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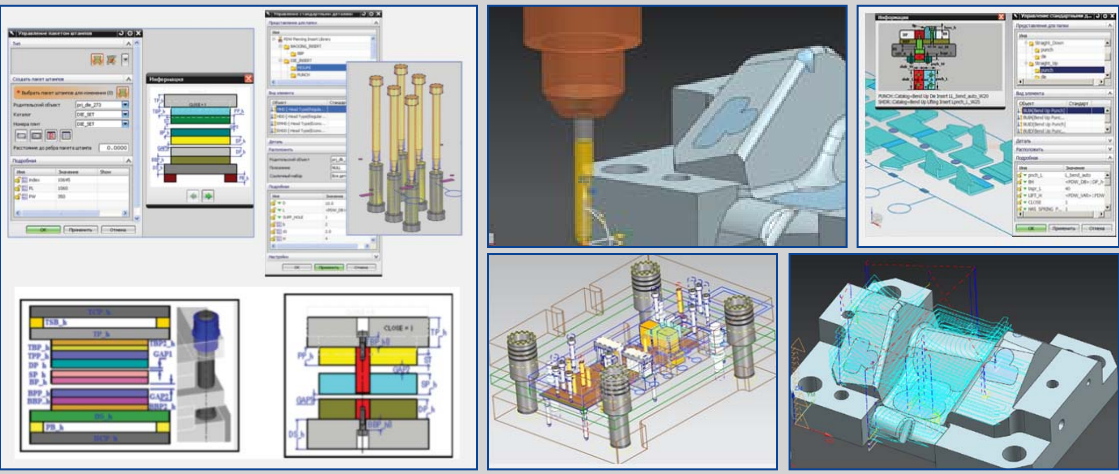
Тольяттинский государственный университет
Институт машиностроения

ЦИФРОВЫЕ ТЕХНОЛОГИИ ПРОИЗВОДСТВЕННЫХ ПРОЦЕССОВ

Электронное учебное пособие

DIGITAL TECHNOLOGIES IN PRODUCTION PROCESSES

Lecturing material



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В учебном пособии изложены основные сведения, касающиеся современных технологий цифровизации жизненного цикла изделий. Представлены обзоры о концепции и принципах внедрения технологии цифровизации, формировании единого информационного пространства, оцифровки производственных процессов, разработки цифровых двойников, принципах взаимодействия людей и роботов, удаленном мониторинге и контроле производственных процессов.

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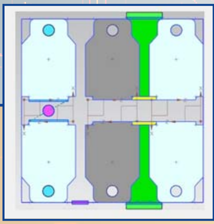

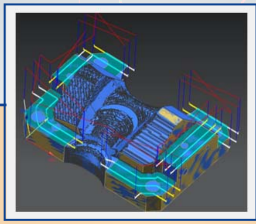

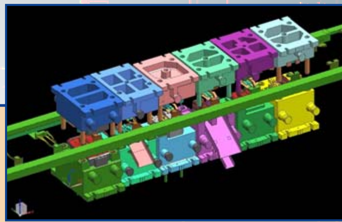

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Contents

About the course

Digital Technologies in Production Processes is a training course which is aimed at developing skills and competencies in the field of product life cycle digitalisation.

The course is developed to enhance professional competencies by fortifying students with knowledge on digital twin design.

The aims are:

1. To provide an understanding of developing the digital environment of an enterprise.
2. To empower students with practical skills to use traditional and custom algorithms and find solutions for problems of modern digital technologies.

The lecturing material is intended for Mechanical Engineering students who are aspiring to advance their knowledge and develop skills and competencies to create the basic elements of digital twins. The course provides a first look at new technologies within an enterprise.

The lecturing material is designed for students of MSc in Design and Technological Support of Machine-Building Industries and for the educational and industrial communities.

1. INTRODUCTION. INDUSTRIAL DIGITALISATION

1.1. The Role of the Digital Revolution

The development and application of science and technology was historically categorised into several steps, which were also called industrial revolutions. Until the 21st century, there were three major industrial revolutions, each associated with the new concepts for facilitation of human labour.

The First Industrial Revolution (from the 18th to 19th centuries) is about the industrialisation. It is a time of energy converting and generating mechanisms and machines. They are extensively used to operate the tool working parts, which makes it possible to develop production and design standardisation. It is also a time of modern capitalist relations; industrial society replaces agrarian society as population grows mainly in cities (fig. 1.1).

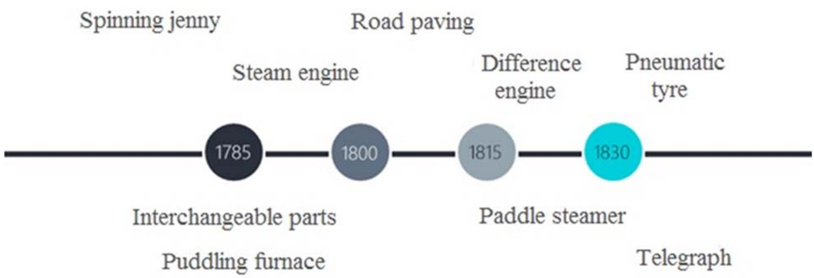

Fig. 1.1. The First Industrial Revolution

The Second Industrial Revolution (from the 19th century to the latter half of the 20th century) is about a wider implementation of mass production methods. It is a time of conveyors and electricity which is widely distributed as a source of energy and used, for example, in household appliances such as refrigerators, fans, lamps, washing machines, etc. Also, data transmission methods – semaphores, telegraph, telephone, radio and television – emerge (fig. 1.2).

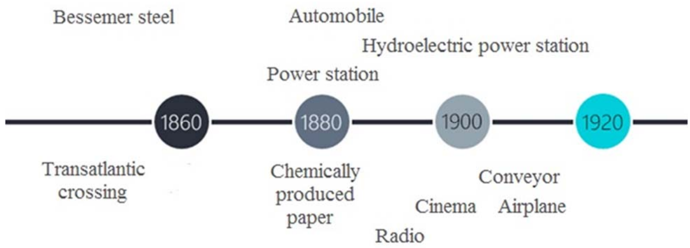

Fig. 1.2. The Second Industrial Revolution

Data transmission networks and computing and communication automation initiate the Third Industrial Revolution in the 1960s. By its end, the computer and the Internet are considered to be the best means of computing and transferring production data. It is computers and sensors now that control machine and mechanism elements. These devices and technologies enable production automation through the use of flexible manufacturing systems and industrial robots or computer-aided design (CAD) systems which are special engineering software products that make it possible to design entities and simulate processes with a computer. This allows the concept of digital production to emerge. There are also tasks that can be solved through globalisation of society and industry, which lays the groundwork for the post-industrial economy (fig. 1.3).

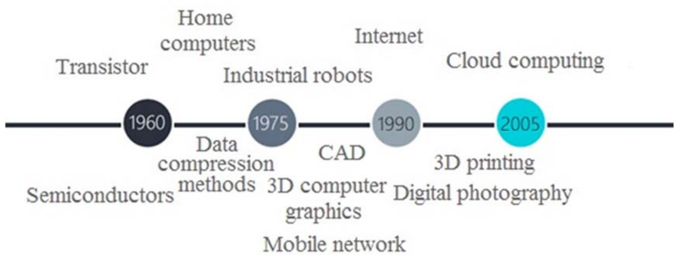

Fig. 1.3. The Third Industrial Revolution

However, in the 2010s, the next industrial revolution was proposed and named the Fourth or Digital Revolution. It is partly associated with the German strategy for technological development which is known as Industry 4.0. At its core is a shift from a central control system to one in the entities and correlation between the virtual environment and the physical world during design and production, as well as process and resource management, etc. The concepts of the Fourth Industrial Revolution are still under development (fig. 1.4).

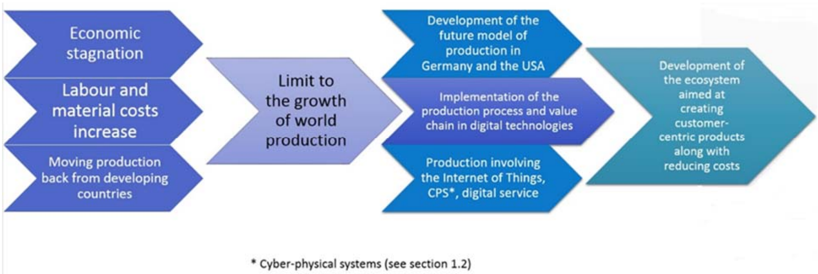

Fig. 1.4. Origins of Industry 4.0

All these steps of science and technology development disrupt traditional manufacturing practices, which allows a production line to shift from manual to machine to automated. Thus, the number of jobs decreases, though skill requirements for those who work in the era of digitalisation increase. In the production environment, for example, the functions of a person involve indirect intervention and control of robots and their operation. The Fourth Industrial Revolution offers something fundamentally new, which is an attempt to automate creativity (fig. 1.5).

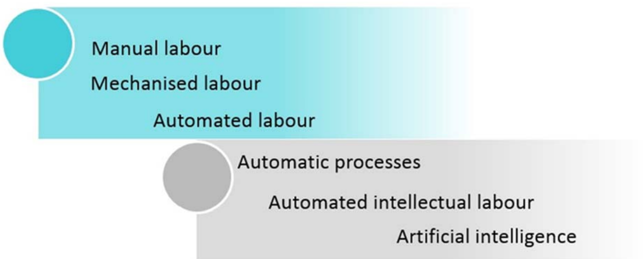

Fig. 1.5. Types of Labour

Self-check questions

1. In what way do you think the industrial revolutions and entity manufacturing technologies, which are the elements of a technological revolution, are connected?

2. Is a CAD system an element of the Fourth Industrial Revolution?

1.2. The Concept of Digitalisation Technologies

The term “digitalization” can refer to the implementation of special automation solutions at a more complex level using modern technologies, while “digital transformation” is the management and creation of new business models using digital technologies. Modern enterprises have to undergo both digitalisation and digital transformation, which should be interconnected. Digitalisation and Industry 4.0 technologies develop, optimise, and elaborate the concepts of the Third Industrial Revolution. A computer is now used for more than calculating a process, modelling an entity, or operating a machine (fig. 1.6).

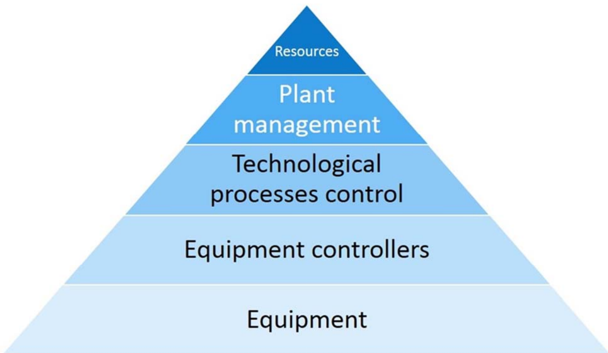

Fig. 1.6. Traditional Automation Hierarchy

The Industry 4.0 paradigm is based on a cyber-physical system. To develop new products, it is necessary to connect machines, control systems and hand tools to a computer and to ensure that there is a possibility of computing inside the entity. The data collected during analysis makes it possible to assess the production process and make a forecast. Using virtual reality technologies and robotic cells, cyber-physical systems can integrate humans. For example, exoskeletons capable of lifting weights are applied in production environment. Also, exoskeletons can be used as items of clothing or prostheses improving human capabilities. For cyber-physical systems, it is necessary to have techniques to interact with people, the environment, and other machines. There are various interfaces for this purpose. In the fig. 1.7, the green marks the physical level, and the blue marks the cyber level of information management, acquisition, and exchange.

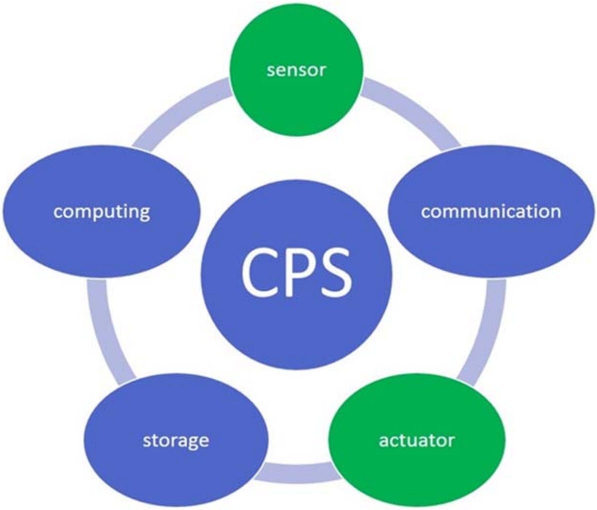

Fig. 1.7. A Cyber-Physical System

Modern production companies face challenges that are qualitatively different from anything before. This requires response actions. New technologies are not immediately introduced into the active production process. Normally, it is start-ups and the private and government procurement system that develop new technologies. Big investments for development of a new technology are thought to mean its success, though it might be driven by ambitious statements.

There are various tools and methods for analysing new technologies such as the Technology Readiness Levels (TRL) method or the technology maturity cycle known as Gartner Hype Cycle which helps to evaluate new digital solutions in terms of expectations and give their launch or shutdown date (fig. 1.8). Some companies – International Data Corporation, KPMG, Reconteur, Accenture, McKinsey & Company, etc. – apply predictive analytics to the digital technologies implementation in Russia and around the world.

The technologies that have emerged during the new Industrial Revolution are used in manufacturing industry, everyday life, social and cultural life.

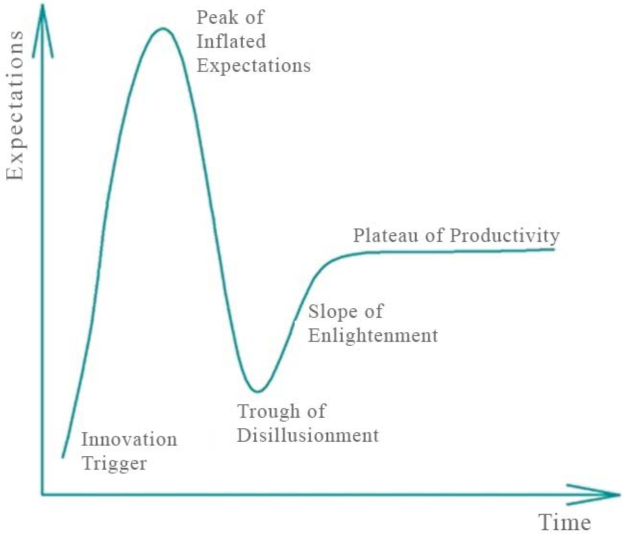

Fig. 1.8. The Gartner Hype Cycle

Self-check questions

1. Which of the following is not a part of an enterprise's cyber-physical system:
– a virtual reality helmet,
– an indoor temperature sensor,
– an RFID tag on an operator's uniform,
– a cloud storage server,
– a 3D printer.

2. In your opinion, how mature are 3D printing, CAE systems, virtual reality tools, and autonomous self-driving heavy-duty vehicles now?

3. Name the stages of Gartner Hype Cycle (fig. 1.9).

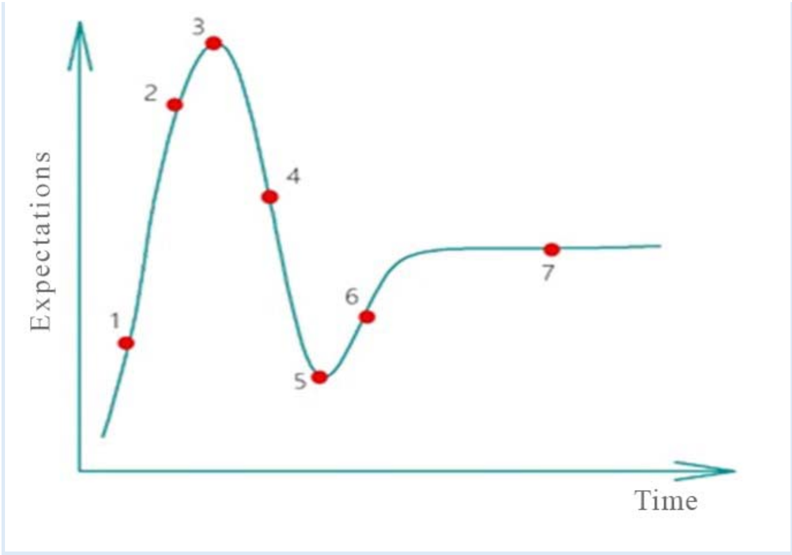

Fig. 1.9. Subjects of Digitalisation

1.3. Elements of Digital Production

The Digital Economy of the Russian Federation National Program (see Section 1.4) divides modern digital technologies into nine “end-to-end” groups: big data, quantum technologies, robotics components and sensorics, neurotechnologies and artificial intelligence, new production technologies, the Industrial Internet, distributed ledger systems, wireless communication technologies, virtual and augmented reality technologies.

Initially, a computer was used to create three-dimensional models of products, equipment, factory floors, and technological processes in computer-aided design systems, as well as to issue two-dimensional documentation (engineering drawings, specifications, and other design documentation). However, using CAD systems as a design tool is an outdated approach of the Third Industrial Revolution because of new challenges faced by enterprises (fig. 1.10).

Fig. 1.10. CAD systems in the Third Industrial Revolution

Modern computers in the production environment are networked to transmit, process and generate data, and often with no people at all. Production becomes fully automated, and complex decision-making and image recognition tasks arise. For example, when analysing a bitmap image, a computer has to learn to find an object in the image rather than see a matrix of randomly coloured pixels in it. Besides, learning from a large amount of data and studying ready-made solutions and cases, a computer has to decide on its own how an object will behave in the physical world. Artificial intelligence technologies currently use artificial neural networks, fuzzy logic, etc.

Training and networking machines, we obtain both a recommendation database and an object that can independently operate machines, manage goods production, their support, and information collection. Equipped with such machines, a factory becomes a digital factory (fig. 1.11).

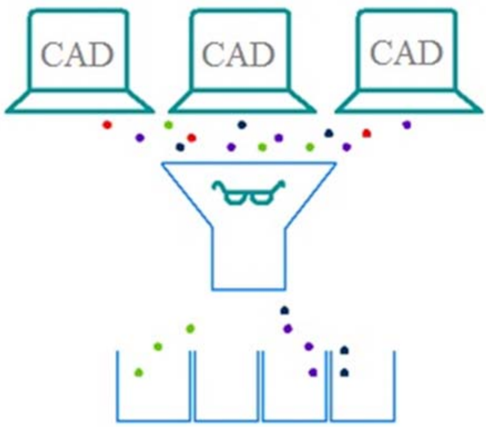

Fig. 1.11. Image Recognition

Machine learning requires the accumulation of a large amount of data as the system needs new volumes of data to learn to make decisions. This causes big data tasks to be set. A manufacturer can connect sensors to a machine, and they will monitor internal and external systems, the environment, interfaces, and human work. Through these sensors, a huge data set will be transmitted every second to the connected computer. It might include data on the quantity of produced parts; material; the state of a tool; the ambient temperature; lubricant contamination; the quality of the gas, hydraulic, and pneumatic systems of a machine; size deviation; run time; equipment depreciation; the standard time for production of a product; the state of an operator, their eye movement, etc. If there are several machines (and there may be a hundred), all the transmitted data can fill all enterprise hard drives within a few minutes. This data is very useful as it helps to diagnose the current state of equipment (and then predict possible failures), to relate machine operation to product output, and to improve quality, ergonomics, and safety. However, this requires powerful computer clusters able to work with such a data set. This leads to a high-performance computing as in terms of globalisation, data on several digital factories can be collected and processed all over the world. For this purpose, Industry 4.0 requires the development of next generation wireless data networks (5G and the next generations), low energy consumption networks (Bluetooth Low Energy), and information distribution using cloud computing (fig. 1.12).

Fig. 1.12. HPC and xG

The processing of large amounts of data is physically limited by the current speed of information processing. To increase the speed to the maximum, quantum information processing methods are now being developed and improved.

Once trained, computers should be able to predict events or provide alternatives. If the enterprise's supply chain of billets has been disrupted today due to a road washout, a trained system should provide a solution to change priorities at the current moment to keep the enterprise operating or to maintain the supply of finished products to retail systems.

The use of modern CAD systems gives rise to smart design technology. Techniques for electronic models, engineering analysis, and digital production preparation constitute a single interconnected structure of a digital mockup. Data processing and collecting machines in the production environment are connected both with the machinery and with the warehouse, automation tools, packaging and logistics stages. This results in the corresponding virtual three-dimensional models of factory floors, warehouses, etc. If equipped with necessary calculations and predictive base, such models become digital twins (fig. 1.13).

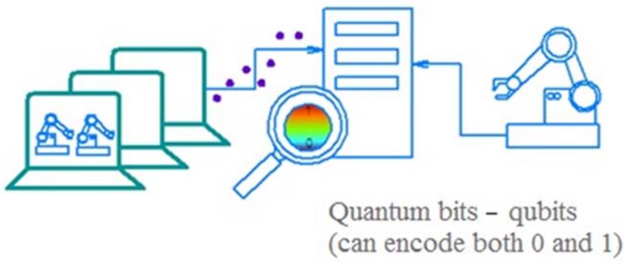

Fig. 1.13. Quantum Computing and Digital Twins

Transferring information to a virtual environment also enables employees to participate in collecting and understanding such data, which allows an enterprise to create virtual and augmented reality objects. When entering a production site and wearing special devices such as virtual reality glasses, which interact with tags, a machine operator or an engineer will see additional data in the form of images, texts, or 3D models that pop up next to the equipment, containers, and automation tools. This data shows a value, such as output or load, and assesses the state of systems, service life, and temperature (fig. 1.14).

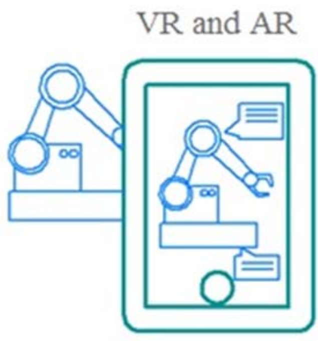

Fig. 1.14. VR and AR

When combined, robot-based real production and a digital factory form a new system of interaction and automatic data exchange networks, which is called the Industrial Internet of Things (IIoT). This requires an enterprise to install all necessary sensors, which collect data and regulate the production process. For example, when the tool temperature in the machine operating area increases, the systems that provide increased cooling must automatically turn on and work until the temperature becomes acceptable (fig. 1.15).

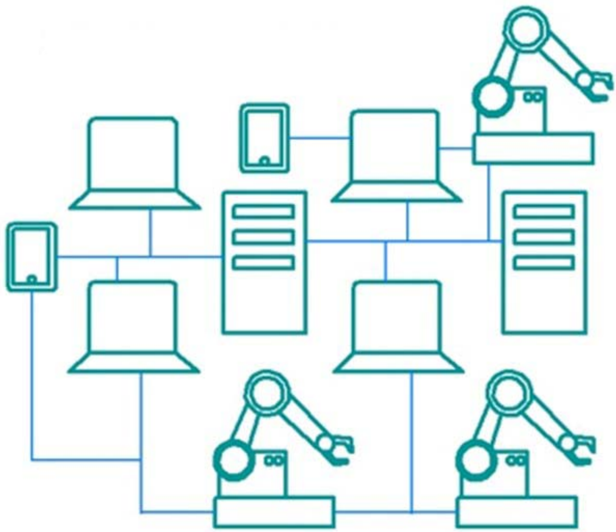

Fig. 1.15. Industrial Internet of Things

Modern production tasks are connected with minimising the cost price and labour intensity while maintaining the quality. For the most part, the cost price of a product unit is determined by material costs. This is the reason why material costs tend to be reduced. This implies the optimisation of product design, technological process parameters, and machine operation. To solve these problems, there are special CAD systems called computer-aided optimisation systems. For example, when developing a model of a bracket that must withstand a certain load under service conditions, an employee can sequentially change its design, reducing the amount of material where it does not affect the strength. However, the employee is unlikely to create a design that allows a minimum of material while maintaining strength characteristics: to do this, it is necessary to handle a huge number of design versions and check them with a CAE system. This iterative process will take a very long time and still will not provide the necessary result due to the human mind inability to consider all possible options and find the optimal one among them. This is when computer-aided optimization (CAO) systems, which can calculate any design with pre-defined properties, are to be used (fig. 1.16).

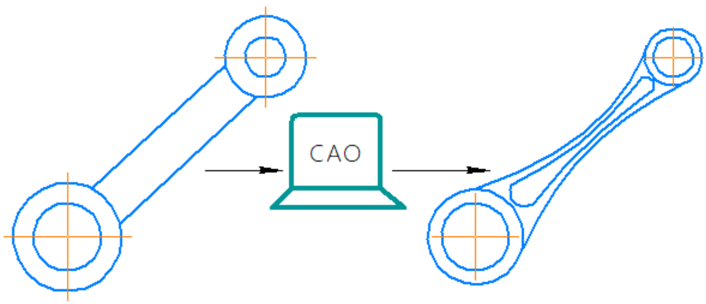

Fig. 1.16. Computer-aided Optimisation Systems

Obtained with CAO systems, electronic models meet the requirements for strength and have a complex shape, resembling natural organic structures, such as honeycombs, vessels, and ligaments. In general, such parts are called structures of uniform strength, and the shape is described in terms of bionic design.

It is almost impossible to produce bionically shaped products using traditional methods. For example, milling, welding, or stamping will only allow one to create a composite structure, but it is often required that a uniform strength design of a part should be a single body rather than composite. In addition to conventional production methods, now there are modern methods such as 3D printing, which combines the techniques of gluing, soldering, and sintering of polymer and metal powder, plastic sheets or threads, and composite materials, as well as liquid solidifying under the laser light or regular light. In these cases, instead of removing material (swarf, stamping waste), it is added, so the production process is called additive manufacturing. In general, such techniques for manufacturing products are called rapid prototyping (fig. 1.17).

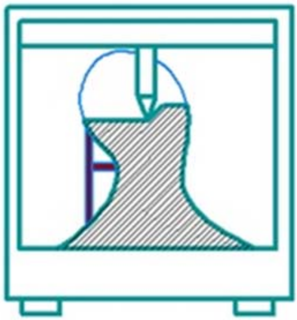

Fig. 1.17. 3D printing

New manufacturing technologies require new materials. The process of developing new composite and synthetic materials currently makes it possible to obtain them on the nanoscale (10^{-9} mm), practically by assembling atoms or by growing elements of atomic lattices.

Reverse engineering technologies, which provide computer-aided quality control and enable one to create an electronic model based on a physical product, are used to create smart digital twins. Quality control is based on the automatic comparison of the manufactured product and its electronic model in the enterprise database. To obtain a model of a specific manufactured product, three-dimensional laser and optical scanners are used. Digitisation provides an opportunity to build any complex model, including sculptural surfaces – reliefs of animal and human bodies, plants, etc. (fig. 1.18).

