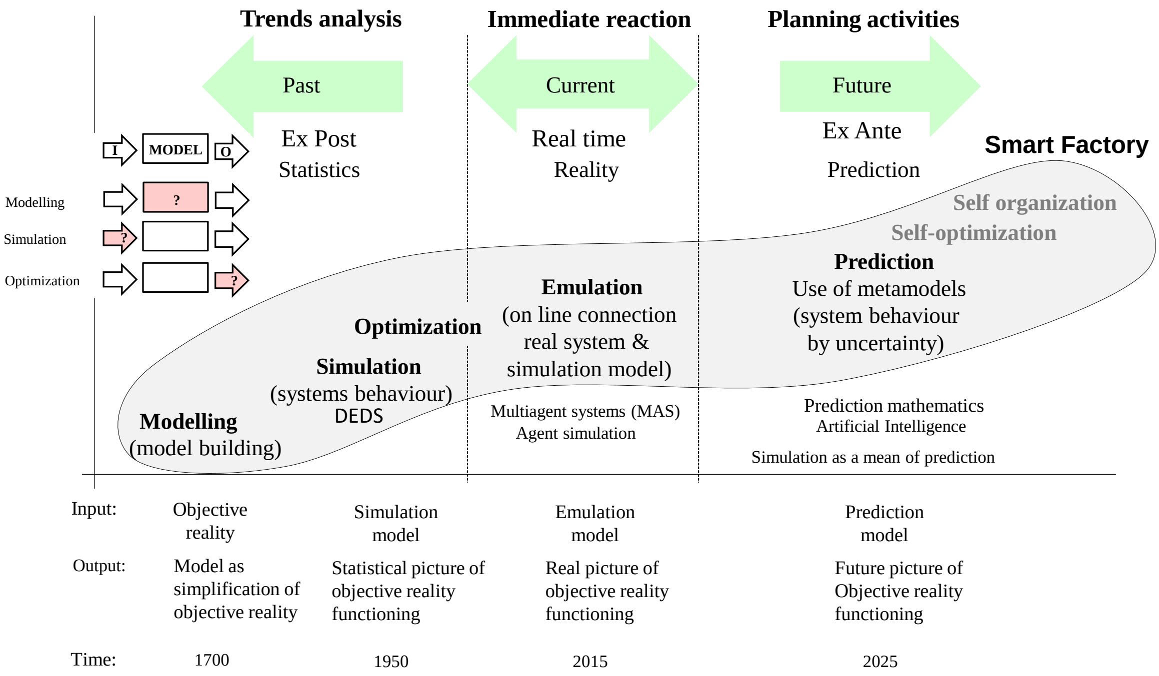


Figure 5-7 Evolution of models

5.10 NANOTECHNOLOGIES

Drexler,K.E. (2013), an American professor, and researcher from the Massachusetts Institute of Technology (MIT), in 1986 in his book: "Engines of Creation" used this term to describe the manipulation of individual atoms in molecular structures to produce precise products. Nanotechnologies make it possible to produce miniature devices with nano dimensions with atomic precision (APM - Atomically Precise Manufacturing). Nanotechnologies work with dimensions of nano meters (nm), where one nano meter represents 10^{-9} m (one billionth of a meter, or 0.000000001 m). To get a better idea, the diameter of a human hair is about 80,000 nm.

When objects are reduced in size, effects arise that do not exist with other sizes of objects, and these are the subject of research. By manipulating atoms in molecules, it is possible to obtain new properties of materials and thus products (Gregor,M.,Gregor,T. 2014).

Molecular nanotechnology represents an inexpensive concept of creating and controlling material structures made of molecules and atoms. It is based on the application of a molecular assembler (grasping and manipulating atoms and creating the desired chemical bonds between them), its incorporation into self-replicating machines and programming, computing, data storage and integration at the molecular level.

An example of a differential gear model proposed by Drexler in 1995 is shown in the Figure 5-8. Nano gearbox is shown in Figure 5-9.

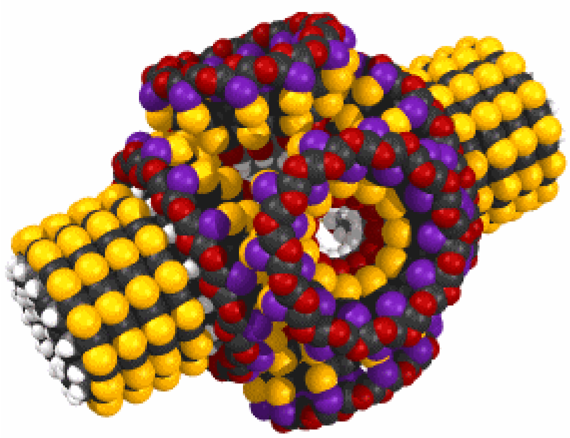


Figure 5-8 Model of Differential Gear
Source: Nanorex (2023)

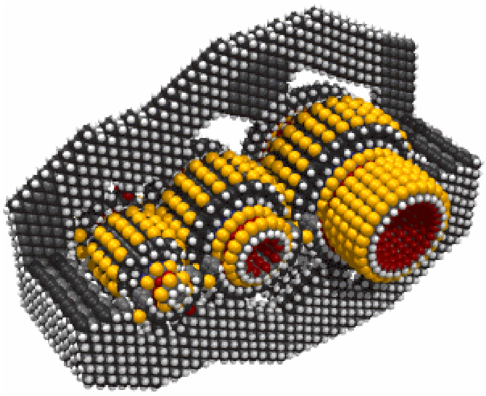


Figure 5-9 Nano Gearbox
Source: Nanorex (2023)

Figure 5-10 shows one of the possible operating principles of the assembly system for nano devices, according to Nanorex.

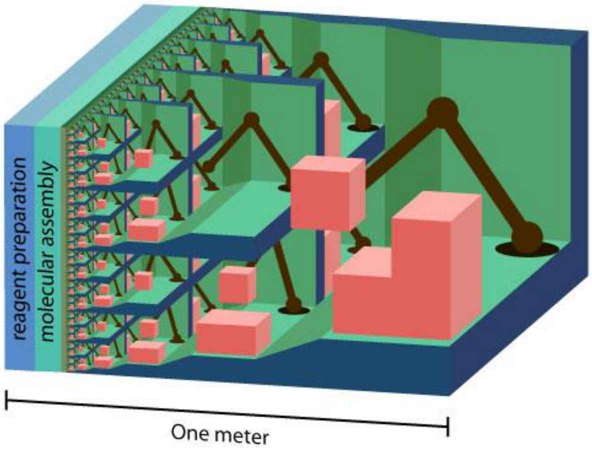


Figure 5-10 Assembly system for nano devices with parallel structures
Source: Zywex (2023)

Figure 5-11 shows a model of a production device, sometimes called a molecular assembly machine (molecular assembler), by Lizard Fire Studios (LFS). In such a molecular assembler, miniature machines combine molecules into larger and larger parts (in the picture they are shown as white cubes), from which more complex devices are subsequently created. This is how, according to LSF, a computer with a billion processors can be made, for example.

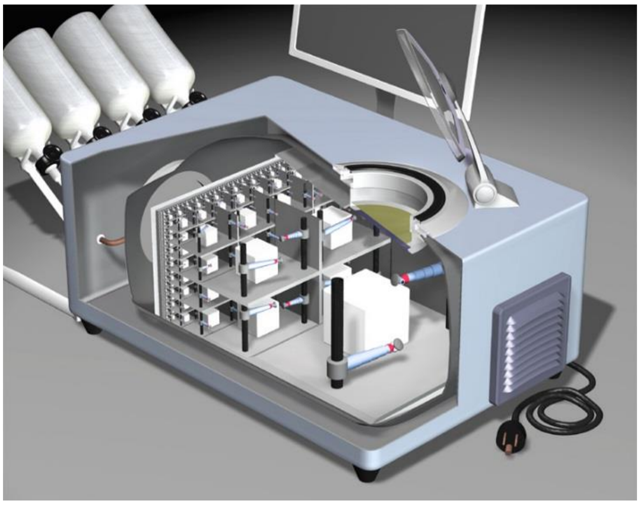


Figure 5-11 Benchtop molecular manufacturing equipment
Source: Nanotech-now (2023)

6 SUPPORT TOOLS FOR FACTORY OF THE FUTURE

When designing, optimizing, or validating processes, tools are used that transfer many of the computing tasks to the computing device. Digitization is already a concept that has an important role in Industrial Engineering. When designing new manufacturing systems, it is envisaged to use software tools and supporting accessories that can achieve a certain level of digitization of processes (Košturiak,J., Gregor,M., Mičieta,B., Matuszek,J. 2000) .

6.1 DIGITAL FACTORY – DIGITIZATION AND INTEGRATION

Designing new businesses represents a complex and challenging problem. The quality of the project determines the future, long-term efficiency of the company. The digital model of the factory (FMU - Factory Mock Up) makes it possible to fundamentally improve communication between design teams, reduce the risk caused by bad decisions and, through higher performance, accelerate innovation and increase the efficiency of the innovation process. The problem of designing future factories is solved by Advanced Industrial Engineering (AIE). The Digital Factory is a revolution, the basis of which lies in the application of digital technologies in the rapid design and testing of new products and manufacturing systems (Figure 6-1).

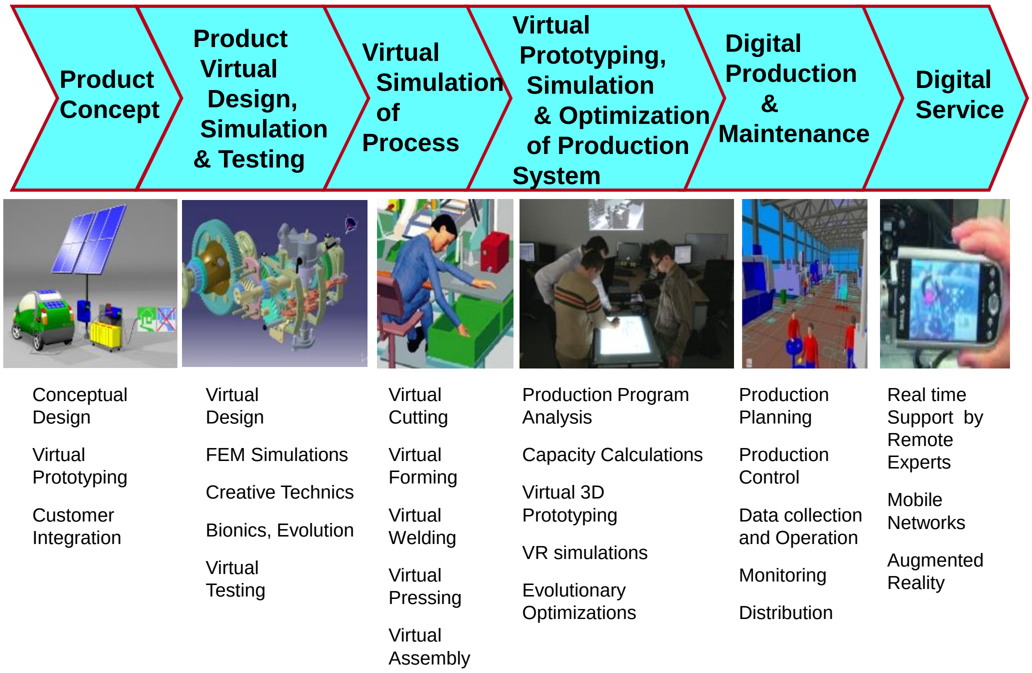


Figure 6-1 Digital Factory Processes

Currently, it is a highly developed concept, which is based on the application of digital models, modelling and simulation (see Figure 6-2), with the potential for fast, highly efficient, final solutions of products and manufacturing systems (Gregor,M., Medvecký,Š., Mičieta,B., Matuszek,J., Hrčeková,A. 2006).

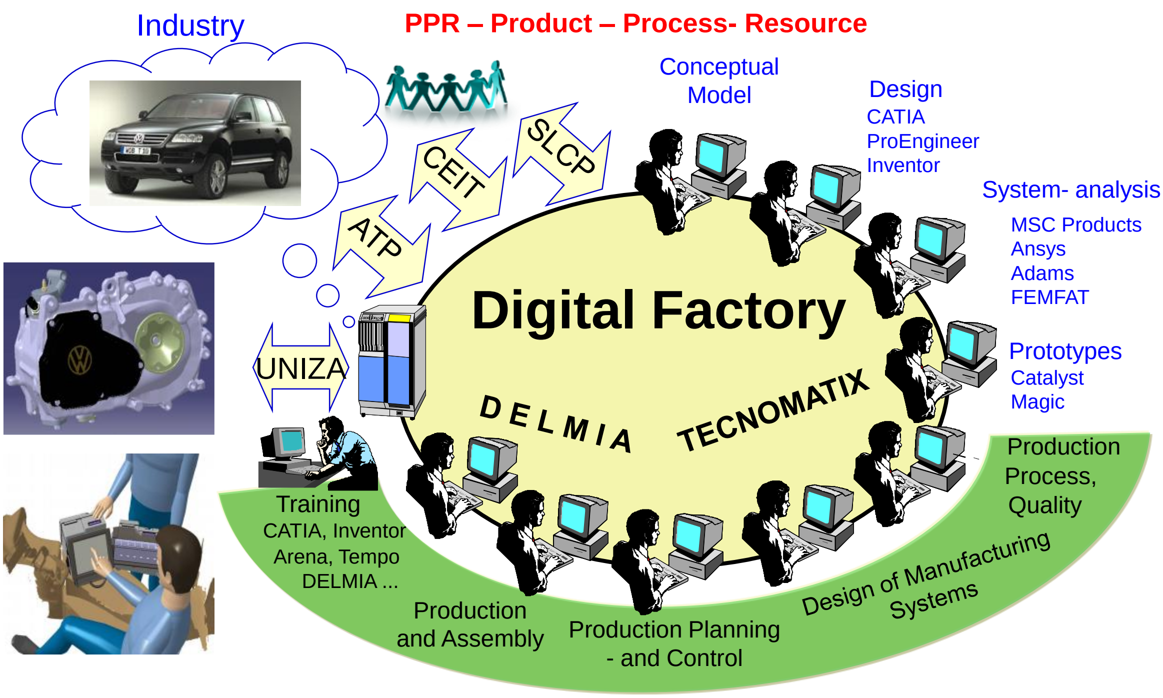


Figure 6-2 The structure of Digital Factory
Source: Gregor,M., Medvecký,Š., Mičieta,B., Matuszek,J., Hrčeková,A. (2006)

The Digital Enterprise concept is based on three elements (Gregor,M. et al. 2011):

- **a digital product** with its static and dynamic aspects,
- **digital production planning** and
- **digital production** with the possibility of using planning data to increase the efficiency of business processes.

The above concept addresses priority areas, chosen based on their impact on the flow of the production process. Each of the areas includes a set of tools that integrates the entire production process from design to implementation itself:

- **systems for designing products** - including modelling, simulation, reverse engineering, digitalization, rapid prototyping, etc.,
- **systems for technical preparation of production** - technological and production procedures, assembly procedures, welding procedures, technical preparation of

production - tools, fixtures and aids, standardization of work, value analysis, cost analyses, etc.,

- **systems for detailing and validating production processes** - NC simulation of production, assembly, inspection, maintenance, welding, production operations, etc. The use of process charts and special bill of materials, which provide a clear overview of the connections and links between processes and resources already in the conceptual stages of the design,
- **systems for production engineering** - complex production scenarios, production layout, industrial engineering, time analyses, design, digitization and simulation of production and assembly systems, determination of availability and utilization of resources, determination, and optimization of worker performance,
- **systems for the integration of people into the production environment** – work activity, ergonomics, time analysis, optimization, education, and development of workers, etc.,
- **systems for production planning and management** - ERP planning systems, scheduling, pull management, uniform production, mixed production,
- **systems for automation and process control** - automatic generation of control programs for control and monitoring of automated production systems, PLC, robots,
- **systems for intelligent solutions in digital enterprises** - research, development, and implementation of intelligent elements in manufacturing enterprises.

The development of a Digital Factory (DF) occurs thanks to the development of information technology and new digital technologies. A Digital Factory is a term used to refer to a digital image of real manufacturing and is used to plan, analyse, simulate, and optimize the manufacturing of complex products. It creates the conditions and directly requires teamwork in the preparation of manufacturing, while at the same time creating quick feedback between designers, technologists, technology designers, standardizers and planners (Gregor,M., Medvecký,Š. 2010a). A feature of a Digital Factory is the ability to solve tasks related to physical objects (for example, product, devices, means) in the digital environment. It is characterized by the possibility of repeatedly using digital models with a high degree of replicability of results (Bangsow,S. 2010).

The use of DF is especially where it is necessary to respond to customer requirements in the field of product variability, short delivery times and low prices (Magvaši,V. 2017). The role of DF is to meet the requirements of manufacturers, who must reassess their processes from the design stage to implementation in both directions due to customer requirements. The possibility of detecting problems and shortcomings of manufacturing and eliminating them before manufacturing begins helps to reduce costs and increase profits. This effect is illustrated in Figure 6-3.

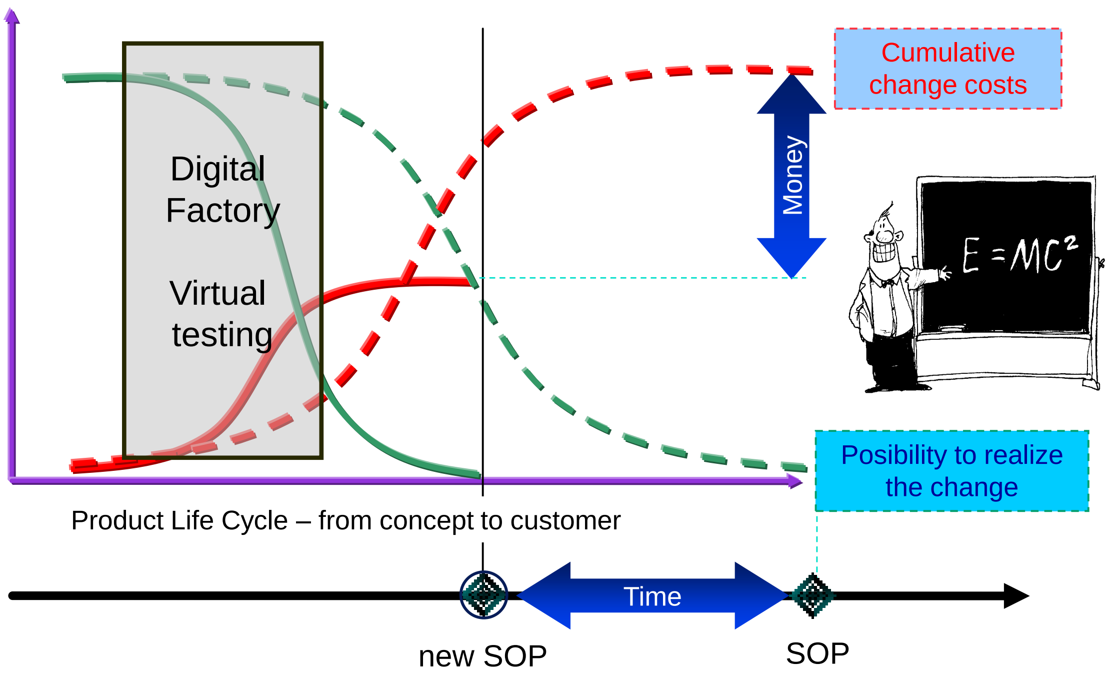


Figure 6-3 from the use of Digital Factory systems
Source: Delmia (2006)

In particular, the technologies of the Digital Factory fall under the supporting tools. These are, for example, technologies of Reverse Engineering, digitization (3D laser scanning), Rapid Prototyping of products and manufacturing systems, or computer simulation and virtual development of products and manufacturing systems (Gregor,M, Medvecký,Š. 2010b). The application of DF is currently implemented for the entire life cycle of the product. For example, with the help of CAD tools, the design of a product and its physical characteristics is possible, at the next stage it is possible to design a manufacturing system for such a product in the digital environment and eliminate all collision states and shortcomings before physical construction or rebuilding of the system.

Such solutions together with the use of virtual reality provide the designer with sufficient space for visualizing his ideas and proposals and presenting them to users. The 3D virtual environment can be used for the interactive work of the design team, while all design professions can solve the design simultaneously if necessary (technological designer, building designer, electrical and energy designer, etc.). Simultaneous design enables the division of the design task into smaller sub-projects and their parallel processing, while a single database is used. Such an approach makes it possible to significantly reduce the project processing time.

3D models, created during the project solution, can be used by all professions, including investors and end users. Established data management and a simple 3D model viewer are fully sufficient for this. 3D models make it possible to check possible equipment collisions or possible collisions during human-machine interaction already during the project solution. Such a work system forces even technology suppliers to create all documentation in digital form. The speed of designing is increased by the immediate exchange of digital data and the building of databases of parametric 3D objects. The created 3D digital model environment of the future company enables the realization of dynamic analyses, simulations. In this case, it literally applies that the entire company is in the computer, and it is possible to carry out many experiments with it and on it, which are inadmissible in a real production system. Such solutions require high-performance computing systems, where the user gets the illusion that what he perceives through animation will take place in production. Digital enterprise systems make it possible to create and store all important information in digital form and use it for decision-making (parts lists, drawing documentation, calculations, standards, control programs, etc.).

Static digital models of production systems are created either directly in a suitable CAD system, or Reverse Engineering, working based on 3D Laser Scanning, is used in their creation (Furmann,R. 2007).

An example of creating a digital model of a production hall in the CAD system environment is shown on Figure 6-4.

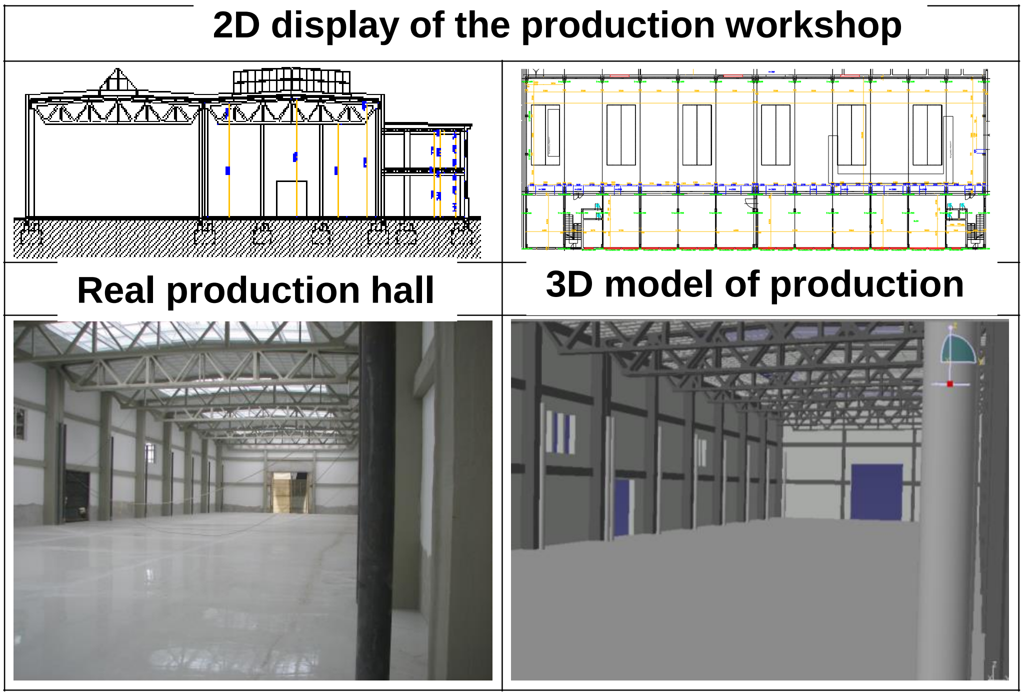


Figure 6-4 Digital model of production hall VL4 in Thyssen Krupp PSL
Source: Furmann,R. et al. (2009)

The creation of a digital model of the VL4 production hall in Thyssenkrupp PSL using 3D laser scanning is shown on the Figure 6-5.

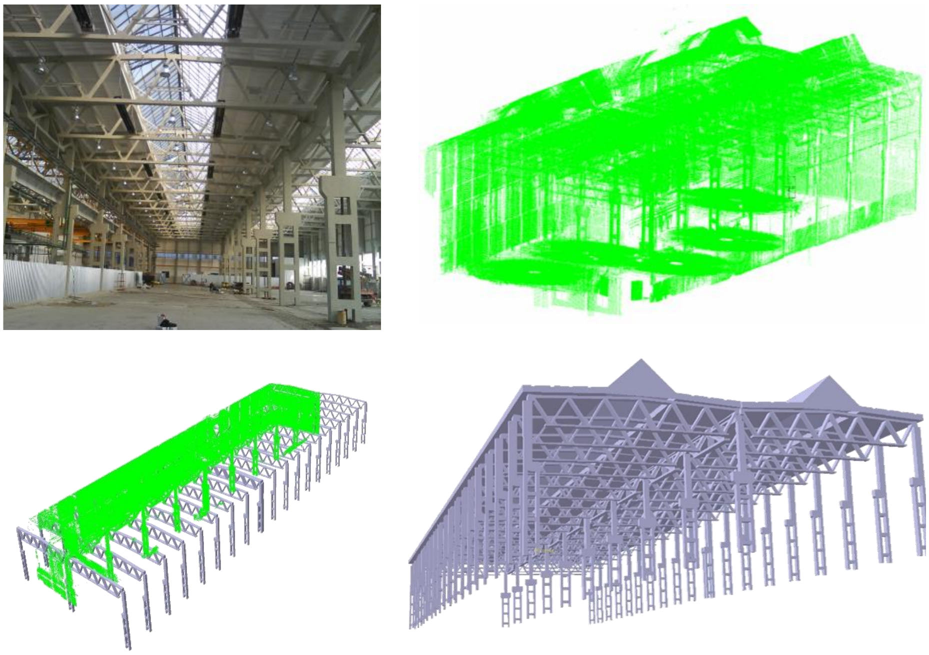


Figure 6-5 Creation of DMU of the Thyssenkrupp PSL production hall
Source: Furmann,R. et al. (2009)

A detailed digital model of the assembly hall is shown in Figure 6-6.

Figure 6-6 Digital model of Production hall in Thyssen Krupp PSL
Source: Gregor,M., Medvecký,Š., Štefánik,A.,Furmann,R.,Mačúš,P.(2016)

Figure 6-7 shows the output of 3D laser scanning of the assembly hall in VW Slovakia.

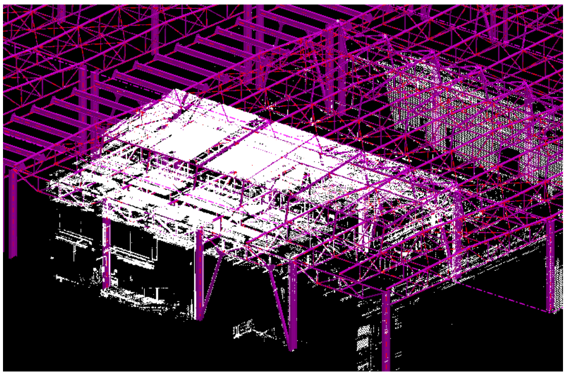


Figure 6-7 Scan of the VW Slovakia assembly hall

The digital model – DMU of the VW Slovakia assembly hall is shown in Figure 6-8.

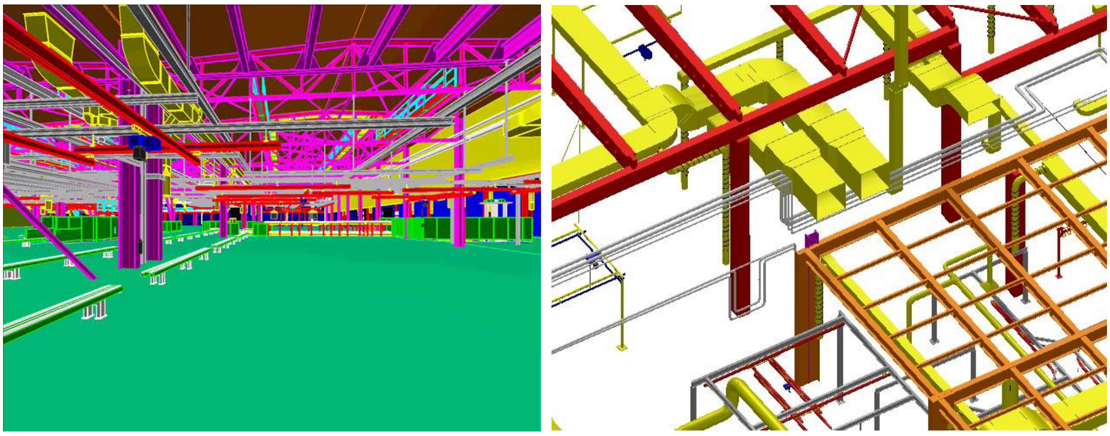


Figure 6-8 DMU models of the VW Slovakia assembly hall
Source: Gregor,M. et al. (2007)

Figure 6-9 shows a complex digital model of the VW Slovakia assembly hall.

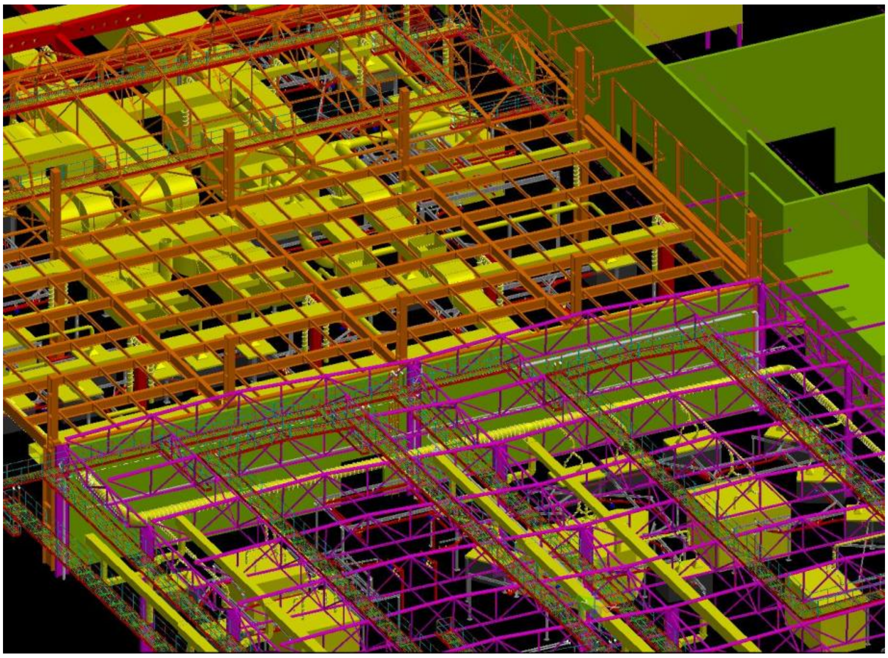


Figure 6-9 Complex DMU model of the VW Slovakia assembly hall
Source: Gregor,M. et al. (2007)

By integrating individual digital models of individual parts of the production system, it is possible to create a complex digital factory model Factory Mock Up (FMU). An example of such a model is shown in Figure 6-10.

