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Robotics in Dental Production

A Methodology for the Design and Simulation of Work Environments

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REFERENCE TO SERIES TOPIC

Although the book „*Robotics in Dental Production: A Methodology for the Design and Simulation of Work Environments*“ focuses on the dental industry, it is fully aligned with the aims and methodological framework of the series Monitoring and Analysis of Manufacturing Processes in Automotive Production.

The core objective of the series — the monitoring, evaluation and optimization of production processes, machines, and measuring systems, as well as the application of digital and robotic solutions in industrial environments — is directly reflected in this monograph. The book extends these principles beyond the automotive context and demonstrates their transferability to high-precision, small-scale manufacturing, such as dental implant production.

Through its systematic methodology for designing and simulating robotic workplaces, the publication illustrates how techniques originally developed for automotive mass production — including process monitoring, digital twin simulation, and quality evaluation — can be effectively adapted for customized and precision-oriented manufacturing sectors.

Including this title in the series thus emphasizes the universality of modern industrial engineering approaches and broadens the application scope of the series towards cross-sectoral innovation in intelligent production systems. It highlights how methodologies validated in the automotive industry can inspire advancements in other technologically demanding fields.

ABSTRACT

As the demand for precision, speed, and reliability in dental implant manufacturing continues to rise, industrial robotics is becoming an essential part of modern dental production. Advanced automation and digital technologies are opening new frontiers in manufacturing; while also calling for well-defined methodologies tailored to the unique requirements of the dental industry.

Robotics in Dental Production: A Methodology for the Design and Simulation of Work Environments offers a comprehensive guide to the design, modelling, and implementation of robotic workstations for dental manufacturing. The book begins by introducing the fundamentals of industrial robotics, including robot architectures, end-effectors, and sensory systems. It then explores the landscape of contemporary dental production, from material innovations to advanced manufacturing technologies, before focusing on simulation approaches and their practical applications. The methodological section presents a systematic framework for designing robotic work environments and incorporates procedures for off-line programming. The book concludes with a detailed case study demonstrating the complete application of the proposed methodology to a robotic workstation for dental implant production. Intended for professionals, researchers, and engineers, this monograph bridges the fields of robotics, simulation, and dental manufacturing. It emphasizes the multidisciplinary nature and broad applicability of robotic design principles — not only within dental production but across any manufacturing domain aligned with the vision of Industry 4.0.

KEYWORDS:.

Robotics, industry, dental implant, simulation, production process

Robotics in Dental Production

A Methodology for the Design and Simulation of Work Environments

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Contents

PREFACE

The development of industrial robotics has fundamentally changed modern manufacturing processes and brought new levels of precision, efficiency, and flexibility. In recent years, automation processes and modern digital technologies have also been increasingly applied in the dental industry, where they contribute to improving the quality, repeatability, and reliability of the production of dental implants and prosthetic components. However, the specifics of dental production — such as the need for microscopic precision, strict hygiene requirements, and a high degree of product customization — require special methodological approaches to the design and simulation of robotic work environments.The main objective of this monograph, entitled Robotics in Dental Production: A Methodology for the Design and Simulation of Work Environments, is to provide a theoretical and methodological basis for the analysis, design, and implementation of robotic workstations in dental production, with a particular focus on the manufacturing process of dental implants. The book combines theoretical and practical knowledge, highlighting the nature and importance of interdisciplinarity in scientific fields — especifically industrial robotics and dental production. The theoretical part of the monograph introduces the fundamentals of industrial robotics, describes the main aspects of modern dental manufacturing, and characterizes the creation and use of simulation models and analyses, emphasizing their importance for optimizing manufacturing processes. These theoretical foundations are followed by the practical part, which presents the methodology for designing robotic workplaces, including the design framework and off-line programming procedures. This methodological approach is verified in practice in the final part of the monograph through the creation of a robotic workplace for the production of dental implants. This scientific monograph is intended for researchers, engineers, and professionals from academia and industry who are involved in the integration of robotics and digital simulation into manufacturing processes, with a specific focus on dental production.

1 Fundamentals of Industrial Robotics

Industrial robots (IR) are an important group of devices used to automate production processes. They consist of a manipulator that imitates the movements and actions of the human hand and is controlled by an operator or operates independently. The design of manipulators, which can be biotechnical or automatic, includes control, power, communication and working elements. A specific part of the working element, which takes the form of various gripping devices, tools, sensors and the like, is designed to perform the tasks for which the manipulator is intended. Automatic manipulators include auto-operators, industrial robots and manipulators with interactive control. From the beginnings of robotics development to the present day, human physical abilities have been the main inspiration for the design of robotic systems. The original motivation for creating robots was to replace humans in performing physically demanding and repetitive tasks, thereby reducing the risk of injury and increasing work efficiency. This idea first led to the concept of a robot as an autonomous device, then to the first attempts at its implementation (as early as the Middle Ages), and finally to the formation and dynamic development of modern robotics and automation.