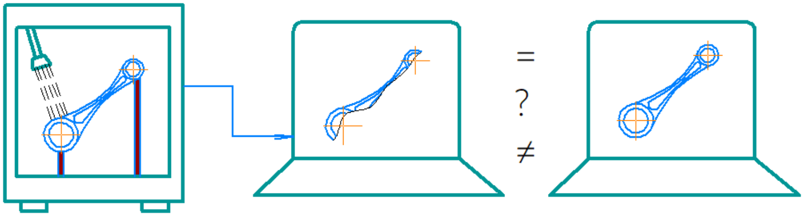

Fig. 1.18. 3D-scanning

However, along with the advantages of reverse engineering, there are problems with its use. For example, it can be used to digitise any purchased product, develop its technological process, and start manufacturing it under a different brand name but with a similar design or shape. To prevent copyright infringement like this, it is necessary to protect intellectual property and develop patent systems, know-how, etc. These practices are related to cybersecurity tasks.

Transferring the management of a digital enterprise to the virtual environment requires the protection of data stored on servers. It is necessary to organise file storage, to implement digital protection and to have files access procedures prescribing the rights of an employee of an enterprise. The simplest solution is data fingerprinting, which is called an electronic signature. If based on biometric data like this, authentication in the virtual factory system is significantly improved. Facial recognition systems recognising images from video cameras, fingerprint scanners, and retina scanners make it possible to organise access to the enterprise premises or to a room.

Enterprise resources are another area where cybersecurity can be applied. Information storage in databases is performed by distributing encrypted information to different devices. The peculiarity of this process is that there is no central administrator. This technology is called a distributed ledger, with unalterable information blocks recorded in a special way to have their own identifier, used to store and transmit information, and added to the ledger. Among such technologies, there is blockchain technology, which can be used to manage payment systems, reliably store documents and automatically compare them with customers' documents (fig. 1.19).

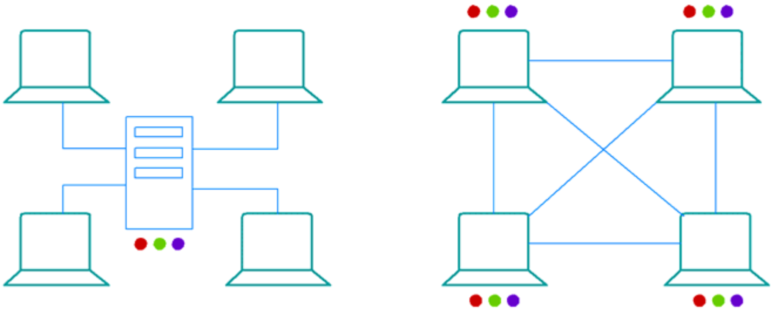

Fig. 1.19. Traditional Systems and a Distributed Ledger System

However, the digital enterprise concept involves other elements besides production. The development of cyber-physical systems for products manufacturing leads to the digitalisation of the interactions between an enterprise and its customers and suppliers through digital and automated warehouse technologies. Such a warehouse has a barcode, QR codes, or RFID tags on each container and storage location. The code is automatically scanned by moving automated guided vehicles, equipped to lift and clamp goods.

Drones, heavy-duty vehicles and other unmanned vehicles are used to move materials and products between enterprises in a digitalised environment (fig. 1.20).

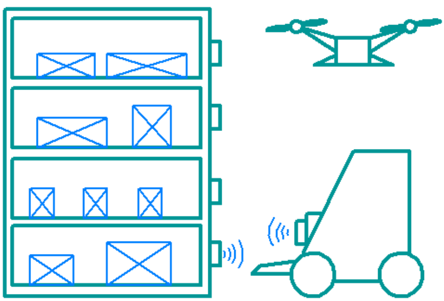

Fig. 1.20. Automated Warehouse

However, a person is still the key element of a digital enterprise, and industrial digitalisation includes operators, designers, and consumers in cyber-physical systems. It is biotechnologies that are helpful in medicine, prosthetics, and workplace ergonomics. It is digital services that are helpful in everyday communication between people and useful for the community as they include the concepts of smart city, smart home, smart transport, etc. Switching to digital technologies is likely to lead to job cuts in most of the service and tourism industries, and cuts in office jobs.

In general, the Fourth Industrial Revolution – like the others before – affects the development of society as a whole. For example, in Japan, Society 5.0, the national programme for the development and implementation of digital technologies concepts, primarily focuses on human development, social problems and their solutions through digitalisation.

Self-check questions

1. What should you do to turn an electronic model of machine assembly into a digital twin?

2. Is it possible to “digitize” the tasks of moving significant goods? Why/Why not?

3. What could be included in your home Internet of things platform?

4. When developing a new design, it turned out that the number of components could be reduced, which would lead to a lighter weight while maintaining strength (fig. 1.21). What digitalisation technologies were used?

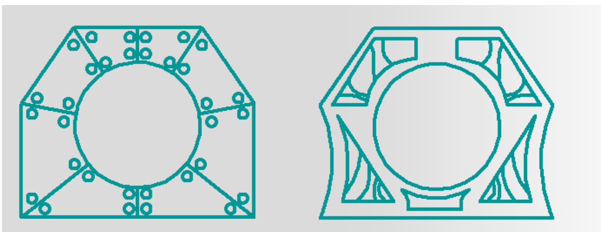

Fig. 1.21. Task

5. A company has a database of electronic models of standard cutting tool. What will machine learning technologies based on a neural network help to do for this database?

6. The founder of the World Economic Forum in Davos, Klaus Schwab, said that the Fourth Industrial Revolution was a challenge that humankind had never faced before. Why?

1.4. Principles of Digital Technologies Implementation

Different countries use different approaches to ensure digitalisation. There are three major development strategies:

1. Government procurement;
2. Support for private initiatives;
3. Private procurement system and national programmes.

Besides the German Industry 4.0 programme and the Japanese Society 5.0 initiative, there are other national programmes and several American and European private initiatives.

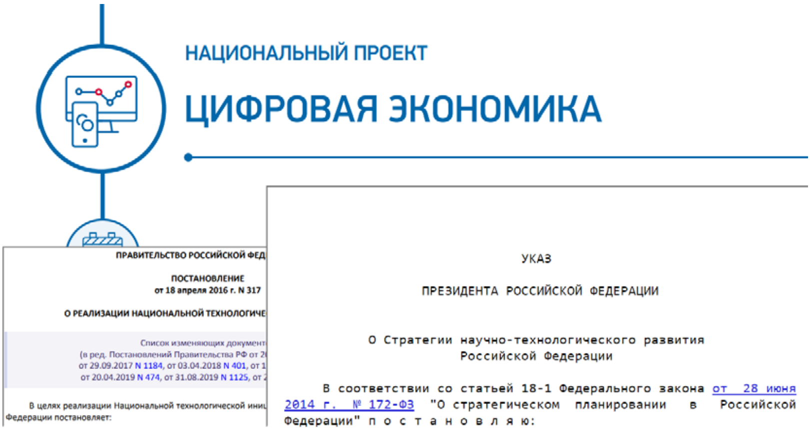

Fig. 1.22. Programmes for the Support and Development of Digitalisation (the Digital Economy of the Russian Federation National Programme[1]; Decree of the Government of the Russian Federation “On the Implementation of the National Technology Initiative”[2]; Executive Order on the Scientific and Technological Development Strategy[3])

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[1] Паспорт национального проекта «Национальная программа “Цифровая экономика Российской Федерации”» : утв. президиумом Совета при Президенте Рос. Федерации по стратег. развитию и нац. проектам : протокол от 4 июня 2019 г. № 7. Документ опубликован не был. Доступ из справ.-правовой системы «КонсультантПлюс».

[2] О реализации Национальной технологической инициативы : постановление Правительства Рос. Федерации от 18 апреля 2016 г. № 317 // Собр. законодательства Рос. Федерации. 2016. № 17. Ст. 2413.

[3] О Стратегии научно-технологического развития Российской Федерации : Указ Президента Рос. Федерации от 1 декабря 2016 г. № 642 // Собр. законодательства Рос. Федерации. 2016. № 49. Ст. 6887.

Currently, there are three programmes for the support and development of digitalisation in Russia: the National Technological Initiative, the Digital Economy of the Russian Federation National Programme, and the Scientific and Technological Development Strategy of the Russian Federation. Within the programmes, there are areas that coordinate economic sectors. Banks, accelerators, and venture funds, for example, are involved in financial and service support, while the National Technological Initiative has presented "road-maps" for the development of seven working groups responsible for the automotive industry, aviation, health care system, etc. The National Technological Initiative is expected to be relaunched as the National Technological Initiative 2.0 in the near future. The Digital Economy of the Russian Federation National Programme introduces a new job position which is Digital Transformation Director (fig. 1.22).

The implementation of digital technologies is hampered by the absence of trained professionals who can work with the rapidly changing technology market. Furthermore, the initial stage of digitalisation requires additional investments as it involves the purchase of sensors, their installation, set-up and maintenance; creating servers for collecting, storing, and processing data; digitising physical objects; creating corporate HR management or accounting systems, etc. It is also necessary to ensure a comprehensive engineering approach and transition to a XaaS service model at every stage of the value chain formation.

The digital maturity assessment helps to measure the use of digital technologies in the enterprise's operations. It also provides guidelines for implementation of digitalisation and a "road-map" based on the finding from assessment of existing information systems, funds, employees' competencies, the executives' desire for digital transformation, the volume of data used in technological processes, interactions with other enterprises, the implementation of new corporate systems or openness to them (fig. 1.23).

Figure 1.24 shows a possible matrix of analysis of the factors evaluated by auditing firms for a particular enterprise. The analysis can be conducted by year, with a predictive evaluation performed.

Fig.1.23. Stages of Digitalisation Level Analysis

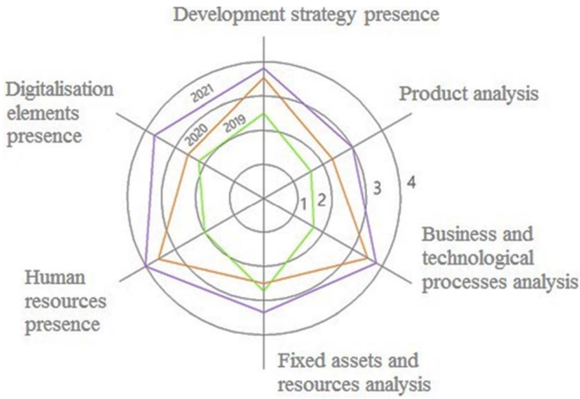


Fig. 1.24. Digitalisation Analysis Matrix

The implementation of digital technologies forms the ecosystem of an enterprise. Ecosystems are enterprise-specific operating conditions which enable modern technologies to be organically implemented and developed, and, just like in natural ecosystems, be able to generate new methods of management, decision-making, design, production, and to optimise business processes, etc. Within a generative ecosystem, the main "product" is information, which can circulate freely and naturally between a manufacturer and contractors (suppliers and customers) (fig. 1.25).

A developed ecosystem requires a review of the enterprise's organisational structure. For example, some companies identify document-centric and data-centric approaches. The document-centric approach makes documents the primary unit of interaction between the employees of an enterprise and usually does not allow anyone to work with the data within the document because even the electronic archive of documents with automated circulation will not allow an industrial control system (ICS) or a cyber-physical system to look into the document itself without an optical character recognition technology.

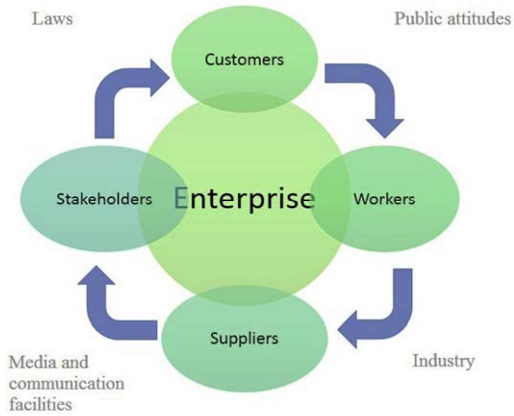


Fig. 1.25. Participants in the Generative Ecosystem

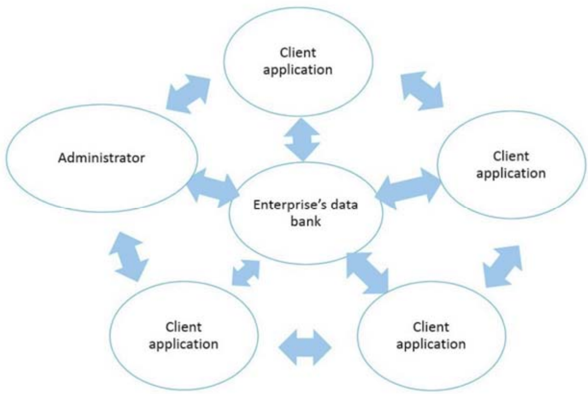


Fig. 1.26. The Data-Centric Approach

The data-centric approach focuses directly on data, and a document is no longer the primary unit of interaction. A user can access data and edit or delete it, which is transferred to the industrial control system (fig. 1.26).

An engineering drawing is an example of a document-centric approach. An old engineering drawing can be digitised and stored as a PDF file in an electronic archive, though it is extremely difficult to revise it and track its life cycle. The data-centric approach considers an engineering drawing to be secondary to the electronic 3D model of the object in the engineering drawing. The ICS tracks any modification of the model, and a great number of engineering drawings can be based on the model.

Adopting the data-centric approach requires a unified data model for an enterprise and contractors as all the transferred data must be perceived the same by each participant. Data change must have the same and predictable impact. A unified data model can be legislated and supported by the government or private companies. For example, there are requirements for a unified data model in cybersecurity or construction (BIM technologies). However, a lot of enterprises release or use their own data models, which might result in having to convert files or market monopolisation by a single ecosystem vendor. The data model structure usually contains the information shown in fig. 1.27.

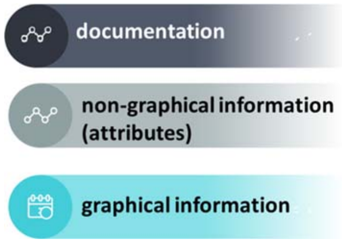


Fig. 1.27. Data Model

The implementation of digital technologies in the production environment used to require the purchase and installation of computer-aided design system, automated management and resource allocation systems. They were often interconnected through a special type of software which is called Product Data Management (PDM) systems. These are the systems that are designed to work with data on a product, equipment, materials, etc., and they are split into two parts, the server side and the client side. The server side stores data, master models, and digitised documents. Data can be stored as relational databases with a corresponding database management system. Conditions for accessing information are specified, depending on an employee's job position. The client side of a PDM system is most often an add-on to the operating system in the form of a special application, where a user registers, enters their own password, and gets access to information for reading and recording files. They can also run specific programmes or their modules using an individual digital number. PDM systems also ensure dispatching and control of information (fig. 1.28).

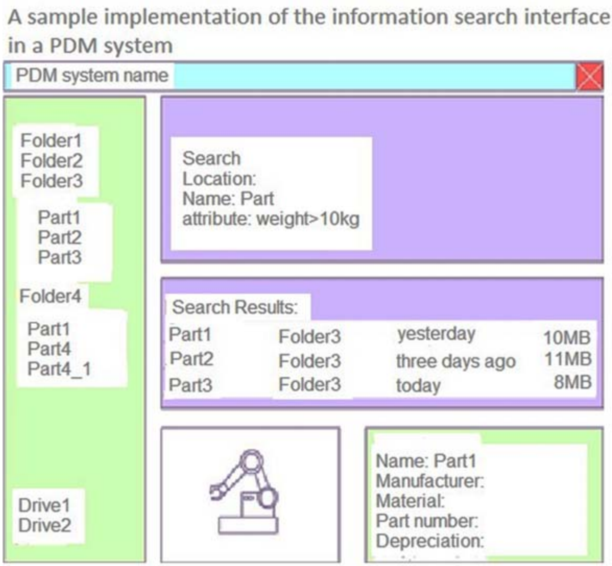


Fig. 1.28. PDM System Interface

The digital transformation of a factory may include three areas – digitalisation of engineering, digitalisation of production, and digitalisation of support (shipment, sales, platform) – which should be integrated into a single system. However, digital technologies can be implemented in stages, for example, digitalisation of the product manufacturing process, digitalisation of the development and verification of the technological process, digitalisation of production preparation, digitalisation of quality control, digitalisation of release, etc.

Self-check questions

1. Why are digital technology platforms of an enterprise or an industry called ecosystems?

2. How do you think PDM functionality differs from operating system functionality?

3. In some countries, data models, for example BIM, are legislated. How can this affect an industry? What are the advantages and disadvantages of this approach?

4. What Russian digital technologies programmes do you know?

2. DIGITALISATION OF AN ENTERPRISE LIFE CYCLE

2.1. Conception of a Digital Enterprise

A digital enterprise (digital laboratory, digital plant, digital factory or innovation hub) involves a description, design and use of process and entity models that match physical entities and processes. It can also be described as "a continuously and systematically updated database" of the entire enterprise and applied to any sector of the economy – banking, utilities, retail, logistics and manufacturing. Within this course, the concept of a digital factory refers to an industrial enterprise in the machine-building industry (fig. 2.1). A digital factory is usually implemented to maximize the equipment efficiency and to reduce the product cost. Another definition of a digital enterprise requires "the interaction of CAD and ERP systems" (see Section 2.3).

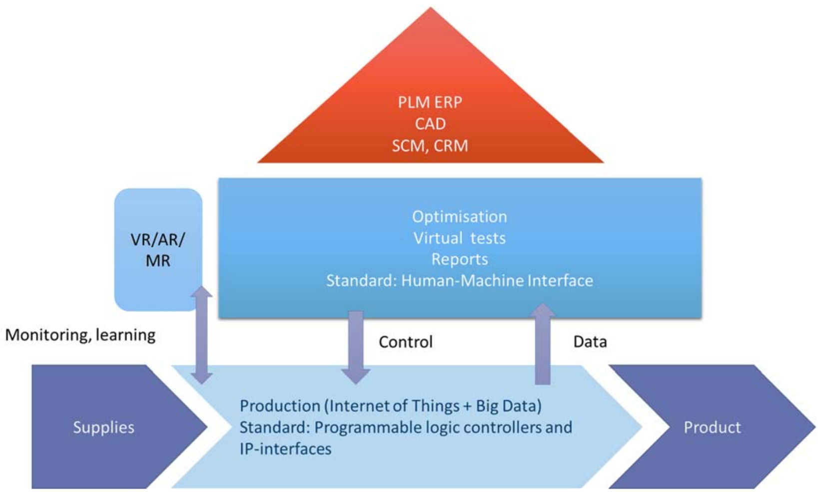


Fig. 2.1. A Digital Factory

Entity-relationship model is an element of a digital enterprise, which is usually an electronic 3D model with additional information applied. Building information models (BIM), for example, are widely used in construction. The entity-relationship model is also called a digital prototype.

A digital enterprise provides information support for all stages of the product life cycle. Cyber-physical systems share a common environment of information exchange, which is the PLM software environment (fig. 2.2).

	Automation	Production Activities	Resource Management	Product Design and Development	Supply Chain
Perfect	Cyber-physical systems				A unified business network of contractors
	IoT	Diagnostics based on big data analysis			
Mid-level 2	Automated control devices	Real-time monitoring	Integrated into production processes	Automation of key processes	Interaction during design and development
Mid-level 1	Automated equipment data processing	Real-time decision-making	Integrated into equipment functions	Automated generation of technical data	Interaction during production
Base Level	Automation in common production systems	Process management	Focused on managerial functions	Process management	Dependence on a parent company
No Digitalisation	none	manual	manual	manual	Phone/mail
					Public private partnership Smart Factory project group

Fig. 2.2. An Example of Digital Factories Levels in South Korea

PLM-systems (Product Lifecycle Management) are designed to manage a digital enterprise in a single environment, a software product supplied by a vendor. A digital technology-based approach to the enterprise management allowing no relationships between the technologies and requiring their work with the single data model in PLC is called CALS (Continuous Acquisition and Lifecycle Support). In Russia, this concept is called product information support.

Both the approaches include the PDM engineering environment, and they are designed for business processes. Within the PLM-system, each user is assigned a role allowing the user to access or change a piece of data in the digital enterprise environment. A design engineer, for example, will have access to three-dimensional modelling of master model tools, but unlike the leading project engineer, they will not have access to change the tool master model (fig. 2.3).

Like PDM, product lifecycle management systems include the server and client parts. PLM-systems have two client applications: thick client and thin client. The former is installed directly on the workstation, while the latter is browser-based and can work on any portable device anywhere in the world, provided the Internet is available (fig. 2.4).

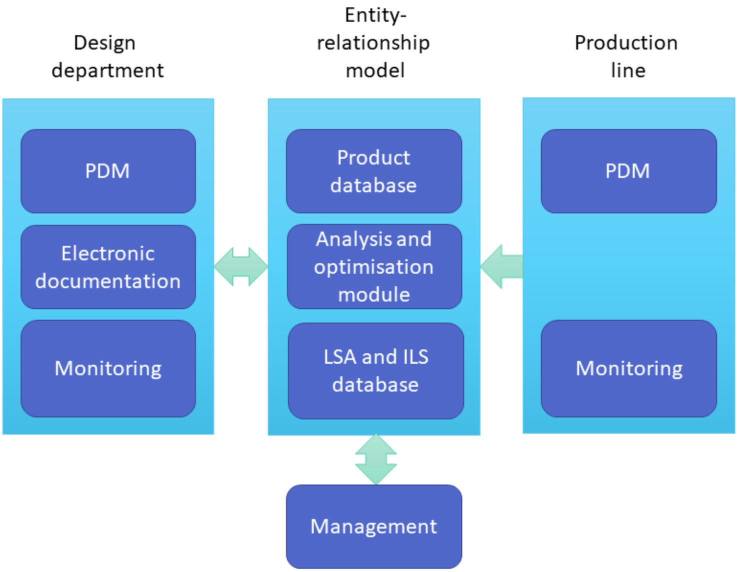


Fig. 2.3. A Common PLM structure

Fig. 2.4. PLM Interface Components

It offers an opportunity to keep working with data outside the enterprise, which increases the enterprise efficiency due to real-time management. The PLM-system helps to integrate the data about the state of equipment, enterprise resources, run-out production and emergency situations at any moment of time. Thus, the employee in charge can stop the production process or completely change it while staying on the other side of the planet.

Solutions for design, modification and analysis of enterprise information models refer to CAD-based three-dimensional modelling. It might include:

– development, test and optimisation of a product;
– development and optimisation of a technical process;
– development and improvement of technical production preparation;
– planning and monitoring.

Digital transformation requires:

1. Production automation;
2. Implementation of digital technologies for simulations and the possibility of virtual / augmented reality;
3. Smart modelling based on simulations and analysis;
4. A distributed hierarchy of processes and entities – from creating work groups to project resource and equipment distribution – to affect planning, machine workload and standard hours.

Virtual operation descriptions, operator guides and any other abstract representation of real work – business processes to document flow – is called workflow. A set of software solutions for such processes is a PLM subsystem. Workflow involves the process approach to enterprise management, and the work can be divided into stages or tasks to be performed or solved by an assigned employee. Workflow should be flexible enough to allow contractors to be added and new tasks to be easily integrated into PLM. The target indicators here include performance control, operating procedures and the right flow within each work group (fig. 2.5).

In the end, design and development of new products is no longer based on a physical entity but on a digital prototype, which is used then to design a smart digital twin of a product. Thus, this prototype is considered to be an entity through which the product co-development, a technological process, workplace, etc. are connected.

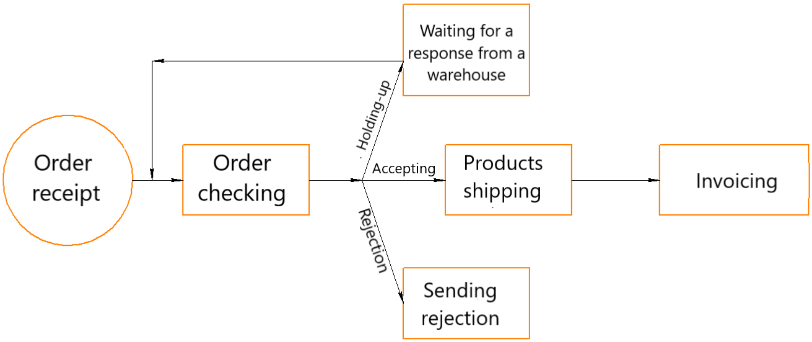


Fig. 2.5. Workflow

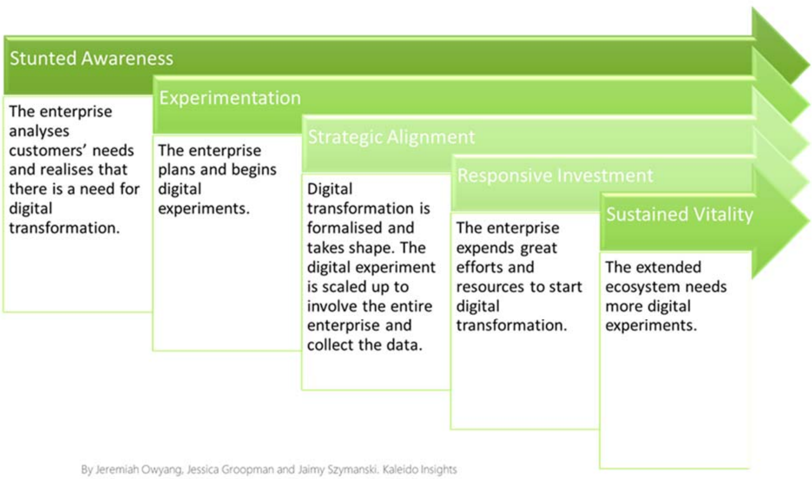


Fig. 2.6. Phases of Digital Transformation

Digital transformation of production can involve:
- defining production standards for all PLC stages;
- collecting primary data for PDM;
- creating a single reference knowledge base;
- synchronizing data and real production entities by connecting sensors and microcontrollers;
- automatic monitoring of enterprise tasks within the created system.

Even small companies quite successfully implement digital technologies to perform local tasks or a pilot project, however due to the wrong production standards, it is quite difficult to ensure top-level digitalisation. One of the approaches to the digital factory operation is a shift from departments to flexible work groups, with employees engaged into the project activities (fig. 2.6).

Self-check questions

1. What has to be done with the electronic model of a factory floor so that it could be used to design a digital factory?
2. How does PLM differ from PDM?
3. What limitations can a PLM thin client have?

2.2. A Single Knowledge Environment

The PLM-system provides a single knowledge and support environment for a digital plant ecosystem. It enables digitalisation of all product lifecycle stages from the concept to service and the disposal of a product. The PLM co-operates the employees' work in the enterprise's common data environment, provides access to any information about operations, business processes or management and organises an information exchange between customers and suppliers (fig. 2.7).

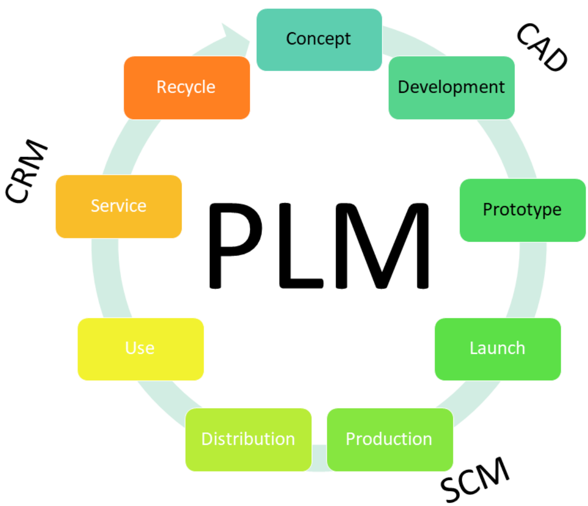


Fig. 2.7. Product Life Cycle

All the data in the PLM-system is represented by an entity-relationship model with a customisable structure that includes parameters, attributes, non-numeric data, symbols, tags supporting multi-criteria queries, advanced search, and the ability to add new data and schedule it for a definite time.