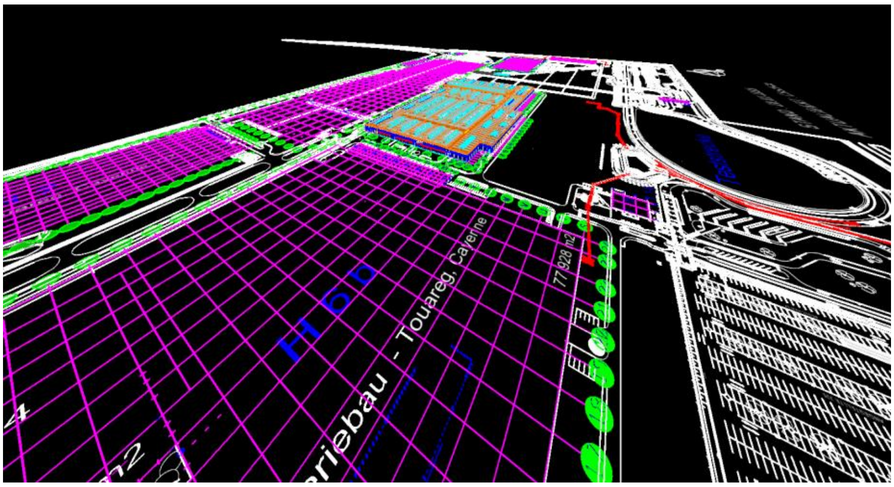


Figure 6-10 FMU model of the VW Slovakia plant
Source: Gregor,M. et al. (2007)

An example of a static digital model of a production line, created using Reverse Engineering and 3D Laser scanning is shown in Figure 6-11.

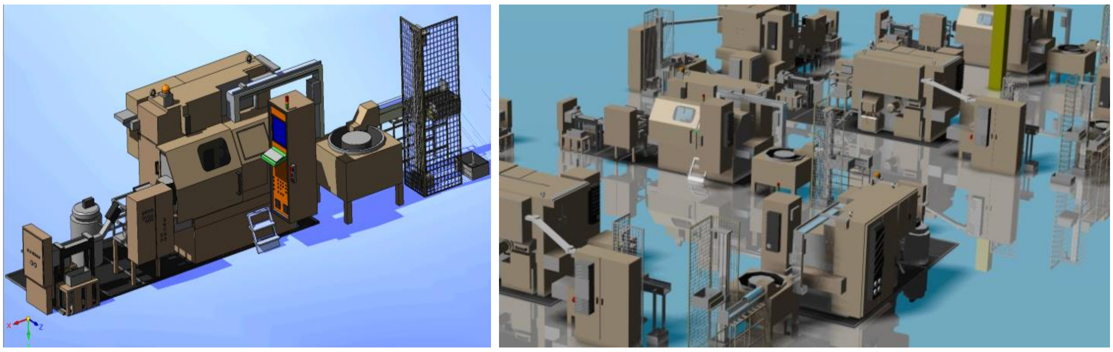


Figure 6-11 Digital model of Schäffler's production line
Source: Gregor,M., Medvecký,Š., Štefánik,A.,Furmann,R.,Mačúš,P.(2016)

If virtual reality is used in the creation of a digital model of the production system, the result is a kinematic digital model. Figure 6-12 shows a real gearbox assembly workplace and its kinematic model.

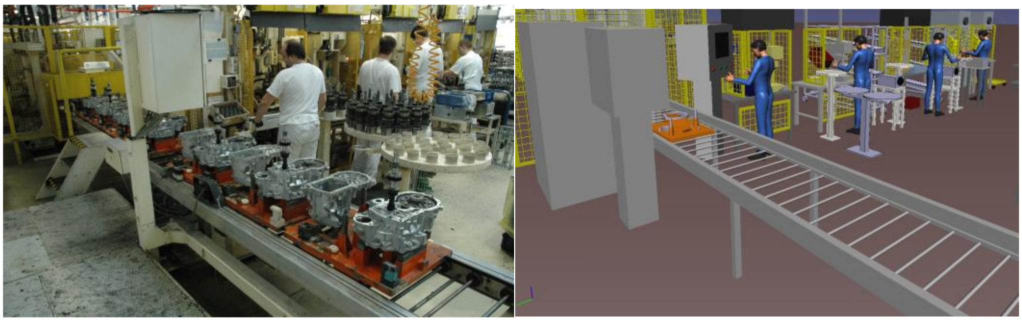


Figure 6-12 Real assembly and DMU model of the assembly workplace VW Slovakia
Source: Asseco CEIT Archive (2023)

A detail of the digital model of the selected assembly workplace is shown in Figure 6-13.

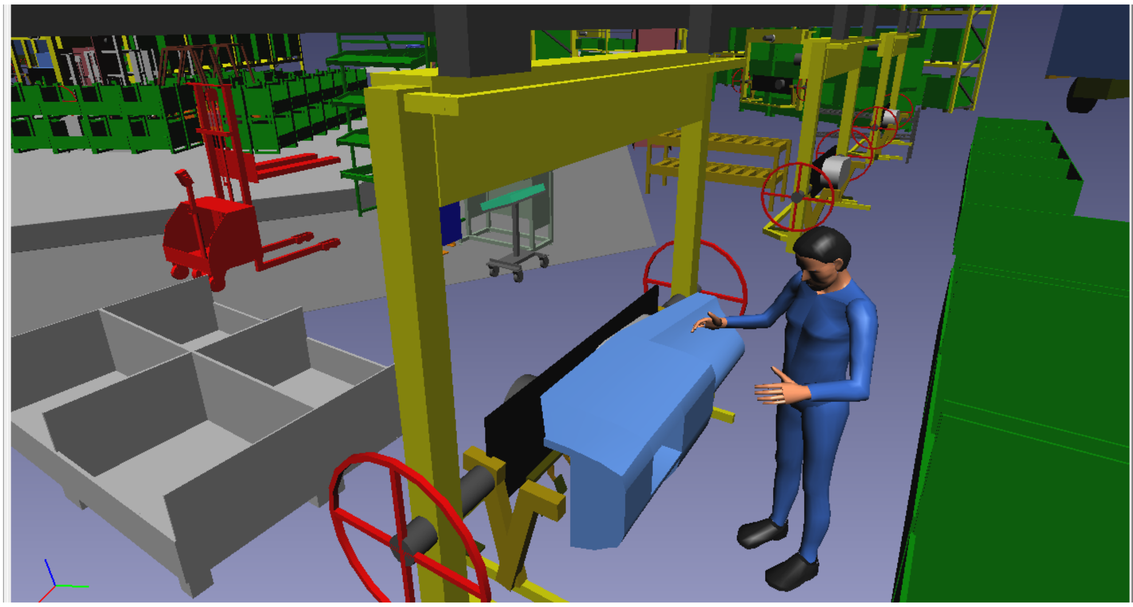


Figure 6-13 Detail of the digital model of the assembly workplace

Figure 6-14 and Figure 6-15 show examples of the use of digital models of assembly workplaces for dynamic ergonomic analyses.

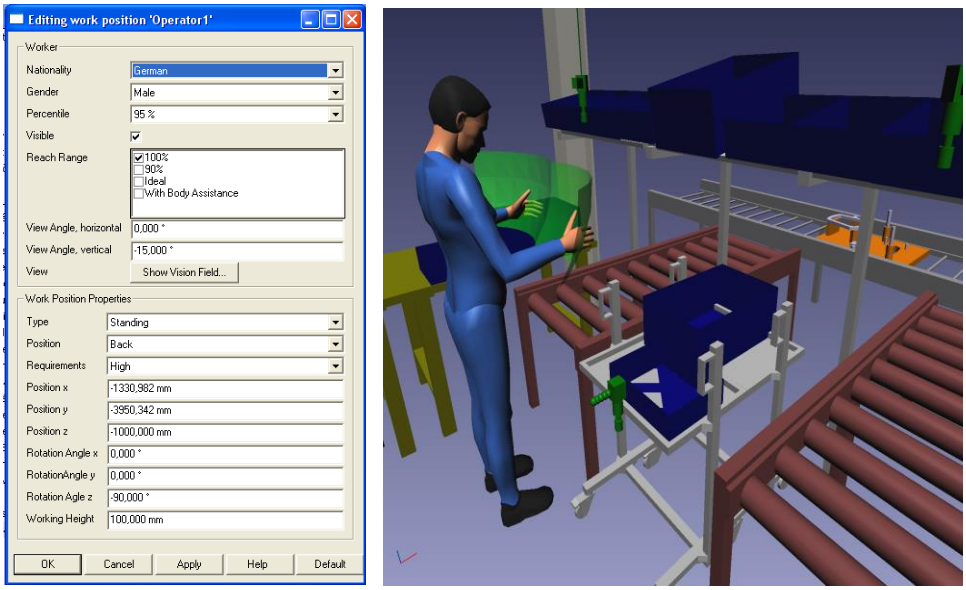


Figure 6-14 Ergonomic analysis of the VW Slovakia assembly workplace

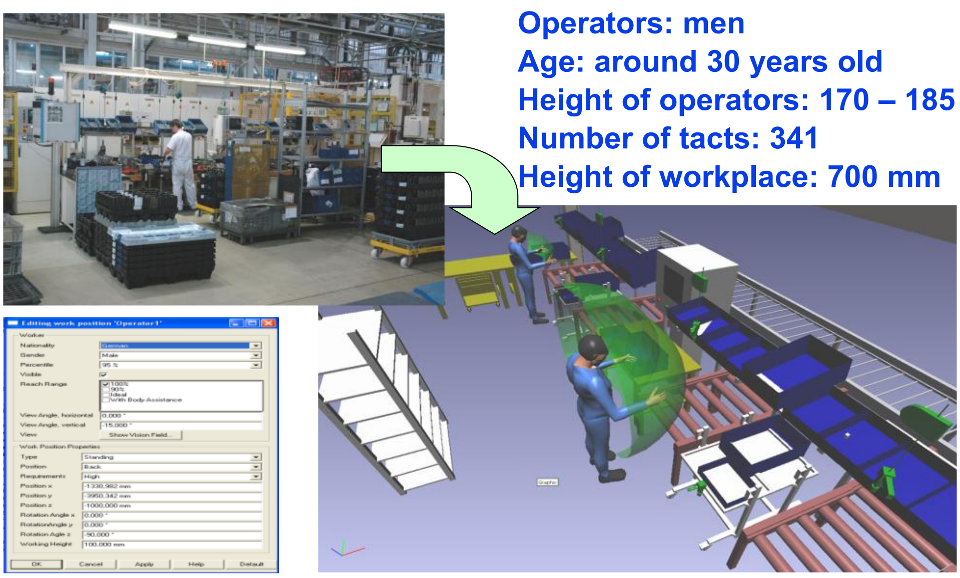


Figure 6-15 Practical implementation of ergonomic analyses VW Slovakia
Source: Asseco CEIT Archive (2023)

Figure 6-16 shows a digital model of material flows and Figure 6-17 shows a digital model of the assembly hall at Whirlpool Slovakia.

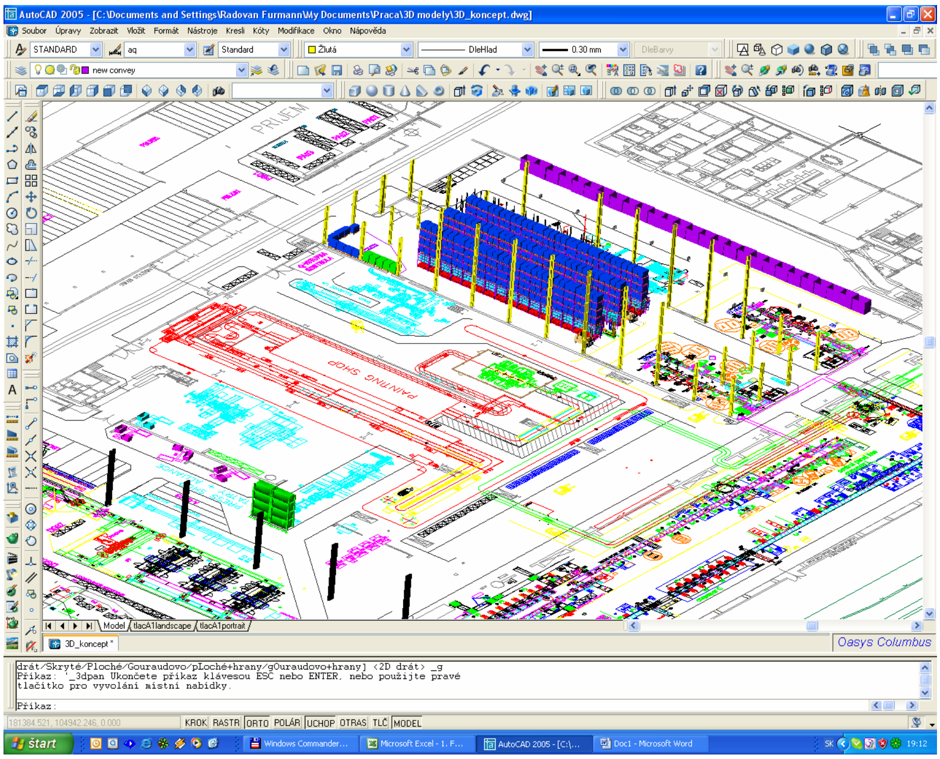


Figure 6-16 Digital model of material flow in Whirlpool

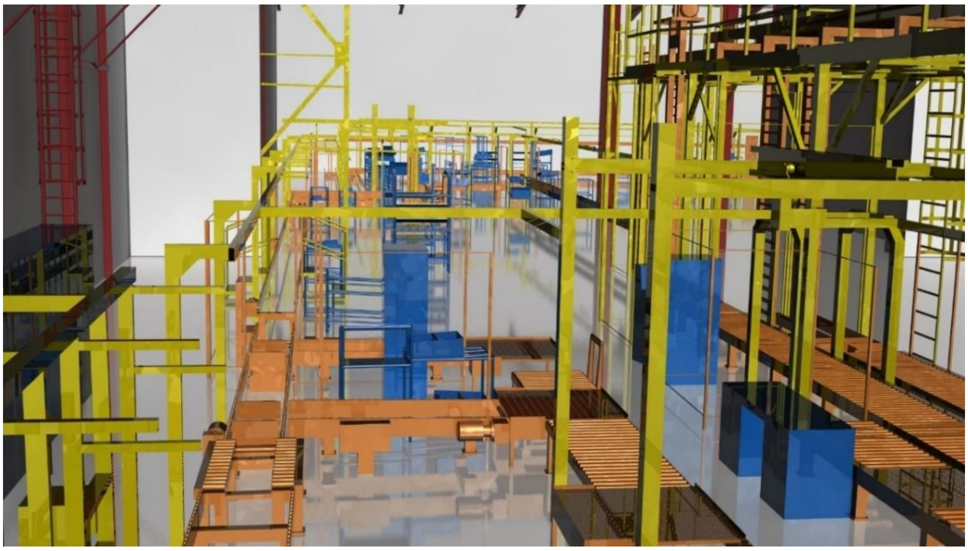


Figure 6-17 Digital model of the assembly hall in Whirlpool
Source: Gregor,M., Medvecký,Š., Štefánik,A.,Furmann,R.,Mačúš,P.(2016)

Figure 6-18 shows a dynamic simulation model of the assembly of gearboxes in the VW Slovakia plant, created in the Quest system.

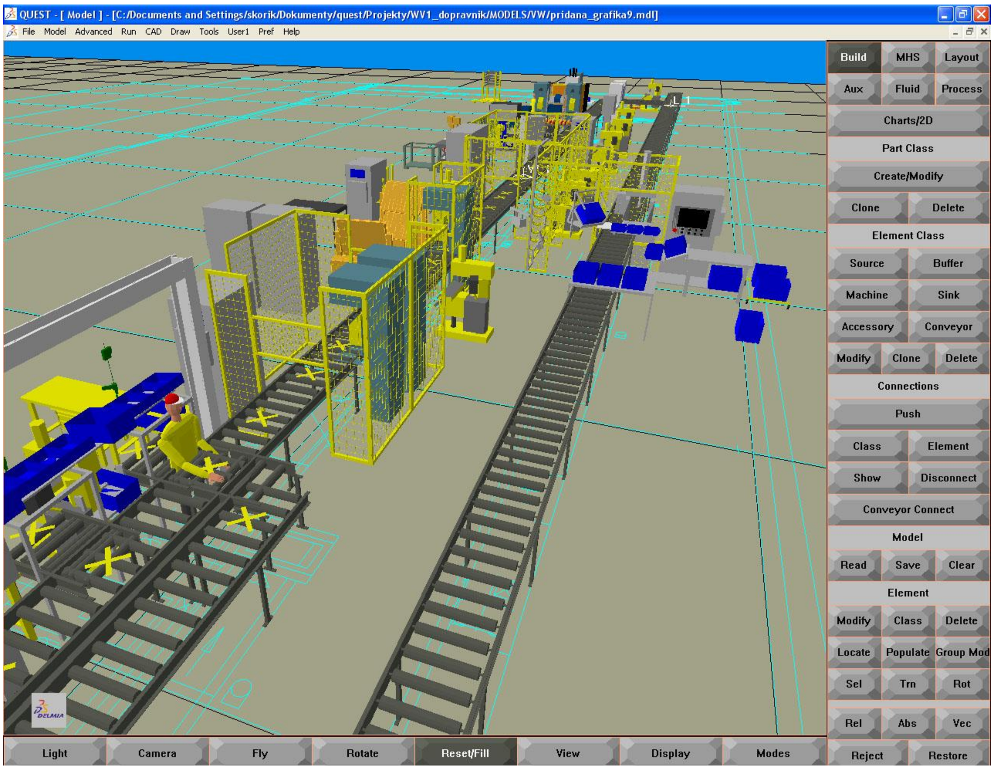


Figure 6-18 Simulation model of gearboxes assembly

Plinta,D.(2001) investigated the possibilities of using simulation in the detailed design of production processes. Figure 6-19 shows the simulation model of the selected gearbox assembly workplace.

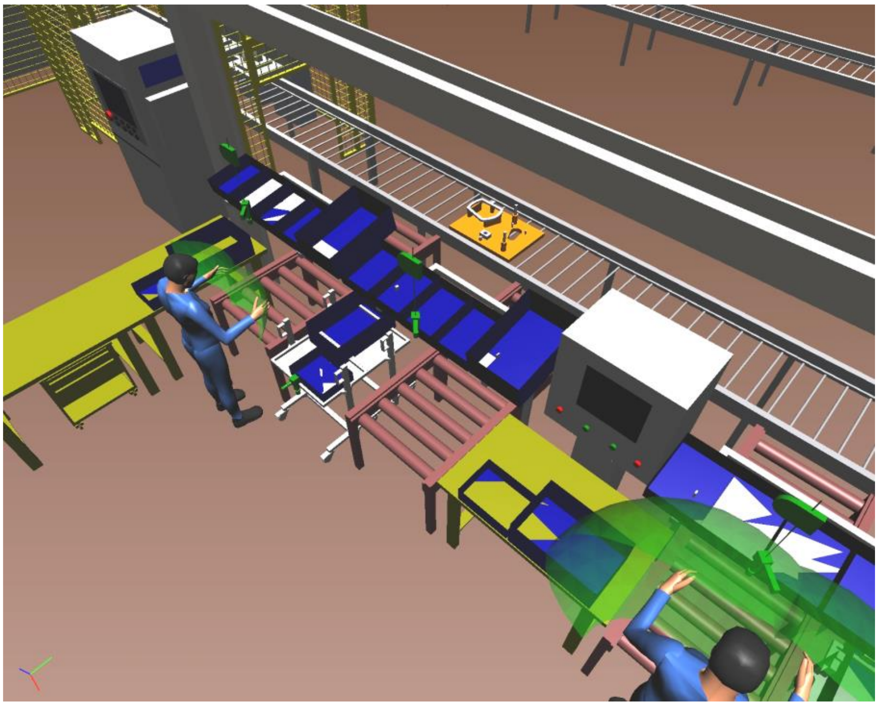


Figure 6-19 Simulation model of the selected assembly workplaces in VW Slovakia

Figure 6-20 shows the process of creating a digital model of Askoll's production cell. A Faro 3D laser scanner was used for 3D laser scanning.

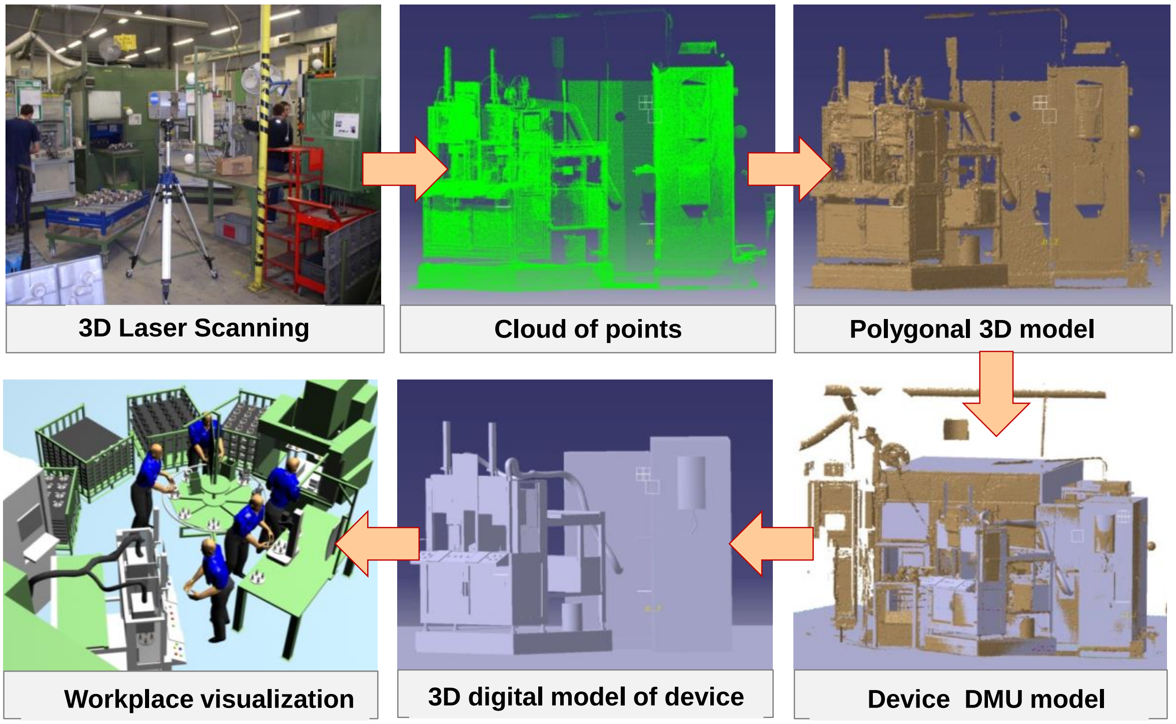


Figure 6-20 Digitization of Askoll's engine assembly workplaces
Source: Gregor,M., Medvecký,Š., Štefánik,A.,Furmann,R.,Mačúš,P.(2016)

Figure 6-21 shows a digital model of the production system to produce large-scale sapphire and YAG single crystals of ATC Crystals.

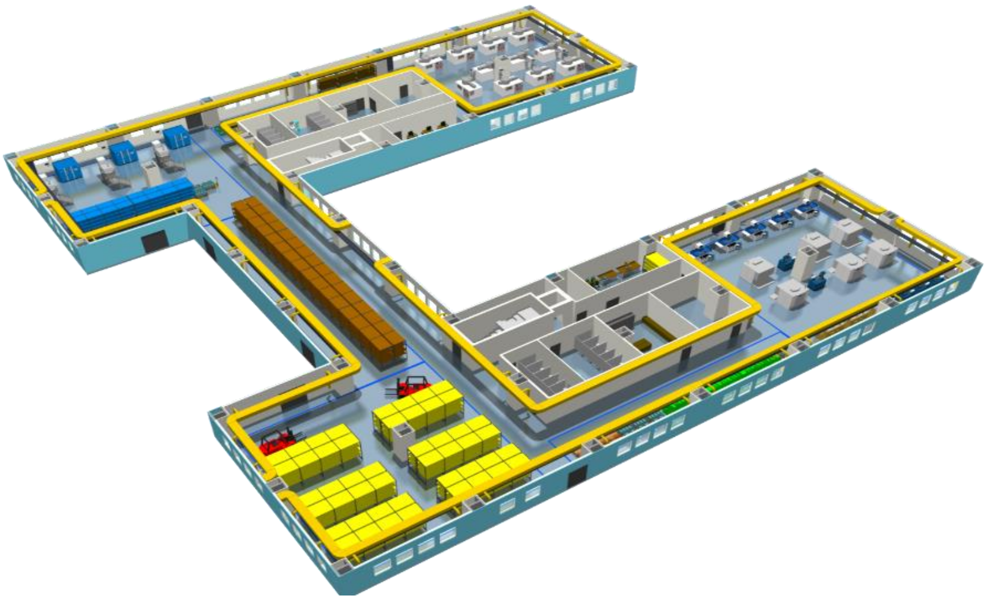


Figure 6-21 Digital model of the production system
Source: Gregor,T. (2018a)

Figure 6-22 shows a simulation model of the production system in virtual reality.

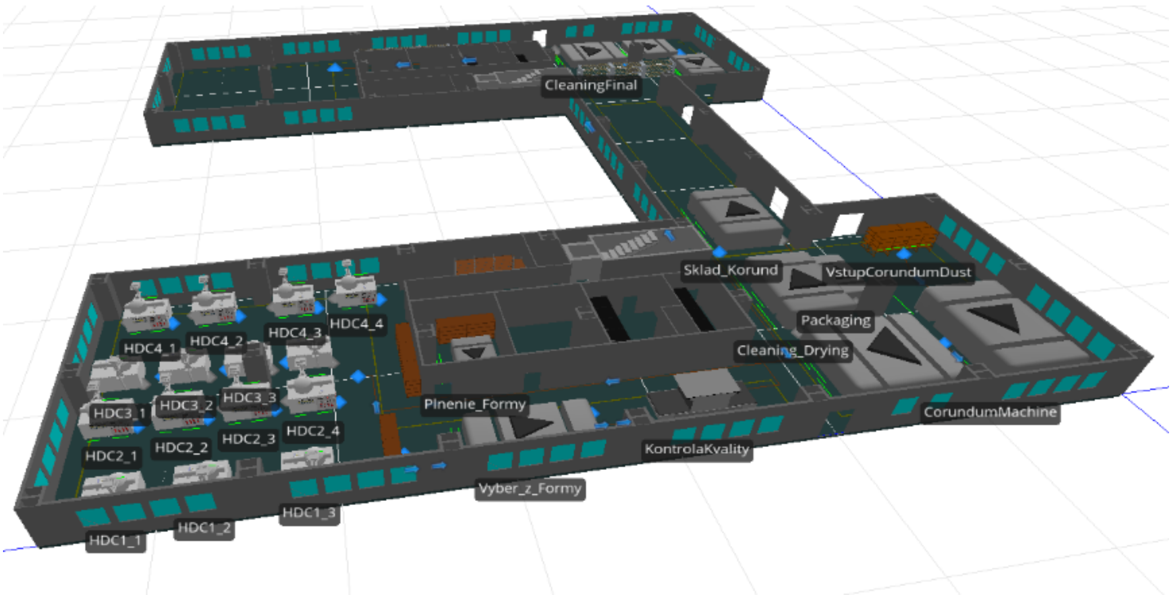


Figure 6-22 Dynamic simulation model of the production system
Source: Gregor,T. (2018a)

6.2 VIRTUAL FACTORY

The development of digital technologies prompted the emergence of a Digital Factory at the beginning of the 21st century. Within the application, the Digital Factory solved a wide range of product, process, and resource tasks. Thus began an era in which all crucial physical manufacturing entities were gradually represented by their digital copies, digital models, also called Digital Mock Ups (DMU). The creation of models made it possible to study and analyse the efficiency and performance of manufacturing even before it is put into real operation (Gregor,M., Štefánik,A., Furmann,R., Škorík,P. 2008). The Digital Factory has created an environment that allows user to work with inputs so that the optimal result is achieved.

The manufacturing process is dynamic and generates a lot of data. For the model to be up to date within the Digital Factory, it is necessary to carry out a data upgrade. Under a physical factory, one can understand real ongoing processes, currently produced products and resources used.

Recently the development in ICT technology has been exposed. Currently, it is possible to apply sensors at a low cost as well as to use new means of communication and systems for manufacturing virtualization. A new revolution in the control of modern factories has becomes virtualization. Digitalization, built on the use of virtual reality technologies, has made it possible to create complex digital models of manufacturing systems. However, these digital models were isolated, artificially separated from the actual functioning of the factory. By integrating digital models with data collected in real manufacturing processes, a dynamic representation of the manufacturing world was created, which already faithfully represents objects and processes in manufacturing through data. Virtualization thus allowed the emergence of a virtual copy of manufacturing systems, which was called a Virtual Factory.

The Virtual Factory represents the dynamics of processes through data. Its basis is a data model that uses real time data obtained through sensors.

A Digital Factory, a real factory and a Virtual Factory form a new paradigm (model) and thus a new manufacturing environment, which is integrated through digital data by the so-called Smart Factory.

The idea of a Virtual Factory lies in the combination of model representation (Digital Factory) and real-time collected data Figure 6-23.