Figure 1 shows a block diagram of the basic robot layout. The diagram includes systems designed to perform tasks, in particular a manipulation system (one or more robotic arms) and, in the case of mobile robots, a motion system that provides translation. It also includes a sensing system that provides the robot with information about its surroundings and a control unit that processes this data and coordinates the activities of the individual subsystems.

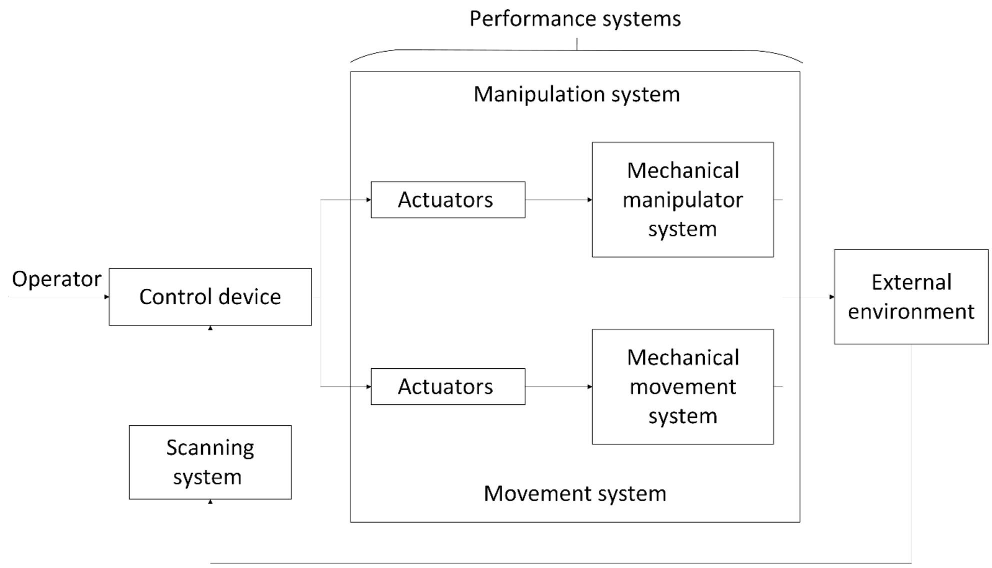

Fig. 1 Functional diagram of a robot

Systems designed to perform tasks consist of a mechanical part and a drive system. The mechanical part of the robotic arm is usually a kinematic chain consisting of movable links with degrees of freedom that perform rotational or translational motion. This chain ends with an end effector, which can be a gripper or other specific working tool depending on the type and purpose of the robot.

Like any other machine, a robot primarily consists of two main components: power systems and a control mechanism with an extensive sensor system. The power systems are further divided into one or more manipulation systems (often in the form of mechanical arms) and a motion system, which is only present in mobile robots. Classifying robots according to their intended use is a key approach to understanding their technical and functional characteristics. One of the main criteria for dividing robots into groups is their purpose, i.e. the area in which they are most commonly used. The dominant category is industrial robots (IR), which are used in various industries and account for approximately 80% of all robots worldwide. Industrial robots are further divided according to the tasks they perform – for example, robots designed for painting, welding, material handling or the operation and maintenance of machines in machining centres, press shops and foundries. In terms of the type of operations performed, industrial robots are divided into robots for main production processes and robots for auxiliary operations related to the maintenance and operation of production equipment. Robots for main processes are considered primary technological equipment, while auxiliary robots can be classified as automation tools. Depending on the scope of tasks for which they are intended, robots are classified as specialised, narrowly focused or universal:

- Specialised robots are designed to perform a single, precisely defined technological operation (e. g. a specific assembly task or the operation of a certain type of equipment).
- Narrowly focused robots can perform several related operations, for example by changing tools or adapting to different production equipment.
- Universal robots are designed to handle a wide range of primary and secondary tasks within their technical parameters.

Increasing versatility expands their potential uses, but at the same time can lead to reduced efficiency in performing specific specialised tasks. From this perspective, specialised robots are usually more efficient, although their market application and production volume remain limited.

1.1 Categorizing of robotic systems

Robotic systems can be categorised based on their design characteristics. These criteria include:

- Drive type: Drive systems used (electric, hydraulic, pneumatic or combinations thereof).
- Load capacity: The maximum weight that the robot can handle or transport.
- Number of manipulators: The number of arms the robot has.
- Working space: The range and characteristics of the area in which the robot can operate.
- Mobility and location: The robot's ability to move and the way it is located in space (e.g. stationary, mobile).
- Design purpose: The specific purpose for which the robot was designed.

Robot drives are usually electric, hydraulic or pneumatic, and are often combined. For example, hydraulic systems are used for more demanding tasks, while pneumatic systems are more suitable for simpler and less powerful operations. Load capacity varies depending on the application, from very low weight for microelectronics to high weight for heavy industry or space applications. Most robots have a single manipulator, but there are also systems with multiple arms (two, three or four), which may be identical or different. For example, industrial robots may have two different manipulators – one for main operations and another for simpler tasks such as ejecting parts.