The structural element of the PLM-system is Item. Whereas the operating system operates with file types stored in folders and on disks, PLM works with "abstract files". The Item is used then to describe documents, products, electronic models, folders and storages, etc. The Item has no file type or extension. The text document, containing information about the product materials, and the product's electronic three-dimensional model are Items that carry different but supplementary information, and are the elements of a higher-level item, such as an electronic mockup of a product (fig. 2.2).

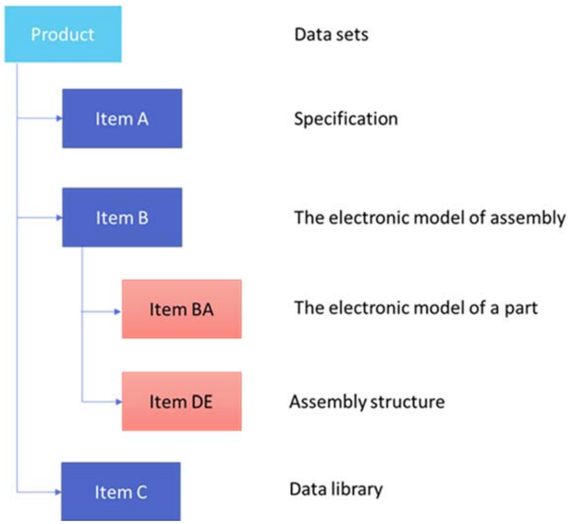
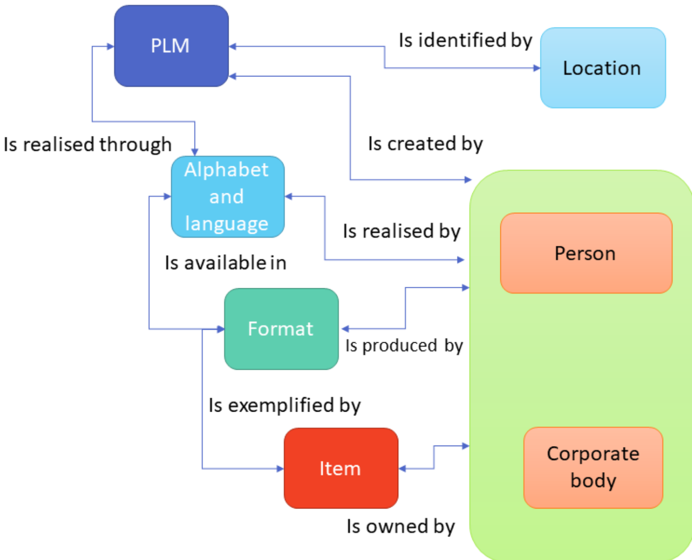


Fig. 2.8. Items Structure

The PLM does not access information in a file; it works with metadata which usually includes elements such as title, file class or subclass, file location, creation date, versions, author, etc. A class or subclass can be an assembly-part relationship, or a master model-execution relationship. When a user accesses an Item in PLM, they can find out everything about it: when it was created, who reviewed it, where it is located, and who can access it.

The Item can be embedded in the workflow process, connected to any project, included in the scheduling, and assigned to the employees who are to work with it. All the items create a hierarchy that reflects the subordination of the items to visualise the actual conception (for example, the "spring" item can be subordinated to the "spring pack") or some attribute (fig. 2.9).



Nisachol Chamnongsri et. Applying FRBR Model as a Conceptual Model in Development of Metadata for Digitized Thai Palm Leaf Manuscript

Fig. 2.9. The Metadata Structure

This approach allows design and development to simultaneously engage design engineers and involve administrative management processes, data collection and innovations. The information access system helps to optimise the design process through a series of versions at any stage and later automation of modifications at subsequent stages.

Some of PLM requirements include:

– interface usability;
– integration with the systems already used in the enterprise;
– Bill of Materials (BOM) management;
– changes management;

– reporting documentation, including quality management documentation;
– interactions with suppliers and customers;
– PDM;
– the support of previously developed processes and solutions;
– flexibility and accessibility for new technologies;
– prompt integration to the production process;
– failure automation.

When using PLM-systems, one of the features is BOM. It might be an extensive list of materials or it might be like a specification. The specification developed at the design stage is called EBOM (an engineering bill of materials). During the product manufacturing process, EBOM can be used to create an MBOM (a manufacturing bill of materials). It no longer contains virtual sub-assemblies and does contain the features ignored at the design stage (coatings, packaging, etc.) (fig. 2.10).

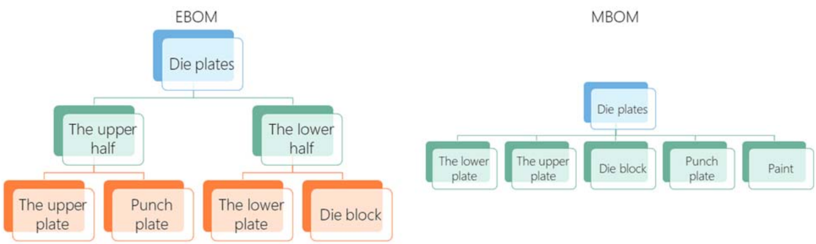


Fig. 2.10. EBOM and MBOM

There are many vendors of PLM software in the marketplace right now. Among the leading products are:
– Vault and Fusion Lyfecycle PLM by Autodesk;
– Windchill by PTC;
– Teamcenter by Siemens PLM;
– Enovia and Delmia by Dassault Systems;
– SAP PLM;
– Ombify Empower PLM.

Among Russian software products are:
– Lotsia PLM;
– T-FLEX PLM;

– Soyuz-PLM;
– Lotsman: PLM;
– NEOSINTEZ.

There are also other vendors and products.

The compatibility of a PLM-system is determined by the standards which are integrated into it during its development or can be taken into account directly at the enterprise. There are development-related, production-related and use-related standards. The basic development standard is ISO 10303 and its Russian counterpart GOST R ISO 10303 *Automation systems and integration. Product data representation and exchange*. According to GOST, the data format should not depend on the operating system, and should use different ways of storing, transferring and processing of information, for instance, about 3D models. For this, it is necessary to use the formal EXPRESS data language that helps to unambiguously describe the data about a specific resource in the PLM-system for application tasks and programs. This set of standards is known as STEP (Standard for Exchange of Product model data) (fig. 2.11). One more popular way of representing data in 3D is the IGES data format. There are also some commercial data formats, such as PLMXML (Siemens). It is based on the XML markup language that helps to create databases and data files based on simple syntax. The application users, who use this format, can create their own data.

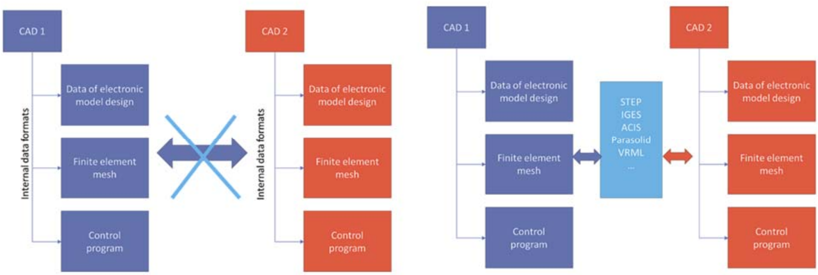


Fig. 2.11. STEP

Among the production-related standards are ISO 15531 and its counterpart GOST R ISO 15531-44-2012 *Industrial automation systems and integration*. The standard describes data collection in the production environment for further analysis and optimisation. The key points here are the events and their time limits, distress and the hierarchy of causes and effects. The events form the documents and processes that are integral parts of production, manufacturing contracts, technological processes and defects.

There are also other standards which define how to work with part libraries, a resource entity-relationship model, a time model, etc. For example, the standard GOST R ISO 15531-42-2010 *Industrial automation systems and integration. Industrial manufacturing management data. Part 42. Time model* regulates the accuracy and correspondence of time at an enterprise, which is important for planning, logistics tasks, making schedules for employees, sending and processing equipment signals. Some standards are set directly by a company and are aimed, for example, to standardise technological and business processes.

If the cloud recourses are used, there are standards for cloud computing, for example, GOST R ISO 17788, 17889 *Information technology. Cloud computing,* CAMP (cloud application management for platforms) regulating resource allocation commands for operations, starting calculations, etc. (fig. 2.12).

Fig. 2.12. Examples of Russian and International Standards in Digital Technologies

Self-check questions

1. Why is it necessary to be guided by standards, including international ones, when developing PLM-systems?

2. What Russian PLM products and platforms do you know?

2.3. Enterprise Resources and Supply Management. Interactions with Customers

Engineering and related data which is stored, uploaded and generated in an enterprise ecosystem as well as processed in the PLM-system is referred to as the general product database (GPD). The rest of the data in the single knowledge environment is called the common enterprise database (CED) (fig. 2.13).

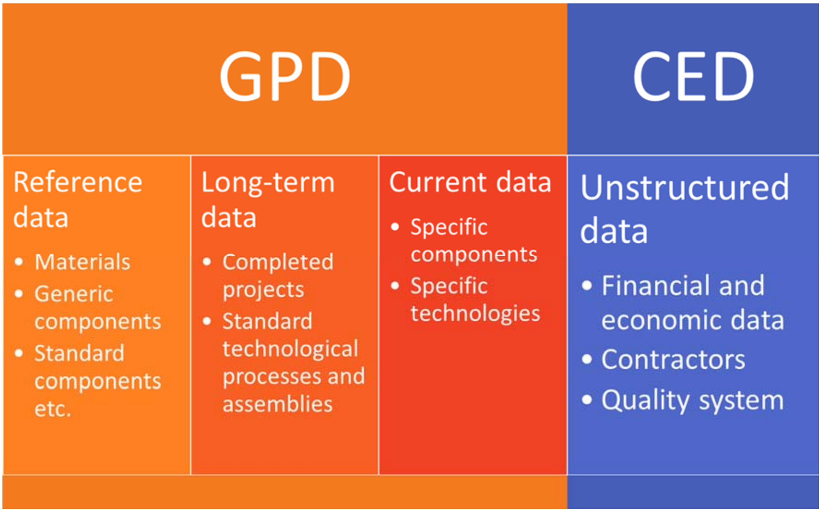


Fig. 2.13. GPD and CED

CED should be integrated into the specific databases used in the MES production system management methodology, ERP production resources management methodology and its components CRM, WMS, SCM, etc. These methodologies are implemented using software products that are divided into similarly-named classes (fig. 2.14).

In Russia, special tools providing data support for enterprise lifecycle stages used to be called MIS (management information system), MES (manufacturing execution system) and APCS (automatic process control system) as well as quality control system, staff control system, etc. Currently, English-language abbreviations of the systems and techniques under discussion in this section are also accepted.

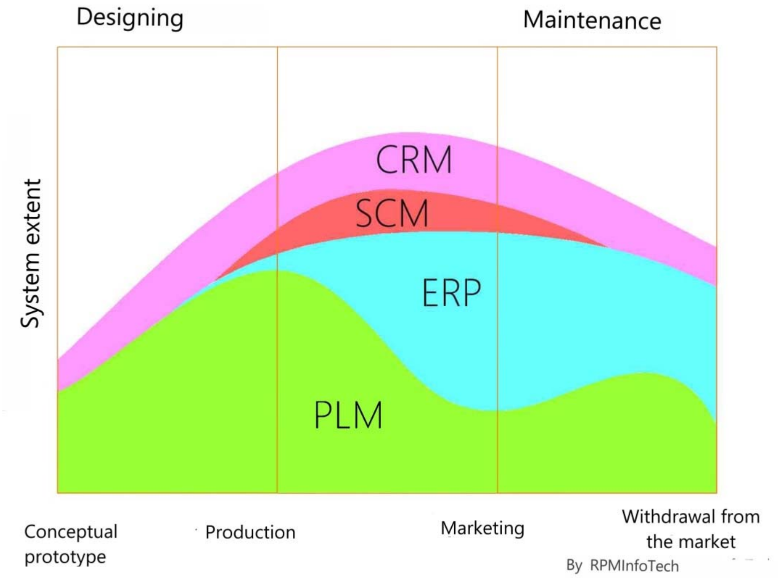


Fig. 2.14. The Impact of PLM, ERP, CRM, and SCM on the Stages of PLC

A unified data model allows information exchange between all the cyber-physical systems of the enterprise. This results in the following possibilities:

1. Operational processes real time control;
2. Synchronisation and coordination of production;
3. Data collection and analysis, and Overall Equipment Effectiveness (OEE) calculation;
4. Computer quality control and report processing;
5. Data preparation and presentation to employees;
6. Response to system disturbance.

If these tasks are integrated in a single software environment, this program becomes a MES-system (Manufacturing Execution System). MES-systems are responsible for planning, resource allocating, and state monitoring of performance of a factory floor, a production line, or the entire enterprise (fig. 2.15, 2.16).

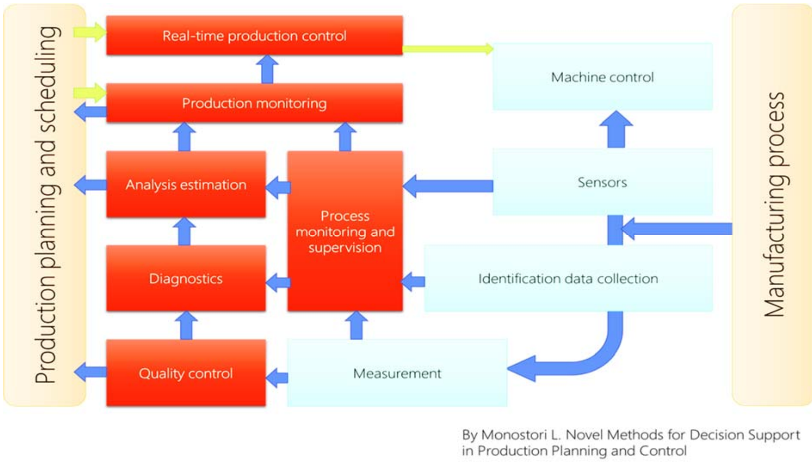


Fig. 2.15. Processes in MES

Fig. 2.16. MES functions-questions

To make it shorter, MES is used to track all the steps of turning raw materials into products. Industry 4.0 affects MES-systems: cloud architecture and IIoT use, direct primary information processing by the hardware, and a service-oriented approach to work.

Applications that directly link the machine and enterprise network to perform these functions belong to SCADA (Supervisory Control and Data Acquisition). They help to monitor the machine state and collect real-time data on the technological process progress (fig. 2.17).

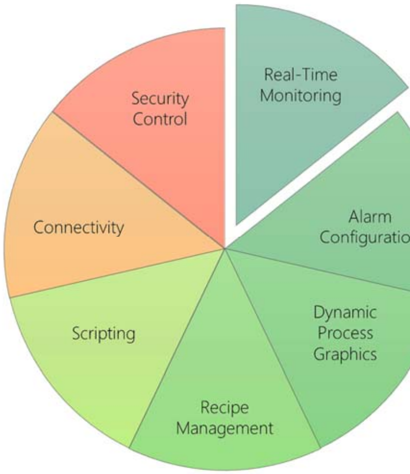


Fig. 2.17. SCADA Features

Machine Data Collection (MDC) is developed to collect and store data from CNC machines. This system is principally used when the digitalisation of the production process has not been completed yet, but it is necessary to ensure the communication between the operator and the machine for immediate rapid data collection (fig. 2.18).

The IIoT system is thought to be replacing the SCADA-system, though we can say that SCADA is entering a new era of smart management and information collection based on the human-machine interfaces.

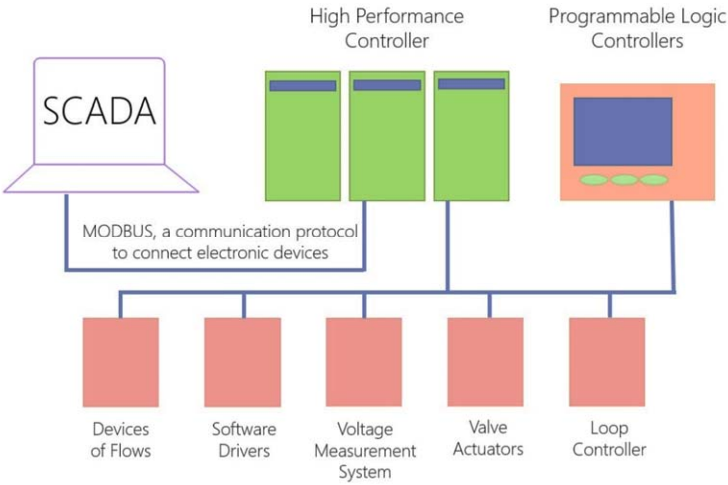


Fig. 2.18. SCADA and Controllers

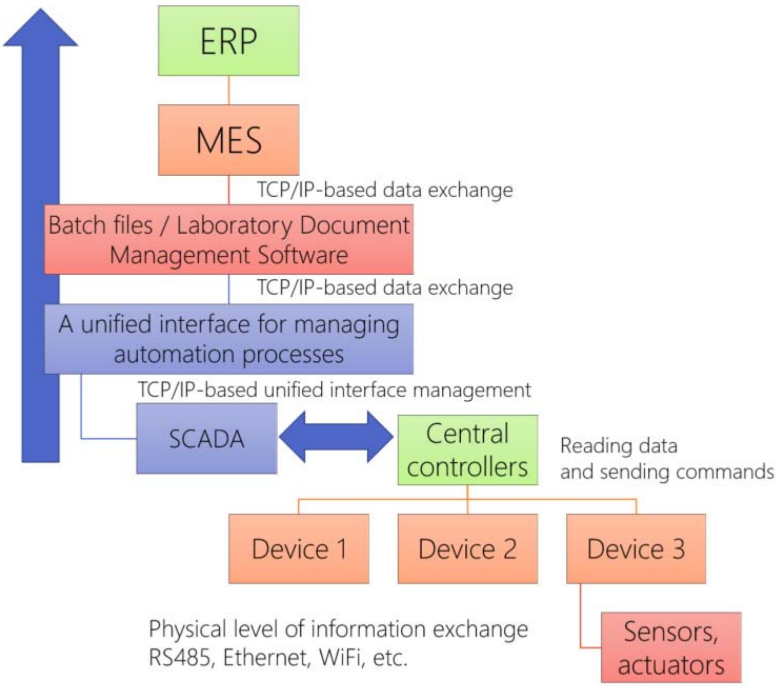


Fig. 2.19. Data Structure in SCADA

The data from MES-systems is sent to planning, quality control and business process employees as well as engineers to optimise the product or process. The analysis-driven optimisation results in reallocation of the enterprise's resources, with standard hours reconsidered and material consumption, equipment loading, logistics schemes, release programmes, etc. changed. The changes are also the area of one more enterprise ecospace conception known as ERP (Enterprise Resource Planning) (fig. 2.20).

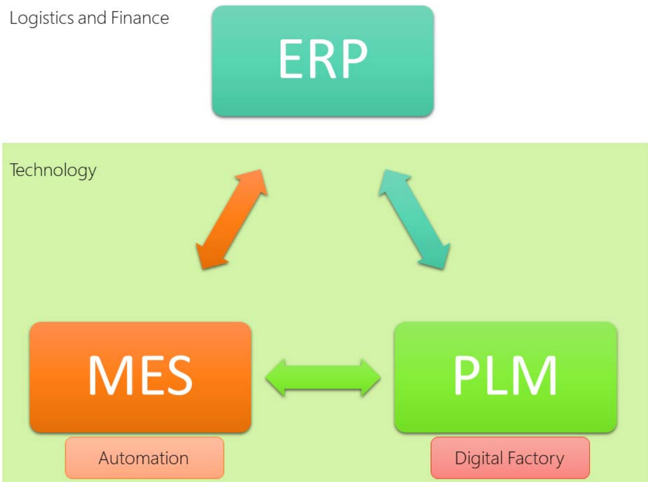


Fig. 2.20. ERP, MES, and PLM

The ERP system is a set of sub-programs which are called modules (fig. 2.21). As a rule, there could be the following modules (its number and options vary from one developer to another):

– HR management;
– equipment and tools management;
– sales and marketing research;
– orders and deliveries;
– company finances and accounts management;
– standard hours, rates of use, equipment loading.

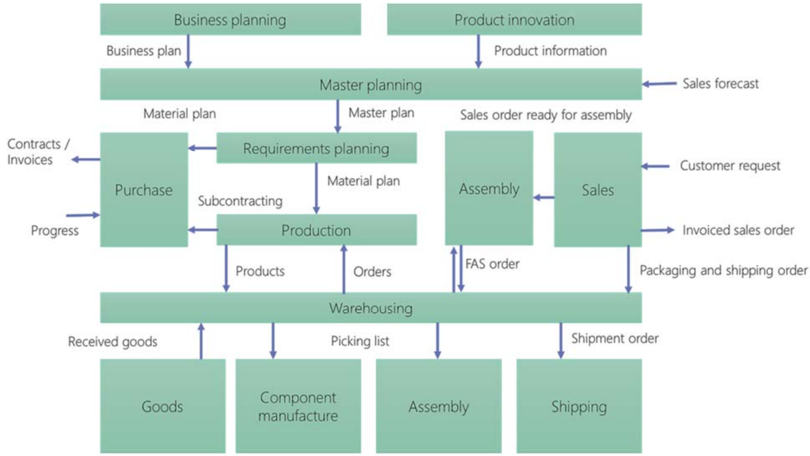


Fig. 2.21. An Example of the Data Flow in the ERP architecture

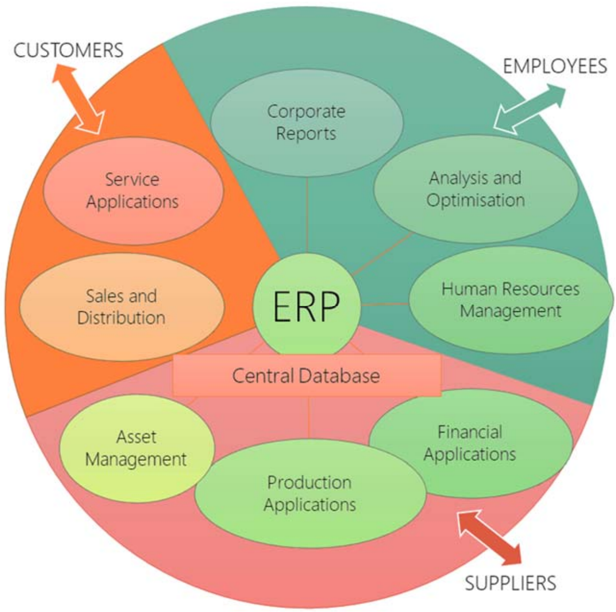


Fig. 2.22. Data Exchange in ERP

Each module involves collecting, storing, and processing data. For example, the HR management module contains data about all employees of the company (their education, competency matrices, employment contracts, work place descriptions, work and rest time trackers, schedules and vacation plans). The equipment and tool management module is closely related to inventory, storage, and warehousing. It is used to apply unique numbers to the required items for automatic warehouses and smart logistics. Orders and supplies management module helps to calculate the necessary amount of materials to ensure the enterprise's efficient operation.

All modules are connected to each other to form a unified system. The ERP approach was derived from an earlier concept of MRP II (Manufacturing Resource Planning) (fig. 2.22, 2.23).

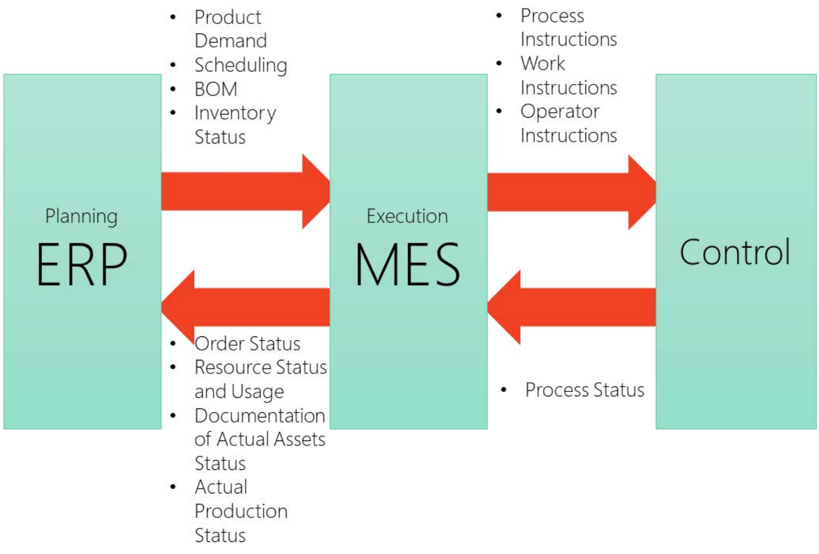


Fig. 2.23. The ERP and MES Relationship

One more important system used in an enterprise's single ecosystem environment is the Customer Relationship Management (CRM) environment, which is a set of software solutions to interact with customers. Aimed at improving the understanding of customer requirements and queries, the CRM system includes customer databases with their requirements, queries, financial solvency, lead times, etc. (fig. 2.24).

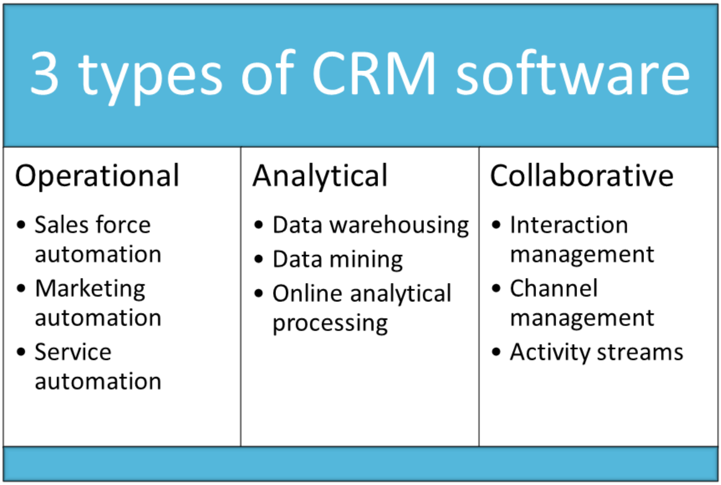


Fig. 2.24. Three Types of CRM

The CRM system analysis provides the strategy of customer-oriented production. The CRM is often a module of the ERP system (fig. 2.25).

Fig. 2.25. The CRM functions

Another important module is the WMS (Warehouse Management System). It aims to automate and optimise the accounting, storage and acceptance processes as well as ex-stock shipment (fig. 2.26).

Fig. 2.26. The WMS functions

The implementation of a WMS requires a contactless data transmission, logistics for transport and items to be moved, and mapping (see Section 3). Also, systems of different levels are used depending on the size of the warehouse. The tags enable an automated inventory to be conducted, and the warehouse sensors connected to the IIoT platform send signals about the storage conditions and security (fig. 2.27).