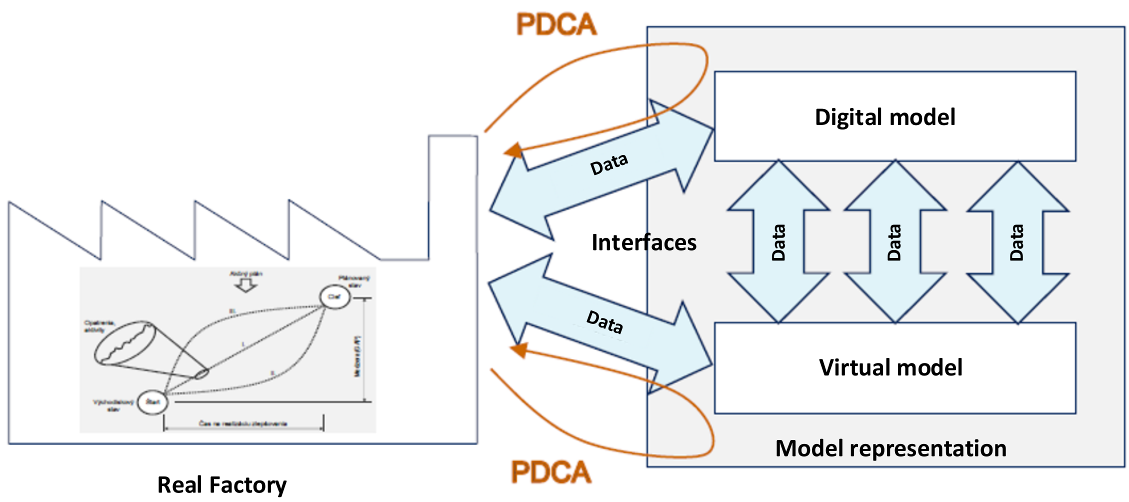


Figure 6-23 Integration of the real, digital, and virtual worlds
Source: Gregor,M., Grznár,P., Gregor,T. (2018b)

The technological possibilities of applying a Virtual Factory are possible mainly due to the use of the latest ICT and sensors in the organization and control of advanced manufacturing, which has been awarded the designation - Internet of Things (IoT). Digital data and virtualized manufacturing environments use another new technology called Cloud Computing to realize fast computing services. These two technologies form the basis for a Smart Factory (Gregor,T. 2018b).

6.3 SMART FACTORY

Modern real factories, using the most advanced technologies, are referred to as Smart Factory. Smart Factory Figure 6-24, or in a broader sense, Smart Industry Figure 6-25 represents the connection of the digital, virtual, and real worlds into one.

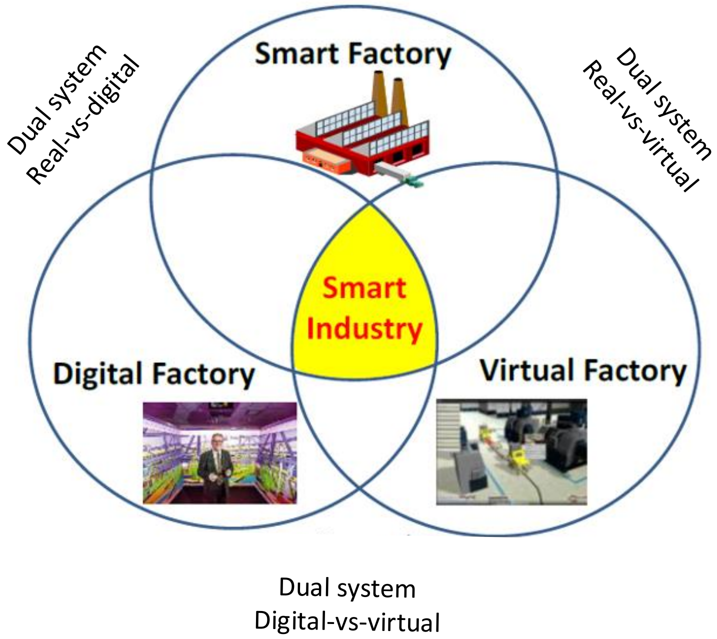


Figure 6-24 Duality in the world of manufacturing
Source: (Gregor,T. 2018b)

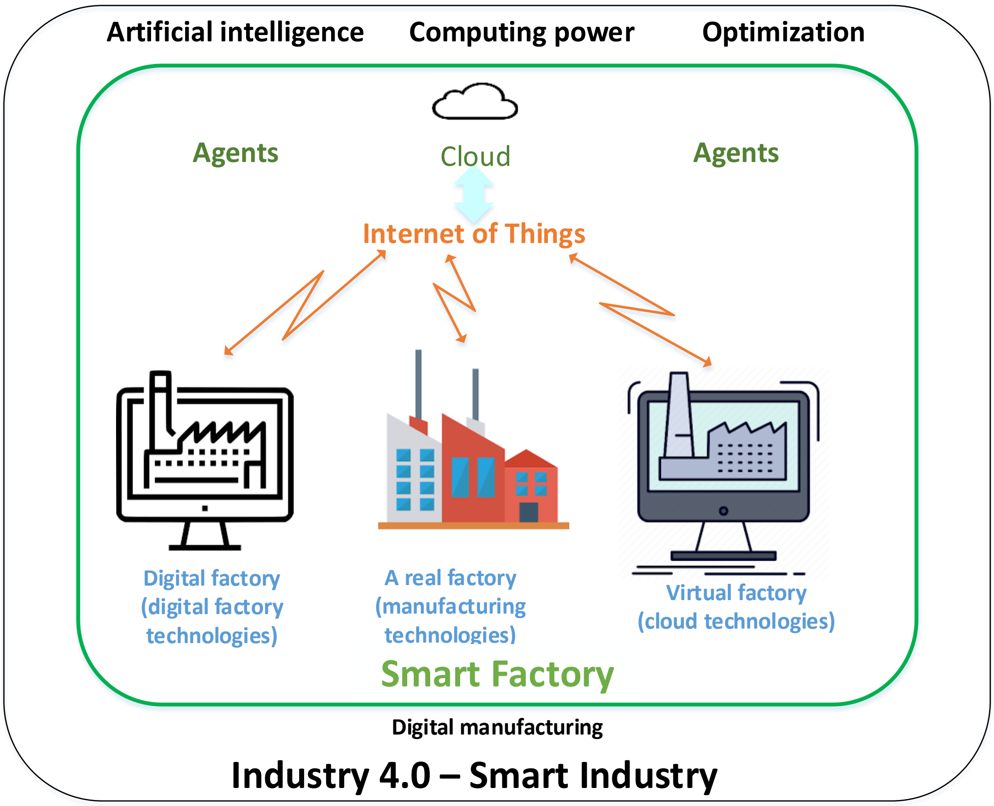


Figure 6-25 Smart Industry Concept
Source: Gregor,T. (2018b)

According to Jovane,F., Westerkämper,E., Williams,D. (2009) at Smart Factory, it is necessary to ensure the integration of data collection, data mining and sensors into a single architecture so that real-time monitoring of resources and sharing this situation in the digital environment for the needs of planning, managing and supporting peripheral actions. The components of Smart Factory by (Jovane,F., Westerkämper,E., Williams,D. 2009) and (Koh,C., Deng,M., 2020) include:

- wireless technology in factories,
- integration of diagnostic systems,
- real-time control and data collection for learning processes,
- location systems for mobile objects,
- integration of factory data control,
- intelligent system for transferring data to request.

Within this framework, the Smart Factory can be considered as a system that collects data on real processes and creates a digital copy (digital twin) in the digital environment, on which it is possible to realize the simulation or emulation of future states (Hodoň,R. 2020). However, Smart Factory does not stop at the realization of the digital twin but uses algorithms and artificial intelligence to perform data mining from historical data, relationship correlation analysis, or future state prediction, evaluate it and based on them, optimize the real processes that take place in the factory. In such an factory, it will be possible to find machines that can learn and perform analyses and predictions for the needs of their own control (Achahchah,M. 2019). With such devices, manufacturing will be more decentralized, devices and means behave autonomously, begin to interact, and create complex patterns of behaviour, emergence.

Smart Factory is still more of a dream than a reality. So far, we are thinking of it more as an ideal greenfield solution, with no relation to existing manufacturing structures, existing products, and today's workers. Such a generational change in manufacturing systems will certainly not occur with the immediate abandonment of existing manufacturing. The changes will be rather evolutionary and will take place gradually. The massive deployment of automation, intelligent machines and robots, or the routine use of the Internet of Things and cloud solutions will take some time. (Gregor,M., Magvaši,P. 2013).

Some OEM manufacturers in the automotive industry are already experimenting with the principles of Smart Factories, as they register individual customers whose number is growing intensively and who want to change the details of their vehicle until its assembly is fully completed. However, the solutions being developed are still very expensive and therefore uneconomical. These are prototypes rather than serial solutions. Today, such "prototypes" are bought by the richest firms, thereby increasing their image as progressive companies. Apple, Intel, and Google are a good example. Such investments are extremely important, without them, the progress towards Smart Factories would freeze.

In condition of Slovak industry most progressive research in Smart Factory area was carried out by Asseco CEIT. In their conception, Smart Factory is a superstructure of the Digital Factory, which extends this concept to a Virtual Factory and thus creates the Digital Twin of the Factory Twin in the virtual environment.

6.4 DIGITAL TWIN

The Digital Twin is a concept of the functioning of future manufacturing systems, based on the application of digital technologies, currently promoted by Siemens. Although the principles of the digital twin have been known for a long time, Siemens has brought the development to the stage of the product that is offered on the market today.

Today, the digital twin is presented mainly at the product level, and its essence lies in the creation of a virtual (digital) model of the developed product, machine, device, etc. The virtual model (digital twin) created in this way can be used at all stages of product development, operation, and improvement. For example, the digital twin of a car makes it possible to reduce the cost of developing and testing a developed car by an order of magnitude. All development and most tests can be carried out through virtual testing and simulations, using a digital model. Physical tests shall only be used for calibration of the test method.

The concept of a digital twin has gradually expanded from the product level to the level of processes, manufacturing systems to the factory level.

An example of the use of the digital twin concept at the device level, which has gradually grown to the level of a comprehensive solution for internal logistics, is the Factory Twin system, developed since 2004 at the University of Žilina.

The rough structure of Factory Twin is shown in Figure 6-26.

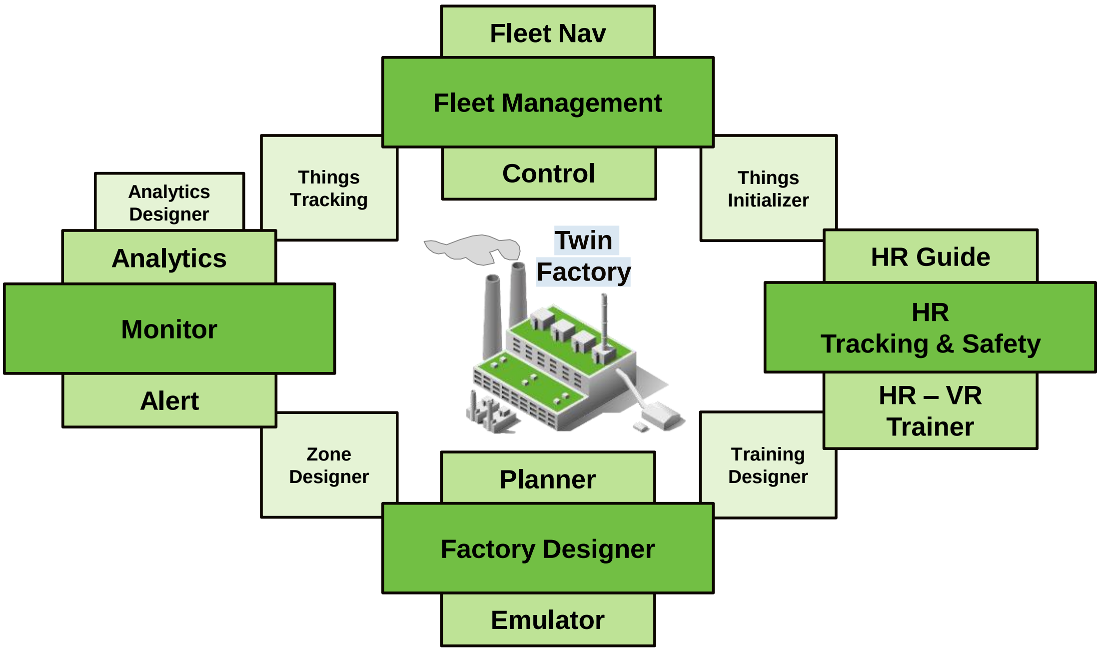


Figure 6-26 Asseco CEIT Factory Twin Rough Structure
Source: (Gregor,T. 2018b)

Asseco CEIT has continued to develop since 2009, and since 2014, the development has been carried out by EdgeCom. At first, the development took place at the level of a mobile robotic system, and its output was the development platform for mobile robotic applications, which is now known as the Ella®. A preview of the Ella® platform's first-generation environment is shown in Figure 6-27.

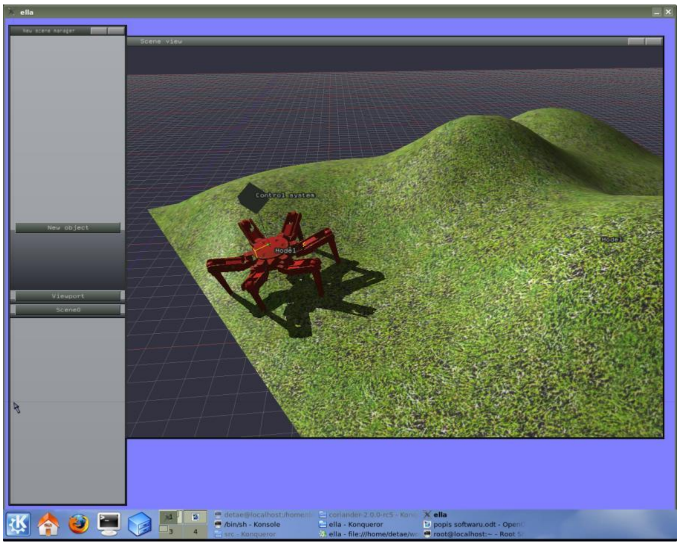


Figure 6-27 Sample from the first generation of Ella®
Source: Michulek,T. (2010)

Figure 6-28 shows the Ella® platform used in the development of mobile robotics.

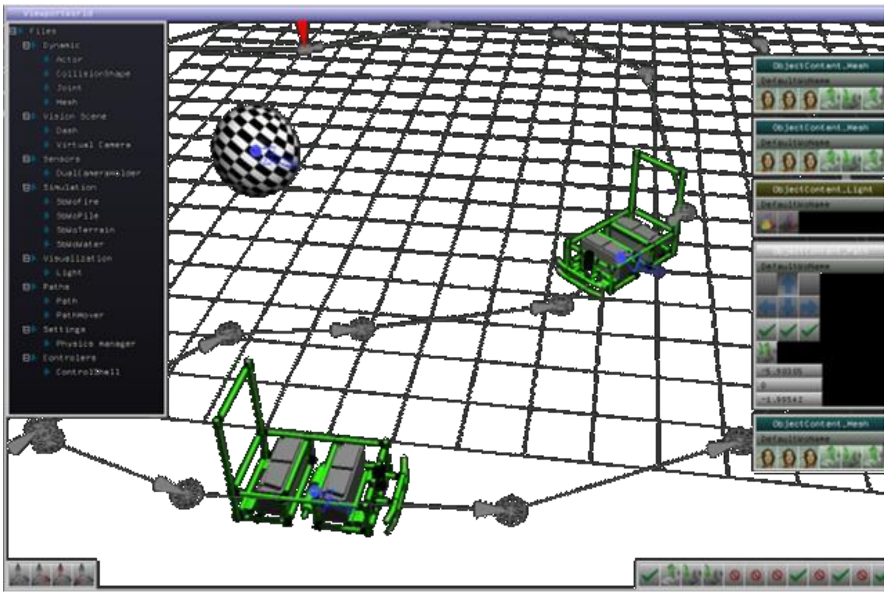


Figure 6-28 Ella® used in the development of MRS for industry
Source: Michulek,T., Capák,J. (2007)

In Figure 6-29, a sample of the Ella® platform is used for simulation in logistics.

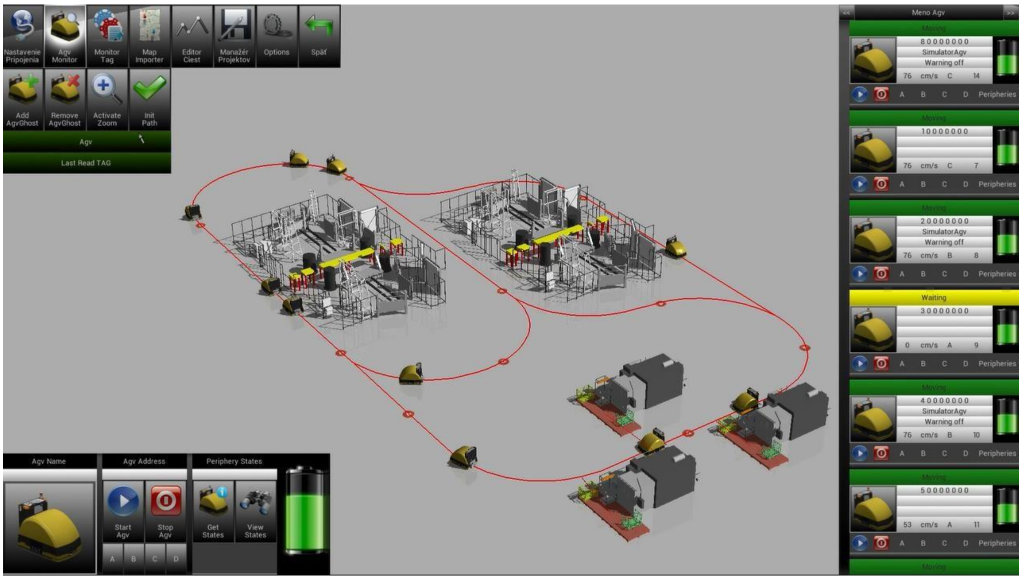


Figure 6-29 Preview of the simulation version of Ella®
Source: Gregor,M., Michulek,T., Capák,J., Mačúš,P. (2009)

Figure 6-30 shows the Ella® platform used for designing and analysing manufacturing systems.

Figure 6-30 Ella® used for the design of manufacturing systems
Source: EdgeCom (2023)

Figure 6-31 shows the most comprehensive form of the Ella® platform, which is used in the development of complex robotic solutions in the industry. This platform made it possible to carry out the entire development and testing of a new product in virtual reality, which significantly shortened the development of its own mobile robot.

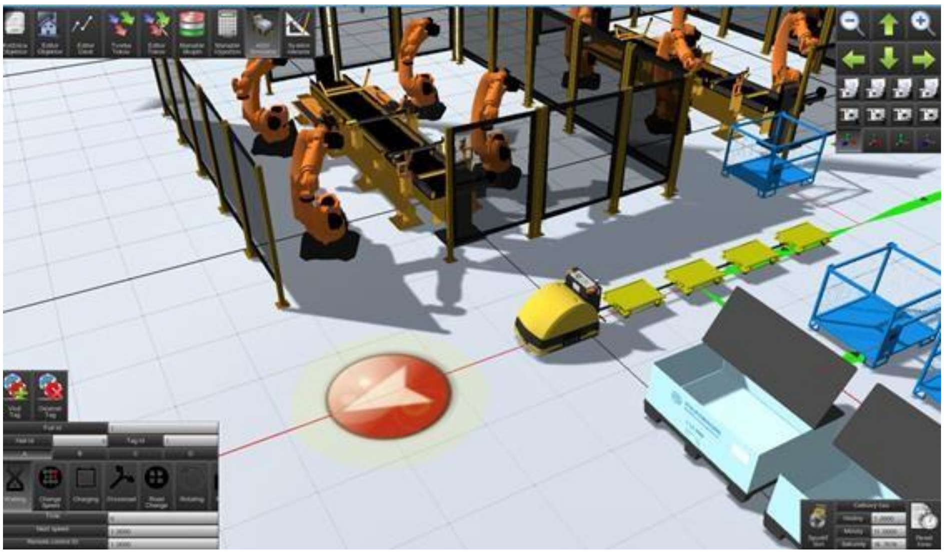


Figure 6-31 Ella® used for the development of complex robotic solutions
Source: EdgeCom (2023)

Ella® platform has been gradually expanded and applied in the development and testing of more complex logistics solutions using autonomous mobile driverless robotic systems -

Automated Guided Vehicles (AGV). The complex systems for internal business logistics developed in this way are currently working in several multinational concerns (VW, Porsche, Skoda, Jaguar, Continental, etc.). The solutions implemented in practice are truly grandiose, with more than 500 AGVs, about 1500 other external devices (automatic loading and unloading stations, towed semi-trailers, conveyors, etc.) working in coordinated projects today.

In 2015, EdgeCom came up with a proposal for an integrated concept for the logistics solutions of the future, which was given the working designation Factory Twin. The new product is developed in co-operation with several strong developer companies. The consortium was formed in which Asseco CEIT took over the position of commercialization of the new product.

The process itself begins with digitization and planning in the 3D environment of the Digital Factory. The design is then rationalized and optimized with the support of dynamic simulation. By designing and validating in the Factory Twin environment, the user can reduce the start-up time of manufacturing to a minimum and avoid expensive complications. Before the actual implementation of changes begins, the factory can already run virtual training of workers in key processes and preparation of personnel for sharp operation, to shorten the learning curve and thus the start-up time. Virtual training takes place in the 3D VR environment of the Factory Twin, which is the digital twin of the real system. After the entire solution is designed, optimized and virtual training runs, specialists implement the proposed solutions in the factory environment – from the deployment of complex automatic logistics systems to the delivery of custom-made manufacturing lines. The operation of these solutions is autonomous, they can self-optimize in real time, communicate with the company's control system, and can respond to changes in manufacturing requirements in real time. The final step is automatic data collection, monitoring and analytics, which deliver a factual digital image of the own factory environment, in the Factory Twin environment, which, with the support of analytical tools, allows for further improvement of the entire system.

The basic technology used by Factory Twin is the real-time location technology or Real Time Localisation System - (RTLS).

The whole solution integrates three worlds, the world of a real physical factory, the digital world – represented by digital models, the dynamics of which can be analysed using computer simulation, and a virtual world, represented by data, which can be optimized using emulation technology (Figure 6-32).

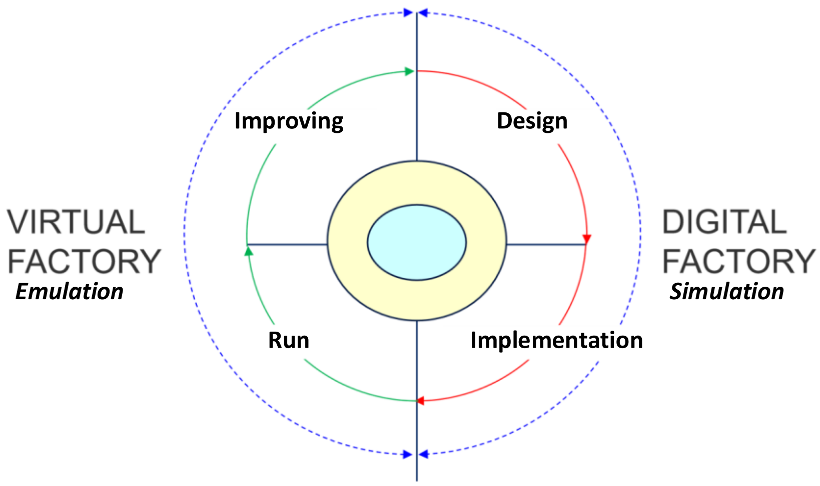


Figure 6-32 Digital and Virtual Factory
Source: Gregor,T. (2018b)

The Factory Twin concept developed at Asseco CEIT is shown in Figure 6-33.

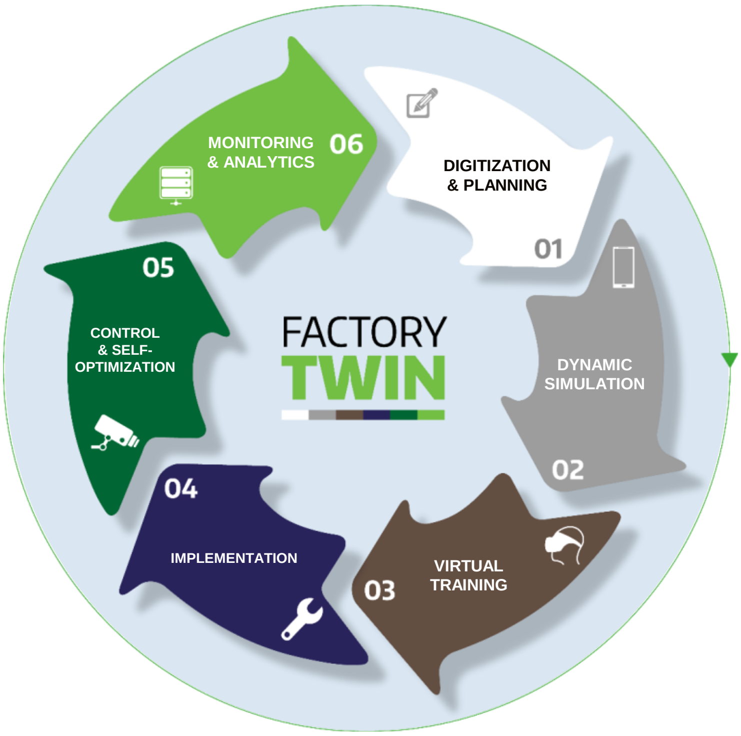


Figure 6-33 Asseco CEIT Factory Twin

Source: (Gregor,T. 2018b)

Figure 6-34 shows selected modules that are used within Factory Twin.

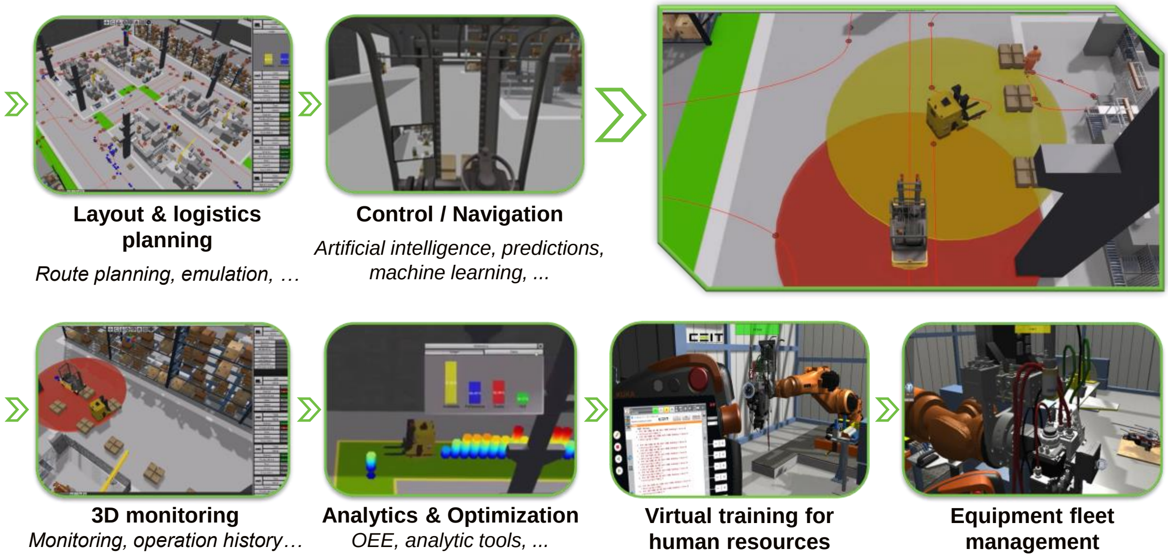


Figure 6-34 Moduls of Factory Twin
Source: (Gregor,T. 2018b)

Figure 6-35 shows the result of the analysis of AGV movement in the production system, in the form of a Heat map.

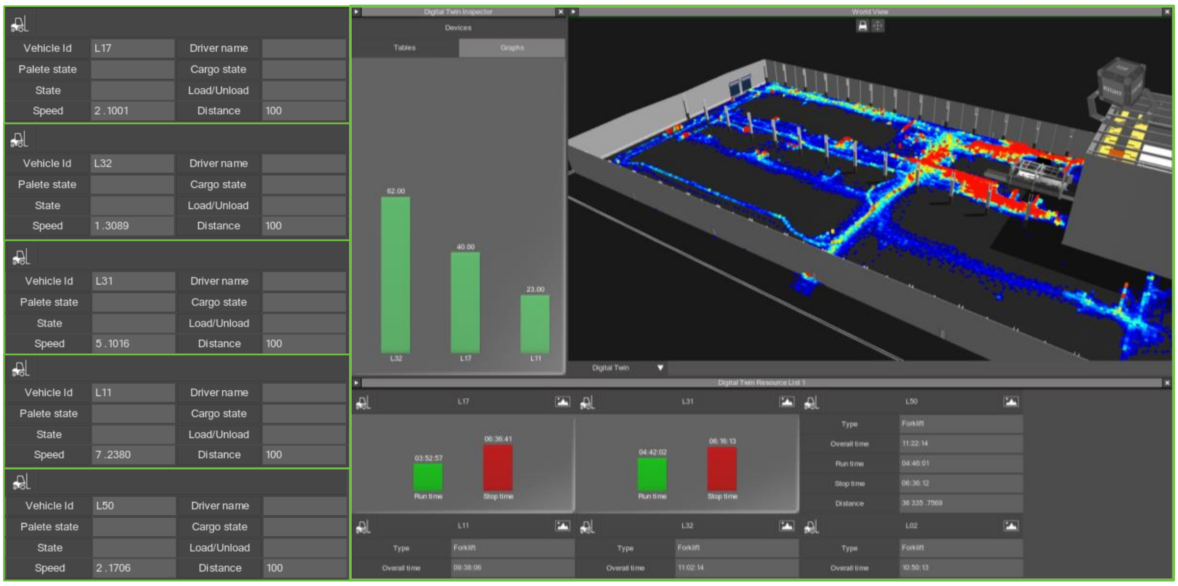


Figure 6-35 AGV movement Heat map in production logistics

6.5 VIRTUAL DESIGN OF MANUFACTURING SYSTEMS

The concept of Virtual Design of Manufacturing Systems can be understood as designing and optimizing current manufacturing processes in a virtual computing environment. By using a computer and adequate computing power, it is possible to create a digital model of the manufacturing system. An important role in virtual design or optimization is played by modelling and simulation, which provides answers to the most important questions in process planning, detailing, and verifying processes and resource simulations. Simulation is one of the most widely used tools for solving tasks in today's industrial world, where we do not know the exact result for specific defined inputs (Grznár,P. 2019). Modelling in the context of simulation is an activity in which, in a virtual environment, we imitate the behaviour of a real or planned object so that it is identical to it in a certain degree of abstraction defined in the objectives of the simulation project. The model is an idealized, simplified and, subject to certain limitations, representation of a certain object or system. It allows the study of the properties of the original object (Hesse,W., Merbeth,G., Frölich,R. 1992).