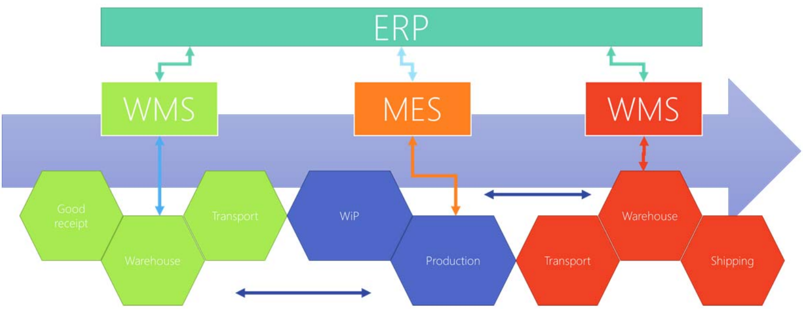


Fig. 2.27. The WMS and the MES

The Supply Chain Management (SCM) systems are developed to manage, plan and record supplies and orders, resource flow and other logistics processes. Supply chain includes processes and data (as well as the method of presenting it) about materials and resources required for production and the enterprises involved in the production process, which is necessary for optimal distribution of goods and services to end customers (fig. 2.28).

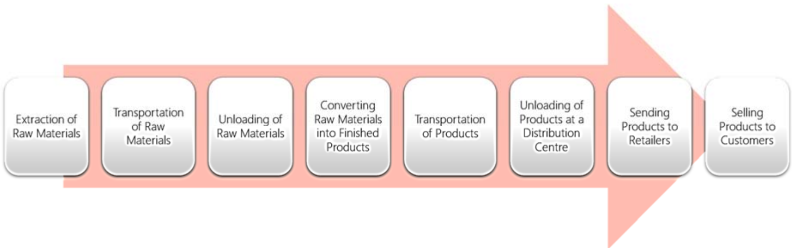


Fig. 2.28. A Supply Chain

Special SCM systems provide solutions for two tasks: planning and execution of the supply chain. The first task focuses on scheduling, forecasting, calculating force majeure situations, and scaling up when the market changes, and the second one on the coordination of the existing logistics chain and collection of data about each stock item throughout all the stages of the supply chain. Deployment of the supply chain at different levels (while implementing the logistics ecosystem into the digital plant ecosystem) assists in reducing the cost of the final product due to the building of an optimal path for the product flows movement (fig. 2.29).

Unlike the earlier approaches to management, the characteristic feature of modern supply chains is their decentralisation. To achieve it, any supply chain participant – enterprises, goods, transport, networks – gets their digital twin in a unified SCM system which helps to interact with other participants. Special web services and mobile applications allow customers to place a purchase order at any time, and personal accounts of the supply chain participants will contain information about the workload, critical deadlines, cost, optimal shipment basis and route.

Fig. 2.29. The CRM functions

To ensure a suitable data exchange between any production process and facility applications, ANSI/ISA-95 was developed. This is a standard that specifies the levels of the enterprise information systems and can be used to transfer data from production applications to corporate applications (fig. 2.30).

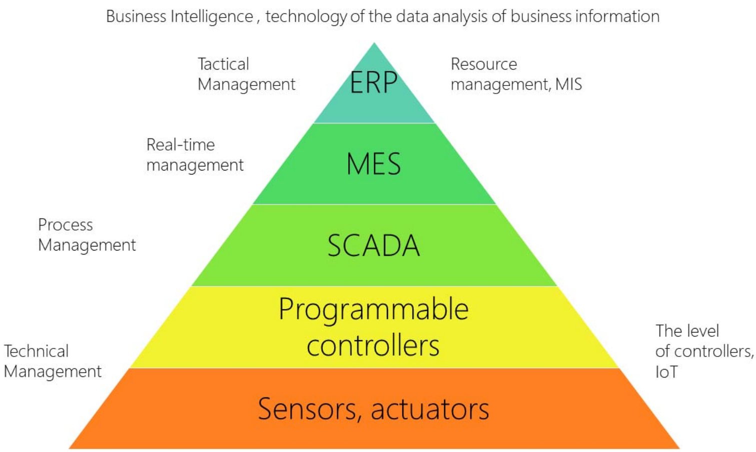


Fig. 2.30. An Automation Pyramid

The upper level is dedicated to business processes, design and production preparation automation and PLC management. The systems responsible for this are ERP, CAD/CAM/CAE/CAO/CAPP, and PLM. Next is the level of production management. It includes the QMS quality control system and MES production management. The lower levels are for Computer Numerical Control (CNC), human-robots interaction, and microcontrollers programming. The upper level focuses on the planning and optimisation of processes and calculation of efficiency, while the remaining ones on the real time functioning and monitoring.

All the discussed software environments operate with a large amount of data. To work with it, big data analysis methods are used. For instance, in the MES systems, they help to collect and store the entire array of data received from sensors. Based on the huge statistics collected, an automated search for relationships or solutions occurs. Also, the resulting dependencies are attempted to be described. It is impossible to analyse this amount of data using traditional methods. Currently, big data tasks are spread over different digitalisation systems, as they are an integral part of almost every new technology (fig. 2.31).

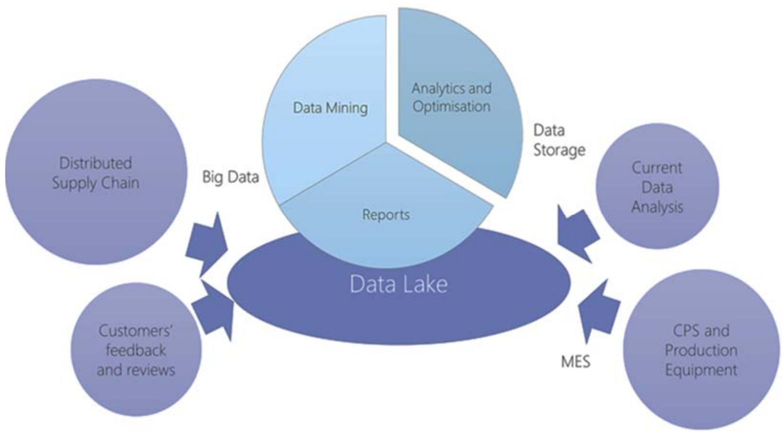


Fig. 2.31. Big Data in MES

Big data may be structured and unstructured. There could be terabytes of data from one machine, and the conception implies its constant increase. The data is collected from IIoT sensors, satellite systems, ERP and MES (fig. 2.32).

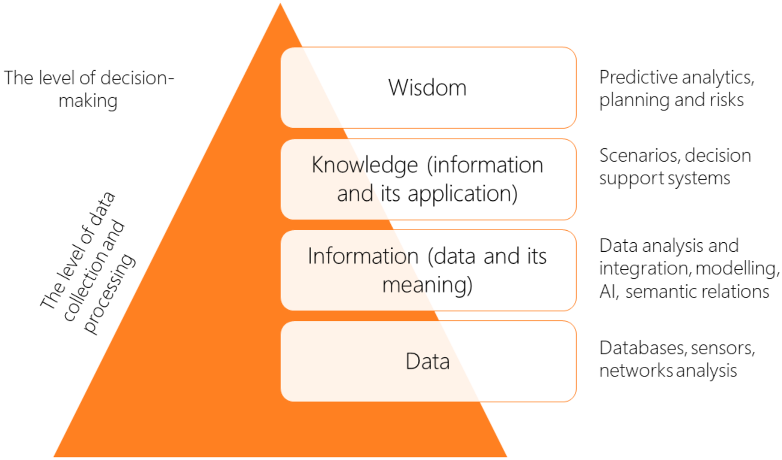


Fig. 2.32. The Data Structure

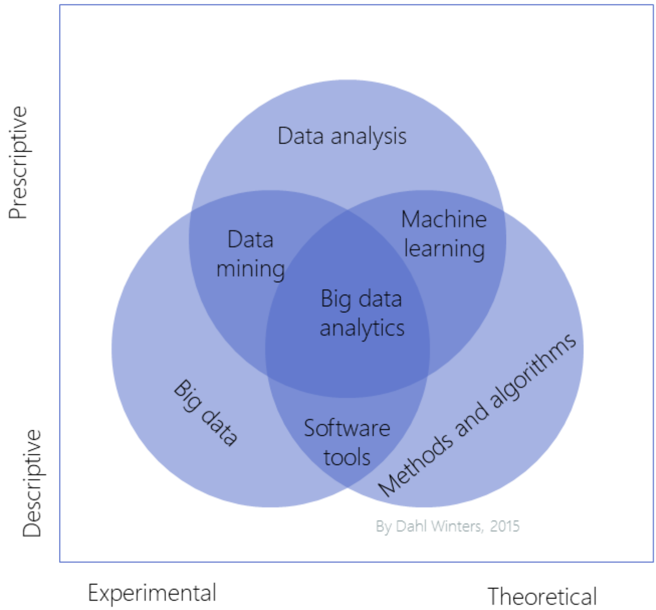


Fig. 2.33.The Data Science Fields

The descriptive characteristics of working with big data are 5 Vs: volume, velocity, variety, veracity, and value. In order to ensure the optimal performance with big data, it is needed to ensure hardware fault tolerance, local computing capability, and scalability without a processing quality loss. Big data analysis requires specific technologies and data processing tools, which are specialised programming languages for statistical processing, NoSQL DB with flexible queries, distributed computing, and a set of ready-made hardware and software systems (fig. 2.33).

Working with the big data that was collected involves:

- erroneous and random data search;
- creating parameters for calculations;
- developing a parameter-based analytical predictive model to determine the target variable.

High-performance computing (HPC) is used to process data and is performed on special equipment, which includes supercomputers and computer clusters (tens of thousands of processors). Modern computing speeds reach several trillion operations per second (10^{15}, teraflops), up to a million trillion operations per second (10^{18}, exaflops). The data transfer rate in HPC systems reaches hundreds of gigabits per second. What makes it possible is the use of cluster central processors and graphics processors, which increases the processing speed and data output speed. There are two ways of data processing: sequential (each task has its own CPU core) and parallel (some CPU cores, especially graphics ones, carry out several tasks). In mechanical engineering, the main task of high-performance computing is to develop big-data-based mathematical models of digital twin elements (fig. 2.34).

By introducing the Industrial Internet of Things, Industry 4.0 is changing the automation pyramid presented in this Section. Now data is no longer exchanged from device to application but between devices/applications and a centralized communication infrastructure (cloud resources more often)/distributed computing (fig. 2.35).

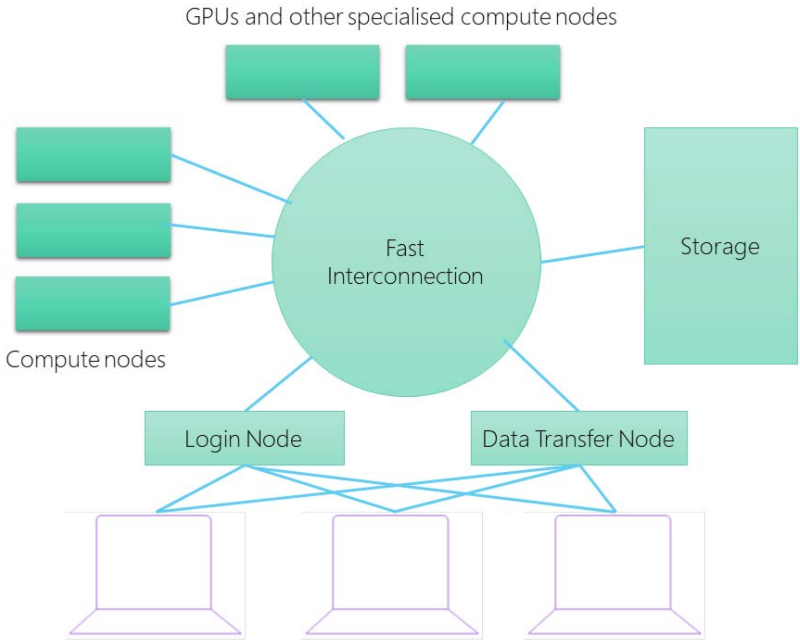


Fig. 2.34. The HPC System

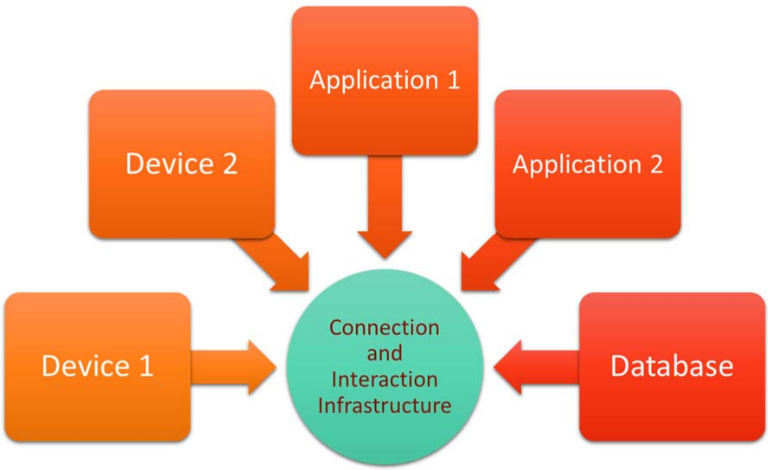


Fig. 2.35. The Impact of IIoT

Self-check questions

1. For each case, offer your own management and automation system from the ones discussed in this Section:
– to calculate the employee's salary,
– to take an inventory,
– to transfer data on the tool wear rate to the equipment tracking center,
– to stop equipment operation in case of an accident,
– to collect data from service centers about critical situations with the product,
– to determine the demand for new products,
– to track transportation costs,
– to determine the stage of accrued expenses,
– to plan a transport route.

2. Big data used to be included in the hype cycle. Take a guess why it was excluded a few years ago.

3. Offer a solution for small and medium-sized enterprises that cannot purchase, deploy, and maintain the entire architecture of high-performance computing networks.

2.4. Digitisation of Production Processes

A PLM system needs to collect and store data from multiple sources in order to facilitate optimisation of design work as well as resource planning. This involves integrating manufacturing equipment, automation systems and workplaces into a single IIoT network through sensors and controllers. Fitted with computing devices, such a network does not merely collect and store data, but is also engaged in data analysis. The problem is that the amount of data from each sensor is enormous.

Implementation of big data analysis in production is often obstructed by older legacy equipment, and fitting certain parts of it with the required data-collecting sensors can be a demanding task. Conversely, the equipment (as an actuator) needs to be able to receive an "assignment" from a microcontroller to carry out a process. Besides, the volume of information required for big data analysis takes rather long to accumulate (at least one year to collect the data from all enterprise equipment). Another limiting factor is the need to purchase specialised data-storing infrastructure and develop self-learning software for predictive analytics. Certification and warranty issues present additional challenges, since all machinery retrofitted with sensors needs to be brought through these procedures again (fig. 2.36).

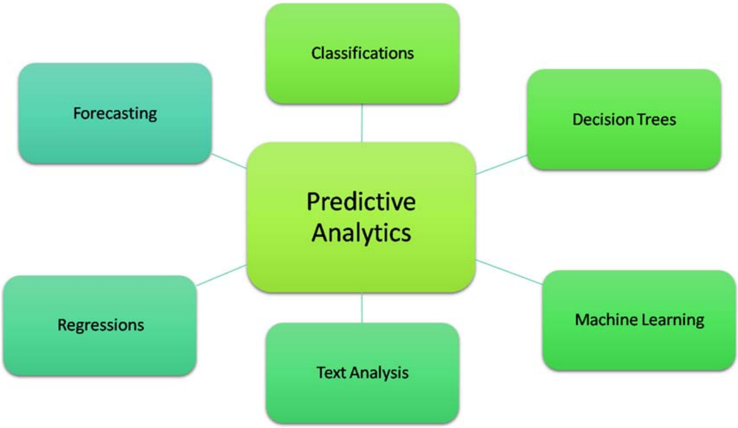


Fig. 2.36. Predictive Analytics Solutions

There are several types of advanced analytics:

1. Descriptive (collecting and processing present data);
2. Predictive (using datasets to determine trends and relations);
3. Prescriptive (searching for optimal solutions for data collection and analysis);
4. Detective (analysing invalid data and eliminating randomness);
5. Cognitive (all the above types combined).

The enterprise's data cannot always be stored and processed using on-premise equipment, especially when the data volume is considerable. This is where PaaS (platform as a service) cloud computing models come into action. This service can be obtained from the enterprise's provider that has the computing infrastructure and the necessary software (fig. 2.37).

The enterprise can buy a kit of production solutions from the cloud platform provider and thus avoid developing or purchasing its own computing systems.

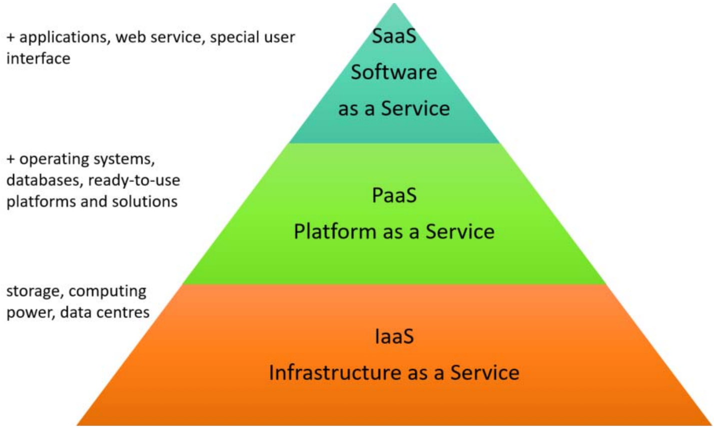


Fig. 2.37. PaaS, SaaS and IaaS

Digitisation of production can involve either objects of production (such as machinery, materials, goods or technological processes) or management and monitoring of employees' activities (such as communication with contractors, planning, analysing bottlenecks in business processes, etc.).

Implementation of digitalisation at a modern hi-tech enterprise begins at the design stage. Production release, quality assessment, minimisation of faults and failures are scrutinised in the virtual environment with the help of CAD/CAE/CAO systems before the physical product prototype is obtained.

Smart design involves digitising objects in order to create their digital twins, which sometimes requires building digital models of the existing equipment. This can be done by means of reverse engineering and photogrammetry (fig. 2.38).

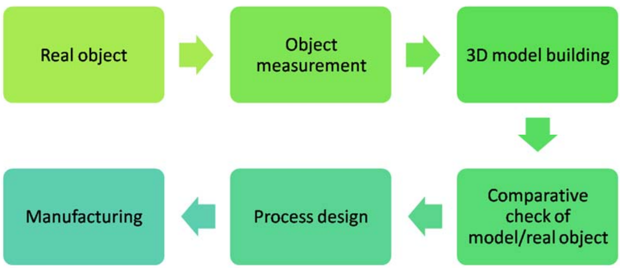


Fig. 2.38. Reverse Engineering

Photogrammetry uses sets of 2D images of an object (e.g. photos taken from various angles) to build its 3D model. It is primarily used in large-scale construction projects, such as modeling buildings and site plans, as well as in handling cartographic and geodesic issues (fig. 2.39).

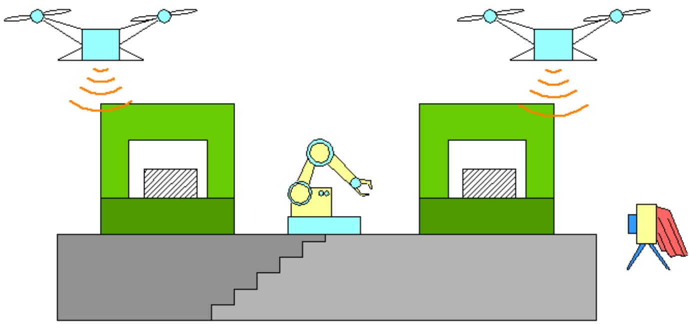


Fig. 2.39. Photogrammetry

Nowadays the dominant technology for more precise modeling of large, medium or small-scale objects is 3D scanning.

3D scanning is used to create a digital point cloud model of an object. The cloud is converted into a polygon or surface model either by the user or automatically. If necessary, this model can be further transformed into a solid one by means of parametric modelling. There is a variety of 3D scanning tools which can serve specific purposes (such as creating a digital prototype of an object by means of its digitisation, duplicating an object by means of additive technologies, optimising construction design of an object) (fig. 2.40).

3D scanning can be contact or non-contact. Non-contact scanning includes laser (or sometimes lidar) and optical scanning technologies (fig. 2.41).

Contact scanning is performed by coordinate measuring machines (CMM). These can be automatic or hand-driven (fig. 2.42).

All modelling techniques are based on measuring the coordinates of keypoints in the uniform coordinate system and importing these keypoints into the virtual environment of a CAD system. Programs of this kind use the keypoints to build polygon meshes or NURBS surfaces. The building rules may vary depending on surface types, technical requirements and capacities of measuring devices used.

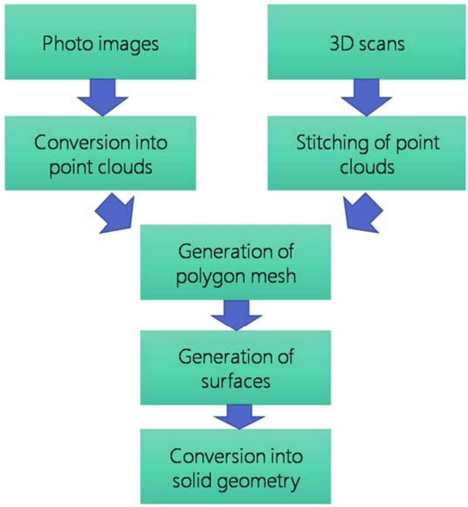


Fig. 2.40. Scanning Steps

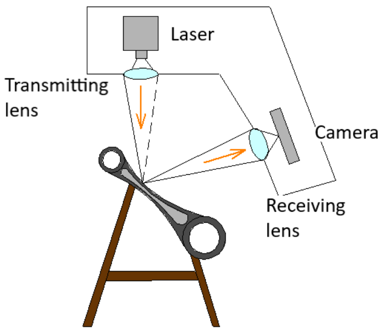


Fig. 2.41. Non-contact Scanning

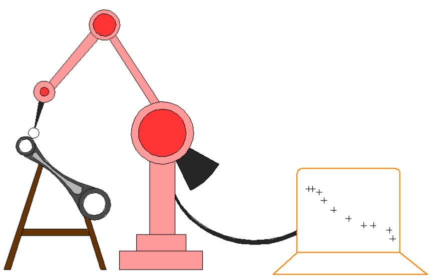


Fig. 2.42. Contact Scanning

Another area where reverse engineering is applied is in retrieving legacy product drawings or process sheets. This is how technological processes for products dating back to 1900s and earlier are retrieved.

The means of handling scanning systems include software products such as CAQC software (Computer-Aided Quality Control) – these act as CAD/CAM applications – and Quality Management System (QMS) which encapsulates the enterprise's product/service quality management strategy. QMS uses statistical methods of collecting and evaluating data (ISO 9001) (fig. 2.43).

Fig. 2.43. QMS Competencies

One of the methods for identifying and monitoring physical entities at an enterprise is telemetry. Its task is to collect data on measurement parameters of entities and transfer it wirelessly. Wireless data transfer relies on tags. Today the most popular tag types include:

– optical (bar codes or QR codes) (fig. 2.44);

– NFC;

– RFID.

Fig. 2.44. QR Redirect to the Official Page of Togliatti State University tltsu.ru

NFC (Near Field Communication) tags enable wireless communication within short distance (10 cm or less). They can be found in pass cards, payment cards, public transport card readers, various mobile devices, etc. NFC tags operate in modes of information recording and data exchange or in passive mode (fig. 2.45).

Fig. 2.45. NFC Advantages

RFID (Radio Frequency IDentification) is flexible to be used in any conditions, including those typical for industrial enterprises, without the risk of being affected by dirty surfaces, gas contamination of premises or shielded or overlapped objects. RFID consists basically of two components: a reader sending signals and an identifier, which is the tag. The read range between them can be significantly lengthy. Apart from that, RFID is able to complement and rerecord data, possesses substantial data storing capacities, does not need power supply, is not exposed to alterations of the environment, and is practically counterfeit-proof. As means of safety control, RFID tags can be attached to containers, automation systems as well as clothing or personal protective equipment. Unlike paint marks, QR- or barcodes, they are durable enough to be widely used in inventory control (fig. 2.46).

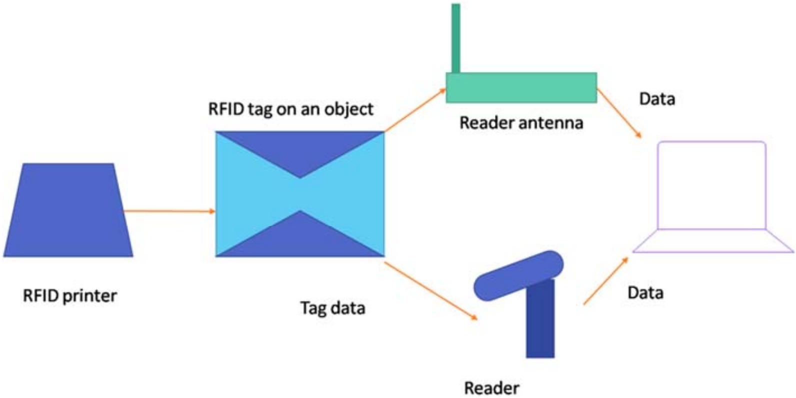


Fig. 2.46. RFID Tags

NFC and RFID are specified by ISO 14443.

Digitisation of production processes can also take advantage of robots and machine vision (see Section 3).

The technology that needs a special focus is virtual reality (VR). The basic requirement for implementation of VR in manufacturing is having appropriate devices – smartphones, specialised glasses or headsets, in some cases literally any items fitted with a camera, sometimes even clothes or special VR rooms. A VR device needs a program which can perform two functions. The first is to create digital data layers superimposed on the real-life image. The second is to overlay interactive elements of videos or 3D models on top of the real objects in camera. A VR headset can add sound effects; some other VR technologies involve tactile interaction.

The variety of such technologies is evolving in three major directions: virtual reality (VR), augmented reality (AR) and mixed reality (MR). VR replaces the entire of the real environment with a simulation, while AR and MR place digital elements on top of the real life image transmitted via glasses or other devices (fig. 2.47).

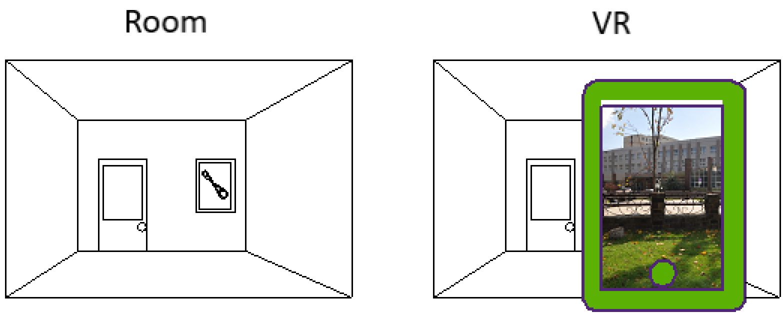


Fig. 2.47. VR

Augmented reality helps to add information about an object, which pops up on the screen near the object when requested – typically a caption text, a bit image, a hologram or a pop-up help standing out of the real world environment. Mixed reality provides interaction between superimposed virtual objects and physical environment, offering an opportunity to vary the depth and level of object integration in the environment. Mixed reality objects are hardly distinguishable from the real ones on the screen (fig. 2.48).

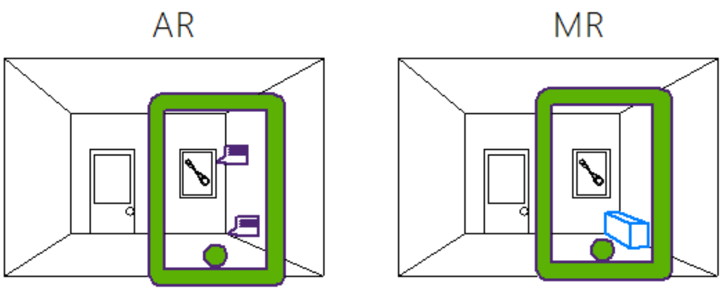


Fig. 2.48. AR and MR

VR involves creating a 360-degree video filled with 3D objects which the user can view or interact with. A real-life object, when fitted with specialised sensors, can be translated into a corresponding virtual model in VR.

Devices that generate AR and MR must be able to identify various objects, typically in the form of tags. Sometimes AR/MR technologies engage tactile interface – by means of special manipulating devices that allow a user to send commands to a 3D object real-time (fig. 2.49).

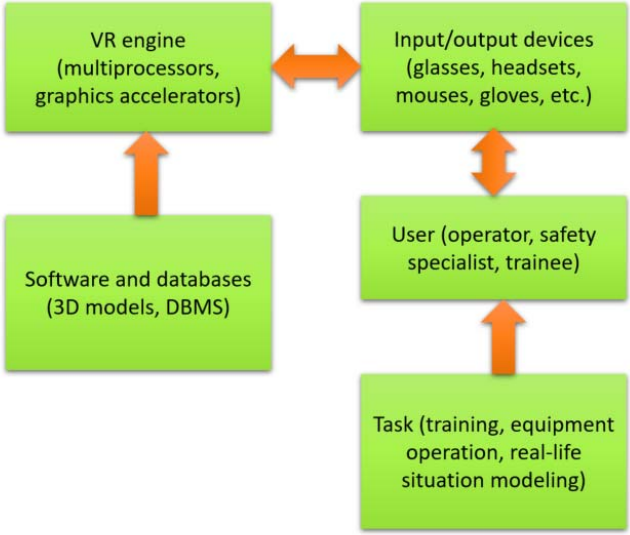


Fig. 2.49. VR Structure

The key factor that defines how real AR images or MR models look is the purpose these technologies are implemented, and the purpose could vary from training activities to designing informative elements, or other. In some cases, conventional graphics (a concept or a prototype) and low-polygon models would suffice. The likeness of the virtual environment to real life is dictated by game mechanics. These also determine the ways objects move and interact, their exposure to gravitational force, sound effects, etc.

MR generating devices manipulate with degrees of freedom in order to place 3D objects or video elements accurately according to the viewing angle and its shifts. The more degrees of freedom a headset or glasses provide, the smoother and more precise the movements of objects would be. The quality of the implemented technologies is determined by user's responding to them appropriately, the way they would act in a similar real-life situation (fig. 2.50).

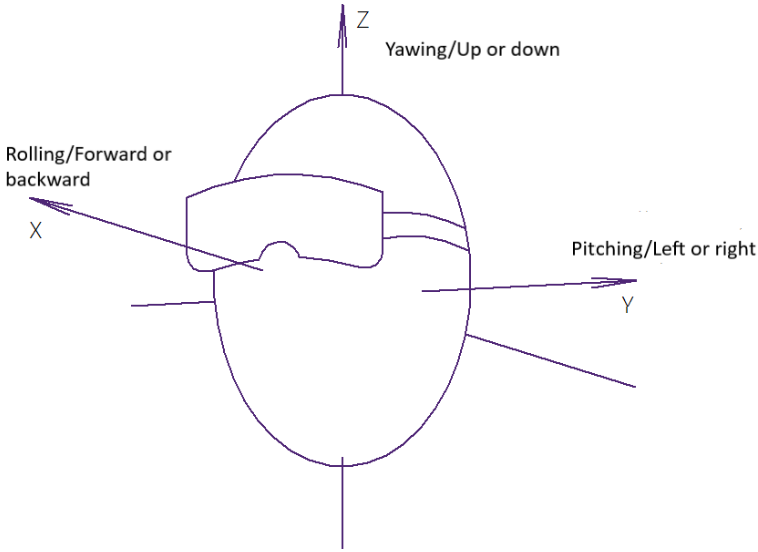


Fig. 2.50. Degrees of Freedom of a VR Device

Mixed reality is considered to be the most prospective technology in manufacturing industry. It serves the purposes of training, remote monitoring, work site organisation, and data collection. Also, it is engaged in various activities concerning instructions and manuals, and enables warning about changes in the environment conditions or user status. MR could be just as useful in other specific tasks: creating 3D objects directly in the environment and providing their interactive analysis, taking measurements impossible in real-life environment, saving history of interactions with people or objects in ERP/CRM/SCM, or carrying out works for reverse-engineering methodology and problem solving. MR and AR are also applied in warehouse activities and logistics for providing pop-up helps and warnings, handling inventory and access issues, or indicating objects with different characteristics. Since machines provide faster response to emergency situations than humans, AR pop-up messages could also help to prevent hazards.

Self-check questions

1. What are the possible drawbacks of using cloud services?

2. What are the advantages and disadvantages of using 3D scanning in quality control as compared to conventional inspection by means of gauges and measurements?

3. Which tag type would you use

– in the steel-casting department,
– in pressure resin casting department,
– in a warehouse for low-volume small-scale products,
– for labeling furniture in an office,
– to build it into a pass card?

4. How could VR possibly facilitate work

– of a safety specialist,
– a traveling crane operator,
– a mechanical equipment operator in the forging shop,
– a warehouse worker,
– a heavy transporter driver?

5. You need to have a team of workers trained to operate a new automation system in a short time. There is only one unit of equipment available for this purpose. Which technology (VR/AR/MR) is better suited for the training?

6. Could VR be of use to an engineer, manager or administrator? Why/Why not?

2.5. Advantages and Disadvantages of Implementing a Single Knowledge Environment

An enterprise introducing a single knowledge environment could yield a number of benefits such as:

– efficiency increased due to optimal equipment layout and resource management;
– planning improved due to standardisation and customisation of processes;
– time of new product introduction reduced;
– rate of risks and failures reduced and product quality increased;

– approval of technological processes taking less time due to application of reverse engineering and optimisation;
– communication and data transmission within projects streamlined by using databases;
– errors predicted;
– production flexibility increased.

However, there are a number of possible drawbacks:

– lack of a single data model;
– high demands for processes requiring near-perfect execution;
– need to plan and develop a big number of task sub-levels;
– need to provide synchronisation with contractors;
– low flexibility of objectives in case of inefficient performance;
– high level of task formalisation caused by lack of personal approach to employees;
– instability of equipment operation in emergency situations;
– employees needed to be trained to work with PLM/ERP/MES and other systems.

These disadvantages are normally eliminated by implementing a single ecosystem and a digital platform. The same problems occur during implementation of a single knowledge environment at an enterprise, and they become less critical as the system is getting more stabilised. In order to weaken their impact, the enterprise should have a clear picture of the aim of digitalisation. There are a few more conditions to consider: the enterprise should undergo a process of optimisation or even completely change the existing approaches to its production processes; come up with an elaborate strategy of implementation (planning of equipment or software purchase, optimisation of employees training); ensure flexibility in manufacturing, handling possible problems and setting quality targets; optimise standard hours for each process with reference to all of the new digital technologies introduced.

Self-check questions

1. The principle of scalability implies that an existing ecosystem is able to expand its methods and technologies on new objects emerging in that ecosystem. Do you think it is possible to apply this principle in terms of a whole industry provided there is an example of successful implementation of digital technologies at one particular enterprise? Why/Why not?

2. Which steps do you consider necessary for ensuring development of a digital platform at an enterprise besides software/equipment purchase and network deployment?

3. DESIGN OF A DIGITAL PRODUCT TWIN

This section discusses the design of a digital product twin. What is a digital twin in mechanical engineering?

In mechanical engineering, a digital twin is a virtual replica of an entity or process (fig. 3.1).

A digital twin could track the data of real-time parameter changes at any stage through the end of its lifecycle, which helps to predict the behaviors of a physical entity or process in the production environments.

Thus, the design and application of digital twins can allow the optimisation of production processes.

The digital twin application makes it efficient to predict possible problems and consequences, which is most likely to reduce costs and improve the quality of a manufactured product.

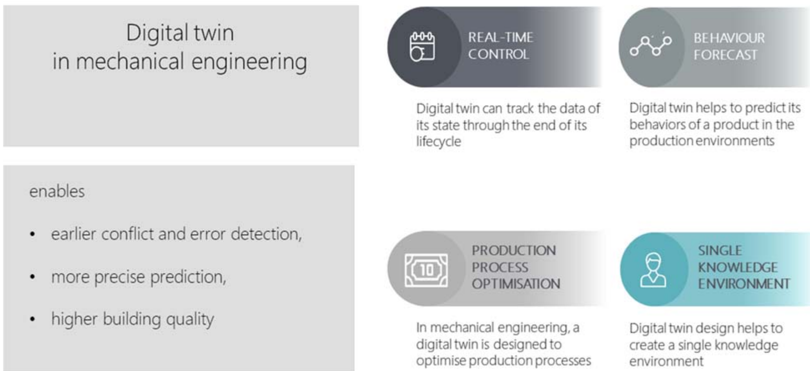


Fig. 3.1. Design of a Digital Product Twin

It is possible, for example, to simulate a factory floor environment by processing and analysing data on fixed and current assets as well as manufacturing processes and by using CAD (fig. 3.2), with a friendly-user system for the files and documentation to be integrated, which supports the entire manufacturing infrastructure and enables the engineers, customers, contractors and other stakeholders to access the purchasing, design, manufacturing and sales processes.

Fig. 3.2. An Example of Digital Twin Design in Mechanical Engineering

In mechanical engineering, there are three forms of the digital twin:
– digital twin of the product,
– digital twin of production and
– digital twin of performance.

The digital twin of a product will be discussed in more detail now.

The digital twin of a product is a virtual representation of a physical product (fig. 3.3).

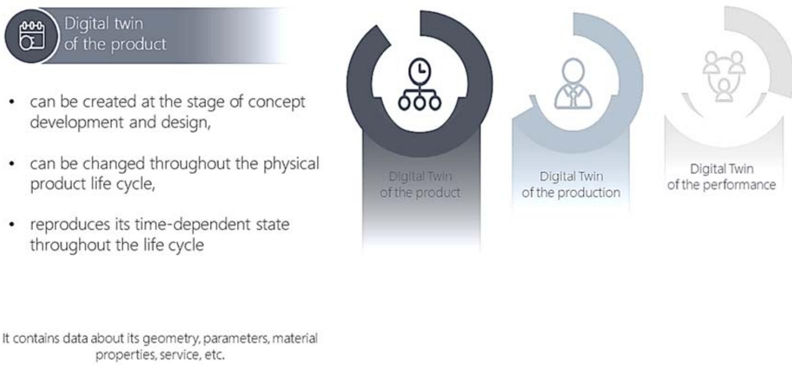


Fig. 3.3. The Digital Twin of a Product

It contains data about its geometry, parameters, material properties, its links to other models, computations, analyses, optimisation and other data.

It is possible to create a digital twin at an early stage of concept development and design.

Throughout the lifecycle, a digital product twin takes changes and helps reproduce its time-dependent state, given the input data on the environmental conditions.

The digital twin technology for product design helps to incorporate the product description to the electronic model and enables the stakeholders to use the product description in each stage of the design process (fig. 3.4).

Thus, the model is a data source for documentation development and release, calculations, tooling design and development, marketing documentation development and other primary and auxiliary processes.

Based on a digital twin-driven product design, a single knowledge environment allows a stakeholder to test if a product meets the functional requirements, make changes and optimise it at an early stage of design and development without building a physical sample.

For example, will the planned car bodywork offer the lowest possible air resistance, or will the electronics operate reliably in the specified environment?

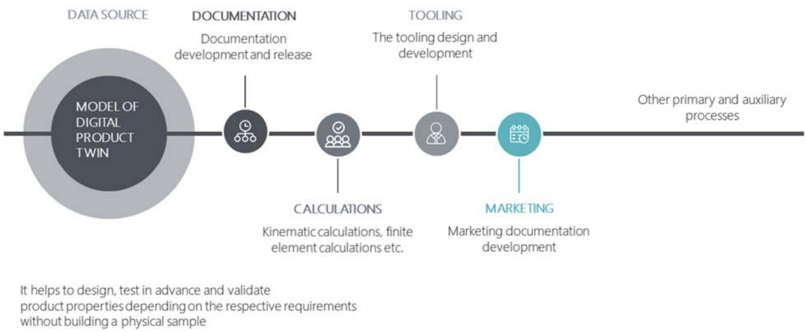


Fig. 3.4. The Model of a Digital Product Twin

An example of a digital product twin can be an electronic model of a digital twin for car, with its software, mechanical and electrical components and physical behaviours integrated into it.

A digital twin offers an opportinity to test and optimise any components: mechanical or electronic components, software or system performance, which will identify various kinds of possible problems and failures before manufacturing a real part (fig. 3.5).

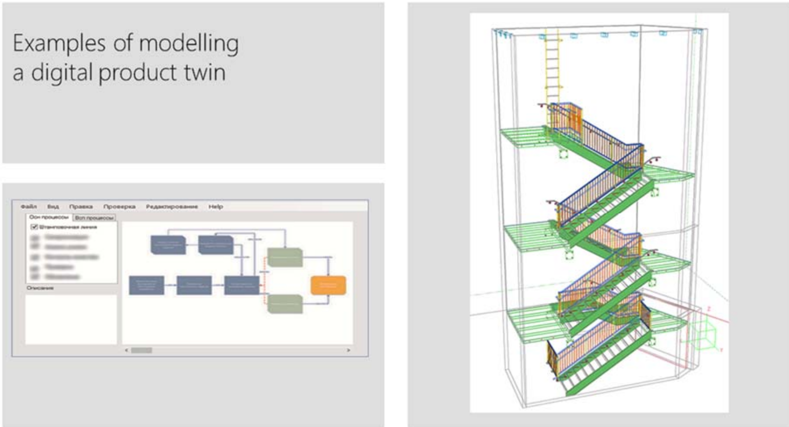


Fig. 3.5. Examples of Modelling of a Digital Twin

The accurate and complete description of a digital product twin determines the tasks, whose solutions would be based on the product electronic description, and the stakeholders' integration into a single knowledge environment.

The shift from CAD and its limits of 3D modeling and design documentation towards providing all the stakeholders with the necessary data indicates that high-level CAD systems are needed. These systems must also create a set of opportunities for lifecycle management (fig. 3.6).

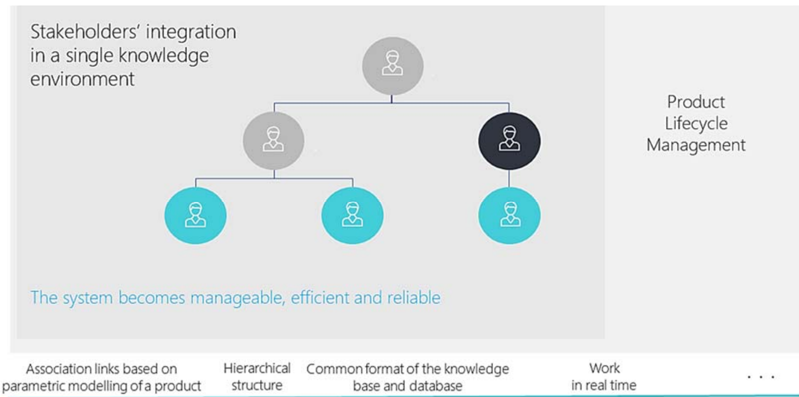


Fig. 3.6. Stakeholders' Integration in a Single Knowledge Environment

A single knowledge environment is based on association links, with the parametric modelling of the product, a hierarchical structure, the common format of the knowledge base and database and work in real time behind them. Thus, the system becomes manageable, efficient and reliable.

It should be noted that a digital twin-driven product design is not 3D modelling only.

The most important stage of designing and applying digital twins is creating a single knowledge environment, which could include (fig. 3.7):

– design specification,
– conceptual design of a product,
– composition and decomposition of a product,
– assembly and analysis,
– tooling,
– documentation,
– quality control of the project design work,
– modification,
– engineering analysis.

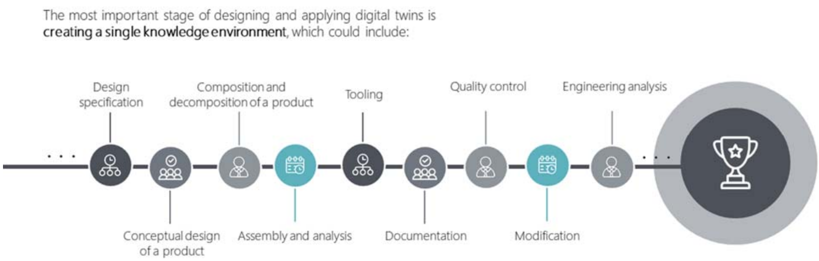


Fig. 3.7. Possible Stages for Creating a Single Knowledge Environment

A design specification (fig. 3.8) is not just a document. Rather, its crucial characteristic is parameter-based and textual data that are association-linked and integrated into the electronic mockup. Thus, this helps to build interconnections between the components of the electronic mockup.

The stakeholders see the changes that the project takes and the element – a part, a mechanism or a node – that is due to change. This approach to a design specification ensures feedback and helps to compare the characteristics of a part or node to the given constraints. Also, the system informs the user if the parameters exceed the limits.

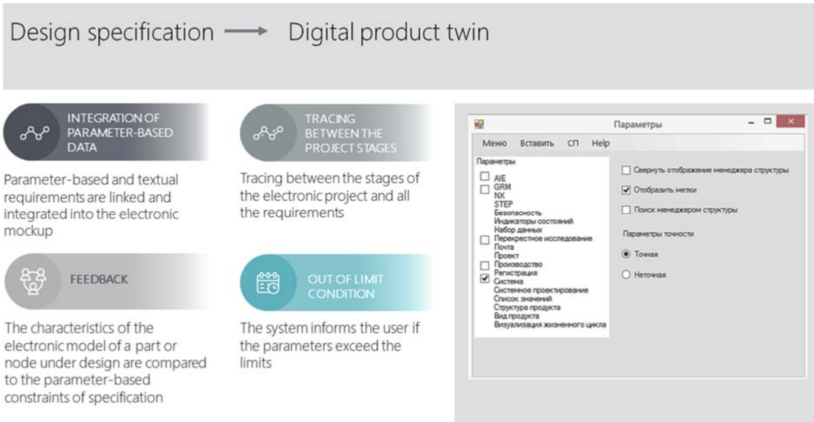


Fig. 3.8. Design Specification

The second stage for creating a single knowledge environment is the conceptual design of a product (fig. 3.9) which aims to work out and document the main design solutions, establish the links between the components and explain how the product mechanisms are to work.

The third stage is composition and decomposition of a product (fig. 3.9), which is realised through inter-model connections plus parameter-based and geometry dependencies between all the components of the model.

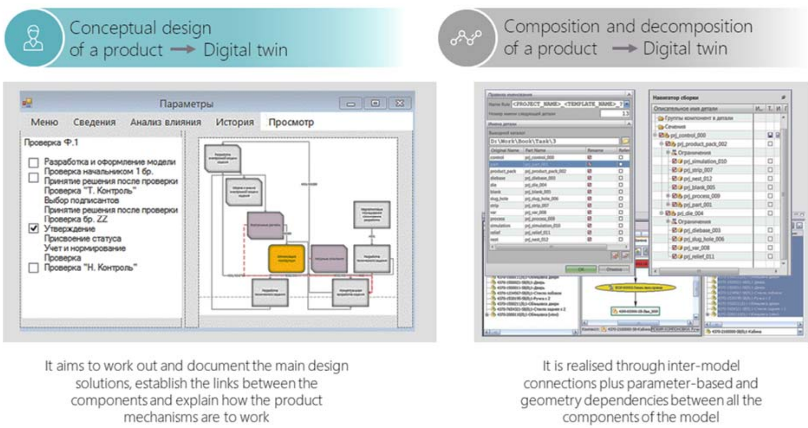


Fig. 3.9. Conceptual Design of a Product. Composition and Decomposition of a Product

The fourth stage for creating a single knowledge environment is assembly and analysis (fig. 3.10).

This stage aims to describe the assembly sequence, assess the assemblability, carry out a number of analyses, such as the clearance check and clash checking, and form component groups.

The fifth stage is the tooling (fig. 3.10). The electronic model of a product can facilitate the tooling design, which is based on association links with the electronic models of a product, the corresponding models of nodes and parts from the standard components database.

Thus, it is possible to develop the tooling at an early stage of design. It is also possible to adjust the tooling, based on real-time monitoring of the changes in the entire project. Establishing association links allows a stakeholder to adapt the standard tooling components for a product that to some extent is similar to those developed before.

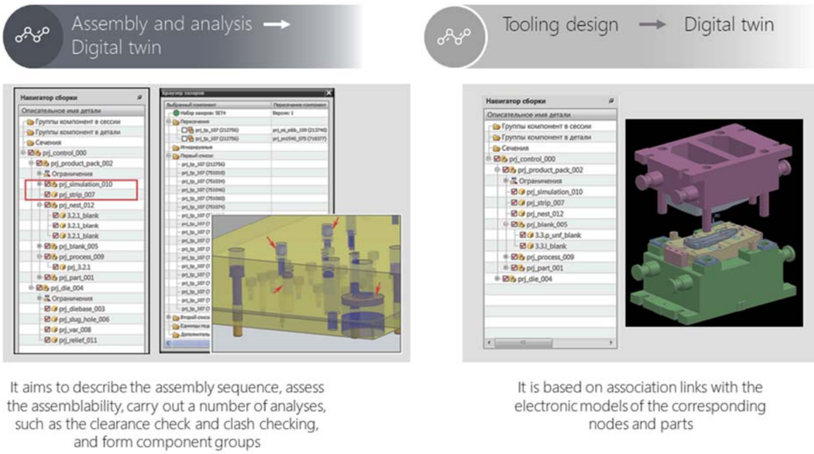


Fig. 3.10. Assembly and Analysis. Tooling

The sixth stage is documentation (fig. 3.11). This stage can end up with traditional engineering drawings or annotations of 3D models based on electronic models of parts and assemblies.

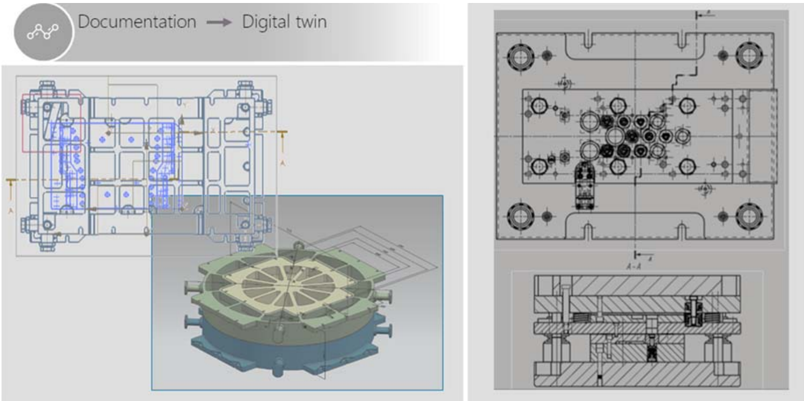


Fig. 3.11. Documentation

The seventh stage for creating a single knowledge environment is quality control (fig. 3.12) to examine the electronic mockup, check the documentation and identify inconsistencies. It might include documentation control, assembly control, control of manufacturing a part with a specific technological process and other types of monitoring the design and development processes.

The eighth stage is modification (fig. 3.12) through monitoring the changes, tracing the changed requirements and assessing their impact on the entire electronic project, as well as comparing the original and updated states.

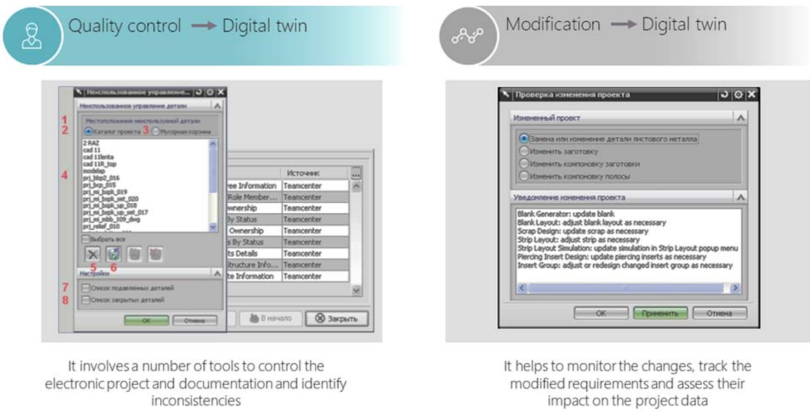


Fig. 3.12. Quality Control. Modification

The ninth stage for creating a single knowledge environment is engineering analysis (fig. 3.13). It involves virtual tests, with the electronic model of a product placed into the specified environment for its evaluation before being realised.

Computation to simulate a cutting tool wear, for example, can include the steps of a tool model design, building and testing a finite element tool model as well as setting boundary conditions to set the characteristics of friction and determine its degrees of freedom and its movement parameters. It is also possible to add the properties of the tool and billet material to the program and specify the conditions for simulation and calculation.

Thus, this helps to develop a computational finite element model that allows a user to perform a calculation, which can result in the values of the wearing depth and rate, the temperature field in the cutting zone, as well as the dependence of the total tool wear on the number of machined parts.

The modelling of the product design as well as calculations are carried out in a virtual environment, which reduces the cost of manufacturing and testing physical prototypes. The use of different materials, such as metals, liquids, gases, polymers, ceramics, biomaterials and others, causes more calculations to be performed, but simulations for these materials allow a user to select the optimal material with the desired properties.

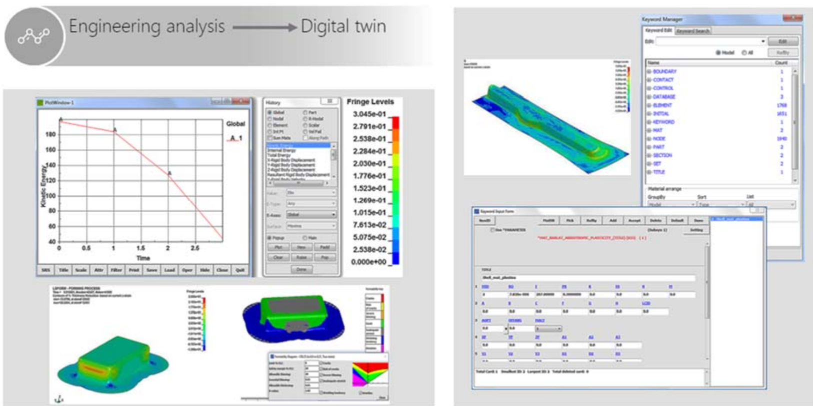


Fig. 3.13. Engineering Analysis

This might be exemplified with calculations of strength or wear, thermodynamic calculations, calculations of natural frequencies and vibration modes, analysis of durability and many other calculations that allow a user to set the work mode with the desired accuracy and evaluate the behavior of the entity (fig. 3.14).