Today, the most commonly used simulation platforms in the design of manufacturing systems are the packages DELMIA, Tecnomatix (Mozol,Š., Gregor,M., Grznár,P., Schickerle,M. 2019), SIMIO (Mota,I.F.D.L., Guasch,A., Mota,M.M., Piera,M.A. 2017) and AnyLogic (Grigoryev,I. 2015). More on the issue of modelling and simulation are devoted to works Law,A.(2014), Gregor,M., Palajová,S., Gregor,M. (2012), or Grznár,P. (2019).

From the PC simulation point of view, two main directions of simulation can be recognized, namely a conventional object-oriented simulation and an agent-based simulation. For simple and complicated manufacturing systems, conventional object-oriented modelling and simulations are sufficient. However, with complex manufacturing systems, which will be common in the Factory of the Future, the designers are faced with the occurrence of emergence. Emergence is a phenomenon in which, due to several simple interactions in a system, a system generates behaviour that cannot be predicted by conventional analytical tools. A complex system is a system in which many components can be analysed, between which there are many relationships, so that the behaviour of each element depends on the behaviour of other elements see (Gregor,M., 2018b) and (Morowitz, H.J., Singer,J.L. 1995).

6.6 AGENT-BASED MODELLING AND SIMULATION

Currently, the exact definition of an agent does not exist, and in many works it has been defined according to the purpose of its use. However, in works dealing with the simulation of manufacturing systems, the definition prevails that an agent is an entity that is placed in a certain environment where it is capable of autonomous actions to achieve its own goals (Siegfried,R. 2014). The agent is characterized by the following characteristics:

- is an identifiable, discreet (usually heterogeneous) individual,
- aware of the position in space (North,MJ., Macal,Ch,M. 2007),
- is capable of autonomous actions and independent decisions (Borshchev,A., Filippov,A. 2004),
- works within a defined environment where it pursues its goals,
- the agent perceives his surroundings and acts in the environment Klügl,F. (2006),
- has the ability to learn to achieve adaptation of their behaviour (Siegfried,R. 2014).

The agent architecture defines the internal structure of an agent's components, agent behaviour, and interactions. At the abstraction level, the internal structure of the agent consists of three components (Siegfried,R. 2014):

- *sensory interface* – allows the agent to perceive the environment in which he is located,
- *effector interface* – allows the agent to interact with the environment and achieve goals,
- *derivator* – the internal component allows the agent to process data from sensors for making decisions and controlling effectors.

In some cases, the knowledge base and the planner are also included in the components. Agent architecture can be divided into two types (Genesereth, M.R., Nilsson, N.J. 1989):

- *tropistic agents* – their behaviour is defined at each point by their current surroundings and current inputs from sensors,
- *hysteretic agents* – they monitor their internal states and their inputs from sensors as well as can use their knowledge to make decisions.

The work Ďurica,L.(2016) or Taylor,S. (2014) are more closely devoted to the issue of agents.

According to (Siegfried,R. 2014), the agent model includes the idea of multiple agents located and acting in a common environment. Such a model usually includes agents that represent different individuals from the system under study. Thus, within a single model, there may be different cases of agents. Agent models are suitable for systems with heterogeneity, autonomy and proactiveness of members, where the characteristics of the individual cannot be neglected. When creating agent models, two aspects must be considered. The first is the mechanism of the dynamics of agent interactions, and the second is who the agent is or can be (Taylor,S. 2014). In agent models, agents have defined decision-making rules, learning rules, and adaptive processes. In the simulation of such a model, the interaction of a pair of agents will be shown, which will create the dynamics of the system (Gregor, M., Gregor, T., Haluška, M. 2015).

Agent simulation is a simulation of an agent model. By simulation, it is possible to observe the interactions of several agents located in the model, where the result of the interactions is the result of the behaviour of the system. Although agent simulation and multiagent systems have common ideas, they are not the same thing, it is important to accurately distinguish between the two concepts. The main difference is that multiagent simulation takes place in a simulated world, while multiagent systems interact with the real world.

The application of agent modelling is already in the physical, biological, social and managerial sciences. In physical sciences (Troisi,A., Wong,V., Ratne,M. 2005), agent simulation was used to model molecular self-construction. The agents were individual molecules, and their behaviour consisted of the physical laws of molecular interaction. In biological sciences (Alber,MS., Kiskowski,MA., Glazier,JA., Jiang,Y. 2003), agent simulation has been used to model the behaviour of cells and their interactions, the functioning of the immune system, tissue growth and disease processes. In the social sciences, agent simulation has been used in works (Epstein,JM. 2002) in generating social instability or (Pan,X., Han,CS., Dauber,K., Law,KH. 2007) to evaluate collective behaviour in the crowd. In managerial sciences (López-Sánchez,M., Noria,X., Rodríguez,JA., Gilbert,N. 2005), an example is the use of agent simulation in the study of market dynamics.

7 THE DEVELOPMENT OF MANUFACTURING PARADIGMS OVER TIME

The development of paradigms over time is associated with changing customer demands and needs. The long-term success of each factory depends on the satisfaction of emerging social and market needs (Mozol,Š., Grznár,P., Schickerle,M., 2020). In view of this, each factory must strive to respond with its manufacturing systems to these trends. In the case of craft manufacturing, universal machines were needed, which were able to produce a wider range of products. However, after the advent of mass manufacturing, these devices were replaced by single-purpose manufacturing lines that were able to meet mass constant demand at low cost of manufacturing and price. However, the markets became oversaturated over time and demand was no longer constant but predictable. The customer began to look for products that matched his requirements at a low price. At that moment, the market ceases to be homogeneous and begins to manifest itself in a wide range of products. For companies to be able to meet these needs, flexible manufacturing systems began to be applied. These were able to produce a variety of outputs in need of market stability.

The development of manufacturing systems and approaches depending on time is illustrated on Figure 7-1.

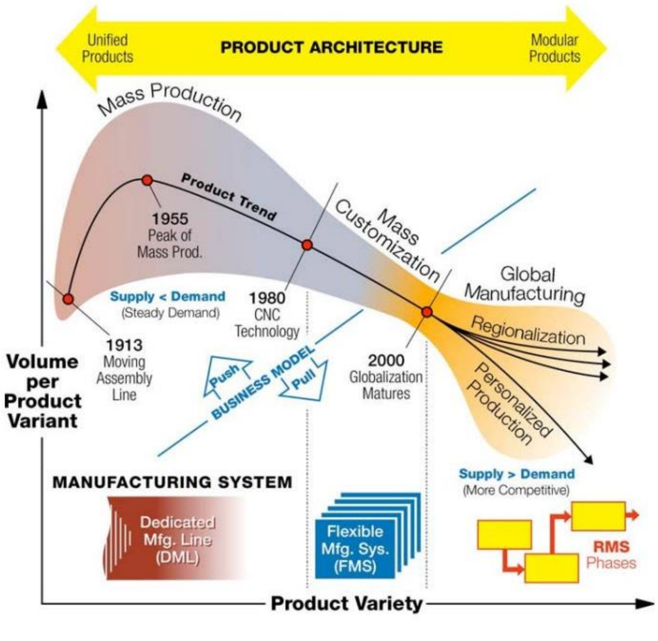


Figure 7-1 Paradigms and their product, process, and business characteristics
Source: Koren,Y. (2010)

However, as globalisation progresses, this market stability is being lost. With the generated fluctuations in demand and this opens the way to Reconfigurable Manufacturing Systems (RMS). These make it possible to adjust the necessary manufacturing capacity depending on market demand, and by quickly adapting their functionalities to produce several variants of products. It is the RMSs that allow the shift to the development of future manufacturing systems designed for personalized manufacturing.

7.1 MASS PRODUCTION OR MASS CUSTOMIZATION?

The manufacturer can use several strategies when offering his products. If it offers a small number of product variants in very high production quantities, it can use the strategy of mass production, also called the *Economy of Scale*. Such a strategy is based on the use of technologies that enable a fundamental reduction of unit production costs, but usually also associated with a reduction in production flexibility. A manufacturer using mass production technologies creates its competitive strategy based on low costs (Figure 7-2).

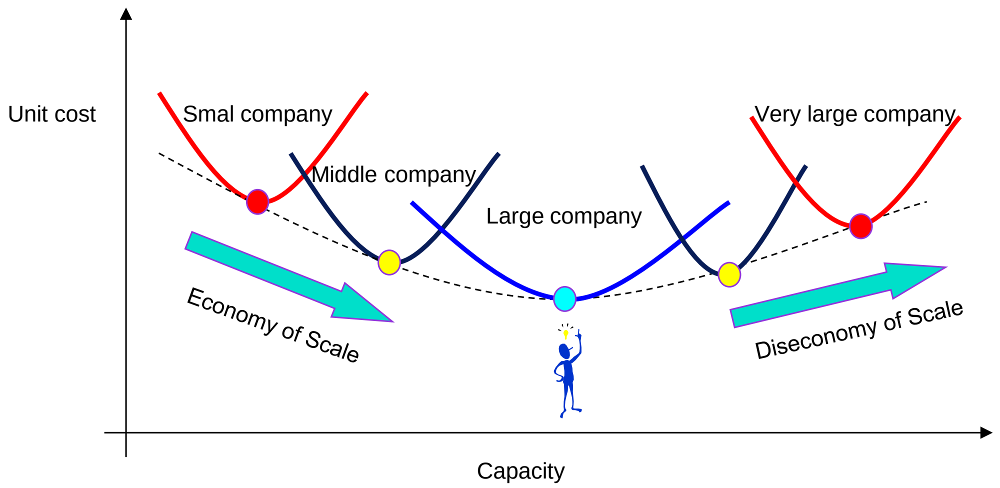


Figure 7-2 Dependence of unit costs and production quantities

Companies can thus compete with either fixed or variable costs. Large companies mainly use competition with high fixed costs (Figure 7-3), which usually represents the automation of production (case of company A).

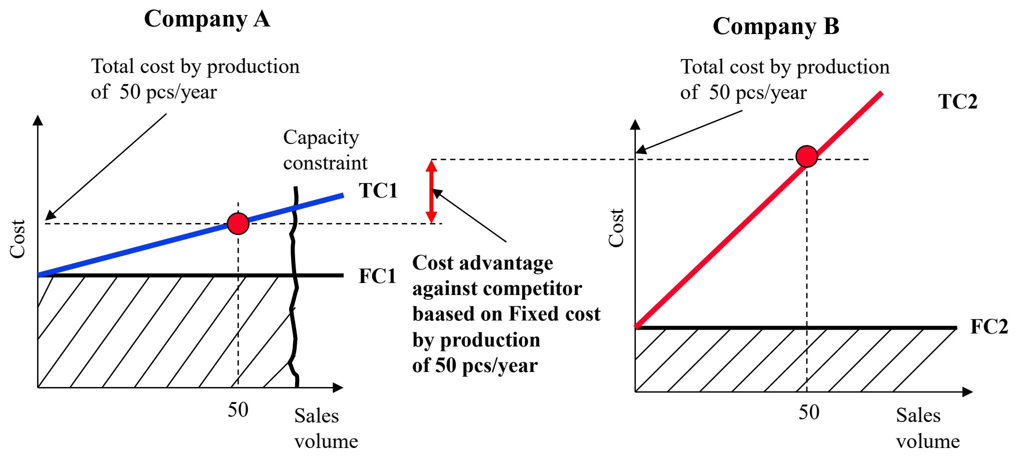


Figure 7-3 Fixed cost competition

For small firms (company B), it is more advantageous to use, as a competitive advantage, low fixed costs and to compete with variable costs (Figure 7-4), which are proportional to sales and thus are not a natural handicap of a small producer.

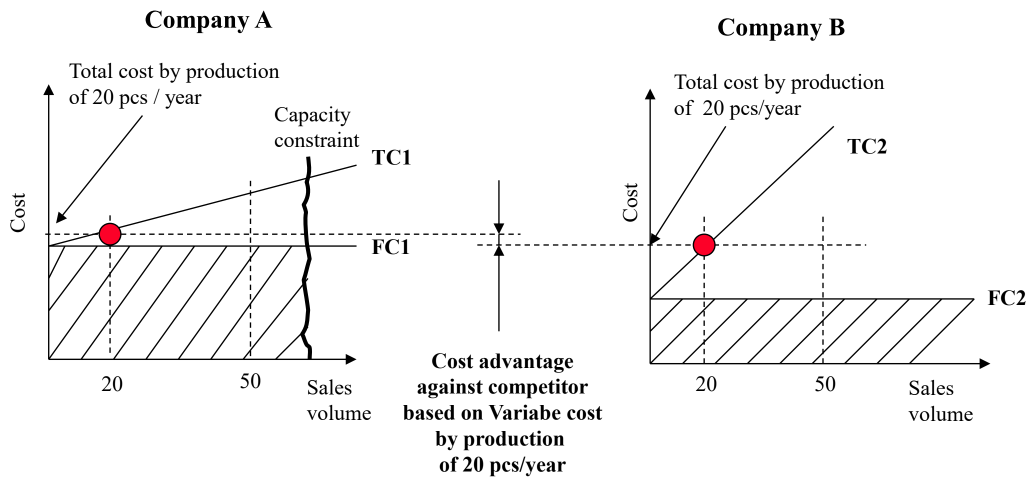


Figure 7-4 Competition with variable costs

Another approach used by manufacturers with a special product offer, i.e. in the case where there is a large product variety, is the strategy of *Economy of Scope*. The advantages of this strategy are based on a special customer offer, where the decision is not made by low costs, but by the customer's special request, for which he is willing to pay a higher price. Such a strategy allows manufacturers to divide markets into smaller segments and thus better target their offer, we are talking about offer diversification (Gregor,M., Haluška,M. 2013b).

On the one hand, the diversification of the supply supports the demand for products, but it also has negative effects for the manufacturer, which are mainly rising production costs. It is a well-known fact that every doubling of the number of variants brings to the manufacturer an increase in production costs at the level of 20 to 35% (Figure 7-5)

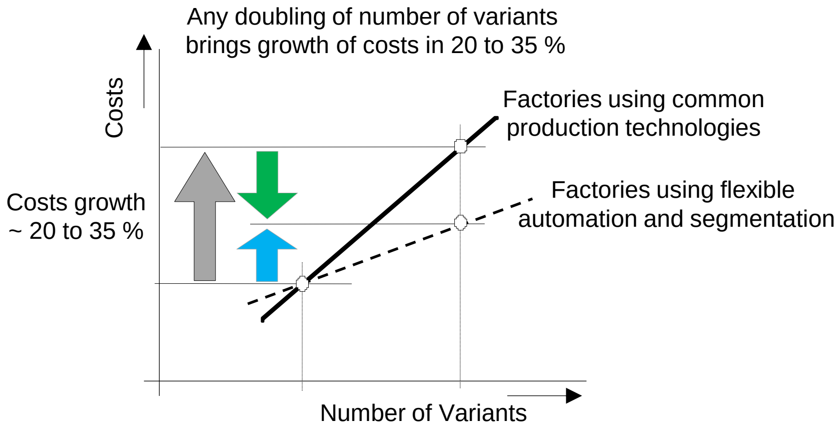


Figure 7-5 Dependence on the number of variants and production costs

As it was shown above, the amount of production costs is directly dependent on the used production technology. A comparison of costs using different production technologies and production volumes is shown in Figure 7-6.

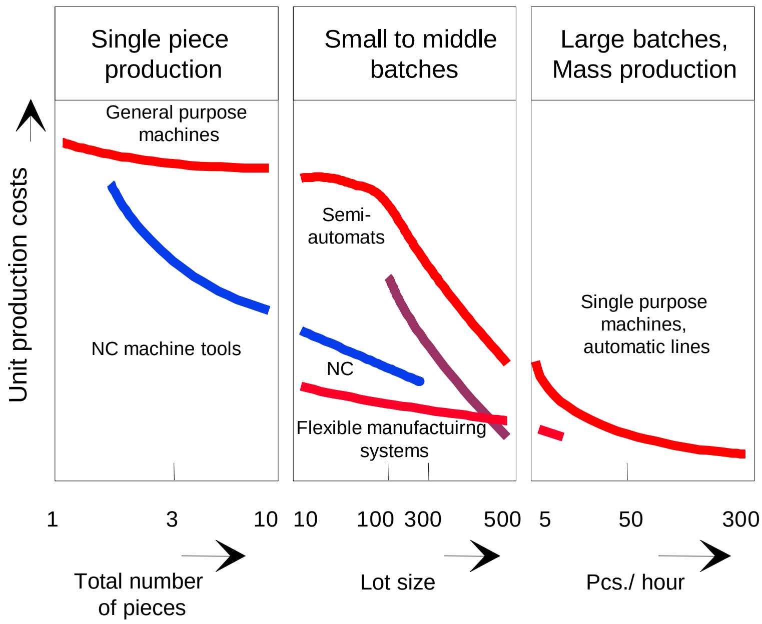


Figure 7-6 Dependence of production volumes and unit production costs

One of the ways to solve the negative consequences of increasing variability is mass customization, often based on modular product concepts and the use of reconfigurable production systems.

Mass customization is a strategy that is based on combining the advantages of both of the above-mentioned strategies, i.e. ensuring a highly diversified offer, at the cost of mass production.

A comparison of the three above-mentioned strategies is shown in Figure 7-7

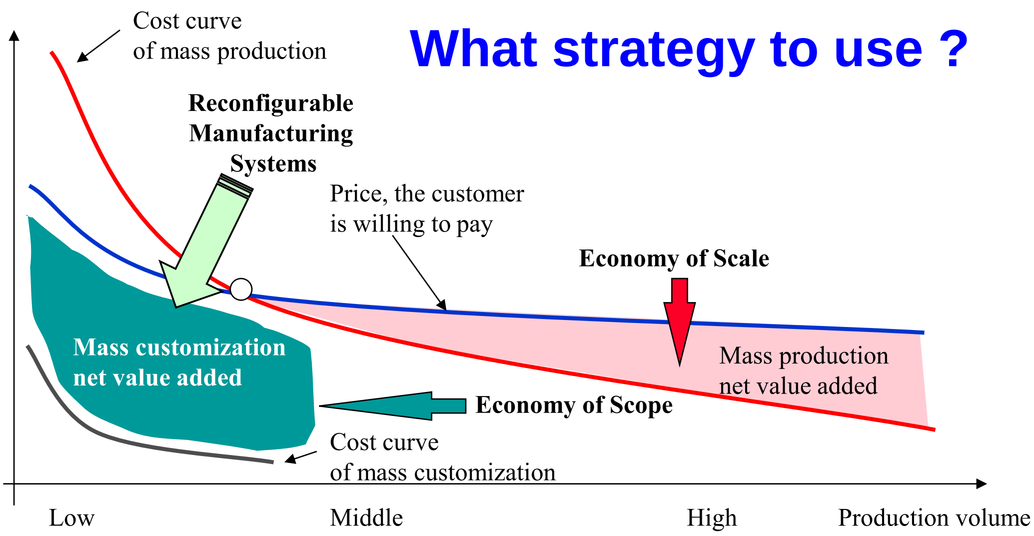


Figure 7-7 Production strategies

Mass customization strategies

Fulfilling the principles of mass customization can be achieved by two basic approaches (Gregor,M. 2013):

- gradual development of a portfolio of products, services, equipment, devices, and skills that will enable the fulfilment of market demand,
- guiding customers to the company's overall ability to meet their requirements quickly and comprehensively.

The mass customization business model usually has two components:

- Variability management – solves tasks such as where is the upper limit of variability and how to manage high variability?

- Quick reaction time - how to produce efficiently, quickly, and cheaply, and deliver customer products?

Mass customization depends on three aspects:

- product variability (customization),
- quantity economy (efficient, low-cost production) and
- quick time to launch new products on the market (time to market).

Koren,Y. (2010) distinguishes four basic strategies for mass customization:

1. **Strategy - Off the shelf**

   It is the simplest strategy. It consists in the production of a standardized range of products in economically recalculated variants. The entire range is distributed through warehouses and retail and sold directly to customers. This strategy is called push.

2. **Strategy - Intensive expansion of product variants**

   This is true mass customization. The customer specifies and orders products with extensions that satisfy his requirements and preferences. Production begins only based on the customer's specification. Because the manufacturer limits the range of variability in advance, this strategy appears to be a push.

   From the point of view of production and assembly, however, the manufacturer operates only based on the customer's specification (his order), which represents a pull strategy. For the reasons mentioned above, we refer to this strategy as a push-pull strategy, sometimes also using the designation: design - sell - produce.

3. **Strategy - Personalization at the point of delivery**

   The manufacturer further modifies the standardized products according to the customer's exact requirements, which he specifies from the place of delivery. It is a primitive form of personalization. The manufacturer pulls the type of product specified by the customer, then manufactures it and pushes it to the customer. We classify this strategy as a pull-push strategy.

4. **Strategy – Personalized products**

In this strategy, the buyer designs his own product specification (individual product). The strategy of personalized products requires customization at the manufacturer, usually in the last stages of production or assembly, while the requirement is a highly flexible or reconfigurable production system, which ensures a short reaction time. This strategy is classified as a pull strategy.

A comparison of the above four strategies is illustrated in Figure 7-8.

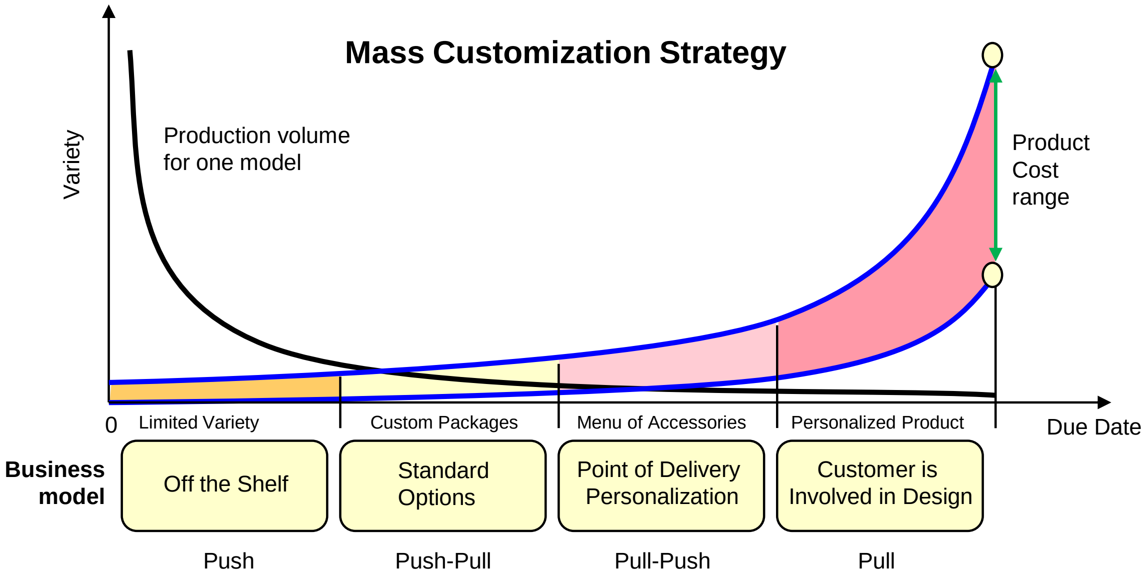


Figure 7-8 Mass customization strategies
According: Koren,Y. (2010)

Mass customization presupposes a manufacturer's ability to identify and occupy latent market niches and rapidly develop technical capabilities to meet narrow, diversified customer requirements. Permanent analysis and identification of market gaps serves to search for groups of target customers with special requirements. Meeting the demands of such customers requires the company to quickly try to imitate the behaviour of existing or potential competitors, especially in quality, costs, and quick response.

The prerequisite for low costs is the application of the principles of the Economy of Scale, i.e. production technologies of mass production.

7.2 PERSONALIZED MANUFACTURING

According to Koren,Y. Ulsoy,G.A. (1997) and Tuck,C., Ong,M.-H., Wagner,H., Hague,R., (2009), the evolution of mass customization can lead to personalization at some levels. In personalized manufacturing, products are manufactured or assembled cost-effectively to meet individual customer requirements (tailored). A typical example of personalized manufacturing is a kitchen unit. Depending on the space of the kitchen and his individual requirements, the customer chooses the preferred modules at the opportunity to immediately find out the price of the kitchen set. The low cost of producing products thus adapted is achieved by dividing the product design process into two phases.

The first phase carried out by the manufacturer involves the design of the basic building blocks or modules of the product (e.g. type, function, shape, material) and the general architecture, which determines how the modules will be connected and integrated with each other, taking into account three aspects:

- mechanical aspect (e.g. brackets, screws, grooves),
- the power aspect (e.g. electric, hydraulic, water),
- the information aspect (e.g. signals and sensor controls).

The next stage is the sale of the product to the customer, in which case the customer is involved in the design. There, the customer, based on a predefined range of modifications, forms the final design, in which the customer learns the price of such a proposal (Wang,J., Kosaka,M., Xing,K. 2016).

The difference between mass customization and personalized manufacturing is that in mass customization, the customer chooses a package that includes both what he needs and what he does not. In contrast, personalized manufacturing allows you to select only what the customer himself requires.

In the field of the automotive industry, the personalization of manufacturing will lead to the result that the customer will have a choice of different seats, different numbers of people, different storage space, different interactive devices, or added equipment such as a refrigerator, microwave, clothes hanger, etc. There will also be a choice of motorization based on the average speed that the car will achieve at the customer's location. This will correspond to preference, security constraints and digital developments in embedded systems. What a product loses its complexity in the field of motorization, for example, an electric car does not need as many parts as diesel/gasoline, will lead to an increase in complexity in the field of installed embedded systems. As a result, this will lead to very different interiors and motorizations for the same models. The design of the product Figure 7-9 itself will take place in virtual reality using a configurator, in which a digital model of the product is created with all variations of components (modules) that can be installed in the product outside the basic structure.

Subsequently, for example, if it is a car, the customer is scanned to detect the anthropometry of the customer and his fellow passengers. Subsequently, the customer immerses himself in virtual reality, where he has prepared a basic model corresponding to anthropometric ergonomic characteristics in several variants.

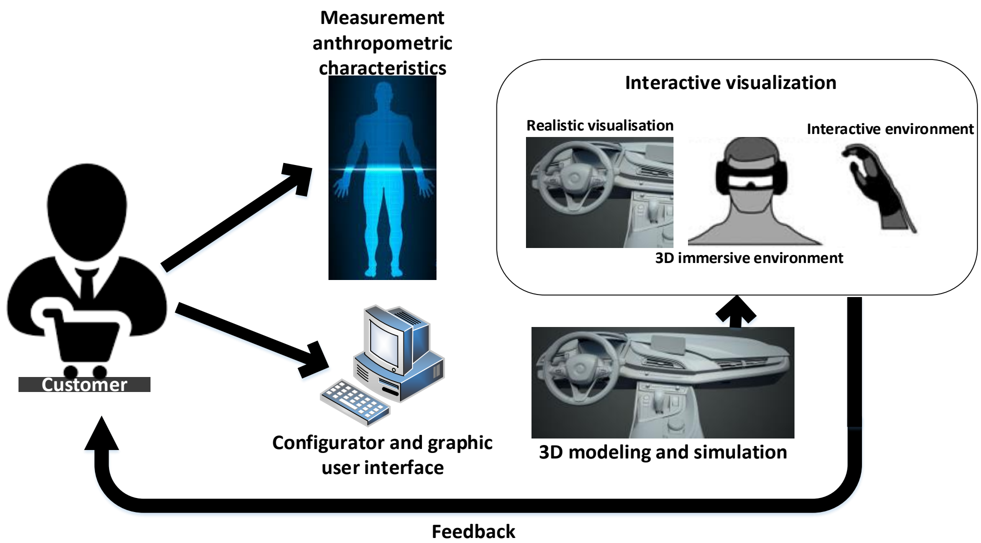


Figure 7-9 Personalized product design process
Source: Koren,Y. (2010)

After this step, the customer adds or removes components (modules), which in the final leads to the creation of the final product design, based on which the order for manufacturing is created. For seats, for example, even after the customer has been selected, there will have to be a possibility of interchangeability, i.e. the seats will be included in the module. This is because the anthropometric characteristics of passengers change with age, and therefore interchangeability must be guaranteed.

Within the framework of the proposal, certain restrictions will apply, in particular in product safety (air beg position, seats), functional limitations (collision states with other components), space (e.g. for legs) and manufacturing restrictions. Likewise, such a configurator will have to connect several suppliers, as several suppliers will be involved in the final product.

7.3 DYNAMIC MANUFACTURING PLANNING

Manufacturing planning is the arrangement of future activities of the company based on the assumed (predicted) requirements for the type and quantity of products or known manufacturing orders when accepting real manufacturing capacities (Gregor,M., Haluška,M. 2013a). This is especially convenient when forecasts tend to be accurate, and the order of fixed orders does not need to be adjusted. It is also based on a certain number of facilities, their availability, and various other constants necessary for capacity planning and scheduling. However, the manufacturing environment is not immutable and there are constant changes in it (internal or external), and these are also reflected in the planning of manufacturing (Grznár,P. 2019). Changing customer requirements and applying personalized manufacturing routinely gets manufacturing planning and control to the limit of efficient manufacturing. Current trends in manufacturing approaches are mainly in the application of agent-based manufacturing. In such manufacturing, each entity in the manufacturing system gradually becomes an autonomous agent capable of autonomous action. Thanks to the application of agents, it is possible to plan manufacturing dynamically with evolving variables over time that represent the individual agents of the system. In this way, it is possible to react much more flexibly to changes such as missing materials, machine and equipment outages, contract prioritization, etc. Reconfigurable manufacturing systems represent the potential in the possibilities of manufacturing precisely in systems whose capacities and functionality are constantly changing over time and the transition from classical manufacturing planning to dynamic is necessary. With a system of Competency islands that uses the principles of reconfigurability, it will be more necessary than elsewhere to use dynamic manufacturing planning and control, since the route chosen by the product may not always be the same as an identical product that was manufactured at a different point in time. The product creates a virtual manufacturing line (Mozol,Š. 2021).