The electronic model of an entity is used then as a solution for performing virtual tests and simulations in a single knowledge environment, which allows the model to be adjusted and verified again. For example, the structural stability test states that the assurance coefficient is low, and it requires increasing the rigidity of a product, which causes its design to be changed and another test to be carried out.

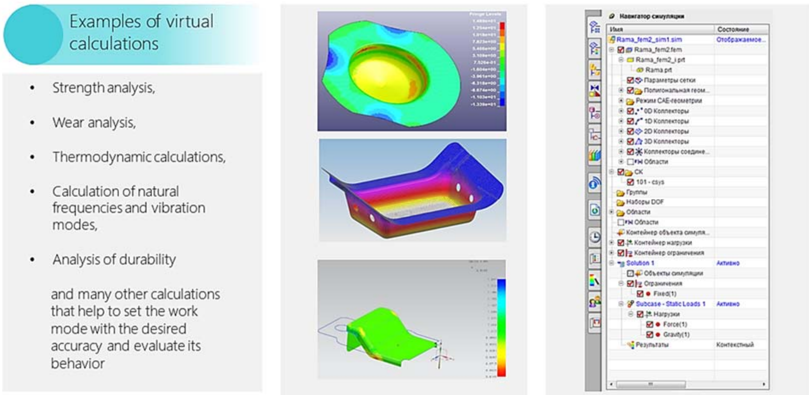


Fig. 3.14. Examples of Virtual Calculations

Another stage of building the digital model of a product could be optimisation of design in the virtual environment (fig. 3.15), which is based on setting the target function with an optimality criterion, as well as setting variable parameters and their constraints. Optimisation involves re-calculating the values of the model variables before the target function is realised.

A user gets a clear picture of how the parameter change value influences the optimisation result. Optimising in a single knowledge environment results in adjusting the electronic model of a product or assembling it, virtual tests and verification to be performed again.

The example is geometric optimisation of the die plate design. The target function of improving the quality of the metal structure with the plate rigidity-based constraint requires a calculation which provides the optimal values of the dimensions and configuration of the structure.

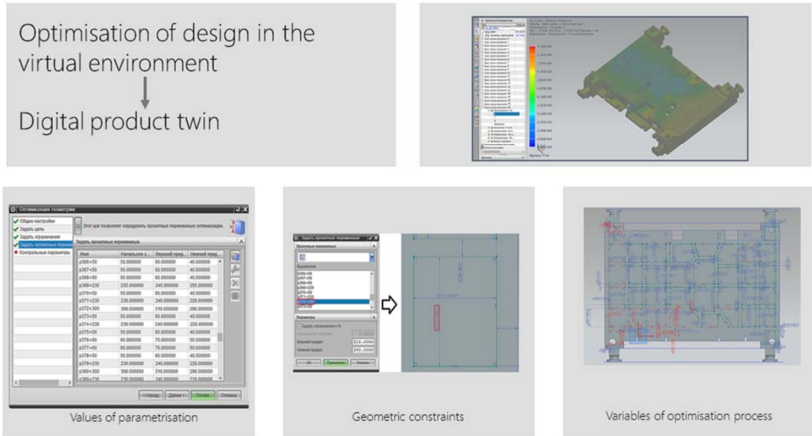


Fig. 3.15. Optimisation of Design

Also, there could be total or partial paralleling of all the stages for creating a single knowledge environment of the digital product twin (fig. 3.16), which is supposed to reduce the design time and the downtime of processes due to the lack of the necessary information.

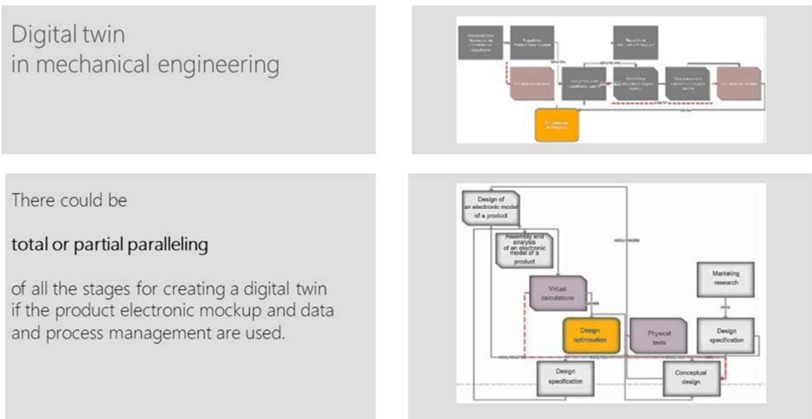


Fig. 3.16. Paralleling of the Stages for Creating a Single
Knowledge Environment

Thus, digital twin-driven product design allows a stakeholder to be flexible and adaptable to changing production and market conditions, which ensures a continuous design process.

Self-check questions

1. Why does a digital twin track the data of real-time parameter changes?

2. What is a digital twin in mechanical engineering?

3. For what types of data can the electronic model of the digital twin be a source?

4. DESIGN OF THE DIGITAL TWIN FOR A PRODUCTION PROCESS

This section focuses on the design of a digital twin for a production process. What is the digital twin for a production process?

A digital production twin is a virtual representation of production processes.

A digital production twin helps to predict problems, evaluate and optimise a production process in order to reduce costs (fig. 4.1).

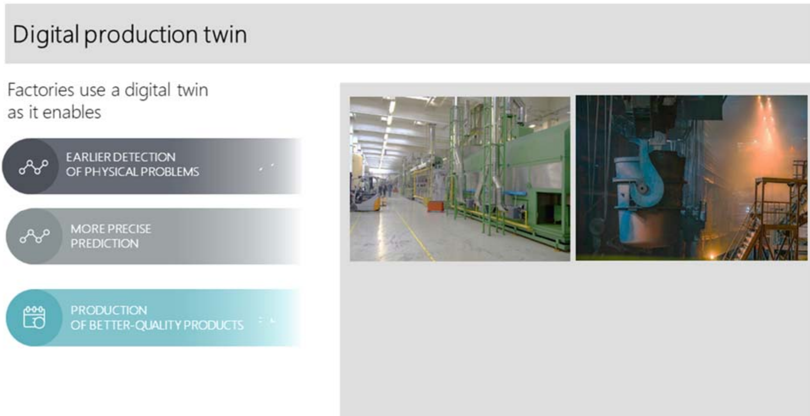


Fig. 4.1. The Utilisation of a Digital Production Twin

Digital twin technology for production line design simulates the operation of equipment and production lines (fig. 4.2). A digital production twin also helps to optimise production processes and offers virtual startup and commissioning at an early stage of production.

Thus, it is possible to detect equipment failures and errors before actual operation begins.

A digital production twin enables the continuous monitoring of the equipment's state and operating parameters by collecting data from machines. This makes it possible to prevent downtime, optimise maintenance and reduce energy consumption.

A digital production twin lays the groundwork for customised mass production.

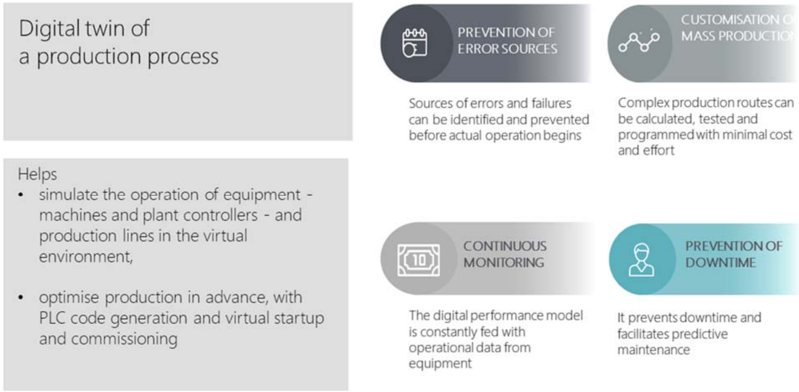


Fig. 4.2. Possibilities of the Digital Twin for a Production Process

Creating a single knowledge environment based on knowledge base and database results in combining the data about the product, technological processes, production capacities and resources (fig. 4.3). It enables real-time management of product lifecycle data. Data flows move from one place in a single knowledge environment to another and allow a user to track the required changes and, for example, to replace the tooling or select a site.

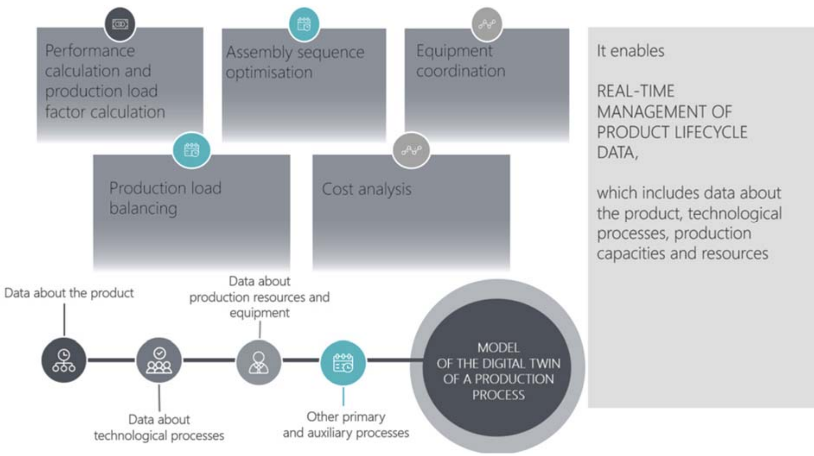


Fig. 4.3. Management of Product Lifecycle Data

Digitalisation of production processes involves management tools for:
— assembly sequence optimisation;
— equipment coordination;
— performance calculation and production load factor calculation;
— production load balancing;
— cost analysis.

This results in a digital, technological process with a complete description of product manufacturing, testing and packaging, as well as resources needed for this.

A user can implement a digital production twin when they are operating on a PLM platform (fig. 4.4) that enables the management of projects, scheduling, data and document storage, communication, the integration with software tools, reporting documentation and other processes.

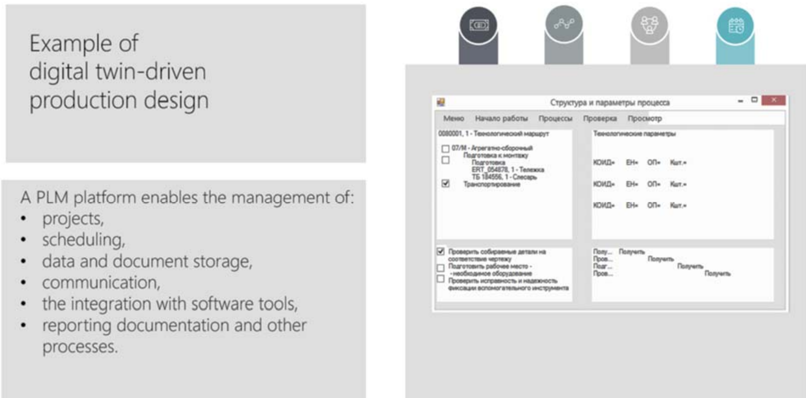


Fig. 4.4. PLM-based Processes

The data management in a single knowledge environment can assist in working with the product electronic description which includes the product electronic structure, the production technology, operation and maintenance data and other information at each stage of a product lifecycle.

It also includes database management and an electronic document system management.

Then, developing a digital twin of a production process involves:
— 3D modeling and verification of technological processes;
— material flow optimisation, resource loading, logistics, and management methods for all planning levels;

– design and optimisation of manufacturing facility layouts;
– preparation, management and control of technological information.

During the digitalisation of production processes, it is necessary to carry out a job safety analysis, as well as an analysis of ergonomics (fig. 4.5).

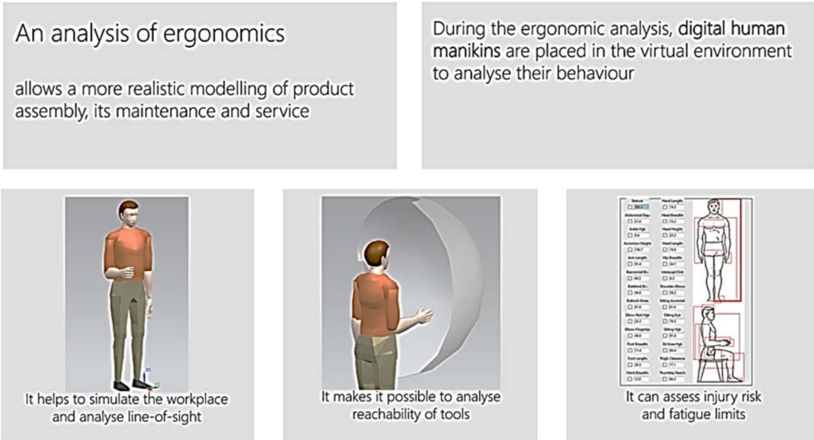


Fig. 4.5. A Job Safety Analysis and Analysis of Ergonomics

This involves route planning for workers, assessment of work-related injury risks, causes of fatigue in the workplace, reachability and accessibility of instruments, assessment of the human effort (fig. 4.6).

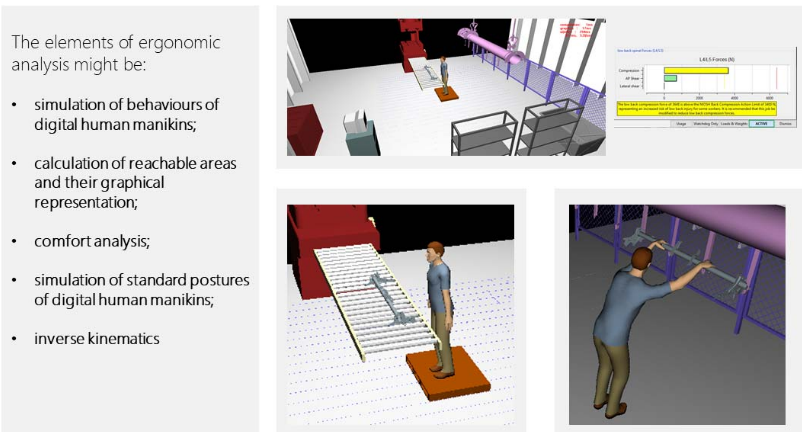


Fig. 4.6. Assessment of Ergonomic Indicators

During the ergonomic assessments, digital human manikins are placed in the virtual environment which is a replica of the production environment.

It enables modelling of assembly processes, which allows a user to validate the assembly sequence or to assess comfort of workplace environment and utilisation of assembly equipment.

Thus, this helps to assess whether or not a structure is buildable and calculate assembly costs.

Self-check questions

1. What is the purpose of using the digital twin for a production process to predict problems and their consequences?

2. What should a digital production twin enable and provide?

3. What could be the components of the digital twin for a production process?

5. DIGITALISATION OF PRODUCTION PREPARATION PROCESSES

The focus of this section is digitalisation of production preparation processes.

Besides the digital twin of a factory, which is a mathematical model of facility functioning, there is also a digital twin of a segment, principally equipment. Unlike the digital production twin, this model is narrow, specific and ultimately thorough (fig. 5.1).

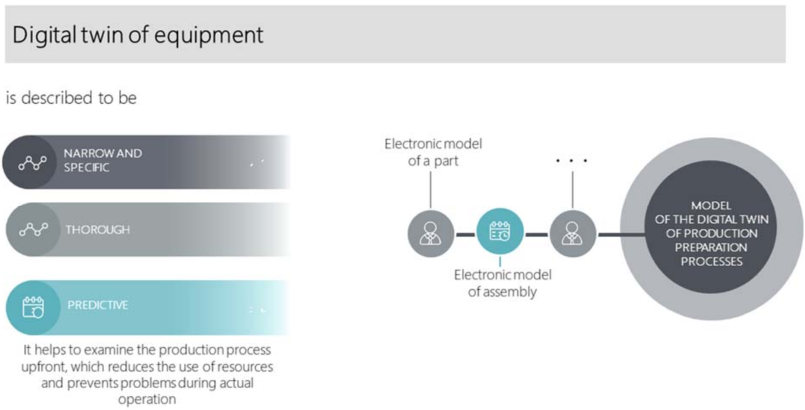


Fig. 5.1. Characteristics of the Digital Twin of Equipment

The founding philosophy of digital twin technology for production preparation processes design is the electronic mockup of a product, and all the electronic design automation tools are based on the electronic model of an assembly unit or a part.

A single knowledge environment helps to perform simulation modeling of production preparation processes, analyse and ultimately improve production efficiency before the product release.

This allows engineers to examine the production process in advance, which reduces the use of resources and prevents problems during actual operation. For example, digitalisation of CNC equipment programming involves preparation of control programs, postprocessing, modeling of machine operation tasks, as well as design of necessary documentation for automated processes (fig. 5.2). This enables the efficient development of control programs for multiaxial milling, drilling, turning, highly automated processing and high-speed milling.

Developing control programs is based on consistent data of different types: 3D models of parts and tooling, technological and design information. This creates association links between design and processing operations, which enables centralised resource management.

The structure of the digital twin of production preparation processes can also include simulation and programming of industrial robots and robotized cells.

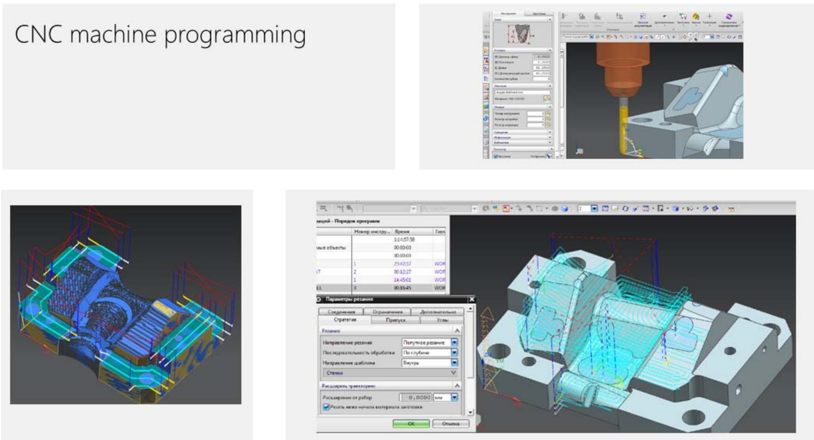


Fig. 5.2. CNC Machine Programming

Digital replicas of standard equipment, for example, could be models of various types of tooling: machine tooling, assembly tooling, welding tooling, thermal tooling, various cutting tools, control devices, as well as technological equipment, robot models, positioners, manipulators, roller tracks, which are used for the modeling of assembly processes, mechanical processing and other technological processes (fig. 5.3).

Digital twins of forming processes and die tooling design are a critical aspect for digitalisation of production preparation processes.

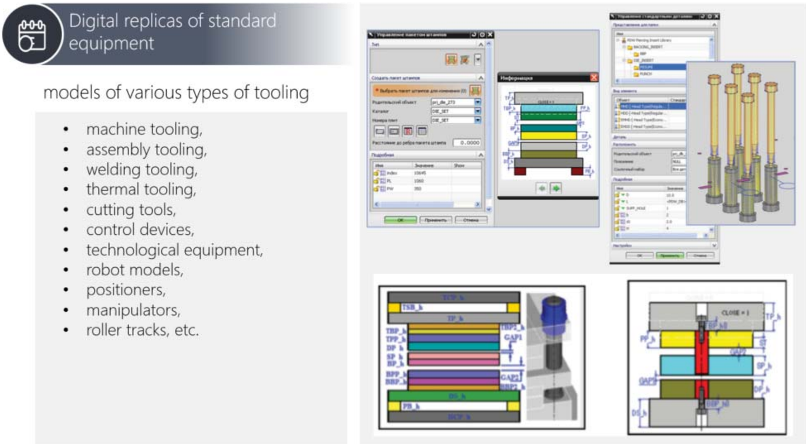


Fig. 5.3. Digital Replicas of Standard Equipment

This stage could provide solutions for a set of tasks (fig. 5.4) such as:

— stamping process design;
— recommendations for the appropriate equipment;
— three-dimensional models of die assembly;
— die operation sequence model, etc.

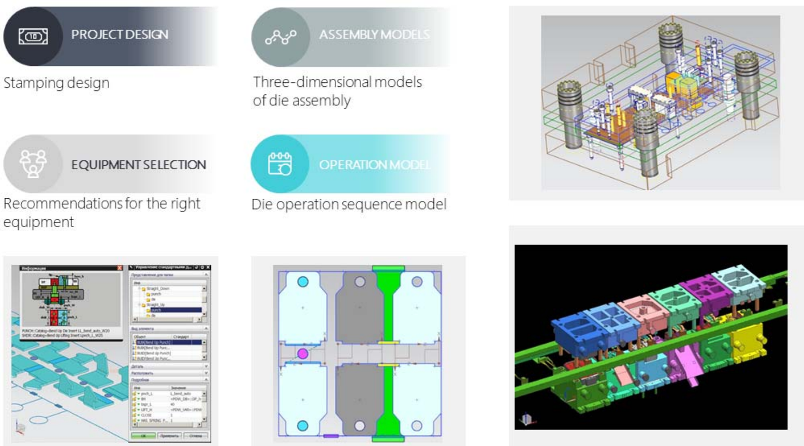


Fig. 5.4. Digital Twins of Forming Processes and Die Tooling Design

Digitalisation of production preparation processes can also include kinematic analysis, which allows the modeling of mechanism behavior and analysis of the mechanism motions under various working conditions. This analysis can be performed for simulation of the modelled mechanisms and the design of kinematic diagrams, which can be used to design and develop mechanisms (fig. 5.5).

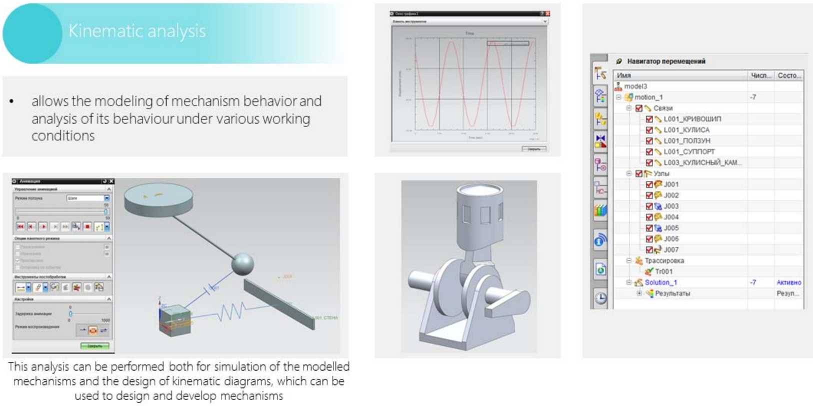


Fig. 5.5. Kinematic Analysis of Mechanisms

During the simulation, sensors measure parameters of the mechanism, such as linear or angular velocity, motion and acceleration, and the system presents the data in graphs and figures. The results of kinematic analysis, such as loads of a mechanism and its pieces, can be communicated to the applications for performing virtual tests.

Self-check questions

1. What are the features of digital replicas of standard equipment?
2. What does digitalisation of CNC equipment programming enable?
3. What equipment could be an example of a digital replica?

6. DIGITALISATION OF PRODUCTION PROCESSES

6.1. Human-Robot Interaction

Human-robot interaction (HRI) is a field of study dedicated to the communication between a human and a robot or other automation tools and the development of AI-supported interface (fig. 6.1). HRI can be separated into two general categories: remote and proximate interaction. During the first type of interaction the human and the robot are not co-located and are separated spatially or even temporally whereas during the second one robots may be in the same room as humans. Remote interaction can be performed not only with a mobile robot but also with a physical manipulator.

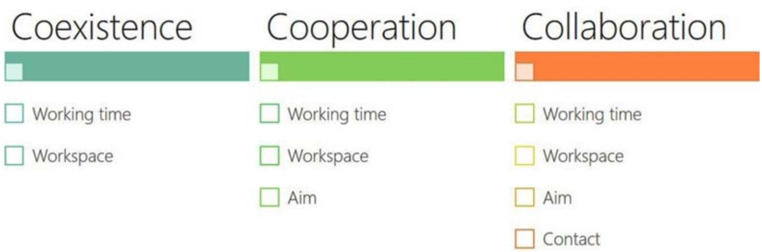


Fig. 6.1. Types of HRI

Interaction is based on data received by robots from their sensors. To accomplish this, most methods of human-robot interaction require creating 3D models. Robots do mapping which means creating a map or a plan of the environment to determine their location in it and their position in space (fig. 6.2). The concept of mapping goes back to the method of simultaneous localisation and mapping (SLAM). Another problem related to the robot's position arises when one needs to set a movement trajectory from one point to another. It is connected with the ability of complex multi-link systems to perform a large number of movements within a limited space and is determined by a numerical indicator called the number of degrees of freedom of a robot.

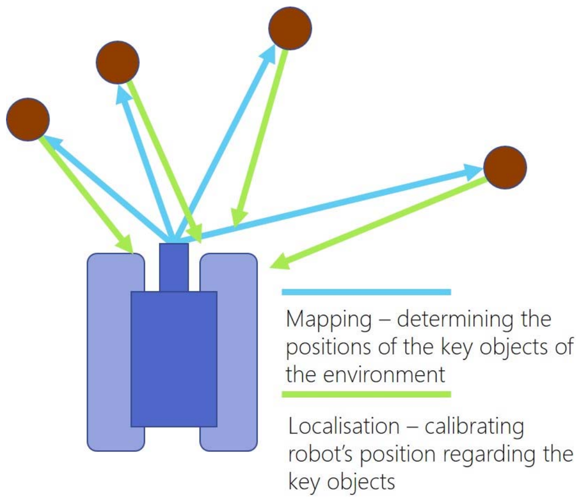


Fig. 6.2. Robot Mapping

The main HRI digitalisation technologies in production are machine learning, pattern recognition, navigation system development, and self-driving.

The recognition task can relate to images (colour, shape, the environment, a specific object, process or phenomenon, etc.), voice and faces, symbols, documents, etc. For example, to train a program that should find defects in product photos, first, you must collect a database of photos with possible defects and then train the program. Such repositories must consist of a huge dataset, which involves using neural networks. To perform simpler tasks, such as character recognition in a scanned document, one can try to de-skew a character to do pattern matching or to analyse the character topology (the number of sides and corners, if there are rounded corners, etc.) (fig. 6.3).

Speech recognition is necessary to operate a robot when one cannot use a physical manipulator or when there is no remote control device (a tablet, a phone, etc.). In some cases, voice control is required if the operator's hands are busy with such activities as driving, logistics, warehouse tasks, and setting up controllers. As an industrial robot often operates in high-noise environments, speech recognition at a production plant can be difficult (fig. 6.4).

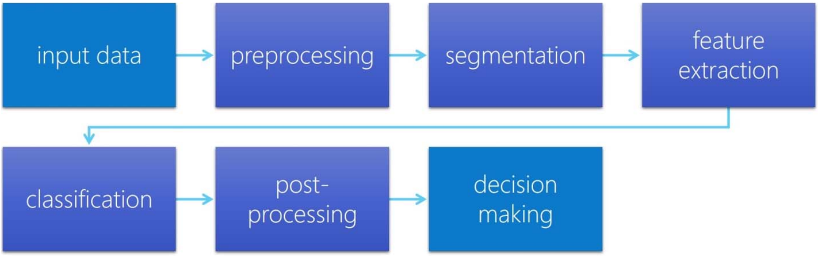


Fig. 6.3. Pattern Recognition Stages

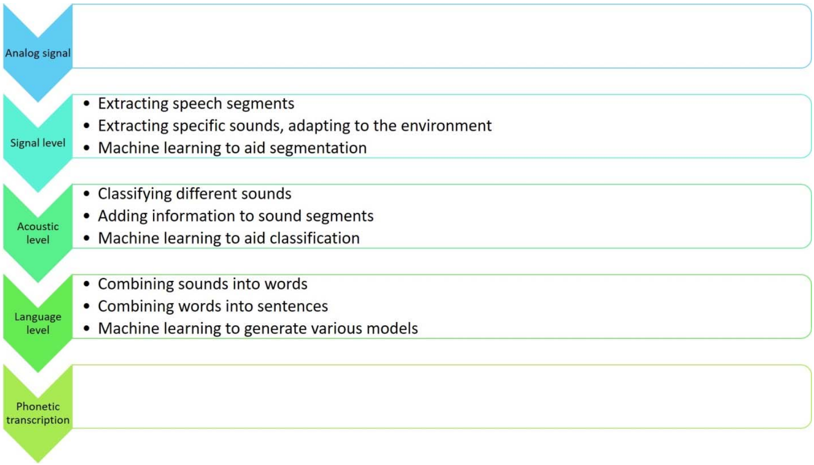


Fig. 6.4. Speech Recognition

More complex recognition strategies are employed at industrial facilities, for instance, recognition of the robot type, stop and go signs, the number of people, including their movement and direction. Currently, a new national standard (GOST R) *Infrastructure Facility Recognition Systems* is being developed.

One of the areas of human-robot interaction is production safety (GOST R 60.1.2.1-2016 / ISO 10218-1: 2011 *Robots and robotic devices – Safety requirements for industrial robots*). Robots move heavy loads, work with toxic and high-temperature substances, rapidly move objects with sharp edges, etc. All this increases the likelihood of industrial injuries and requires special approaches to mapping. Production plants can also utilise social robots, such as help systems, voice search systems, recommendation systems, and training systems.

To improve an operator's safety, a facility can also use cobots, that is collaborative robots. They carry out their functions using a system of physical manipulators like ordinary industrial robots, but besides that, they are able to track the actions of an operator in close proximity. A graphic interface is completely sufficient to program such a cobot. They are generally used when complete automation of the process is unattainable. One of the possibilities is to use cobots together with laser trackers, which are a type of measurement and digitising devices. Based on a 3D reference model, such a tracker can indicate points in space with its laser. These are the points where a cobot should perform some work with the help of a physical manipulator. However, what cobots can do is limited by their size and pre-requisites (fig. 6.5).

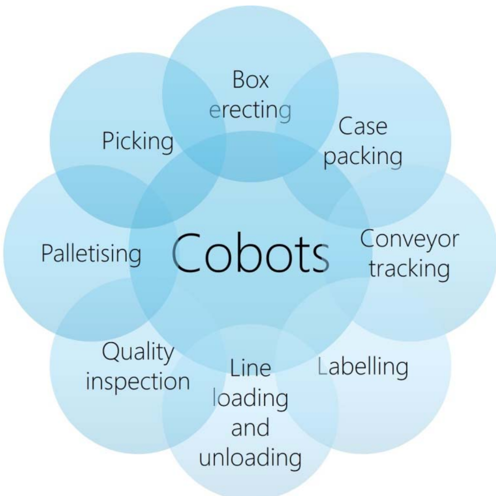


Fig. 6.5. Cobot Functions

Not only does a person control a robot, but a robot can also track a person's state or movements. There are methods to track such things as eyes, movement, temperature, appearance, and uncharacteristic human movements. Eye tracking has been widely applied in manufacturing industry as part of machine vision technology for some time. It uses special glasses (trackers) that track the gaze point of an employee in charge of production processes. If there is a discrepancy between the actual and the expected gaze point, the device sends a signal urging the operator to focus on the specific point (fig. 6.6).

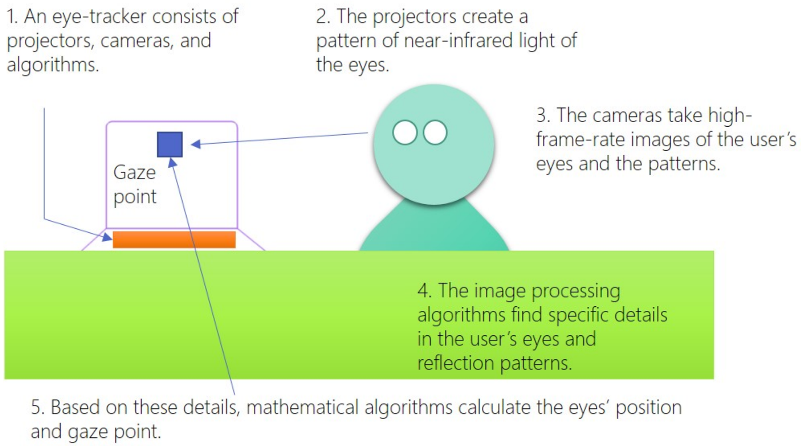


Fig. 6.6. Eye Tracking

In addition, the same device can monitor the operator's health status, their focus on a specific object and signal if the operator is asleep or unconscious. Machine vision can also track labour misconduct: whether the employee does not wear a uniform or it does not comply with the safety requirements; whether there are any foreign objects, or whether a person is part of the staff or not.

Among other things, human-robot interaction includes navigation systems (fig. 6.7). Their development is necessary to carry out logistics tasks both small-scale ones, e.g. moving a self-driving loader around the warehouse, and to transport cargo between contractors. As a rule, automation equipment and transport at warehouses or workshops use RFID tags to determine which container to pick up at its location and which trajectory to choose. Other tasks of automatic navigation include: monitoring the safety and integrity of the cargo transported, signalling, information about the checkpoints cleared, parking times, refuelling, actual amount of load, etc. Based on specific standards (GOST R 55534-2013 *Global navigation satellite system. Road accident emergency response system. Test methods for navigation module of in-vehicle emergency call* *system;* Navigation Data Standard, etc.), satellite navigation systems and vector maps of cities and roads help users to move goods over long distances. There are also "smart" roads which can transmit information about dividers, road signs, open hatches, and unexpected obstacles.

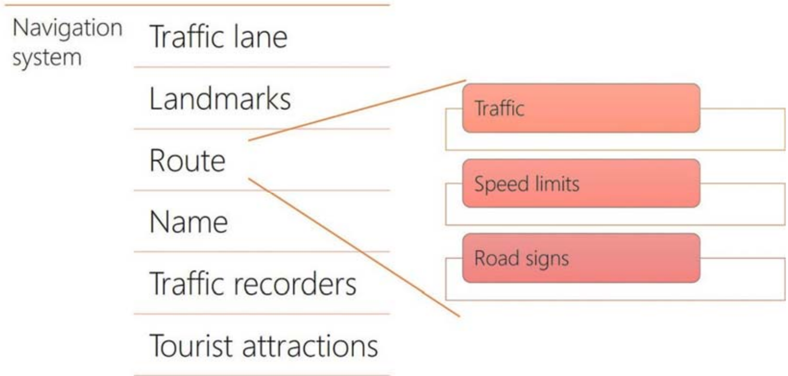


Fig. 6.7. Navigation System Database

Self-check questions

1. Why does a robot need mapping in terms of HRI?

2. Give examples of how pattern recognition technology can help with warehouse operations, equipment modelling, access to the facilities, and the operator's safety assessment.

3. Why is the use of cobots limited?

4. In what way does eye tracking facilitate and control the work of a driver, a welder, or a supervisor?

5. You are buying a robot manipulator for your warehouse. What else does your storeroom need to have besides the robot and the pattern recognition software?

6. Looking at robot sales in 2019, we can see that approximately the same number of robot manipulators and service robots were sold. Nearly half of the service robots sold were warehouse and logistics robots, a third comprised robots to control various operations, and the rest was evenly divided between such types as robots for protection, robots with human-to-human interface, cleaning robots, and exoskeletons. Why?

6.2. Remote Monitoring and Control of Production Processes (Sensors, Controllers)

These days the machine operators' work is limited to the passive control of the production process. To perform this, they have special devices that are installed on machines or supplied with new equipment. The devices in question include sensors and microcontrollers, and together with hardware, networks, and distributed management tools, they constitute the IIoT platform. Sensors are used to collect information about any parameter, such as temperature, network voltage, the environment quality, any visible damage present, etc. A microcontroller is a device that connects hardware and a server or a cloud. One needs microcontrollers to send commands to actuators (devices to perform and process commands, e. g. servomotors, locks, lighting fixtures, etc.) and to make decisions (stop work, change the speed, the rotational speed, or the in-feed, etc.) (fig. 6.8).

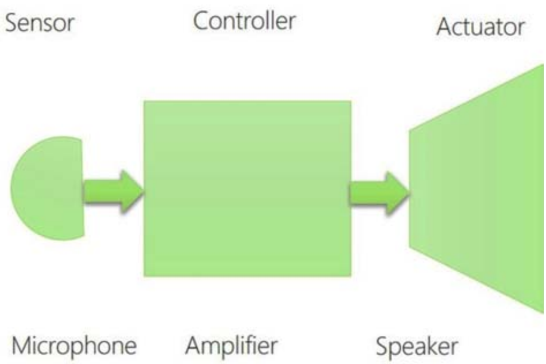


Fig. 6.8. Sensor – Controller – Actuator Example

Sensors and microcontrollers are used to create a unified cyber-physical system of a factory floor. The other peripheral device elements included in the IIoT object system are RF modules (to receive signals from mobile devices using RFID, Bluetooth, and NFC tags), actuators, batteries, and other energy sources or the network. To deploy the IIoT, it is absolutely necessary to have a microcontroller, a battery, and an RF module. A microcontroller can actually work without an actuator if its sensor only transmits a signal to the IIoT network and does not require any action (fig. 6.9).

Fig. 6.9. IIoT Data Transfer and Actions

It is possible to manage data by means of building the IIoT architecture. A modern one consists of several parts:

1. Data from sensors is transferred to a data centre (enterprise servers or a cloud), and commands are transmitted to microcontrollers;
2. Data in the data centre is visualised, processed, and analysed.

The first part is virtually the same to carry out any IoT deployment task. The second part is specific since specific data must be analysed using specific mathematical models of processes (fig. 6.10).

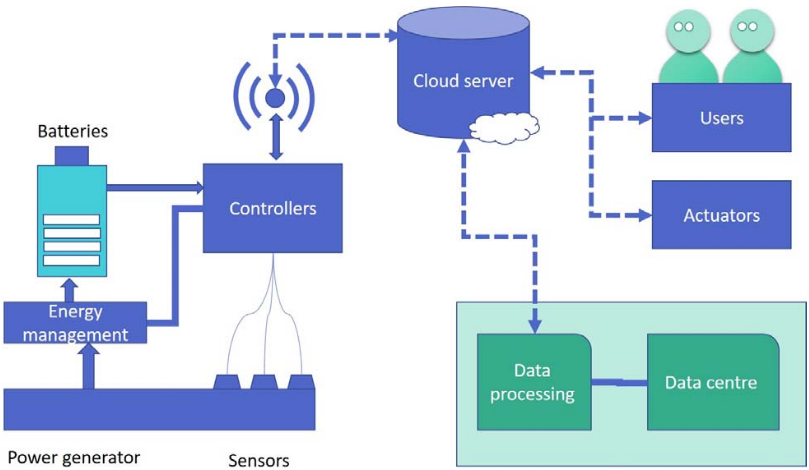


Fig. 6.10. IIoT Networks

For example, the same sensors can collect data about the billet heating temperature, but this information will be processed differently for the aluminum alloy hot stamping process and the contact welding process. When choosing sensors, it is necessary to consider the accuracy and range of measurements of the process, its energy efficiency, installability, dimensions, etc. Also, one should not forget about the scalability, which is the principle of increasing the volume of data processed without any loss of quality if the IIoT is deployed at the pilot site. Sensors are energy efficient since most network objects are wireless and use batteries and accumulators. If a device requires frequent battery replacement, it no longer meets the IIoT principles, that is minimum human involvement.

The first part of the IIoT architecture includes a generating ecosystem which is a set of servers that transmit data from sensors and microcontrollers to the cloud. There are network data transfer protocols such as MQTT (the IoT standard) to transport messages between devices, Wave, Zigbee, and Bluetooth to communicate and integrated SCADA systems to program microcontrollers.

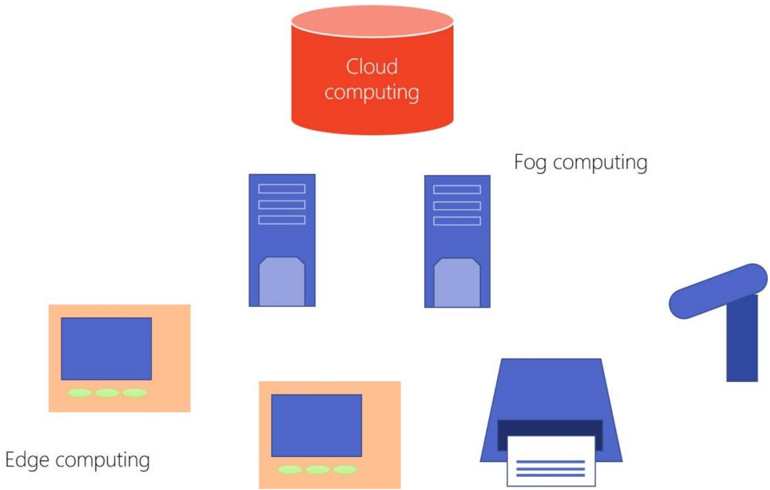


Fig. 6.11. Edge, Fog, and Cloud Computing

The second part of the architecture consists of big data storage and processing servers. Modern technologies allow one to use distributed computing locations, and cloud computing generally serves the purpose (see Section 3). In this case, the equipment and devices themselves can generate or process some of the information. Such distributed computing paradigm is called edge computing. In case of force majeure, this option is mandatory for initial data processing before sending it to the cloud or the company's servers. Devices for such preliminary analysis are called gateways. If one needs to process a large amount of data, the gateways send it to the server. If computing is performed between the hardware and the cloud, it is called fog computing. The last two methods are “closer” to the company”s employees, which means the higher speed of data processing and analysis. In addition, transferring some of the work to the enterprise hardware reduces the load on the cloud. These models are used for real-time problem solving (fig. 6.11).

Company devices can be managed in the following ways (fig. 6.12):

1. The device configuration analysis (equipment, workplace);
2. Service management (starting and stopping operations);
3. Application management (upgrading, installation);
4. Remote management using network protocols;
5. Setting numerical values of an object or a process;
6. Raw data storage, the ability to reset, etc.

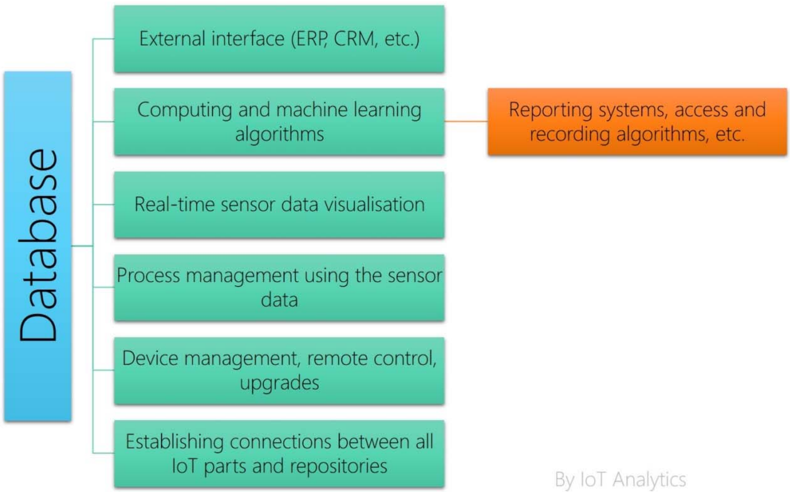


Fig. 6.12. IIoT Functions

However, equipping the hardware with sensors and controllers is not enough to deploy the IIoT. It is also important to create an analytical decision-making centre. To do this, not only should the amount of data convenient for a specialist be collected but also the descriptions of cases and situations in which the result that was obtained based on a specific number of factors should be clear.

Currently, one remote monitoring problem is cybersecurity. Modern enterprise cyber threats are part of research on targeted cyber attacks such as the APT (Advanced Persistent Threat). This term describes the attack itself, its strategy, and the people who perform it. Modern technologies, especially machine learning, are also a possible way of creating cyber threats.

As for the manufacturing industry, such IIoT control systems as sensors and actuators are most often attacked. The fact that a single network connects all the company's devices allows an attacker to hack any of them (especially the peripheral ones, such as a security camera, a workshop thermostat, or a loader light) and get access to all the data of a company. To improve security systems, manufacturers and buyers of the IIoT devices develop regulation rules: more complex identification, password generation, etc. Also, a company should implement certain organisational measures to deal with its staff and to develop an optimal architecture of the IIoT components so that there are no undesirable objects and gateways which can provide hackers with the access to the data about the enterprise.

Monitoring the IIoT network infrastructure includes: protection from botnets (a network of "infected" computers) and DDoS attacks to prevent hardware failure; tracking standardised data transfer protocols as well as the integrated functionality of devices and applications, including mobile ones; recording and storing new accounts with private access. Protection must be maintained at all levels of the digital plant model (the so-called end-to-end security) including a sensor, data transfer, a channel, a data bank, and an IoT application (fig. 6.13).

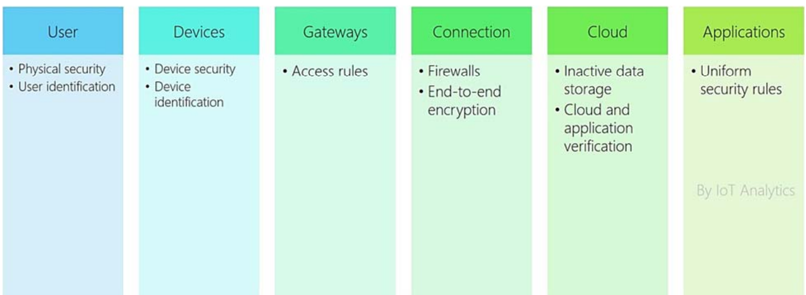


Fig. 6.13. Cybersecurity Elements

Self-check questions

1. Which components of the IIoT system should be installed to accomplish the following tasks: unlock doors, replace a tool bit, stop the

machine when a foreign object is detected in the work area, reduce the refrigerant level in the injection mold, check the necessary materials in the warehouse, track the operator's movement in the designated workshop area?

2. Give an example of a production situation where an actuator is not necessary.

3. Your plant performs such operations as heating the billets and then forging them, using a steam hammer. The IIoT system includes manipulators, a furnace, and the hammer. Which parameters can be monitored directly by the hardware sensors, and which ones is it better to analyse in the cloud or a company network?

4. A wristband with a built-in speaker tracks how often you bring your hand to your face and records the data in the smartphone app. In what production situations can this be of use?

5. What kinds of data can hackers collect in the extractive industries, the machining industry, or the biomedicine industry?

6. Section 2.4 states that some experts expect SCADA to disappear due to the IIoT development. What could have prompted such a conclusion? What does it have to do with edge computing?

6.3. Digital Performance Management

Enterprise performance management is defined by its flexibility and planning production volume, manageability and process transparency. Digitalisation can take an enterprise from monthly production or extraction plans to hourly demand monitoring. Performance management systems help to analyse a value chain, and after that, the profit-and-cost sources in the product life cycle can be spotted (fig. 6.14).

A digital plant ecosystem consists of a large number of components, parameters, and life cycles. To effectively manage parameters, people, processes, products, and resources, we can use system engineering tools. System engineering is a special interdisciplinary methodology which is utilised where life cycles are more complex and extended, and thus traditional management methods can no longer be applied to such a cumbersome system. For example, if a product artificially exceeds its lifecycle threshold, then over time the underlying technologies become obsolete, and new technologies are difficult or impossible to integrate.

The efficiency of the system implemented is determined by stakeholders who can be both individuals and enterprises. Stakeholders have specific roles, such as customers, coordinators, support, and quality improvement. They also have their own requirements that must be considered during the development of a product (fig. 6.15).

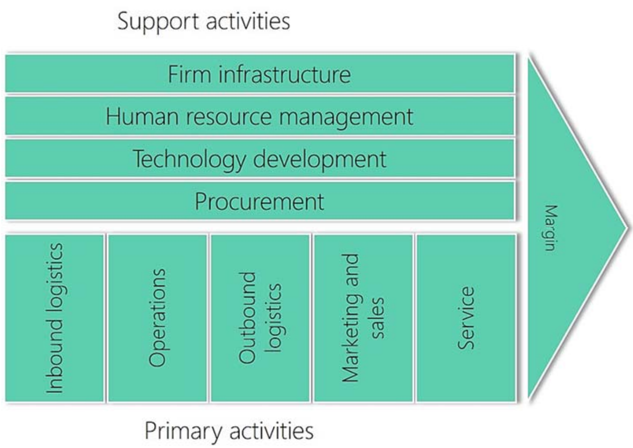


Fig. 6.14. Value Chain

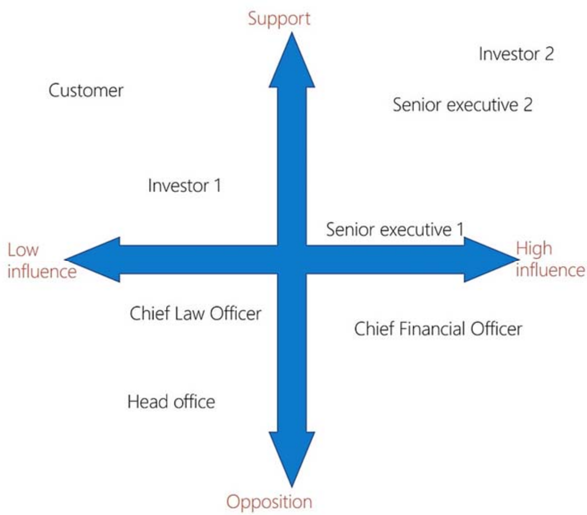


Fig. 6.15. Stakeholders

International standards (e. g. GOST R ISO/IEC 15288-2005 *Information technology. System engineering. System life cycle processes*) are implemented for multiple utilisation of system engineering practices. They describe regulations and instructions related to production and professional activities and help create recommendations to convert all the contractors' requests into a competitive and innovative product. They also provide extensive definitions of lifecycle stages. There are framework standards (e. g. the ones defining the disposal stage) and detailed standards (e. g. a standard for welded joints), and the latter can include enterprise standards – the so-called de facto standards.

While developing a product life cycle, one of the system engineering tasks is to determine the resources or assets involved in production in order to successfully manage them. To do this, there are techniques and software called asset performance management (APM) or enterprise performance management (EPM). Such software allows one to optimise equipment operation, calculate profits, determine possible failures and efficiently use assets during their entire life cycle. Large private and state companies have assets spread over a large area. APM / EPM aims to digitise the entire asset tracking system with minimal human involvement and manage it through a single platform with strict cybersecurity requirements (fig. 6.16).

Fig. 6.16. APM

As a rule, the calculations are carried out using the asset turnover ratio. APM / EPM applications are also a compulsory component of the predictive capabilities of the smart digital product twin, so they use a single database of the equipment, its depreciation, the warehouse status, the amount of resources, etc. In addition, this system can perform the inventory and accounting of the enterprise assets.

Since digital technology implementation at large companies can be impeded by the complexity of systems, the scaling principle is applied. First, the pilot project parameters are calculated, for instance, implementing the IIoT to make a specific product at a specific time (the program horizon). Then, priority areas to implement digitalisation are identified, using a limited production perimeter. If the pilot project provides promising results, the developed digitalisation programs are deployed at a site, a factory floor, and an enterprise, using a scaled platform, after which a technical solution is developed and implemented. However, the scaling stage is quite complex.

Self-check questions

1. What is the flexibility of a modern mechanical engineering enterprise?

2. There are ready-to-use scalable template solutions based on the industry experience which help to implement APM at a modern company. What are the advantages and disadvantages of this approach?

6.4. Automation of Intellectual and Physical Labour

The focus of this section is not traditional types of labour automation, such as mechanisation and automation tools, automated lines, manipulators, etc.

Modern artificial intelligence technologies allow one to use machine learning in mechanical engineering. There are two types of such learning: inductive (learning by precedents) and deductive. The first type helps find common patterns based on particular cases while the second type creates knowledge bases based on the analysis of the data collected. Machine learning is based on mathematical disciplines, such as statistics; optimisation; classification, clustering, and retraining tasks; data analysis; artificial neural networks.

At the core of machine learning by precedents is a set of object parameters or process parameters, which makes up training data. The data in question helps find a universal dependency. The dependency is characterised by a quality parameter, that is how well it describes existing and predicted objects and processes. If the task is to establish relationships by mapping example input-output pairs, it is called supervised learning. However, if there are no triggered reactions, but the task is to find dependencies between a set of parameters, then it is called unsupervised learning (fig. 6.17, 6.18).

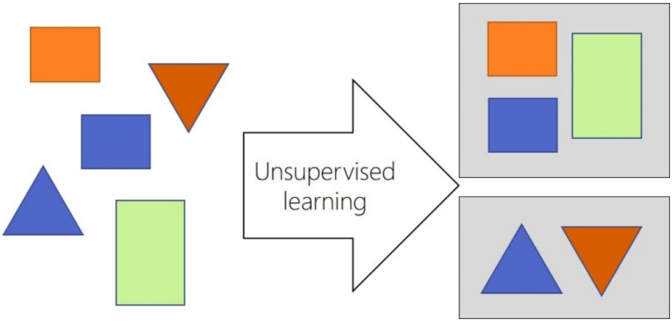


Fig. 6.17. Unsupervised Learning

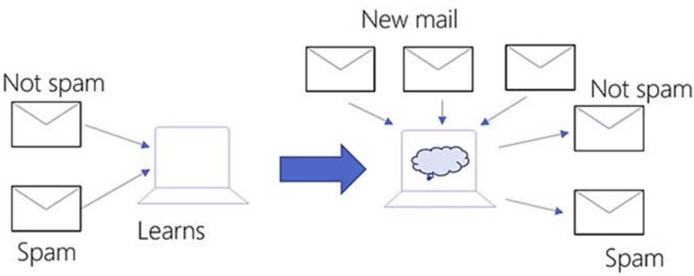


Fig. 6.18. Supervised Learning

Artificial neural networks (ANNs) is a type of machine learning technology. It is a mathematical model consisting of receivers and transmitters (processors) that send signals to each other and that are called artificial neurons. Synapses provide the connections between neurons and help to change the data based on a certain numerical value which is called the weight. Synapses change the data from the input layer of neurons through the hidden layer to the output layer, for example, from an image processing sensor to the object recognition in that image. Each layer of neurons can search for connections at the previous layer. Neural network training is performed using a set of objects with set parameters. This set of parameters uniquely defines the object class. If the number of objects is sufficient, the trained neural network can itself find and define a class object which has not been previously defined in this way. The number of classes determines the number of neurons in the output layer (fig. 6.19).