8 NEW MANUFACTURING CONCEPTS

All new manufacturing concepts strive to fulfil one main goal and that is adaptability, the ability to immediately respond to rapid changes in the environment, also referred to as turbulence. Adaptive manufacturing systems currently represent the pinnacle of scientists' efforts to formulate the contours of the future manufacturing environment. It is possible to approach the requirement of adaptability in several ways, which is why scientists have developed and tested a whole group of new manufacturing concepts, such as reconfigurable manufacturing systems, competency islands, multiagent systems, etc.

Turbulences are sudden and unexpected changes in the company's environment, to which the company must react flexibly. Turbulences affect the company's production the most, which must be able to quickly rebuild the production system.

Early warning systems are used to warn company management against the occurrence of turbulence. Such a system sends the first signal for the demand for future reconstruction. If the company captures it and processes it correctly, it can develop a strategy for future reconstruction well in advance and thus minimize downtime and costs.

The goal of creating an early warning system is:

- timely registration of changes in the surroundings and inside the company,
- quick transfer of information about the change to the place in the company (to the workplace, to the responsible person) where they must deal with the changes,
- identification, analysis, and evaluation of changes primarily in terms of their impact and further development into the future (development scenario processing),
- making a decision whether it is still necessary to deal with the change, i.e. identify its cause and take follow-up measures.

According to Gregor,M., Medvecký,Š., Mičieta,B., Magvaši,P. (2013), the company can formulate one of the following decisions based on the evaluation of the information about the requirement to rebuild the production system:

1. There is no need to deal with reconstruction - the company continues to operate the existing production system, which can meet all new requirements.

2. The situation requires monitoring of the existing state - if the pressure to change will continue and the existing production system will no longer be able to fully respond to it, the enterprise must decide to rebuild.

3. The reconstruction must be solved immediately - this situation occurs when the company does not reflect on the need for change, detected by monitoring, and its result is usually high reconstruction costs.

Turbulence means a new challenge for the designers of production systems and the production companies themselves, especially for their Industrial Engineering departments. A critical challenge for manufacturers has become:

- short times for introducing new products to the market (time to market),
- high product variability,
- low production volumes, often significant and rapid fluctuations,
- low product prices.

8.1 COMPLEX PRODUCTION SYSTEMS

The development of the dynamics of complicated production systems could be at least partially predicted. The new industrial revolution Industry 4.0 has brought a huge growth in the applications of the industrial Internet of Things and sensor systems that enable the collection and processing of data and information in real time. Sensors and real-time data make it possible to use the autonomous control of elements of the production system. As a result of the autonomous behaviour of elements and subsystems of production systems, the classic paradigm changes, and complicated systems are transformed into ***complex systems*** by these changes. Any system with a large set of autonomous elements (entities), with existing complex relationships, connections, and elements of randomness, becomes a complex system. Complex in this case simply means that the development of the system is not predictable.

Complex production systems, especially in the automotive industry, using industrial Internet of Things technologies, therefore require a completely new production planning and management system, which will allow to handle the complexity of problems and predict the future behaviour of the system.

For practical purposes, it is appropriate to distinguish four basic types of systems (Schuh, G., 2005):

- *Simple systems* – have few interdependent elements and exhibit simple behaviour.
- *Complicated systems* – they have many elements, between which there are interdependencies, the behaviour of such a system is deterministic.
- *Complex systems* – usually these are systems that may have few elements, but between which there are complex interdependencies, which may show a high number of variants of their behaviour. Total control of such systems is not possible.
- *Complex and complicated systems* - they have many elements, between which there are complex interdependencies. Such systems show a high ability to change system elements over time.

Author (Grosmann,C. 1992) represented these four basic types of systems in graphic form, which is shown in Figure 8-1.

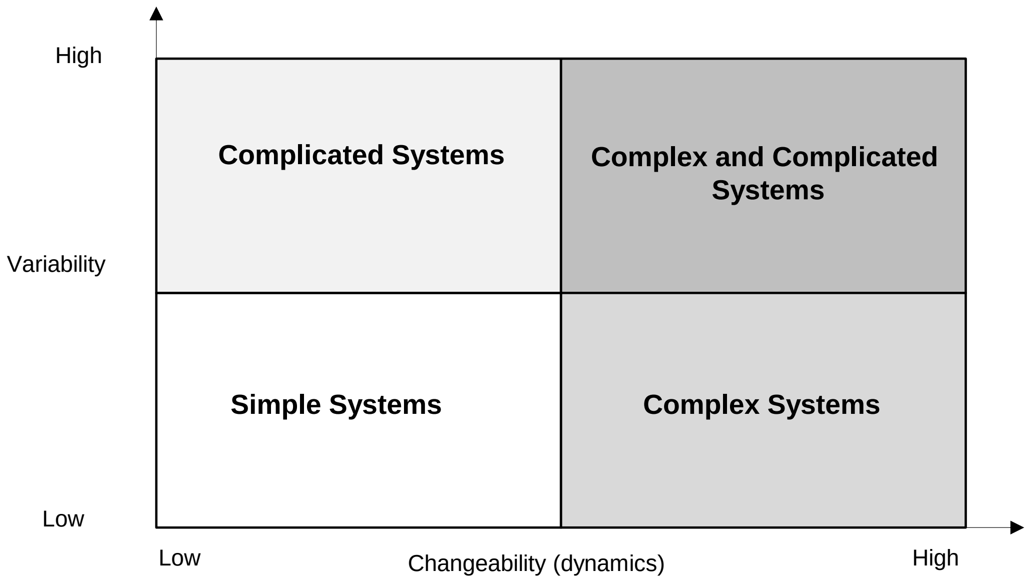


Figure 8-1 Four basic types of systems
Source: Grossmann,C. (1992)

According to Bauernhansl,T. (2017), Fraunhofer IPA distinguishes two types of complexity, as can be seen in Figure 8-2.

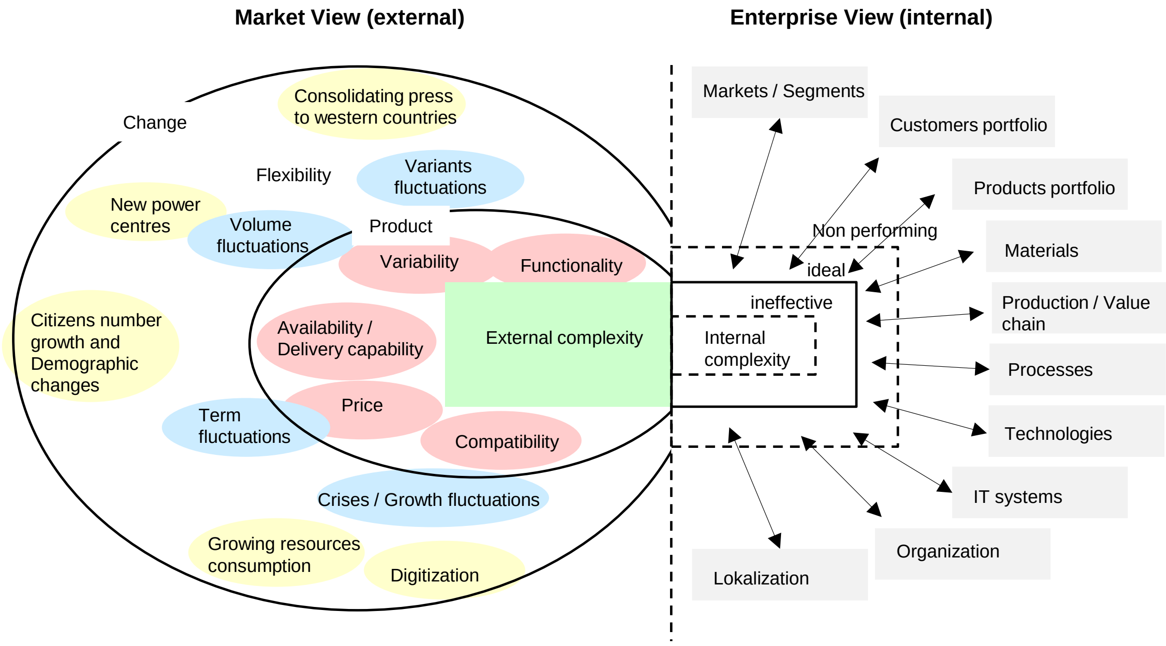


Figure 8-2 External Versus Internal Complexity
Source: Bauernhansl,T. (2017)

Basic properties of complex systems include (Mitchell, M., 2011):

- *Complex collective behaviour*

  A large group of entities form complex networks through mutual relationships. The behaviour of the entities is relatively simple, without central control. Many such entities form collective activities that give rise to complex behaviour, hard-to-predict patterns of behaviour that so often fascinate us.
- *Sending signals and processing information*

  Such systems produce and use many signals and information, both internal and external to the system.
- *Adaptation*

  Such systems show adaptive behaviour, that is, based on learning and evolutionary processes, they change their behaviour in such a way that their chances of survival or success in their actions are improved.

The main characteristics of complex systems are shown in Figure 8-3.

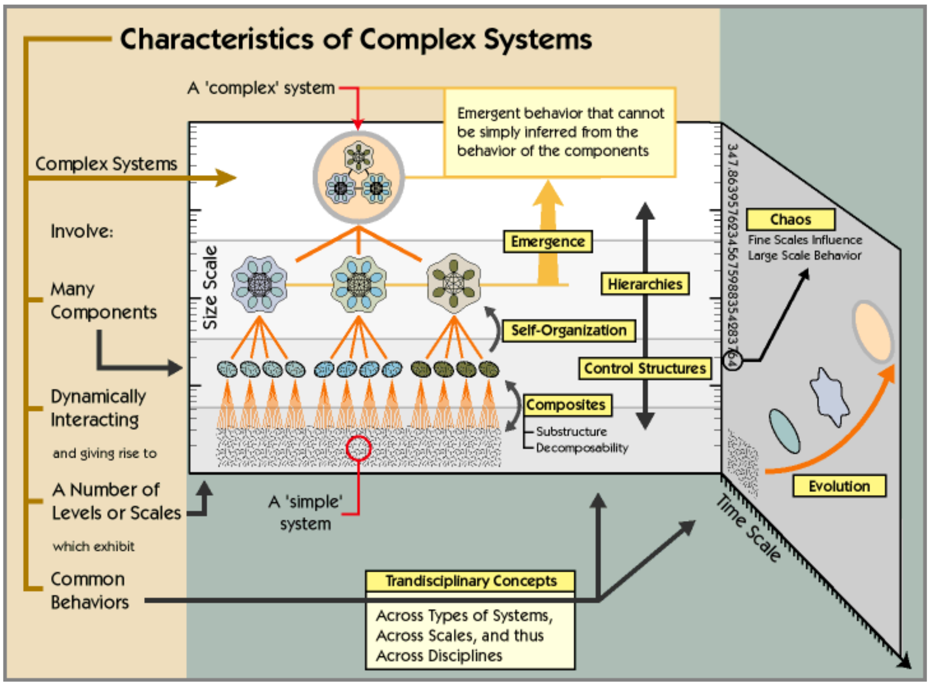


Figure 8-3 Characteristics of complex systems
Source: Necsi. (2012)

For the formulation of characteristics related to complex systems, such as production systems, we can use the characteristics of large and complex systems (Stefanescu, R., 2008):

- complicated structures, both the number of subsystems and the relationships between them,
- uncertainties in the complete definition of technologies and direct relationships,
- difficulties in determining inputs, outputs and direct relationships between the number of inputs and their corresponding outputs,
- heterogeneity of real relationships,
- quantity, quality, and manifestation of some properties determined by energetic and informational internal changes of the system,
- large geographical spread and the impossibility of precisely defining the distribution of systems and elements,
- concentrated functions with cumulative effects, with dynamics and difficulty in managing interactions,
- complex conditions for regulating the variability of shapes, directions, and stimuli,
- enhanced dynamics of states and threshold sensitivities,

- interdependencies with different relational degrees,
- multiple strategies of creation and development, evaluation, and management of parameters,
- parametric dynamics amplified for all states or for different stimuli and during the lifetime of the system,
- the complexity of behaviour because of the type of mixed human-machine structure,
- fast rhythm of transformations, not just states but also functions,
- cybernetic character, self-regulation, and informational decision-making, to which energy-informational relations are added during the operation of the system,
- the nature of the value of determination and stratification in time and space of subsystems, i.e. their functions as well as the weight of their contribution to achieving goals.

8.1.1 Complex adaptive systems

Complex adaptive systems (CAS) form a special group within complex systems. They are defined as several interacting parts (agents) that evolve and adapt in their environment over time. Interactions have the character of unpredictability, while the interconnection of these actions forms systemic patterns. Such systems are non-linear, stochastic, and already contain feedback mechanisms and adaptive mechanisms. CAS systems are characterized by the emergent behaviour of its entities (elements), which causes the overall behaviour of CAS to oscillate between predictable and unpredictable behaviour. The issue of complex systems was elaborated in more detail in the work of Gregor,M. et al. (2018b).

8.1.2 Complexity Indicators

Several authors have tried to create a classification of complexity measures. Practical classifications can be found, for example, in the work of Crutchfield,J.P. (2003).

In the work De Toni,A.F., Nardini,A., Nonino,F., Zanutto,G. (2005), a classification of complexity measures, suitable for production systems, was proposed:

- *Deterministic complexity:* the focus is on the random behaviour of the system. These rates are maximized for random strings.

• *Statistical complexity:* the focus is on the structure of the system.

If we examine complexity from the point of view of the methodology of creating complexity measures, we distinguish two classes of complexity:

- *Computational theory:* the calculation of the measure usually requires a mechanism, usually a universal Turing machine (Universal Turing Machine - UTM);
- *Information theory:* refers to Shannon's entropy formula.

This classification uses the terminology of the Santa Fe approach, for more details see the works of Feldman, D.P., Crutchfield, J.P. (1998) and Gell-Mann, M. (1995).

Based on the above, De Toni, A.F., Nardini, A., Nonino, F., Zanutto, G. (2005) proposed a matrix for the classification of complexity measures (see Figure 8-4). A more detailed comment on the mentioned matrix can be found in the cited work.

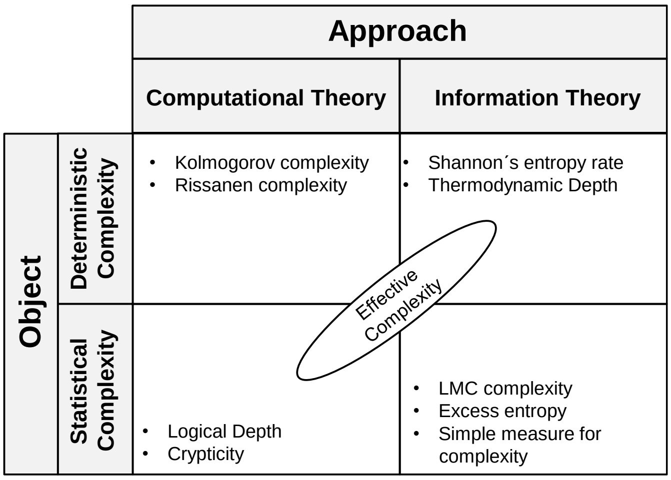


Figure 8-4 A proposed classification for measures of complexity
Source: De Toni,A.F.,Nardini,A.,Nonino,F., Zanutto,G.(2005)

De Toni,A.F.,Nardini,A.,Nonino,F., Zanutto,G.(2005) conducted a more extensive survey of proposed and used measures of complexity. In their work, they describe the most used measures of complexity in production systems, which are known as:

- Static index of complexity
- Dynamic index of complexity

8.1.3 Static index of complexity

This index was proposed by Frizelle,G. (1998). The static complexity index is related to the variability of the system, which is associated with its planned state. It is determined according to the relationship (Calinescu, A., Efstathiou, J., Sivadasan, S., Schirn, J., Huaccho, H.L., 2000):

$$H_{static}(S) = -\sum_{j=1}^{M} \sum_{i=1}^{N} p_{ij} log_2 p_{ij} \qquad (1)$$

Where:

M - number of resources (i.e. machines, equipment, etc.)

N – the number of possible states in which resource j can be

p_{ij} – the probability that resource j is in state i.

The authors define a "planned state" as an association between product i and resource j that will operate according to a planned schedule.

8.1.4 Dynamic index of complexity

This index represents the amount of information necessary to describe the state of the system when it deviates from the planned states. It can be calculated by studying the behaviour of the queue see (Calinescu, A., Efstathiou, J., Sivadasan, S., Schirn, J., Huaccho, H.L., 2000) using the relation:

$$H_D = -P\log P - 1(1-P)\log(1-P) - (1-P)\sum_{i=1}^{M} \sum_{j\epsilon NS_i}^{N} p_{ij} \log \quad p_{ij} \qquad (2)$$

Where:

P - is the probability that the system is in the planned state (the one determined by the relevant schedule),

p_{ij} – the probability that resource j is in the "out of control" state i.

The work De Toni,A.F.,Nardini,A.,Nonino,F., Zanutto,G. (2005) give examples of methods of calculation and use of several types of complexity indices.

A relatively comprehensive overview of complexity indicators was prepared by Modrak, V., Soltysova, Z. (2017), who used and tested selected measures of static complexity as part of their own research for production lines and proposed their own approach to measuring complexity in production.

8.2 RECONFIGURABLE MANUFACTURING SYSTEMS

Since the 90s of the last century, efforts towards flexibility through production technologies, which enable the growth of the flexibility of production machines or the entire production system, have been referred to as reconfiguration. The first attempts were mainly focused on the reconfiguration of production machines. These were divided into functional components, the replacement or codification of which resulted in a change in flexibility.

The concept of the ability to change, the type of flexibility required for the entire enterprise, is known as changeability. Some authors understand it as a new dimension of flexibility.

Changeability represents the potential that enables rapid adaptation even outside the given corridors, in relation to the organization and technologies, without significant investment. Author (Reinhardt,B. 1997) defined this concept as a combination of resilience and responsiveness. He understood flexibility as "the possibility for change within the provided dimensions and scenarios" and responsiveness as the potential of the ability to react beyond the expected dimensions and corridors.

Frequent changes in the types of products and their production quantities require the reconstruction of the production system. Every such production interruption means for the company a loss of production capacity and thus a loss of potential profit. Therefore, the speed of rebuilding the production system, its reconfiguration, is one of the critical factors of business efficiency. Reconfigurable production systems (RMS) represent an advanced way of production, an adaptive production system, capable of adjusting its production capacity due to fluctuations in product demand and adapting its functions to new products. RMS is usually designed for rapid change of structure, hardware, and software elements within the selected product family. Such production systems are designed as modular, using reconfigurable production machines and equipment. They often work based on a plug and produce approach, which enables very fast integration and the use of the latest technologies.

Basic characteristics of RMS include:

- *Customization* (flexibility limited to a family of parts) – design of the flexibility of a production system or machine, limited to a family of products (customized flexibility).
- *Scalability* (design for capacity changes) – the ability to easily modify production capacity by adding or removing production resources (for example, machines) or by changing reconfigurable elements of the system.
- *Convertibility* (proposal for changes in functionality) – the ability to easily transform the functionality of existing systems, machines, and control systems to meet new production requirements.
- *Modularity* (elements are modular) – integrability of operational functions into units that can be manipulated between alternative production schemes to achieve optimal production procedures.
- *Integrability* (interfaces for rapid integration) – the ability to integrate modules quickly and accurately through a set of mechanical, information and control interfaces that enable integration and communication.
- *Diagnosability* (design for easy diagnosis) – the ability to automatically determine the current state of the system and its management, for the detection and diagnosis of the root causes of equipment or product errors and the quick correction of operational problems.

Reconfigurable production systems bring a significant reduction in the time of production reconstruction and thus positively affect the profitability of the company, as shown in Figure 8-5. This advantage that reconfigurable production systems offer companies, their ability to quickly in a short time adapt to a new production range, is also called ramp up time.

The rebuilding time represents the period that the new (reconfigured) production system needs to achieve stable, planned production parameters (production volume, lead time, quality, etc.).

Reconfigurable production systems represent a new generation of innovation in production. They have become a reality, and today the world's research workplaces solve many research tasks connected with their design and practical implementation. Reconfigurable assembly and logistics systems are especially important for Slovakia, given the existing structure of our industry.

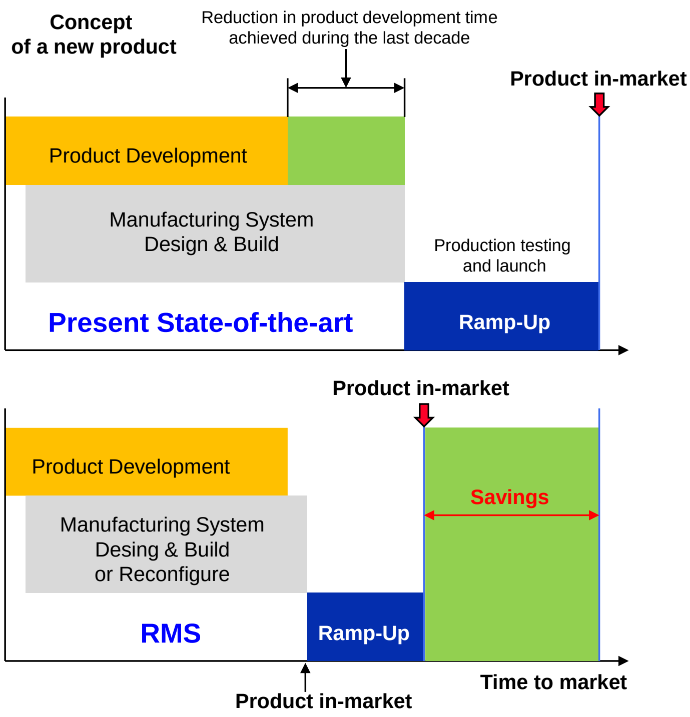


Figure 8-5 Benefits of RMS

8.2.1 Configuration of the production system

A critical factor in the success of RMS is its appropriate configuration. It defines how the machines, tools, transport system, control software, etc. should be arranged so that RMS efficiency is maximum. A simple example of two configurations of production systems, created from three machines, is shown in Figure 8-6.

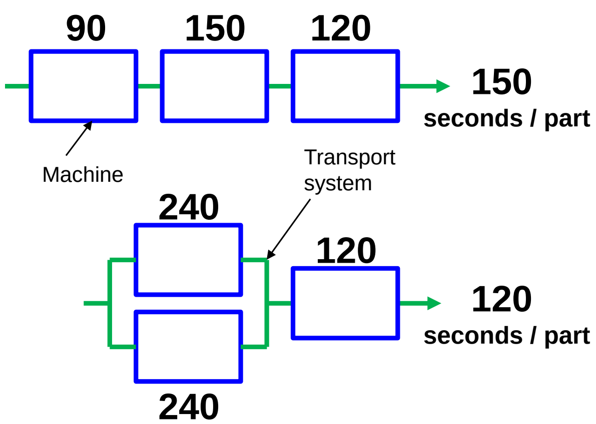


Figure 8-6 An example of two different configurations of production systems

Source: Koren,Y. (2010)

An example of creating three configurations of production systems from six machines is shown in Figure 8-7.

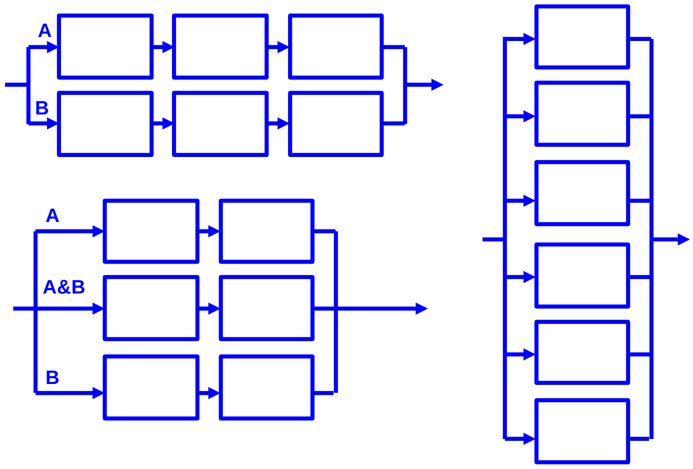


Figure 8-7 Three configurations of production systems created from six machines
Source: Koren,Y. (2010)

Classification of RMS configurations

From the design of production systems, we know the simple relationship of calculating the capacity requirement of machines in the production system. This one has the form:

$$N = Q * \frac{t}{MC} * R \tag{3}$$

Where:

Q - planned daily production volume (pcs)

T - planned unit production time (min./piece)

MC – daily time capacity of the device (min.)

R – equipment operational reliability (%)

How many possibilities of arrangement (configuration) of the production system are there?

Let:

K – number of possible configurations

N – number of machines

m – number of ways of arranging machines, then, according to Koren,Y.(2010), there is a total number of K-configurations of the production system, composed of N machines with a maximum of m ways of arrangement:

$$K = \sum_{m-1}^{N} \binom{N-1}{m-1} = 2^{N-1} \tag{4}$$

The number of possible configurations with N-machines, assembled in exactly m-ways is equal to:

$$K = \left(\frac{(N-1)!}{(N-m)!(m-1)!}\right) \tag{5}$$

The number of different configurations of the production system for different number of used machines is shown in Figure 8-8.

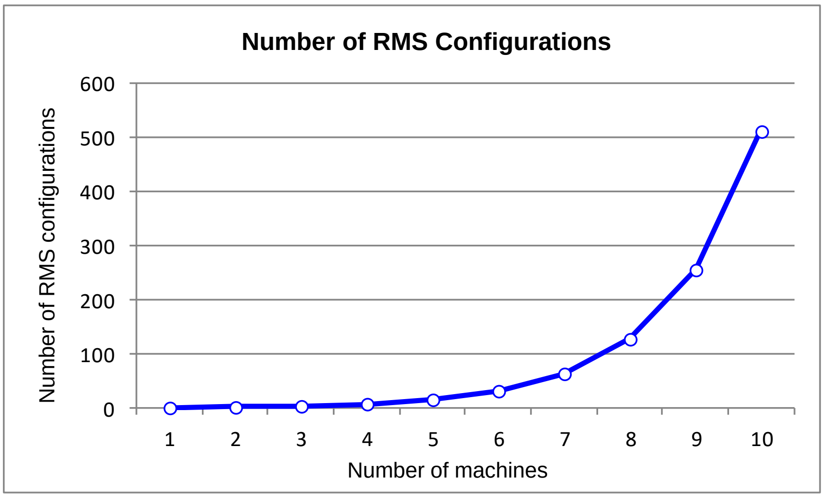


Figure 8-8 The number of configurations depending on the number of machines

For example, for N=7 machines assembled in seven different ways, the result is K=64 configurations. If the configurations are assembled in exactly three levels, we get K = 15 configurations.

Mathematically, the results of both equations can be put together in a triangular format, known as Pascal's triangle (see Figure 8-9). This is thus a useful mathematical tool in determining the number of possible configurations.

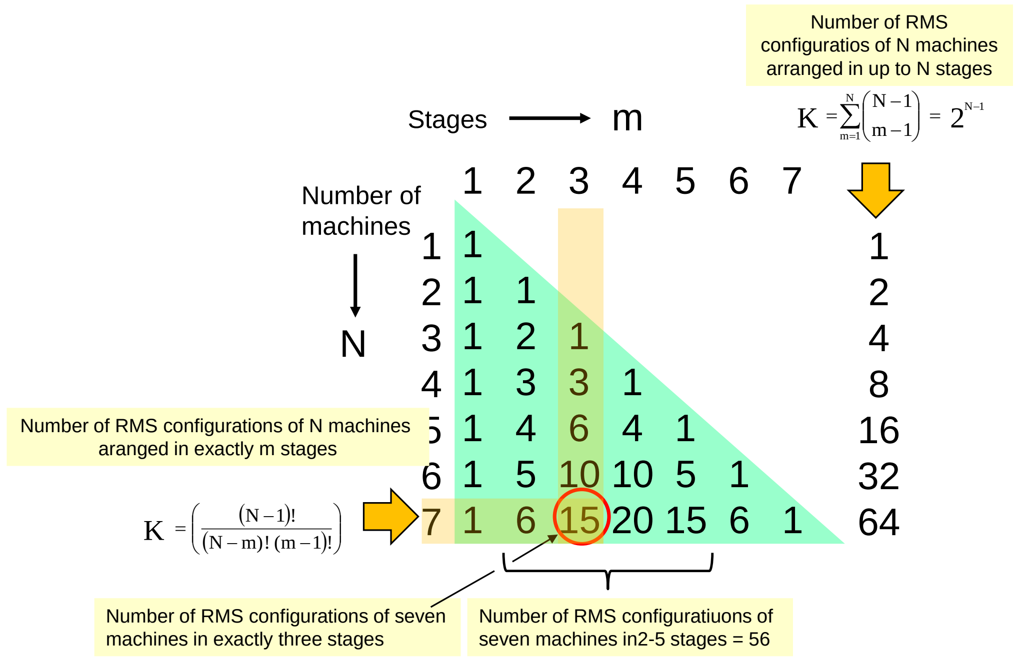


Figure 8-9 Pascal's triangle for determining the number of RMS configurations According: Koren,Y. (2010)

Value for N-machines assembled in m- ways = (value for N-1 machines assembled in m-1 ways) + (value for N-1 machines assembled in m-ways). In Figure 8-9, for N=5 and m=3, we get the number 6, which is the sum of 3 + 3 of the previous row N-1 = 4 machines with two and three assembly methods.