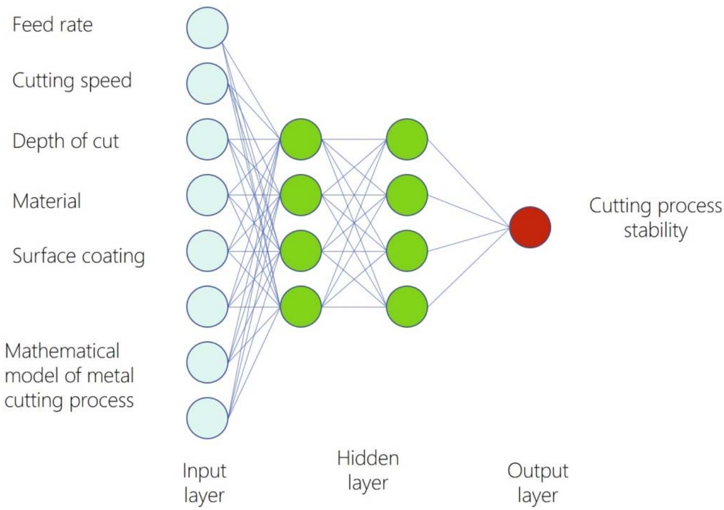


Fig. 6.19. Example of a Neural Network Model

Neural networks in mechanical engineering help to make decisions and manage processes (the so-called neuromanagement); classify and cluster data; recognise objects, voice; and identify users. Neural network has the following advantages:

– it is resistant to extraneous and uninformative signals received by its neurons;
– it can work under the conditions of uncertainty and incomplete data;
– it is flexible as synapses can reconnect and their number can increase.

The automation of intellectual labour leads to greater use of calculations in design. The main task that engineers face is to optimise such things as product design, process parameters, equipment operating modes, flow alignment, etc. Modern product design optimisation solutions will include topology optimisation. It is based on multiple CAE (computer-aided engineering) calculations of all possible product configurations that are limited by certain requirements, for example, fixture points, structural elements, volume, strength, etc. After calculating all possible design shapes, the CAE system selects the one that meets the optimisation criterion, for instance, the minimum weight or cost of the product. The result is a very complex product geometry that is described in terms of bionic design. These designs consist of smoothly connected elements that resemble the natural shapes of plants, bones, and animal ligaments. They are not possible to be obtained by traditional methods such as milling, but their obvious effect, for example, a reduction in weight, economy, and strength, contributes to their use in modern production (fig. 6.20).

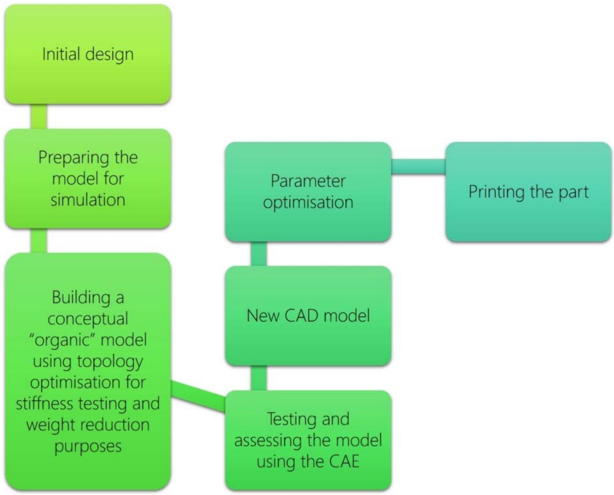


Fig. 6.20. Topology Optimisation Stages

Modern production utilises additive manufacturing technologies for optimisation purposes. Unlike traditional methods, which create the product geometry by removing parts of a larger billet and producing waste material, additive technologies add material to the base. They do not usually imply complex post-processing and mechanical engineering technologies. The materials used include plastic, photopolymers, gypsum, wax, metal powders, sand, and composites. There are the following ways to add material:

– bonding polymer sheets together (sheet lamination);
– selective laser sintering or selective laser melting;
– photopolymerisation, also known as stereolithography (SLA);
– fusing metal/polymer filaments;
– 3D printing.

Additive technologies create products in stages: either layer by layer or batch by batch of liquid material. These batches measure in micrometres. All methods are based on a 3D model of the product. Such models are generally created using CAD, then they are prepared for use, that is they are converted to specific formats, for example, .stl, and receive additional data about accuracy, quality, roughness, number of layers, etc. Creating a product step by step helps control the shape and obtain the geometry of solid objects that cannot be achieved by traditional methods without using assembly, such as milling and stamping. Rapid prototyping requires specific equipment (laser printing machines and printers). CAM systems control the working body of the machine as well as the milling cutter position of the CNC machines, and it requires creating a specific trajectory (the control program of the machine or the printer) and calculating the optimal parameters (fig. 6.21).

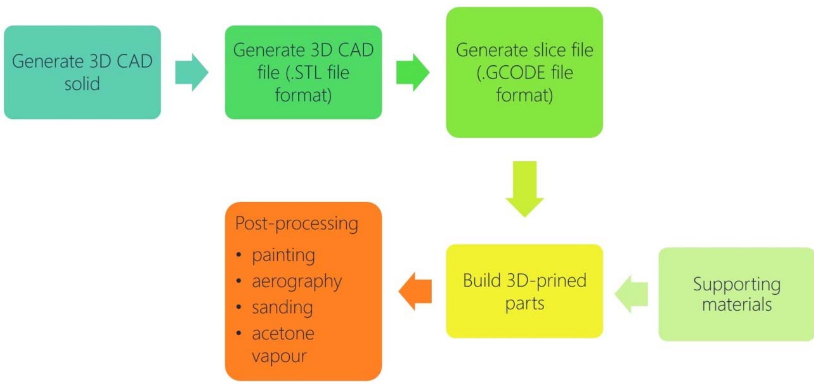


Fig. 6.21. 3D Printing Stages

Technologies that can create metal or composite products have great potential in the field of mechanical engineering, so the most rapidly developing method is selective laser melting (SLM) (fig. 6.22). There is a powder bed in the melting chamber, and a thin layer of metal powder is evenly distributed onto it. The laser beam heats the selected slice of the distributed powder, which leads to its sintering and builds a layer of the part. The powder bed moves down, a new layer of powder is distributed again, and the beam forms the next layer. Supporting frames can be used if needed. After that, the powder is removed, and the product can be sanded or polished if necessary. This technology is used while working with metals: steel (stainless and tool), cobalt, chromium, titanium and aluminum alloys. The parts produced by means of SLM are used in the same way as those built with the help of the traditional production method.

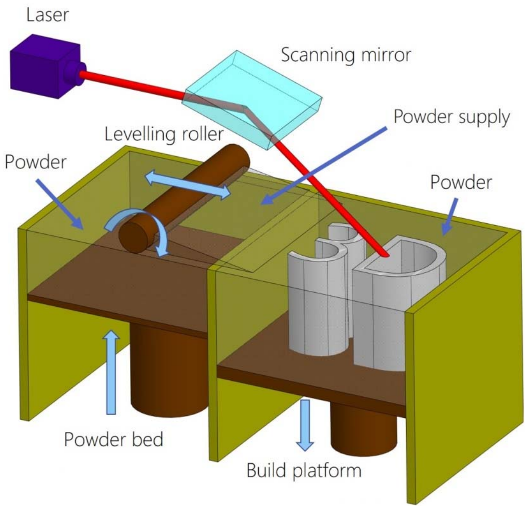


Fig. 6.22. SLM 3D Printing

The most widespread method is still 3D printing or FDM technology (Fused Deposition Modelling). The filament materials can include thermoplastics such as acrylonitrile butadiene styrene (ABS). The material is heated and melted by an extruder head and then deposited onto the build tray, forming a layer of the model. After completing the layer, the build tray moves down, and the print head melts the filament for the next layer. The resulting parts often require post-processing, that is smoothing out the layer lines, due to the thicker layers compared to those obtained by the SLM technology (fig. 6.23).

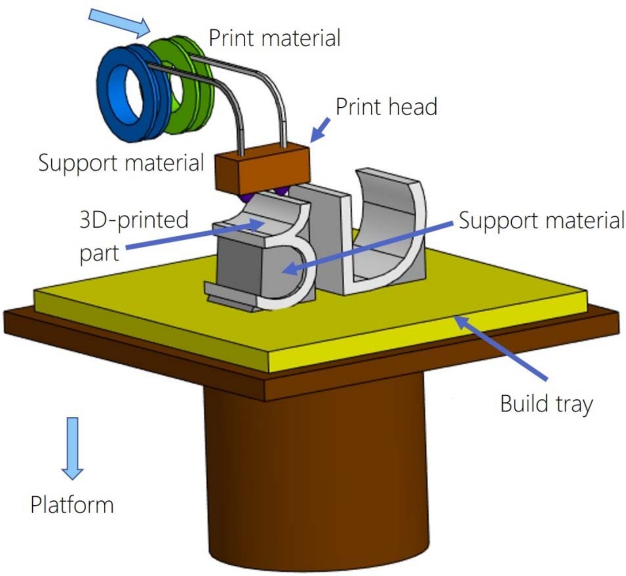


Fig. 6.23. FDM 3D Printing

Additive technologies offer an opportunity to create products of any complex shape and with high accuracy (up to 20 microns) quickly enough. However, at present, the main problems are obtaining the powder composites with the required properties, the complexity of implementing the technology in mass production, and the size restriction.

One of the labour automation technologies is related to transferring some functions of a PC operator to robots. This technique is part of the Robotic Process Automation (RPA) (fig. 6.24). Robots of this type are virtual; they are trained through watching the standard actions of an operator when working with documents in the program, searching for the information, performing successive steps of actions, and then the robots repeat what they have learned. They perform actions in the same way as an operator, moving the virtual mouse over the desired fields of the graphical user interface of the program and pressing the keys of the digital keyboard.

For example, if it is necessary to constantly search for information in separate databases of an enterprise (in archives, in electronic documents of different formats, in accounting and control systems), such a robot can use optical character recognition and, using a set of regulations, make a report for further use in the digital plant.

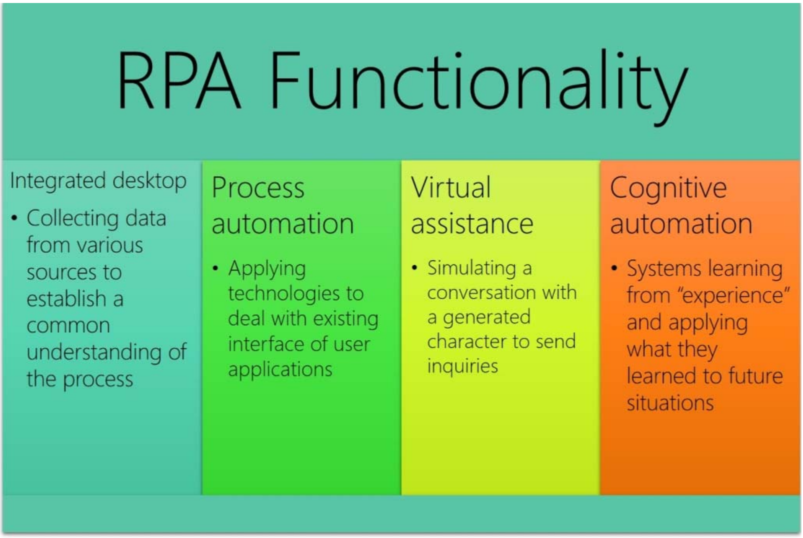


Fig. 6.24. Robotic Process Automation (RPA)

Digitalisation also manages the process of employee training or skills development, and working with the simulations of the digital twins as well as the elements of virtual reality are of great use in this regard.

Physical labour can be enhanced by embedding the operator's role in the cyber-physical systems of enterprises. This requires the operator to be able to interact with the IIoT platform, which, in its turn, requires wireless data transfer methods. These networks are most often local and are generally called WLAN (Wireless Local Area Network). To be able to interact with such a system, operators and other employees can have wearable computers (or body-borne computers). This includes VR and AR devices, such as smartwatches and mobile phones with corresponding applications. Industrial wearable computers can perform the following functions: analyse the environmental parameters and the operator's physical state, perform localisation and navigation, control access to the premises, control the quality of the wearer's actions or the objects he/she is looking at, record images for training purposes, maintain operational communication, and carry out routing automation. Sensors of body-borne computers, for example, AR glasses, can receive voice and visual commands. For instance, a warehouse can have an RFID tag, which will send up-to-date data to the operator's glasses when he/she enters the building (fig. 6.25).

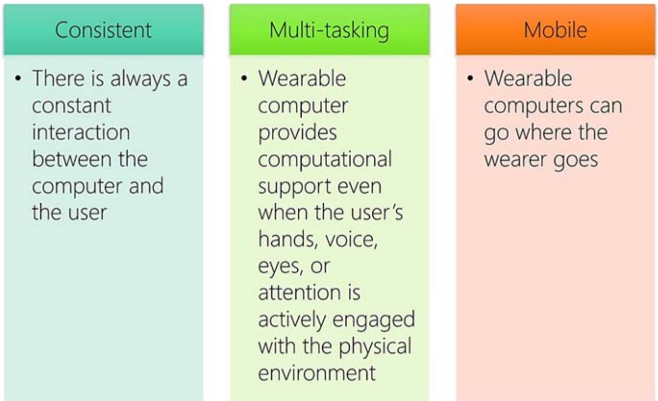


Fig. 6.25. Functions of Body-borne Computers

Using exoskeletons and encapsulated suits is a separate area of physical labour digitalisation in the HRI. Such industrial solutions are necessary in logistics, warehousing, lifting heavy loads, and working in an aggressive environment. Exoskeletons can be used locally (for lower or upper limbs), have different carrying capacity, and the gripping mechanism with a different number of degrees of freedom. They reduce injuries and increase the efficiency of a person's work.

Self-check questions

1. The company collected data on the degree of the tool bit wear and the quality of the items produced. Which training mode can you choose to find the dependency between the product quality and the state of the tool: supervised or unsupervised learning?

2. The company received data on the wear of all tools – tool bits, milling cutters, broaches, etc. It is necessary to cluster wear types by

grouping elements of the set by attributes. Which training mode will you choose?

3. You need to build a neural network that will allow you to predict the temperature changes of the billet during the turning process. How many output layers of neurons are necessary for that?

4. What is the danger of using a small sample to train the neural network?

5. What are the disadvantages of using computer-aided optimisation (CAO)?

6. What is the main advantage of the SLM technology over the FDM in manufacturing?

7. The FDM produces lower surface quality due to the more prominent layer lines than the SLM technology. Why?

8. Which of the following are wearable computers:

– a VR helmet,
– a digital wristband,
– tagged workwear,
– a pass,
– a robotic lifting arm.

7. DIGITALISATION OF EQUIPMENT MAINTENANCE AND REPAIR PROCESSES

The strategy for managing fixed assets, or EAM (Enterprise Asset Management), is closely connected with APM applications. It aims at developing strategic plans for managing all the company assets and their operating modes throughout the PLC. EAM applications help to calculate labour performance, reduce the cost of equipment repair and maintenance, and improve the efficiency. Also, they can be used to coordinate everything related to maintenance, repair, spare parts warehouse replenishment, and funding of these practices (fig. 7.1).

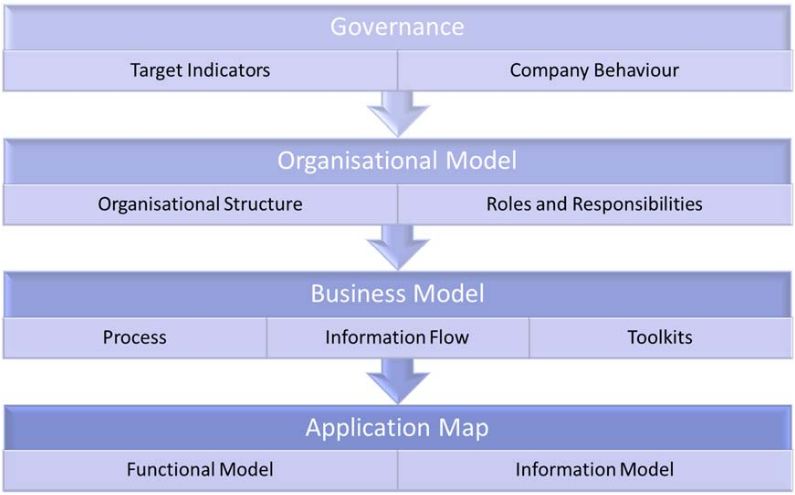


Fig. 7.1. EAM Structure

When developing the concept of a digital factory, it is necessary to perform an EAM analysis, as it helps to estimate the need for new equipment launch or IIoT-based sensors, provide licenses for the enterprise software products, conduct an inventory and perform an analysis of manufacturing modernisation (fig. 7.2).

Fig. 7.2. EAM-components

Maintenance and repair operations (MRO) affect the entire PLC. Two traditional types of MRO, preventive maintenance and scheduled maintenance, are not flexible enough, which means that there is need for digitalisation. EAM determines the RCM (Reliability Centered Maintenance) principle that maintenance aims to ensure the equipment reliability. Placed on the equipment control racks, special programs and devices detect possible failures in operation and prevent them. Sensors can register the start-up time and shutdown time, control the correctness of the program execution, identify a person, and provide a summary analysis (fig. 7.3).

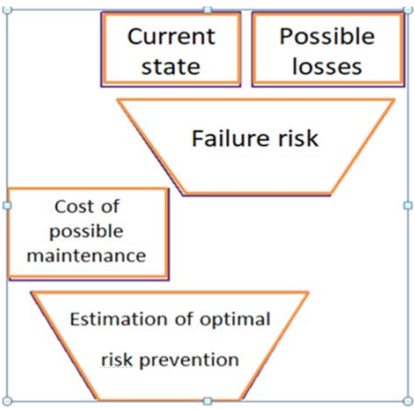


Fig. 7.3. Risk Management

This strategy employs the concept of reliability for the production processes, which are important at any enterprise. Each item of equipment is assigned its own “criticality” indicator, which determines its type of maintenance, from no maintenance to every-minute sensor-based monitoring. It should be noted that the strategy does not mean the ongoing maintenance to provide the ideal state of the equipment since the effectiveness of this approach is low while the cost of maintenance is high. If equipment has high criticality level, there is more funding for its maintenance rather than maintenance of lower criticality equipment, which can longer have no planned maintenance as it has a longer residual life. This approach can be called state-based maintenance (fig. 7.4).

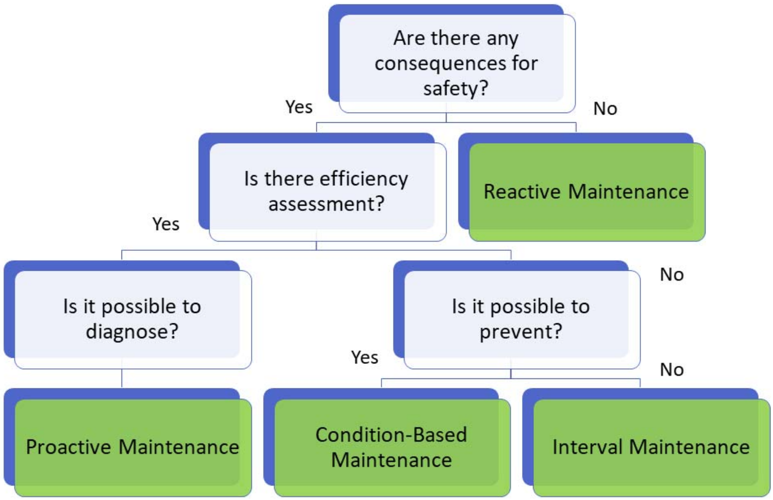


Fig. 7.4. Types of Maintenance

Based on the ongoing monitoring and diagnostics through sensors, the maintenance of high criticality equipment within RCM strategy is known as Predictive Maintenance (PdM) (fig. 7.5). This technology makes it possible to shift from scheduled maintenance by using digital twins for the equipment in operation which helps to:

1. Collect the data on equipment parameters and the state of its nodes;
2. Detect malfunction;
3. Predict failure;

4. Design a maintenance plan;
5. Optimise the allocated resources.

Predictive maintenance aims to detect a time point when the equipment performance indicators are at the start of decreasing, rather than a time point when the equipment fails to operate and requires replacing. It is the monitoring of the equipment state that currently provides a large amount of big data collected and processed at the manufacturing enterprises.

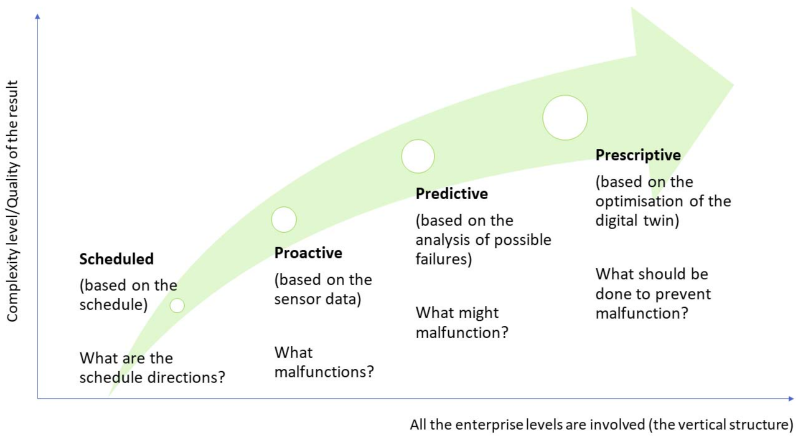


Fig. 7.5. Predictive Maintenance

It is possible to enhance the maintenance efficiency through Total Productive Maintenance (TPM), which aims to reduce all possible losses – from equipment failure to the commissioning of other equipment. The management system involves the equipment service life maintenance, operators from all services, calculation of unexpected losses, prevention of idle running and losses during equipment commissioning and decommissioning (fig. 7.6).

A numerical indicator in this framework can be the Overall Equipment Efficiency (OEE), which is calculated by multiplying the three factors (availability, performance, and quality of equipment) (fig. 7.7). To perform the OEE calculation, IIoT network sensors help to collect the data about shift length, breaks and downtime, ideal cycle time, reject count and total count. According to modern standards, this value should be around 85 %.

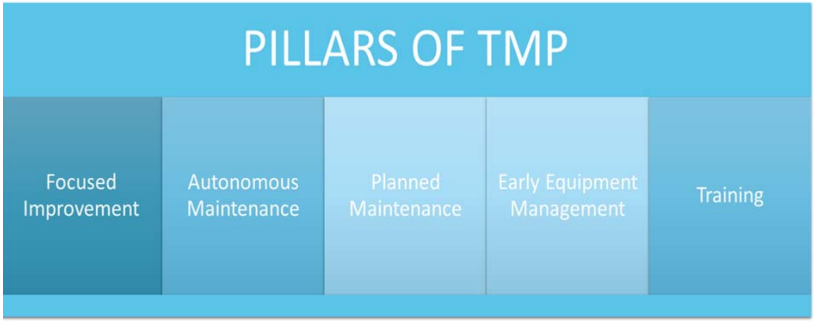


Fig. 7.6. Pillars of TPM

Perfect Production 100%		
Availability	Available time (100%)	Planned downtime
	Operating time (<90%)	Availability loss
Performance	Production capacity (100%)	
	Actual production (<95%)	Performance loss
Quality	Actual Production (100%)	
	Good production (<99%)	Quality loss
World-class OEE 85%		

Fig. 7.7. OEE

Self-check questions

1. What are the advantages of predictive maintenance over scheduled maintenance?

2. What is the connection between the mentioned concepts and SCADA systems?

3. Why is it extremely important to monitor equipment state for the machine learning system?

4. Is a VR helmet for training operators an EAM asset? Why?

CONCLUSION

Digital Technologies in Production Processes is a training course which helps to provide an understanding of developing the digital environment of an enterprise and to empower students with practical skills to use traditional and custom algorithms and find solutions for digitalisation of product lifecycle processes.

The widespread implementation of digital technologies means the implementation of intelligent and interconnected machines and systems and involves changes in graduates' qualifications to meet the requirement of being able to use new digital tools.

The digital world needs specialists who are lifelong learners and self-motivated and who have soft skills allowing them to find a new look at familiar things.

The requirements for specialists are undergoing changes, with a focus on new key competencies such as big data analytics, the ability to work with large amounts of information to optimise processes and enhance the quality of forecasting the results to be achieved.

Specialists have to be fluent in digital technologies, highly adaptable to the digital environment and experienced in modern digital techniques, and these specialists are in demand.

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Glossary

Big Data is a common name of objects of scientific and industrial research related to obtaining, processing and generating data.

ERP is a group of methods and software tools designed for the rational management of financial, labour, material and other resources of an enterprise.

MES is a group of methods and software tools for managing the production processes of an enterprise.

PLM is a group of techniques and software tools aimed to form a single knowledge environment of an enterprise and to manage information units in this environment.

SCADA is a group of methods and software tools used to monitor machines and enable their interaction with enterprise systems.

Rapid prototyping is a technology used to build the initial product concept for a test, analysis, etc.

A **cyber-physical system** is a single structure that joins and connects physical objects and tools for processing, collecting and storing information.

Remote interaction tags are means of remote transmission of information with the help of reading devices.

Predictive analytics encompasses techniques of collecting and analysing information to forecast the consequences of the current process.

Predictive maintenance encompasses techniques of planning and carrying out maintenance activities as suggested by estimations of the current behaviour and state of equipment.

The **Industrial Internet of Things** refers to interconnected means of production and systems of data exchange and processing, which allows for data analysis to make decisions.

Reverse engineering is a technology through the application of which it is possible to create a virtual model based on a real object.

Virtual reality technologies encompass techniques and tools for superimposing virtual three-dimensional models on the physical environment, which allow for varying degrees of interaction.

A **supply chain** is a system of organisations and people, contractors and counterparties, involved in managing and converting the resources or supporting the product release.

Digital transformation is the development of a business strategy to adapt and integrate digital technologies into an enterprise's management, design, production and information analysis, which also allows for support of the infrastructure.

Digitalisation is the process of developing and implementing digital technologies to perform manufacturing tasks.

A **digital twin** in mechanical engineering is a virtual replica of an entity or process.

A **digital production twin** is a virtual representation of production processes.

A **digital factory** uses a group of tools, techniques and technologies for building a virtual replica of each entity and production process, which is updated on an ongoing basis and which is also an interaction model.

The **Fourth Industrial Revolution** is the concept of a new qualitative transition of the world's production, service and household activities from automation systems to cyber-physical systems.

An **enterprise ecosystem** is the result of generating and managing the enterprise necessary information for management and decision-making in "natural" conditions.