8.2.2 Research on the area of RMS

RMS are systems capable of rapid change of the manufactured product, which significantly reduce the time required for conversion and thus increase the capacity utilization of equipment on the line. Their application requires a new approach in which reconfigurable machines, fixtures, tools, logistics and a reconfigurable control system play a dominant role (Westkamper,E., Zahn,E. 2009). Reconfigurable manufacturing systems were first developed in more detail by prof. Y. Koren (Koren,Y. Ulsoy,G.A. 1997), (Koren,Y. 2010). He understood RMS systems as a comprehensive approach by which it is possible to ensure the necessary adaptability of manufacturing systems. His work was preceded by research of Liles,D. H., Huff,B.L. (1990). They defined RMS as a system capable of adapting the configuration of the manufacturing system to meet dynamically changing manufacturing requirements. According to (Haluška,M. 2015), the structure of the RMS is similar to a modular manufacturing system. Authors (Bi,Z.M. et. al. 2007) also commented, according to which this connection can be found in works (Weston,R. 1999), (Chirm,J.L. Mcfarland,D.C. 2000), (Harrison,R., Weston,R.H., Monfared,R.P. 1988), (Kaula,R. 1998). The difference between modular manufacturing systems and RMS is defined by the authors (Bi,Z.M. et. al. 2007), namely, that the RMS is designed to adapt to changes in the conditions of indeterminacy of the manufacturing environment, and this is done by reconfiguring hardware or software resources. Thus, they extend the RMS definition of Y. Koren to: *RMS can reconfigure hardware and managed resources at all levels of functionality and organization for the needs of rapid adaptation of manufacturing capacities and functionality in response to sudden changes in the markets or regulatory requirements.* Reconfigurability is the operational ability of a manufacturing system to adapt its functions and capacities to a specific family of products. It results in the required flexibility of the manufacturing system. In contrast to reconfigurability, elasticity is fixed in the manufacturing system. Reconfigurability and elasticity condition the adaptive ability of the manufacturing system, which is achieved through a change in its structure. Such a structural change makes it possible to adapt the functions and capacity of the manufacturing system to new requirements. The condition for effective reconfigurability is the requirement to minimize the effort spent and maximally reduce the time required to implement changes (Bauernhansl,T. 2017). ElMaraghy,H.A. (2009) designs RMS with the help of simultaneous connection of the design of the manufacturing system and the product family. In her work, she describes that the formation of product families within group technologies and cell manufacturing takes place using the tools of cluster analysis. These are used to define boundaries between different product families that result in a multitude of differentiated sets, each of which contains a certain number of components, components or products that are similarly manufactured or have a similar geometric shape. These techniques are used in group technologies and cell manufacturing. However, at work AlGeddawy,T., ElMaraghy,H. (2009), they suggest using compliance analysis to analyse the product family in a Delayed Product Differentiation (DPD) environment. Conformity analysis is mostly used with the complete composition of the product, that is, including parts, modules, and subassemblies, rather than individual parts with different characteristics. The aim of this step is to recognize the common nature of a product, this leads to a metric of similarity between products rather than identifying different product groups. The method can be applied in the design of manufacturing lines for the purpose of product differentiation in the DPD environment. At work ElMaraghy,H. (2009) the use of product aggregation is recommended and to observe the limitations that must be respected when sequencing assembly steps. According to Haluška,M. (2015), the reconfigurable manufacturing system represents an adaptive system that is able to adjust its manufacturing capacity taking into account fluctuations in demand and adapt its functions to new products. The aim of the RMS design is to quickly change the structure of hardware and software elements within the selected product family. Such manufacturing systems are designed as modular, using reconfigurable manufacturing machines and equipment. They often work on the basis of plug and produce access, which allows for very fast integration and use of the latest technologies (Koren,Y. 2010). The two authors Haluška,M. (2015) and Vavrík,V. (2019) addressed the issue of reconfigurability of manufacturing systems in more detail. First author proposed a solution with which it is possible to reduce the time it takes to design a reconfigurable manufacturing system. The proposed solution allows the design of reconfigurable manufacturing systems with new quality and high efficiency of operation. This is achieved using a mathematical model suggested for the design of reconfigurable manufacturing systems, which was verified in the work using dynamic simulation. At the same time, multicriterial optimization criteria were used in the work to assess the generated solutions. Figure 8-10 shows a simulation model of a reconfigurable manufacturing system for a specified manufacturing program.

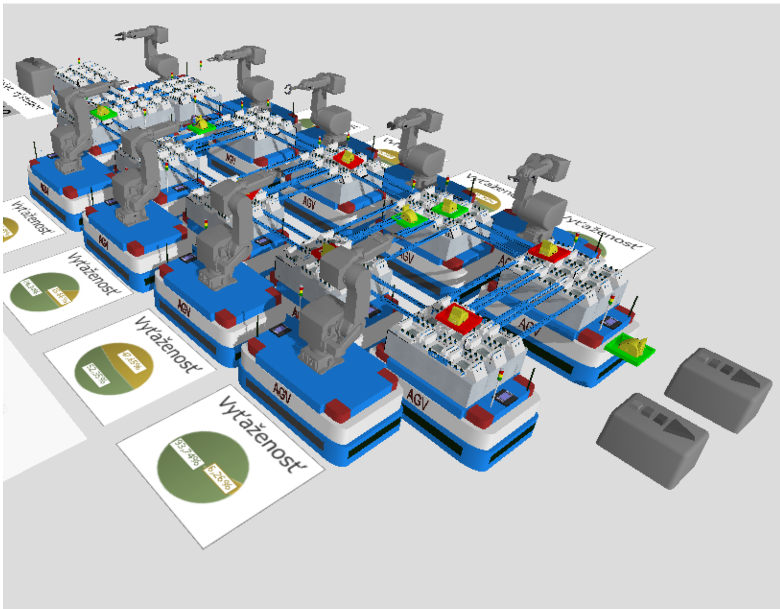


Figure 8-10 RMS for a specified manufacturing program
Source: Haluška,M. (2015).

Author Vavrík,V. (2019), focused on the methodology of designing manufacturing lines using reconfigurability elements. This methodology, together with the application created in MS Excel, allows the creation of a configuration that optimizes the capacity utilization of the manufacturing line. As well as ElMaraghy,H., AlGeddawy,T., Azab,A. (2008) and Haluška,M. (2015), it uses the principles of aggregating products into a product family, but compared to the former on the basis of operational similarity. The designed system helps to maximize line utilization in the short time required to design the system configuration in which this state occurs.

The output of the Vavrík solution is an environment that enables the design, dynamic testing, and optimization of projected reconfigurable production lines, while also including in detail the effects of the failure rate of individual entities of the production system (see Figure 8- 11).

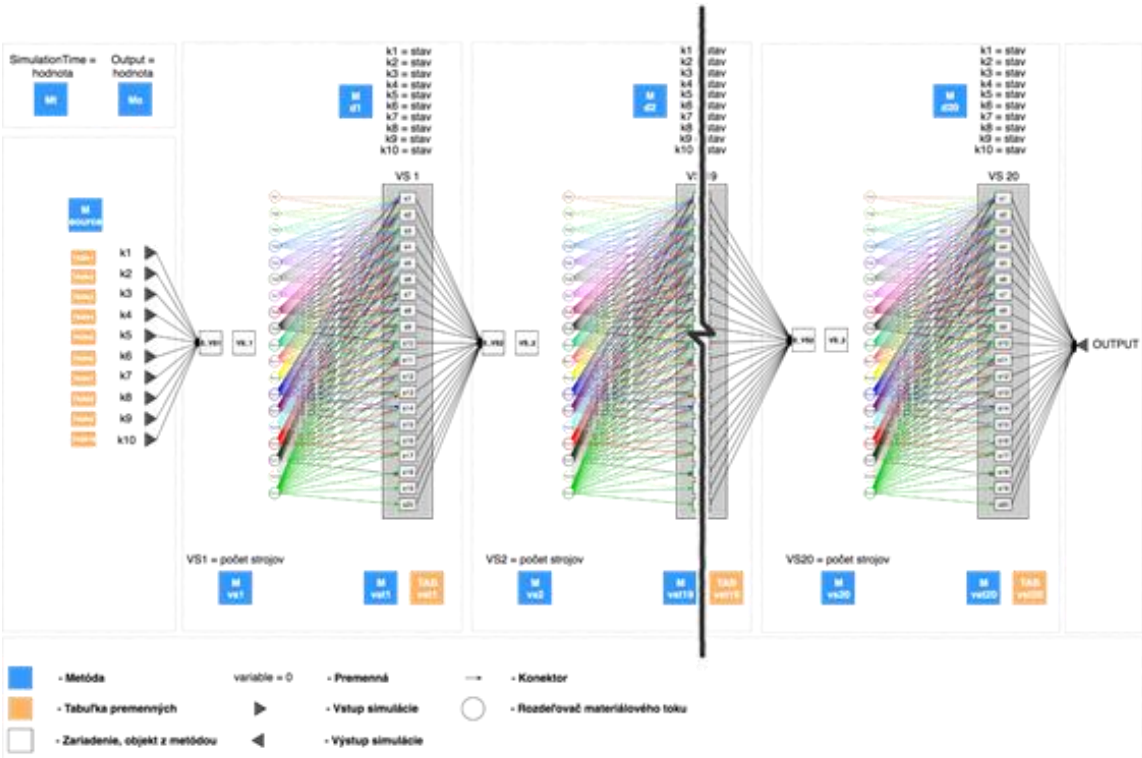


Figure 8-11 Simulation model of a reconfigurable line
Source: Vavrík, V. (2019)

Figure 8-12 shows a simulation model of a reconfigurable line created in the Simio simulation system.

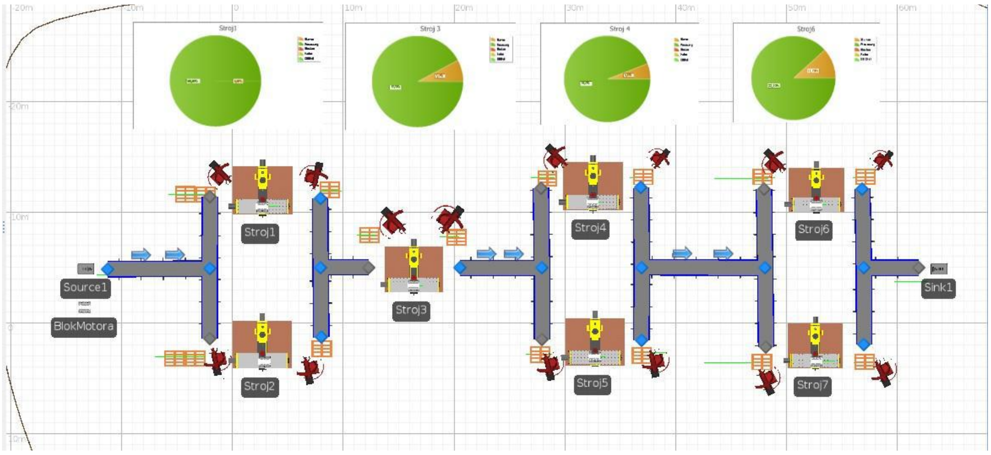
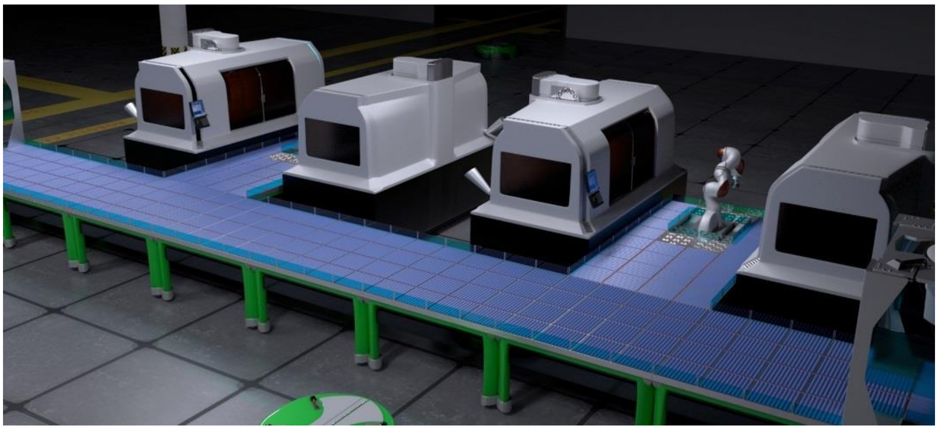
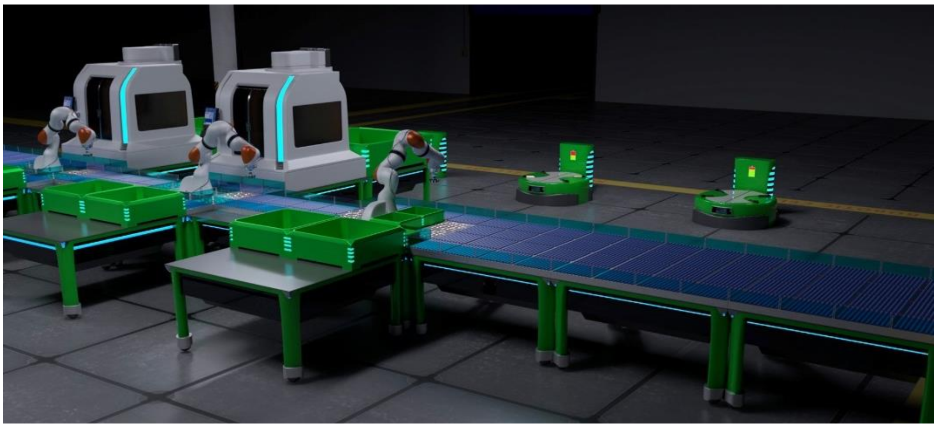


Figure 8-12 Graphs of line machine utilization in the Simio simulation system

Figure 8-13 shows a visual comparison of a static reconfigurable manufacturing system and a dynamic reconfigurable manufacturing system.



(a)



(b)

Figure 8-13 Comparison - static RMS (a); dynamic RMS (b)
Source: Vavrík,V. (2019)

8.3 COMPETENCY ISLANDS

The set of services provided by a given workplace is also referred to as its competence (hence the name competency island). The basic principle of functioning of competence islands is shown in Figure 8-14.

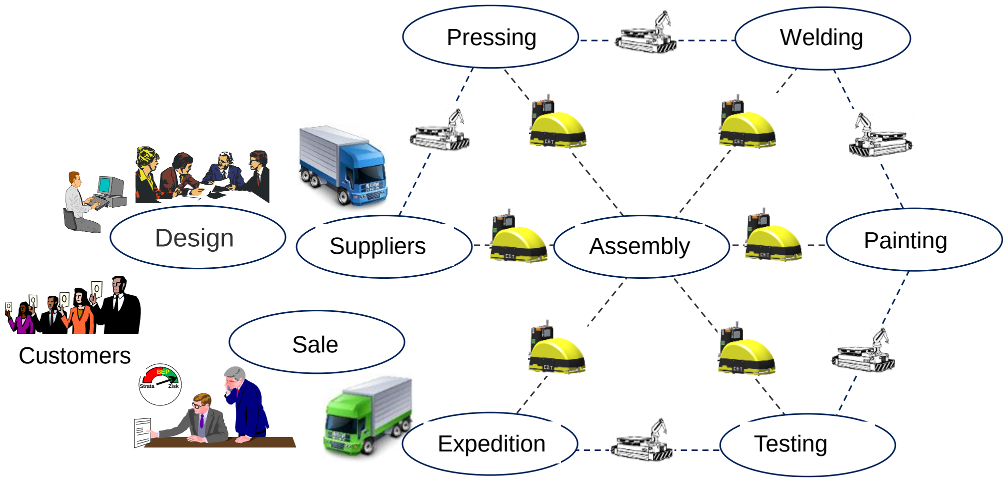


Figure 8-14 The concept of islands of competence

What fundamentally differentiates this concept from the well-known concept of production cells, or the concept of production islands is the changed role of the product (Gregor,M., Grznár,P., Gregor,T. 2018a). In the case of production cells, product processing was clearly defined by the production process and a fixed sequence of operations at the workplaces of the production cell. In the case of production cells, the execution of the sequence of operations was controlled by a superior control system. It used the principles of so-called push control, which meant that the time sequence of all operations was planned in the production schedule and the task of the control system was to perform such operations accurately.

In the case of competence islands (Figure 8-15), the product represents an autonomous entity of the system. In the processing process, this entity follows its own individual production procedure, i.e. the product itself manages the planning and performance of individual production operations. It plans its individual "route" during processing in the production system, allocates the necessary resources (competence island capacities, means of transport, transport system, etc.) and informs about the need to reconfigure the workplaces that are to perform the required operations. The product becomes the central element of the competence islands concept.

Figure 8-15 A special AGV with the autonomous product
Source: Assesco CEIT Archive (2023)

Competence islands in production take the well-known concept of production islands to a qualitatively new level (Gregor, M. 2018b). Competence islands represent workplaces that provide the performance of defined operations with the manufactured product. We can imagine them as virtual production lines, created dynamically, virtually, based on a real need. Competence islands will be equipped with cooperative robots, able to work safely and reliably with people. During the transition period, people will also work in the competence islands. The long-term goal is complete automation of production.

The existing large-scale manufacturing method, organized rhythmically in the manufacturing halls, working in manufacturing tact, will no longer be able to respond to future customer requirements. Today's "static" manufacturing and assembly lines will be replaced by a set of autonomous workplaces, the so-called *competency islands* (Figure 8-16). These can be imagined as virtual manufacturing lines, created dynamically, virtually, based on a real need.

New manufacturing systems should therefore be conceived as small, highly flexible manufacturing units that are deployed where there is sufficient real demand. Such manufacturing systems will be designed for the manufacturing of the selected product family, which requires their concept to be built on the principles of reconfigurable manufacturing systems.

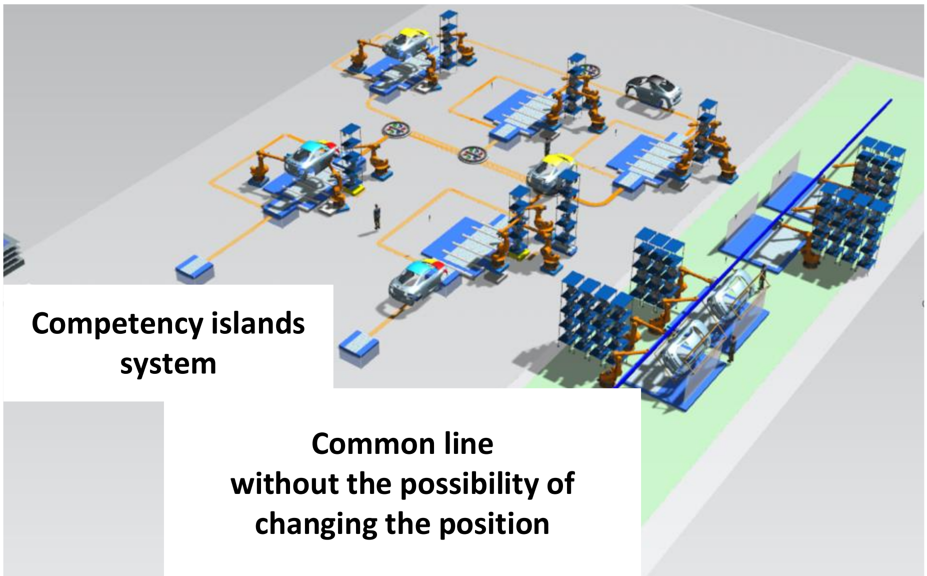


Figure 8-16 Current automotive assembly line versus Competency islands
Source: Mozol,Š. (2021)

The activities of future manufacturing systems will be organized completely differently. Classic manufacturing and assembly lines will only be maintained where it is still profitable for the economy. Future manufacturing will seem like complete chaos to an outside observer. It will seem to him that material, semi-finished products, work in progress, or mobile robots move unplanned, chaotically. However, each of them will follow a strict logic of the superior level, which will allow him to behave relatively autonomously. So, in fact, it will be organized chaos. For manufacturing control, principles observed from nature will be used, which offer evolution-proven, optimal practices.

Smart mobile robots, mobile robotic systems and platforms will gain a strong position in future factories. Thousands of such robots will ensure the movement of work in progress and their processing in a seemingly chaotic world.

Manufacturing will be organized as a living organism, resembling an anthill, in which ants seem to run chaotically, but they are strictly organized, specialized, and each of them performs strictly defined tasks that the survival of an anthill requires.

The product, manufacturing facilities, technologies and the entire manufacturing system will change. Manufactured products, manufacturing equipment and means of mobile logistics will become intelligent and communicate with each other. They will exchange and share all the necessary data and information in real time.

Mobile robots transporting a product in progress will move between the competency islands, with the product itself determining the required operations and planning their order. The observer will not see the classic manufacturing line, he will observe the seeming physical chaos, but behind it will be hidden a virtual line (its digital and virtual data model), formed from the Competency islands, necessary for the manufacturing of the customer product.

Future manufacturing will not be structured according to the manufacturing rhythm of the line, as is the case today, but according to the content of the work that needs to be done. Already in 2013, Audi patented a new way of manufacturing cars that will no longer use today's line concept. Functional relationships and not fixed cycle times should play a decisive role in it. According to Audi, this type of manufacturing environment will not only be suitable for small manufacturing factories but will be especially advantageous for those types of manufacturing that work with high volume, highly variant manufacturing and whose goal is high flexibility and efficiency. Such systems will be able to respond much more effectively to fluctuations in demand, rapid changes in manufactured models, requiring various manufacturing technologies. Audi claims that the manufacturing islands will be much more efficient than today's line concept.

8.3.1 Cooperation in future production systems

In the first real solutions of competence islands, people will cooperate closely with robots. This will require a completely new approach to manufacturing systems design. For human-robot cooperation to function effectively, today's robots must change fundamentally. The capabilities of industrial robots will be gradually expanded, mainly by sensory systems and new types of actuators and motors, which will ensure "collaborative" behaviour of the robot. By the term robot in this case, we mean all types of robotic systems, i.e.: industrial robots, mobile robots, and humanoid robots.

Literally, the development of mobile robots must gradually undergo a revolution. Today, they most often work as tractors or load carriers (material, tools, etc.). The first mobile automated robotic platform, known as Mobile Automated Platform (MAP) was developed at the University of Zilina in Slovakia, which consists of a mobile robot on which an automatic robotic arm is installed (Figure 8-17).

Figure 8-17 An example of a mobile automated MAP platform

MAP forms one of the basic elements of the concept of competence islands, whose principles were described in several works by Gregor, M. et al., (2017), Gregor, M. et al. (2018a), Gregor,M. et al. (2018b).

8.4 COMPARISON OF NEW MANUFACTURING APPROACHES

Each of the named manufacturing approaches has its own characteristics, areas of application and specific problem that they solve.

The manufacturing approach of manufacturing with a quick response is characterized by the fact that the application can achieve the optimization of the activities of the factory both internal and external at the process level. Thus, it is usable where it is difficult to apply Lean control. It is suitable for low-volume and highly variant manufacturing, where each product has a specific form, different from the others.

Manufacturing using reconfigurable manufacturing systems is characterized by the possibility of rapidly changing its hardware (equipment) and software (programs) components so that a rapid change of the manufactured product can be achieved, at the lowest possible time required for conversion, thereby increasing the capacity utilization of equipment on the line. The application of such systems is especially anticipated by manufacturers who are forced to react quickly to changes in market requirements, which, from the application point of view is suitable for manufacturers (subcontractors) for final assembly. They are suitable for manufacturing with high variability from the point of view of the product family and related statements. The difference between Quick response manufacturing and RMS is that the first is more focused on processes, while RMS are focused on changing manufacturing capacity as such from a hardware and software perspective.

The Competency Islands are a manufacturing approach, where manufacturing is divided into a manufacturing island, where there is no strong link between the islands, and the transport of the product in progress is ensured, for example, by means of mobile automatic platforms and, for example, the configuration of islands and elements using mobile robotic systems. The primary purpose of the application is the same as for the RMS, with the difference that the Competency Islands are intended primarily for the final contractors of the product. The approach is designed for the manufacturing of a wide range of products of the selected product family.

8.5 FUTURE MANUFACTURING WILL WORK AS LIVING ORGANISMS

Future manufacturing and its organization will gradually approach more the emergent functioning of living organisms than mechanical automatons. The manufacturing system is a multifactor system. Its model is dynamic, not static. Therefore, it cannot be said that the efficiency of the manufacturing system is a function of low stocks or short running periods. Manufacturing efficiency depends on a large set of factors that change dynamically over time.

Today, we manage manufacturing systems in a similar way to how doctors treat the sick. We diagnose possible problems, categorize them, and "treat" them according to established and proven procedures. Future manufacturing systems will resemble living organisms. That is why it is important for future Industrial Engineers to study and understand the basics of biology and medicine.

8.6 THE PRODUCT BECOMES THE CENTRAL ELEMENT OF MANUFACTURING

The manufactured product will behave in manufacturing as an intelligent entity, capable of communicating with its surroundings and capable of organizing its processing completely autonomously. Such a product will determine the sequence of its processing itself, allocate the required capacity in the relevant Competency Islands and call a mobile robot to ensure its transport in manufacturing. For such a system of organization to work safely and reliably and perform the required tasks, this will require new ways of planning and managing manufacturing. With a very large number of intelligent elements (entities) in the manufacturing system, there will be complicated relationships and situations that today's hierarchical control can no longer effectively address. Therefore, researchers are experimenting with new control approaches, based on the relative autonomy of the individual elements of the manufacturing system and their behaviour, which will resemble that of intelligent, living organisms. Therefore, in addition to real objects, there will also be virtual representatives in manufacturing, whom we now refer to as *digital twins*.

Methods and tools supporting the transformation of physical systems into virtual ones are developed evolutionarily. The dynamics of the development of such systems are shown in Figure 8-18.

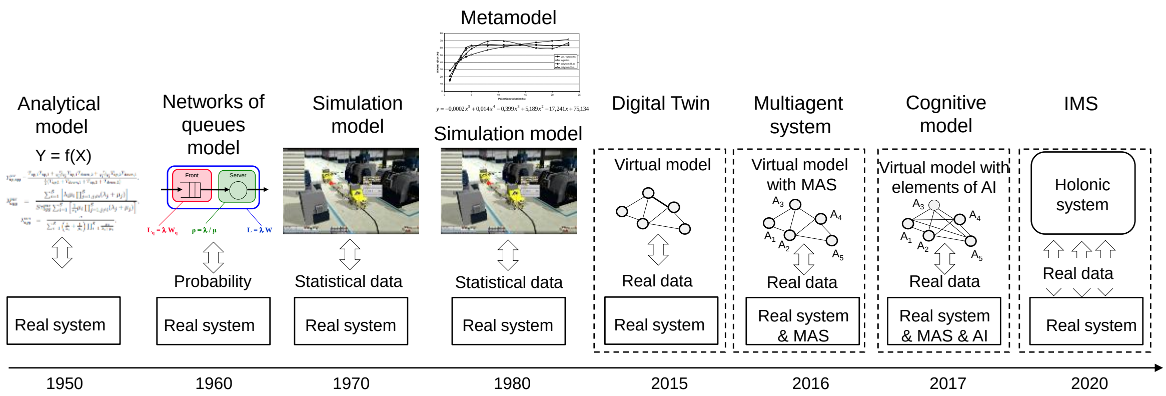


Figure 8-18 Evolution of a real system – a virtual model

The level of abstraction is very high for reconfigurable manufacturing systems. These are made up of several layers, as shown in Figure 8-19.

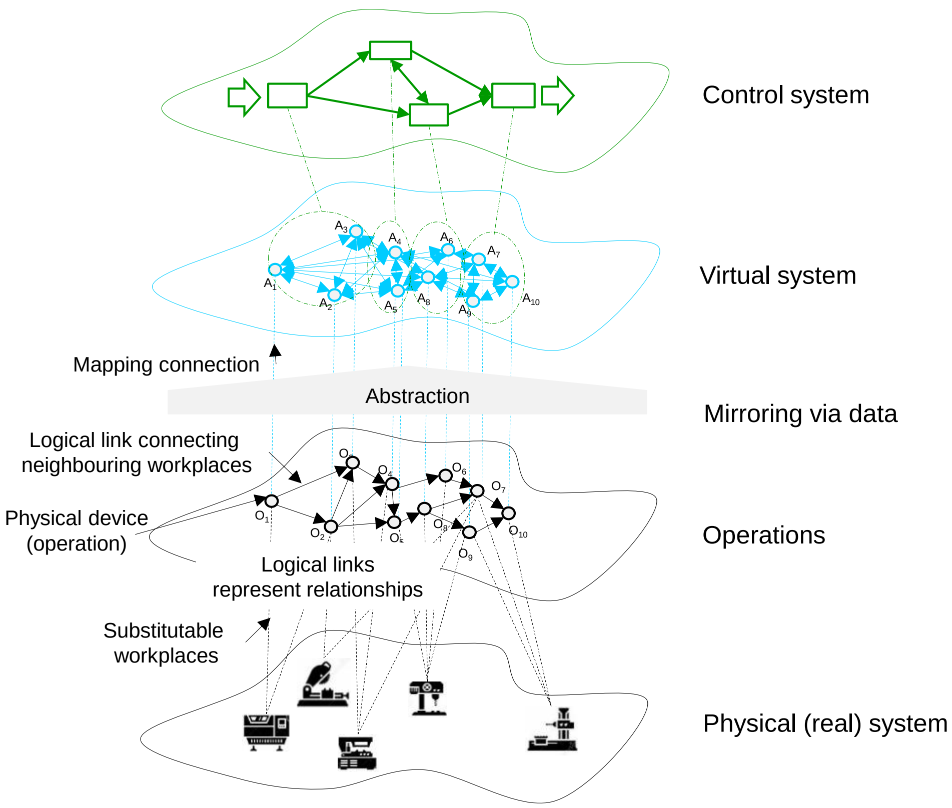


Figure 8-19 Mapping a real system to its virtual model
Source: Gregor, M. et al. (2017)

Virtualization brings several advantages its practical application requires the transformation of critical elements of virtualized systems. The control system, the rough structure of which is shown in Figure 8-20, must also undergo a decisive transformation.

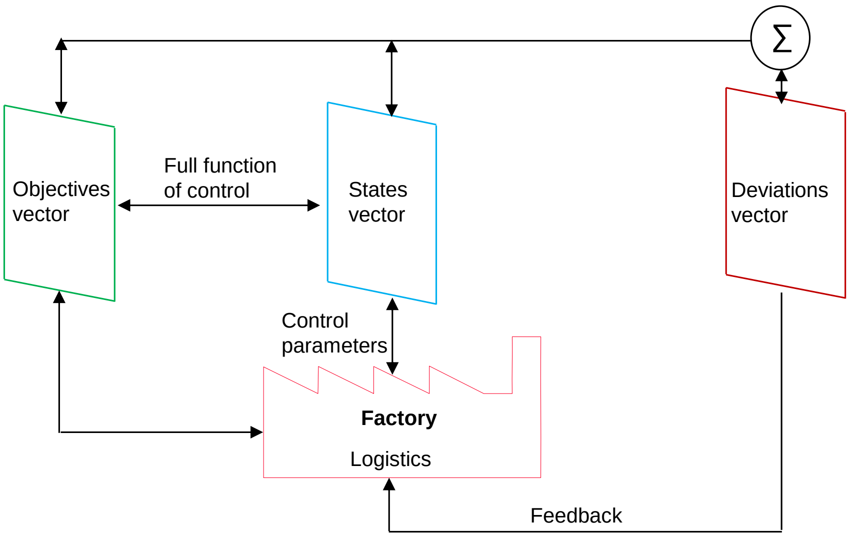


Figure 8-20 Basic factory control structure
Source: Gregor, M. et al. (2017)

As can be seen from Figure 8-20 for factory control, three basic representations (vectors) are needed, which include a vector of objectives, a vector of states and a vector of deviations. In practical design is concept of the control system shown in Figure 8-21.

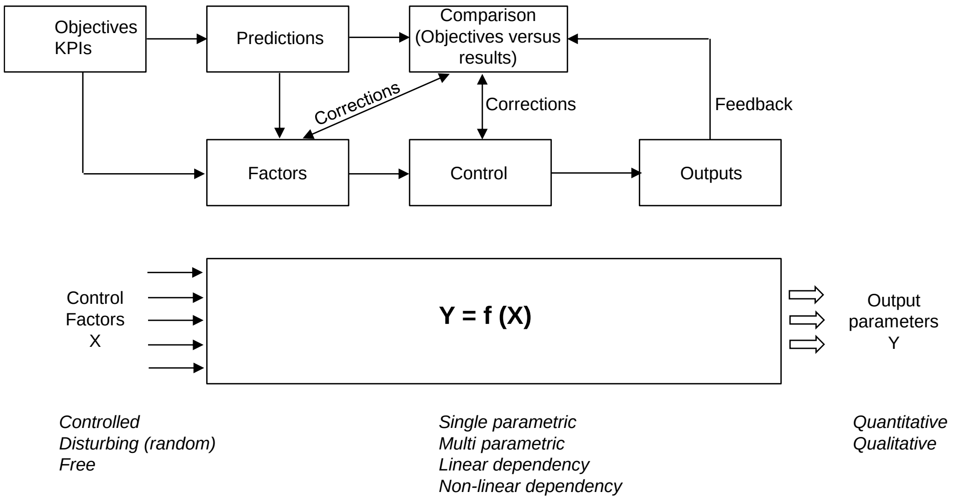


Figure 8-21 Factory control system concept
Source: Gregor, M. et al. (2017)

The control concept using virtualization already includes prediction mechanisms that allow the control system to "see potential scenarios of the future." The data structure for such a control concept is shown in Figure 8-22.

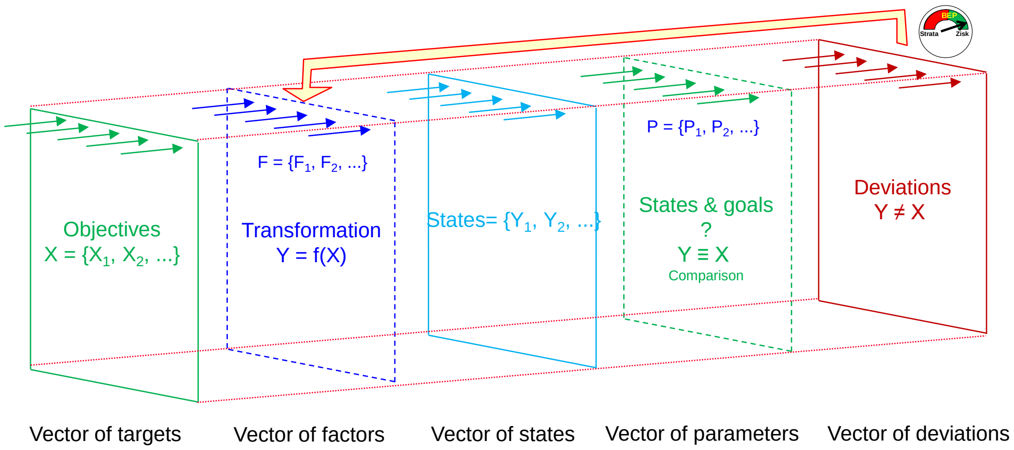


Figure 8-22 Data structure of the factory control system
Source: Gregor, M. et al. (2017)

The concept of the control system structure for mobile robotics used in internal logistics is illustrated in Figure 8-23.

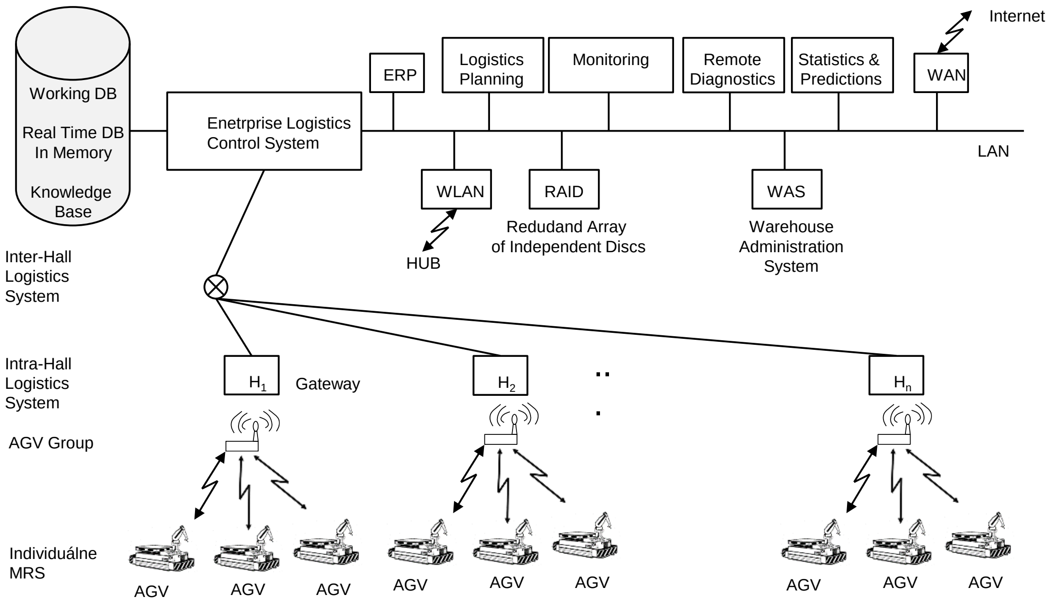


Figure 8-23 Structure of MRS control in logistics
Source: Gregor, M. et al. (2017)

An example of a real control system for Asseco CEIT's mobile robotic systems is shown in Figure 8-24.

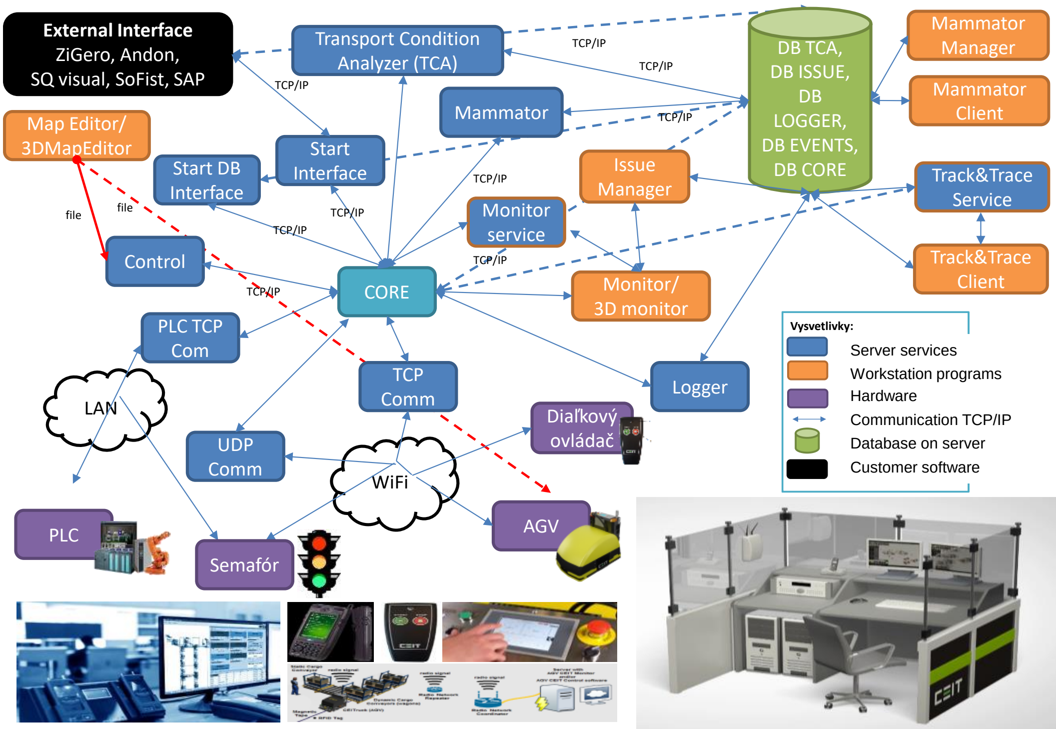


Figure 8-24 The structure of real MRSs control in logistics
Source: Asseco CEIT Archive (2023)

8.7 VIRTUAL MANUFACTURING AND SMART AGENTS

Author (Dreher,C. 2007) developed a vision of future manufacturing in Europe, in which the priority is based on the whole system understanding point of view of the manufacturing processes dynamics, i.e. the holonic system.

Internal dynamics and emergence in a complex system are created by agents and the action of relationships between them. The use of multiagent systems (MAS) is therefore advantageous for the control of complex manufacturing systems. Manufacturing is increasingly understood as a complex system to which the holonic concept can be applied; therefore, research has also begun in the field of Holonic Manufacturing Systems (HMS). Christensen,J.(2003) refers to such systems as Agent-Based Manufacturing (ABM).

Agent simulation and system dynamics have become a new tool for investigating and analysing the dynamics of complex manufacturing systems.

8.7.1 Holonic concept

The term holon was introduced in the twentieth century by the Hungarian writer and philosopher Arthur Koestler, who showed that almost every element in living systems can be understood in real time both as a whole and as an individual part of the whole. The new term "holon" is a combination of the Greek word "Holos" (whole) and the Greek suffix "on" (particle/its part, or being, existence). The holonic system can then be understood as a system consisting of subsystems, but at the same time such a system is a part of some larger whole (system). A set of holons with their properties creates a holonic organization, called holarchy, which is characterized by the fulfilment of common goals. Holarchy enables the creation of structures and the representation of the behaviour of complex systems, often referred to as social systems.

System autonomy guarantees holonic stability and the ability to effectively resolve system turbulence. Holonic manufacturing systems have several following characteristics (Botti,V., Giret,A. 2008):

- Autonomy – Each holon must be able to generate control (monitoring) actions and implement measures ensuring system stability through its own plans (strategies).

- *Cooperation* – Holons must communicate with each other, execute acceptable plans, and execute actions.
- *Openness* – The system must be able to adapt to the integration of new holons, the removal of existing holons and the modification of the capabilities of current holons.
- *Reconfigurability* – The ability of the holon to change its functionality quickly and cost-effectively.

The HMS architecture, using multi-agent systems, was proposed by (Bussmann,S. 1998).

A holon is essentially a set of tasks that can be generated by agent interactions within different organizational units. An elementary particle of the holonic system is represented by an intelligent agent (Haluska,M., Gregor,M. 2016).

Intelligent agents are independent and autonomous systems that perform their nested functions. They can represent hardware and software systems. They can educate each other and work simultaneously in real time. The general architecture of the agent system consists of three main components: perception, recognition and action (Gregor,M., Haluška,M. 2013b).

The purpose of perception is to receive data inputs through sensors and convey them to the recognition module for processing. This process can be based on filtering and priority rules (task importance).

Recognition is based on the processing of perceptual information and decision-making rules. This process may require various intelligent systems methods, such as the implementation of appropriate learning. The recognition mechanism must be able to deal with unexpected situations and adapt to new ones as quickly as possible within its competences. Due to this fact, the agent must have a very dynamic and flexible structure.

Commands (recognition) are implemented through the action, for example the robot walking or its automatic stopping when a spatial barrier is identified. During the agent's action, signals of the given environment can change, and new information can be obtained. This can be immediately perceived by another agent, who registers the given situation, evaluates it and then implements the relevant actions.

Each holon performs distinct functions, and their individual behaviour helps other holons to form system-wide behaviour.

8.7.2 Holonic architecture with support for an agent-based control approach

Intelligent agents are carriers of knowledge that enable them to perform actions efficiently. An agent can also produce specific knowledge through agent requests. Agent communication must be standardized from a given point of view. Standardization of the communication protocol will ensure an effective exchange of information and knowledge. The distribution of knowledge can in this respect be represented by a knowledge protocol that ensures the effective exchange of information and knowledge.

Within holonic manufacturing systems, holons are represented by clusters of agents through which tasks and orders are transferred. Agent control is based on priority rules supporting the assignment of relevant agent tasks. The negotiation itself is carried out in a multiagent system. A multiagent system can be represented by synthetic autonomous software.

8.7.3 Multi-agent systems

According to Gregor,M., Haluška,M. (2013a) - a Multiagent system - (MAS) can be considered elementary parts of distributed Artificial Intelligence, which are a conceptual framework for modelling complex systems. A MAS is defined as a loosely coupled network consisting of solvers of generated tasks. The MAS platform points to the distribution, autonomy, interaction (i.e., communication), coordination and organization of individual agents".

A multiagent system (Figure 8-25) consists of a group of agents operating in a specified area (Salman,A. 2009). Each agent in MAS has only partial knowledge, but complete autonomy. For an agent to act independently in the MAS structure, it must have the ability to independently process information and make autonomous decisions in interaction with other agents of the given area. Each agent in the MAS can act independently, which allows it to cross the boundaries of the specified area. Thus, through communication and cooperation, the agent obtains information and knowledge from other agents.

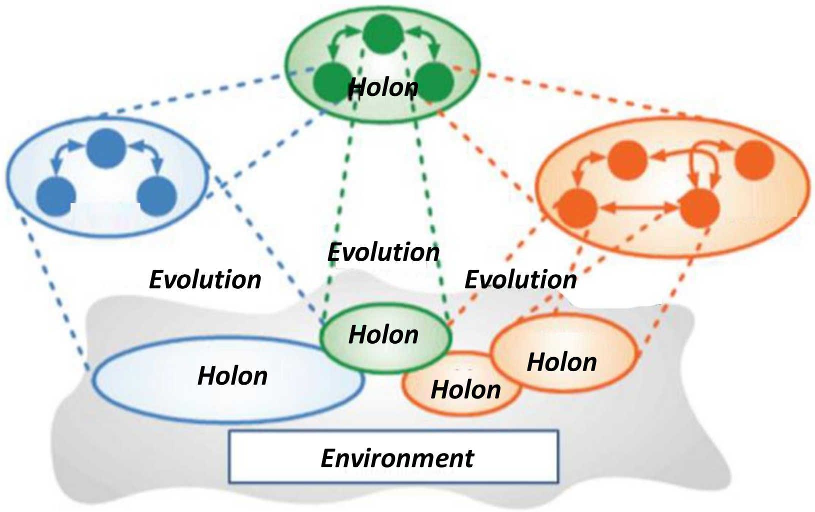


Figure 8-25 A multiagent system generating holons
Source: Monostori,L., Váncza,J., Kumara,S.R.T. (2006)

MAS can be formed by various hierarchical and heterarchical (including holons) organizational patterns, such as teams, coalitions, markets, which provide the achievement of system-wide goals.

In the past, expert systems were designed for the purpose of managing intelligent production systems, which lacked low performance and a low level of learning. Over time, a new framework began to develop, which is based on the cognitive architecture of human perception and problem solving (behaviour). These shortcomings have been eliminated by multi-agent systems, as shown in Figure 8-26.

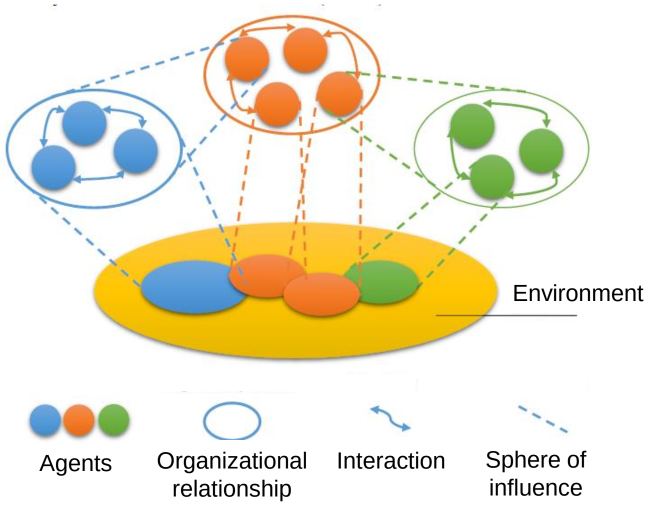


Figure 8-26 General scheme of MAS
Source: Ďurica,L. (2016)

A multiagent system (MAS) can be considered as the elementary parts of distributed Artificial Intelligence, which are a conceptual framework for modelling complex systems. A MAS is defined as a loosely coupled network consisting of solvers of generated problems. The MAS platform points to the distribution, autonomy, interaction (i.e. communication), coordination and organization of individual agents (Haluška,M. Gregor,M., 2016).

Intelligent functions of monitoring and control systems

Authors (Gregor, M., Haluška, M.,2013a) proposed a MAS for intelligent manufacturing monitoring and control, the structure of which is shown in Figure 8-27. As can be seen from Figure 8-27, the structure consists of four horizontal layers and three vertical subsystems (monitoring, control, executive).

The horizontal layer located above the distribution system control is represented by semi-autonomous agents with various levels of data abstraction and information-transformation mechanisms. The middle layers (negotiation and reactive) interactively act on the distribution control system and through the given approach the organizational process receives perceptual input and generated actions. To ensure the efficient functioning of the monitoring and control subsystem, the given subsystems must be separated into several layers. This shortcoming can be eliminated by effectively categorizing the monitored events and thereby allowing the planning agent to generate behaviour (actions). The process of generating actions within agent control is based on the hierarchical control principle.

Individual system layers interact with each other (top-down and bottom-up systems). The initialization of the bottom-up system function is realized based on the assumption of control through the action of the lower layer on the hierarchically superior one. Initializations occur because of negotiation rejection (incompetence of the subject), which shifts the task to a higher solving layer. Top-down is translated because of a higher agent level using the functions that are presented in the lower layers and thereby simultaneously trying to achieve their goals. System flow control occurs due to the transfer of the monitoring input to the lowest level. The system initializes the bottom-up function and passes tasks to the negotiation layer if the reactive layer cannot transform the given input. The top-down system is subsequently implemented based on the successful transformation of the negotiation procedure. Otherwise, control is transferred to the meta-control layer, where internal system conflicts (turbulence) are resolved, or information is sent to the appropriate operator to perform the necessary intervention. In the remaining part of the system model, agent functions will be discussed within individual layers. A detailed description of the structure and functions of the proposed MAS is provided by (Haluška,M. 2015).

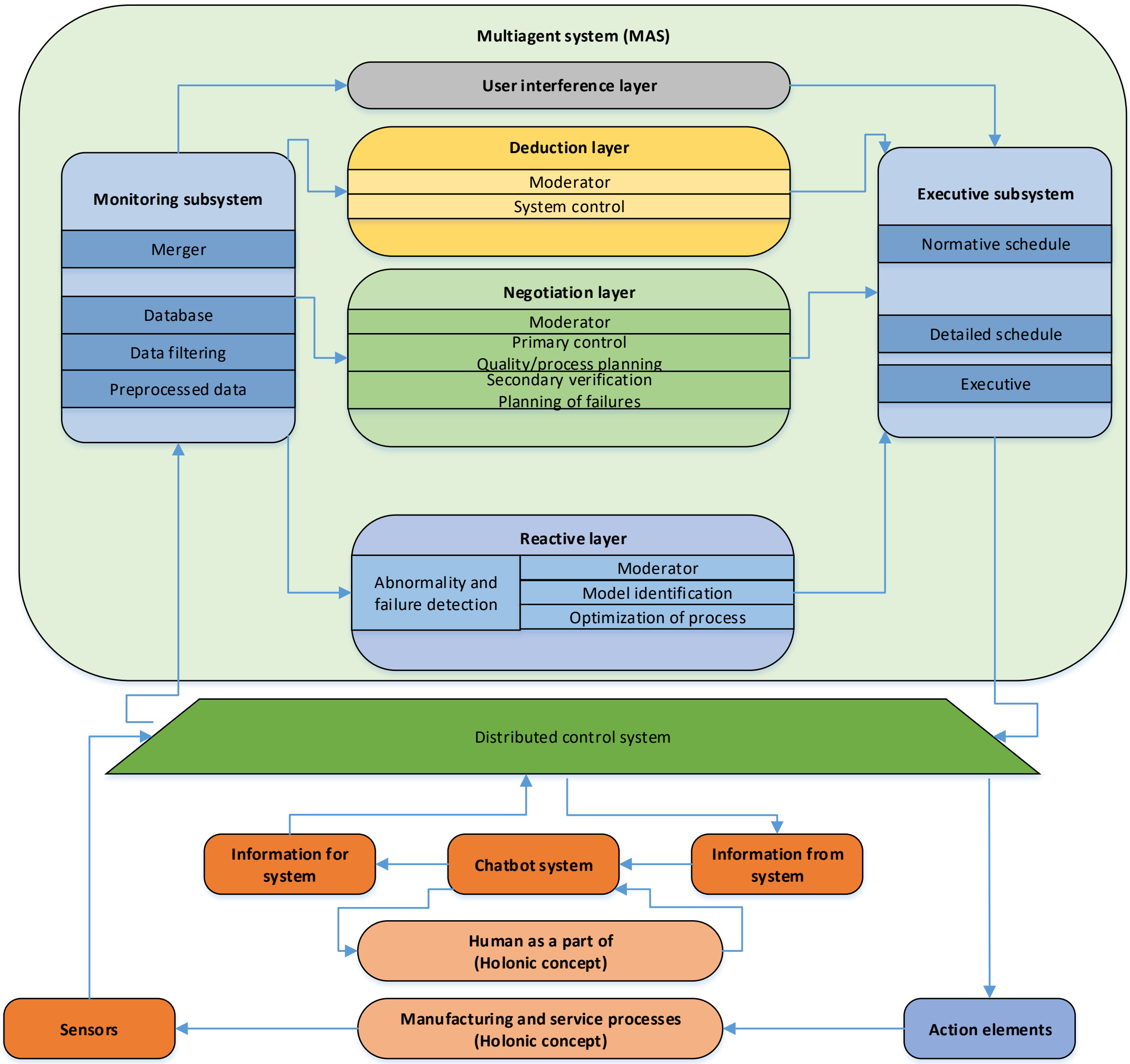


Figure 8-27 Intelligent monitoring and control system architecture

Monitoring subsystem

The task of the monitoring subsystem is to hierarchically examine the data and categorize it into different abstraction levels. The data flow is processed based on a functional agent, the task of which is to acquire data and then check it. The relevant agent detects coloration deviations and missing data. The identified abnormalities are subsequently filtered and removed by means of the agent. The data stream is then subjected to further statistical processing that estimates deviations and investigates changes in the steady state. The statistical data are then transferred to the central one of the executive subsystem to adapt to new situations. Based on legal competences, the agent of the relevant subsystem agrees to the possibility of initialization of the data-transformation process. The transformed data is subsequently stored in the relevant base entity. The data fusion agent groups data for the identification of critical operating variables for the purpose of subsequent effective process planning and, at the same time, performs an effective evaluation of situations (external environment).

Reactive layer

Agents in each layer directly react to events that occur in the environment. Agents begin to cooperate and evaluate situations based on their own autonomous identification of the occurrence of abnormal events, error detection and isolation measures. The integration of the presented agents will result in an increase in operational performance. The detection of a localized fault allows the isolation tasks to be initialized through the acquired knowledge. Agent techniques use neural fusion of historical data, modelling practices and fuzzy graphs. These approaches are based on analytical models, network states and heuristic methods. The identification agent of the reactive layer has the task, based on the external environment (organization), to expand the disposition of the knowledge base. The agent will use the identification package of the knowledge base to create variable models and predict changes in process variables, through which it will estimate new parameters (autonomous learning), increase the overall resistance against forced isolations and replace erroneous sensory signals (autonomous recalculations). The optimization agent has the task of efficiently using available resources and materials. As a result of the limitation of operation, the agent obtains current manufacturing plans and quality indicators from the real environment, based on which it formulates new optimization tasks and generates new plans supporting compliance with the required quality. Subsequently, the optimizer transforms the represented tasks, adjusts faulty processes and quality indicators.

Negotiation layer

Proactive behaviour is achieved in the system at the negotiation layer, which is responsible for managing system actions during stable and variable operation. Through the given layer and the integrated logic mechanism, the plans will be implemented based on the predefined plans found in the respective libraries. The derived framework can be based on considerations (model and case). Case-based reasoning provides a wide range of benefits, e.g. propose a possible solution to current problems that are inadequately defined. The given principle reduces the time for justifying the tasks presented. Case-oriented reasoning generates a negotiation model that deals with problems, understanding, and learning while integrating the results into an integrated memory of the logic mechanism.

The negotiation layer supervises the system through two agents. The first agent represents the controller (primary) that manages the system during stable operation. The agent uses a library of product quality profiles, transformed plans and manufacturing processes. Due to the defined requirements, the given negotiation agent retrieves a set of cases that best match the required attributes and quality specifications. The successful implementation of the given process ensures the transfer competence of the tactical plan to the executive subsystem. An unsuccessful process initializes the activity of the model optimizer, which adapts the models to the agent. In the given process, communication takes place between the primary negotiation agent and the modelling, simulation and optimization agent, which generate optimal data for operating conditions (e.g. pressure, temperature). The tactical plan is sent to the user layer if further adjustments are needed. The subsequent acceptance of the tactical plan enables the effective initialization of the activity of the executive layer. The primary controller agent monitors current quality and stores tactical plans in its own library. Through tactical plans, he should then fulfil the requirements for the subsequent creation of the future manufacturing plan.

The second agent has a backup system control function. The agent has a library in which the recalculations of fault plans are stored. Plans consist of programs that integrate to the need for initialization of sensor tuning (calibration), reconfiguration of actuators, controllers, and generation of failure scenarios. The programs also serve predictive maintenance to optimize procedures. During the occurrence of abnormalities, the backup agent delegates judgments to the detection and isolation agent located in the reactive layer. Based on these ratings, the backup agent retrieves the most matching role from their library. Based on the given action, it notifies the user interface agent about generating abnormalities, possible causes and corrective measures. The interface agent has the task of informing the user and providing him with materials for performing the necessary actions or approving the status. The backup agent can intervene due to system performance degradation (in critical situations). Interaction with the user interface agent may be initialized due to variable manufacturing quality.

Deductive layer

The inference layer provides monitoring, evaluation, and control capability to all agents. For example, the inference layer may obtain inconsistent information or targets through the coordination of the reactive layer and the monitoring subsystem. The same situation may arise in the transformation subsystem, which may not acquire the ability to efficiently meet the schedule generation schedule (using the negotiation agent). A meta-controlling agent can notice and simultaneously categorize given situations. With the help of implemented negotiation and observation skills, he can develop a strategy for an effective solution to the presented situations (longer time horizon of implementation). The meta-agent coordinates agents to achieve system robustness and coherence. The relevant agent evaluates the trustworthiness of other agents' behaviour by monitoring its internal states.

A meta-agent essentially represents a rule-based expert system that codifies system behaviours and agent interactions. Agent behaviour is influenced by hierarchical agent behaviour within a single structure that has defined goals. The agent is informed about the achieved results, current ongoing activities, assigned activities and why the given behaviour was adopted (meta-reasoning). The interference mechanism helps the meta-agent, through intensive search and generation of alternative behaviour, to resolve agent conflicts in order to continuously improve agent coordination. Based on the given principle, the agent can learn and create new types of behaviour.

User interface layer

The process monitoring entity and the control system implement their functions simultaneously through the user interface. The user interface receives different types of information from different layers and subsystems:

- Information about faulty components and their possible causes (detection and isolation agent),

- Based on a justified fuzzy graph (detection and isolation agent), information on failure scenarios is obtained,
- Information on system recommendations, such as instructions for restructuring system control, predictive maintenance plans, and other reactive or proactive measures.
- Information on manufacturing quality and material transport,
- Information on internal diagnostic activities, data trends and performed tasks.

The most important task of the user interface is to transparently present critical information about data and work overload.

Executive subsystem

Requests for generating plans are transferred by the negotiation layer and are subsequently implemented through the executive subsystem. The given subsystem consists of a hierarchically organized scheduling and executive agent. The scheduling agent decomposes plans into sub-plans that have short-term time frames. Sub-plans are subsequently decomposed into simpler tasks with the help of the given agent. Finally, the plans are implemented through the corresponding agents and the system results are transferred to the monitoring subsystem.

To ensure the productivity of future manufacturing systems, the implementation of an innovative software platform with an open control architecture based on a multi-agent approach to coordinating internal and external system turbulence is required. Future manufacturing enterprises can implement the given control approach to quickly introduce the required products to the unpredictable market environment, which recursively generates corporate profit.

The issue of multi-agent systems and their application in logistics control of complex manufacturing systems was discussed in detail by Ďurica,L. (2016), who proposed and practically verified the architectures of several solutions for multi-agent control of mobile robotic systems.

8.7.4 Future application of Multi agent system

The future manufacturing will be represented by two worlds, the real world, and its virtual image, also called the virtual world. These worlds will be integrated with each other through data. Manufacturing data will be collected and processed in real time. Almost immediately, information will be available about each object in manufacturing, what it is doing, what condition it is in, what it plans next, what it lacks, etc. The status of each product, machine, tool, device, preparation, robot, or human will be immediately scanned and the processed information will be sent to the control centre. This information will be compared with the next step in the processing of the products, and based on this, a sequence of future steps will be generated, and the necessary decisions will be made for further processing of the product. The virtual world will allow, if necessary, to carry out simulations of the future state and predictions of the effects of the necessary control measures.

Managing such an emergent system is a complicated process. The control system cannot control everything on its own. Therefore, most objects must behave and act completely independently, that is, show autonomous behaviour. In such a case, the control system shall retain a planning, coordination, and control function. Self-driving performance will be provided by autonomous agents (Figure 8-28).

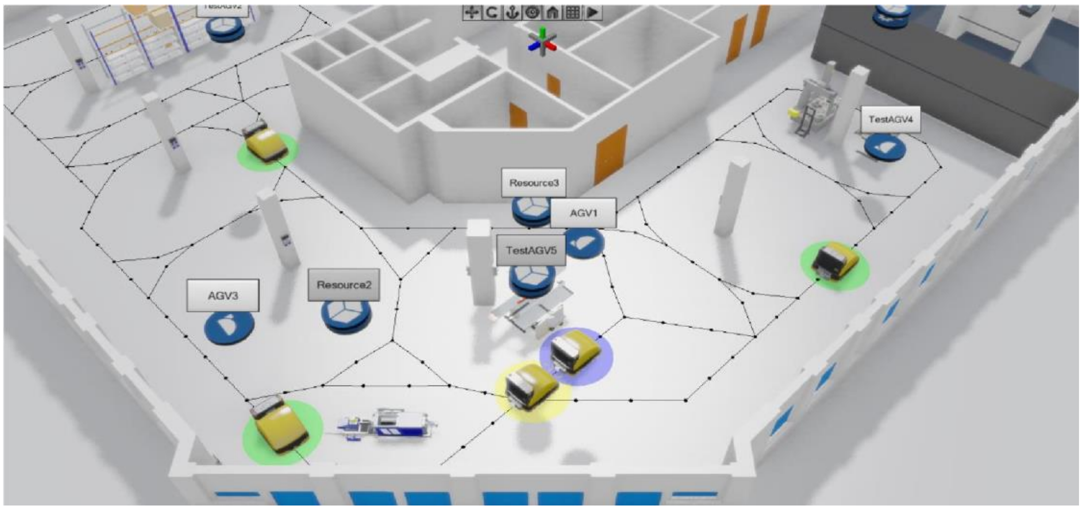


Figure 8-28 Simulation of multiagent control of mobile robots
Source: Ďurica,L. (2016)

Each entity in future manufacturing will be able to communicate with other entities. Although individual entities will have a certain degree of autonomy, their behaviour will be supervised, and their activities planned and controlled by a hierarchically superior control system (agent) that will determine the virtual flow of information and material at the factory. This new control approach is referred to as *holonic control*. Real-time interaction of entities with each other in manufacturing will bring tremendous growth in the volume of data. Therefore, the main challenge for Factory of the Future becomes the collection and processing of data. Future manufacturing will be much more complex. Every element of it, from the product, through manufacturing facilities to testing, will be equipped with intelligent and cognitive abilities, capable of identifying, classifying, recognizing, and making decisions. New manufacturing systems will generate unimaginable amounts of data that will need to be intelligently filtered, aggregated, represented, and stored in a reduced form.

These features will be supported by a new technology called the Internet of Things. The future manufacturing environment will need to ensure that each manufacturing entity has immediate access to the collected data. Cloud computing technology will enable this. Such amounts of data will require new forms and methods of data transmission. More importantly, such data cannot remain unused and form what has come to be referred to as *data cemeteries*. The obtained data will form a raw material for further processing using *Big Data* methods and technologies. The algorithms being developed will be able to search for "invisible" connections and relationships in existing data and use them to predict and support decision-making. The new algorithms will be intelligent and are therefore also referred to as *Smart Data*.

Thus, according to some experts, future manufacturing should use a new control system, based on the concept of holonic control. Such control should control and supervise all processes at the factory. In this, it will be supported by mobile wireless sensor networks. If such control were to lose sight of the ongoing processes and the overall situation, there would be total chaos in manufacturing. Therefore, researchers also focus on non-centralized control concepts, with the concept based on the use of agents and multiagent control looking the most promising. The use of the concept of agents is promising mainly because it allows elements of autonomous behaviour to be easily integrated into the control. In practice, autonomy means that individual entities will be able to implement certain decisions, without the need for approval and often without the need to communicate with the superior level.

This will help to significantly simplify the entire control of Factory of the Future and significantly increase the reliability of manufacturing systems.

8.8 INTELLIGENT MANUFACTURING SYSTEMS

An Intelligent Manufacturing System (IMS) is a socio-technical system with the autonomous ability to identify systemic changes and environmental impulses, their causes, and use the acquired knowledge to learn, adapt and react to all changes in the surrounding environment in a way like how a person reacts. With repeated inputs, the learning of the system deepens. In humans and sometimes in animals, we talk about intelligence. For technical systems, the name Artificial Intelligence is more often used. Intelligent manufacturing systems emulate human intelligence through artificial intelligence technologies. Artificial intelligence relates to the development of information technology.

The 21st century will be characterized by the development and implementation of "smart solutions" in all areas of human life, including the economy. Manufacturing and technology are becoming intelligent.

Production systems have experienced a literal revolution in the last decade. From hard production lines, through automated production systems, flexible production systems to reconfigurable production systems. The direction of further development is clear and unambiguous, the future goal is intelligent production systems capable of working completely autonomously. Such systems must be adaptive and able to rapidly reconfigure and self-organize. Their management must be distributed, using the principles of multi-agent systems (MAS). Intelligent sensors, collecting and evaluating huge amounts of data right on the spot, will become a natural part of such production systems. Results will be communicated through the Internet of Industrial Things, and complex and computationally intensive tasks will be performed in cloud computing systems.

The development in the field of IMS began already at the end of the 50s, with the appearance of computers and the rapid development of ICT technologies. A period of tumultuous development followed. We can characterize the present as a "halfway" state. A lot has already been done in the field of new production technologies (additive technologies, nanomaterials), information and communication technologies and management of production systems. However, scientists face much more demanding tasks, the complexity and complexity of which we can hardly imagine today.

Today's advanced production systems already possess a certain degree of "intelligence". However, the essential part of their development still awaits us in the future.

There are attempts to standardize solutions for intelligent manufacturing systems in the world, mainly within the global research project Intelligent Manufacturing Systems. An example of an IMS structure, designed in Slovenia, is shown in Figure 8-29.

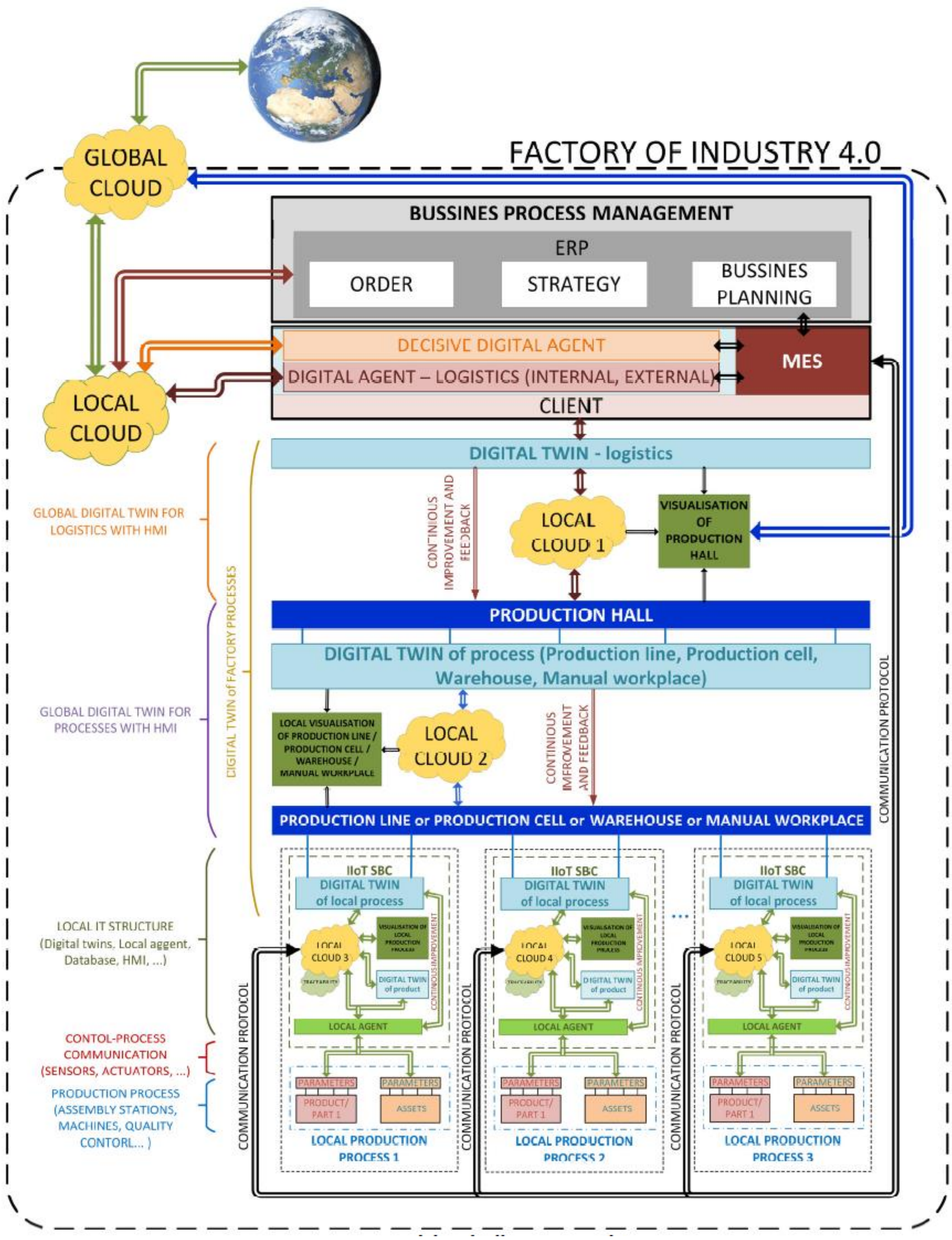


Figure 8-29 IMS structure

Source: Resman,M.,Pipan,M.,Šimic,M.,Herakovič,N.(2019)

The complexity of advanced production systems, using massive sensors and robust decision-making algorithms developed on their basis, becomes so high that it can only be mastered using the theory of multi-agent systems (MAS). The use of MAS in the management of production systems brings a paradigmatic change to the production environment, production processes become complex, and a completely new concept of management and organization of work in future production systems must be designed to handle the complexity.

Complexity and its depth can be explored and represented using complexity theory. The control system, i.e. the brain, of future production systems will use the analogy of the organization of the human brain. Its nervous system is a sensory and communication system. Action members are intelligent workplaces and intelligent mobile robots. Such a control system uses analytical mathematics for predictions of future states, and we can describe this type of control as predictive control. It uses simulation and emulation as a means of validating decisions made. This creates an action dynamic control system with multiple feedback.

8.9 ZIMS – RESEARCH AND DEVELOPMENT PLATFORM

The reaction to the latest trends in the field of future production systems was the creation of a research platform (Figure 8-30), which was named ZIMS (Zilina Intelligent Manufacturing System). This research platform was created in cooperation of the University of Zilina, company Asseco CEIT (spinoff of the University of Žilina), technological and industrial partners.

ZIMS uses the most advanced technologies for the design, optimization, and operation of future production systems (Factory of the Future - FoF), mainly in the field of: Digital Factory and Digital Engineering, virtual development of products and production systems (Virtual Engineering), Reverse Engineering, digitization (3D laser scanning), Rapid Prototyping of products and production systems, virtual testing, computer simulation and emulation, etc.

The layout of the ZIMS workplaces was organized based on the logic of the innovation development process, starting with an idea, its presentation in virtual reality, the development of a product prototype and its testing, the design of production processes, the configuration of the production system using digital enterprise technologies, and ending with the practical implementation of the product in the production system.

ZIMS is a new, open collaborative environment, supporting creativity, inventing new solutions and their practical implementation in the form of new innovative products. This environment fully supports experimentation with the new, unknown and the search for non-traditional approaches to solving existing problems. ZIMS also serves as an incubator of the latest technologies.

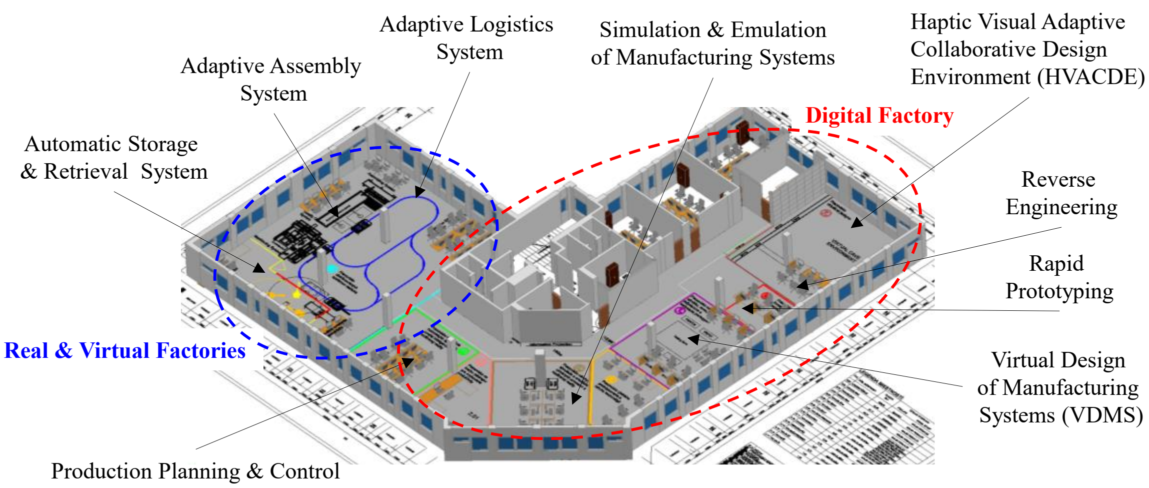


Figure 8-30 ZIMS Layout

Figure 8-31 shows the principle of the built knowledge environment that will support the system of learning from process activities (Gregor,M., Medvecký,Š. 2015).

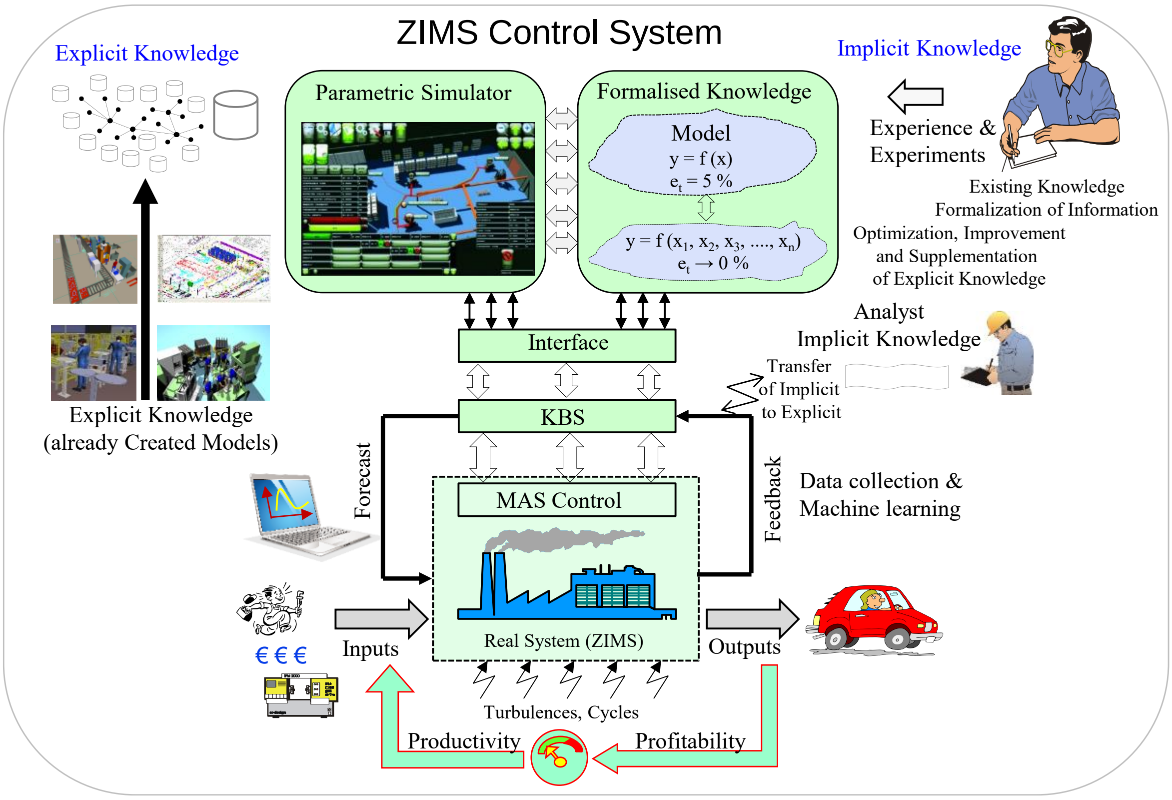


Figure 8-31 The System for Learning from Processes

This approach is verified within research, in the field of technologies for the industrial production of large-scale optical single crystals.

8.9.1 Modular Production System

The Modular Production System (MPS) is one of the workplaces being built in ZIMS and it represents a pilot project for an intelligent, modular production solution. The MPS structure is shown in Figure 8-32. As can be seen from the MPS layout, this system contains all the critical components of an advanced manufacturing environment and a suitable space for creative ideas and their verification through simulation and real tests.

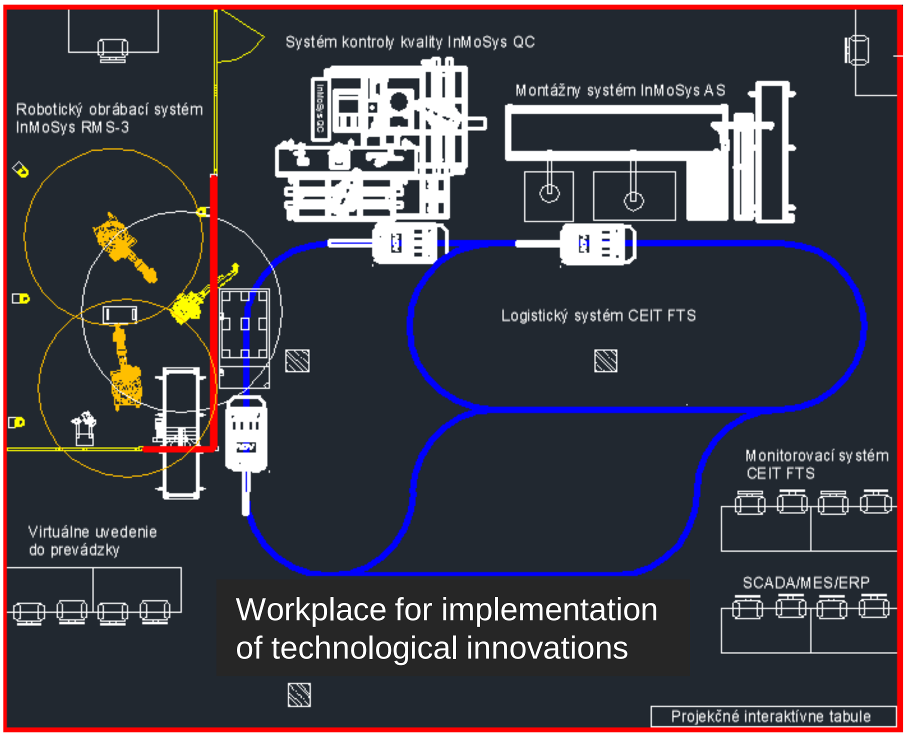


Figure 8-32 MPS Layout

Above the technological base are built information systems intended for data collection, their visualization, archiving and further processing due to the creation of balances regarding production and operation. At the same time, within the software application superstructure, these information systems can also be used as emulation and simulation tools.

The information systems used are mostly represented by standard SCADA/HMI systems such as Simatic WinCC and Control Web. Within the framework of MES systems that are not currently implemented, several variants intended primarily for integration and testing are being considered. The development of new modules for the simulation, emulation, and visualization platform Ella®, which was mainly used for planning logistics systems, is taking place at this workplace for the purpose of visualizing process data and monitoring and controlling production.

MPS is a research-experimental workplace where five of its subsystems are developed (Rofár,J., 2013a), Rofár,J. (2013b):

- intelligent modular quality control system – InMoSys QC,
- intelligent modular assembly system – InMoSys AS,

- intelligent in-house logistics system based on mobile robotic systems – InMoSys AGV,
- intelligent robotic machining system – InMoSys RMS-3 a
- intelligent storage system – InMoSys ST.

The principle of MPS operation can be described simply based on the logic of product processing. It begins with the input of material from the InMoSys ST input-output storage system, from where the material is transported to the InMoSys RMS-3 workplace, where it is processed into the desired shape (volume, shape, surface, dimensions). The part processed in this way is transported by InMoSys AGV to the InMoSys QC quality control workplace, where control activities (accuracy, dimensions, surface…) are carried out. The high-quality parts are further transported by InMoSys AGV to the assembly workplace of InMoSys AS, where they are assembled with other parts into the final product. The final products are transported to the InMoSys ST input-output storage system.

Figure 8-33 shows the modules of the InMoSy QC system of the MPS concept.

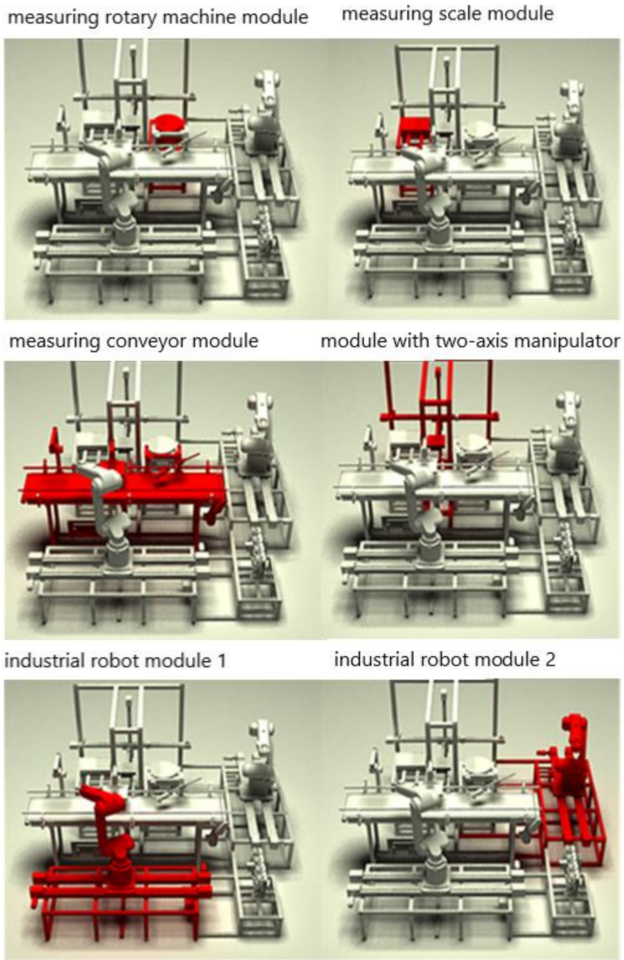


Figure 8-33 InMoSys QC Modules

Figure 8-34 shows the real version of the InMoSys QC workplace module.

Figure 8-34 Real implementation of InMoSys QC in ZIMS

An example of the intelligent storage system InMoSys ST of the MPS concept is shown in Figure 8-35.

Figure 8-35 InMoSys ST

Figure 8-36 shows the MPS assembly workplace.

Figure 8-36 MPS automatic assembly workplace

Figure 8-37 shows the MPS transfer line.

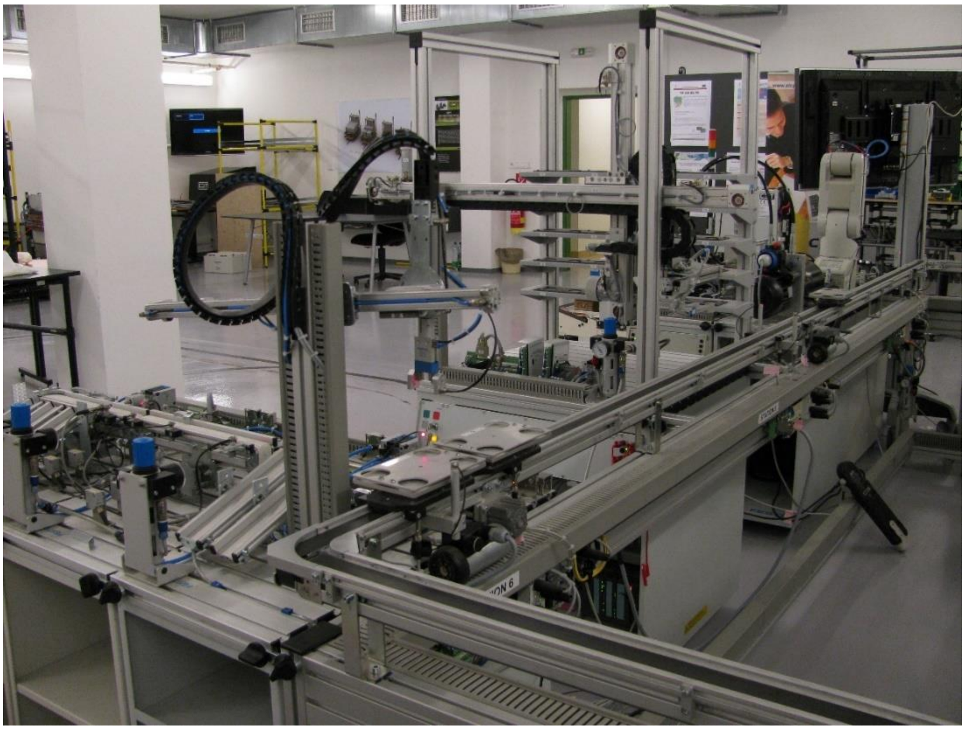


Figure 8-37 Transfer line of MPS

CONCLUSIONS

Nature exists as a complex, self-organized, holonic system. Also, man is formed by small, autonomous units - holons, which together form larger self-organized, complex units, and this form a complex holonic system - man. Nature created biological systems and, through evolution, allowed their further development, towards the highest form of organized matter – intelligent systems. Biological systems represent the most efficient and powerful manufacturing systems known to mankind today. These systems serve as role models for scientists in creating "artificial" mechanisms, imitating nature, for the manufacturing of new products.

Changes in customer requirements make manufacturers deep wrinkles. Without customers, there can be no manufacturing, and therefore manufacturers carefully listen to the voice of their customers. The smarter ones even try to anticipate customer requirements and, if they can, gain a great competitive advantage.

The growth of requirements for new customized products puts high pressure on completely new concepts of manufacturing systems. These must have high flexibility, which can be ensured through reconfiguration. New manufacturing concepts will require completely revolutionary ways of planning and control manufacturing. These must be based on holonic principles, autonomy and applications of artificial intelligence and evolutionary principles.

Although changes do not occur immediately, developed countries pay a lot of attention to research into future manufacturing concepts. A group of leaders in cooperation with industry, are working on a new manufacturing concept to ensure the future competitiveness of industry.

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He represented the Slovak Republic in expert working groups at the European Union level and acted as a UNIDO expert in the field of productivity. He worked in the presidium of the Association of the Automotive Industry of the Slovak Republic and the Association of the Mechanical Engineering Industry of the Slovak Republic.

In 2008, he was awarded the ***Personality of Science and Technology of the Year 2008*** by the Minister of Education of the Slovak Republic.

In 2013, the President of the Slovak Republic awarded him the highest state award of the Slovak Republic, ***the Order of Ľudovít Štúr, 1st class, for extraordinary merits in the development of the economy, science and technology and the dissemination of the good name of Slovakia abroad***.

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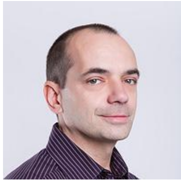

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Slovak Productivity Center

The Slovak Productivity Centre (SLCP) is a national organization established in 1998. Since 2006, the SLCP has been actively cooperating within the European technology platform ManuFuture EU. Since 2005, SLCP has been a member of the lean manufacturing global network organized by the American Lean Factory Institute (LEI - USA)."

At the national level, the SLCP focuses on supporting the growth of productivity and competitiveness of Slovak industry and thus increasing the quality of life of all citizens of the Slovak Republic.

Every year, the Slovak Productivity Centre organizes the National Productivity Forum, an international platform for the exchange of information, knowledge, and experience in the field of innovative approaches, supporting the growth of competitiveness, productivity, the development of innovation and the knowledge economy.

In cooperation with the Ministry of Economy of the Slovak Republic, the Slovak Productivity Center awards selected organizations and individuals with **the National Productivity Award**.

The idea of creating the Slovak Productivity Center originated at the Department of Industrial Engineering, University of Žilina in Žilina. SLCP's cooperation with several domestic and foreign universities is aimed at supporting the development of youth entrepreneurship, innovation, and the knowledge economy. SLCP is closely involved in the development of applications related to the construction of Industry 4.0.

SLCP provides consultancy activities and implements projects to increase productivity and competitiveness in industry. The portfolio of products and services is divided into main groups: education and training, operational audits, productivity measurement and analysis, productivity improvement projects, simulations, and dynamic analyses of the operation of manufacturing and logistics systems, short-term manufacturing planning and control, Industry 4.0 issues.

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Changes in customer requirements make deep wrinkles for manufacturers. There can be no production without customers, and therefore manufacturers listen carefully to the voice of their customers. New concepts of production systems implemented within Factory of the Future will enable manufactures to better respond to changes in customer behaviour and thus achieve better results than the competition.

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