The type and characteristics of the working space of a robotic manipulator define the area around it in which the robot can perform manipulations without moving, i.e. with a stable base. The working space of a manipulator is the space in which its end effector can be located in all potential positions given by the movement of the individual parts of the manipulator. The geometry of the working space is influenced by the coordinate system in which the end effector moves and the number of degrees of freedom of the manipulator.

The mobility of a robot depends on the existence or absence of a relocation system. Robots with a mobile system are referred to as mobile, while robots with a fixed system are stationary. Depending on their purpose, robots use almost all known types of relocation systems: from ground wheeled and tracked systems to systems designed to move in water, deep underground, in the air and in space. Walking is a specific mode of movement in robotics.

The location of robots in operation determines whether they are stationary (fixed to the floor), mobile (e.g. moving along a ceiling track) or integrated into other equipment (such as servo machines). The design of a robot is adapted to the environment in which it will operate. Therefore, there are different designs, such as standard, dust-resistant, heat-resistant, moisture-proof or explosion-proof robots. Robots can also be divided according to their control method into software-controlled, adaptive and intelligent robots.

The movement of each robot joint can be either continuous (following a contour) or discrete (with positioning). In discrete control, movement is performed through a defined sequence of points (positions), with the robot moving between these points sequentially, without trajectory control. The simplest type of discrete control is cyclic, where the number of positions for each joint is minimal, often only two – the start and end positions.

Robots are commonly classified according to the speed and accuracy of their movements. These two closely related aspects define the dynamic properties of robotic systems. The speed and accuracy of robots depend on the parameters of their manipulators and motion systems.

The speed of a manipulator is determined by the speed at which its end effector moves. In the case of universal robots, the speed of the manipulator is usually divided into the following three categories:

- Low: linear speed up to 0.5 m/s.
- Medium: linear speed from 0.5 to 1-3 m/s.
- High: speeds above 1-3 m/s.

State-of-the-art robots can achieve manipulator speeds of up to 10 m/s and more. Speed is crucial for many robotic applications because it affects productivity. However, increasing speed comes at the expense of accuracy. The accuracy of the manipulator and motion system is measured based on positional deviation (for discrete movements) or deviation from the desired trajectory (for continuous movements). Accuracy is often expressed in terms of absolute error. In general, the accuracy of universal robots can be classified into three groups:

- Low: linear error of 1 mm or greater.
- Medium: error in the range of 0.1 to 1 mm.
- High: linear error less than 0.1 mm.

Robots with the lowest accuracy are typically used for less demanding tasks, such as moving materials. Conversely, robots with the highest accuracy (achieving accuracy in microns) are used in industries such as the electronics industry.

Compared to the human hand, modern robots suffer from a problem of decreasing accuracy with increasing range of motion of the manipulator. In humans, these parameters are to some extent separated due to the division of movements into coarse (fast) and fine. The above parameters (speed and accuracy) serve as criteria for the classification of robots and determine their type designation. For example, it can be a "light pneumatic industrial robot with cycle control for operating presses in plastics production" or a "hydraulic industrial painting robot with trajectory control".

The technical level of robots is determined by several parameters that complement their classification parameters. Some of these parameters, such as speed and accuracy, can be expressed numerically. Unlike classification, where parameters assign a robot to a specific category, the assessment of technical level takes into account the exact numerical values of these parameters.

In addition, the technical level of robots is also assessed on the basis of reliability, the number of simultaneously active degrees of freedom and the time required for programming. Derived and combined indicators are also used, such as the ratio of load capacity to robot weight, the ratio of manipulator output power to drive power, relative dimensions, kinematic and dynamic control characteristics, programmability, and economic efficiency. These derived indicators are not used to specify particular robots, but rather as criteria for optimisation during design and for comparative evaluation.

Currently, mechanical manipulators predominate in robotic handling systems. These are spatial mechanisms, typically with an open kinematic structure of links connected at joints with one or two degrees of freedom, allowing rotational or translational motion. The drive is provided by a system, often independent for each degree of freedom. At the end of the manipulator is the end effector. The degrees of freedom of the manipulator are divided into translational and rotational. Translational degrees of freedom are used to move the end effector within the working space of the manipulator, while rotational degrees of freedom are used to rotate it. The minimum number of translational degrees of freedom required to move the end effector to any point in the available working space is three. To improve handling capabilities and perform more complex motion paths, such as obstacle avoidance, and to increase response speed, manipulators are commonly equipped with redundant translational degrees of freedom, which, however, significantly complicates the robot and increases its cost. Common manipulators have an average of 4-6 degrees of freedom, but there are also manipulators with 8-9 degrees of freedom. The maximum number of degrees of freedom required is three. These are commonly achieved by means of kinematic joints that allow angular movement, thereby rotating the manipulator's end effector around its longitudinal axis and two other mutually perpendicular axes.

The design of manipulators is primarily defined by their kinematic structure. The type and location of the drives and mechanisms through which the movement is transmitted to the individual joints of the manipulator also play an important role. In addition, balancing devices are often used in the design, which also significantly influence the overall concept of the manipulator.

In terms of efficient transmission of motion from the motor to the manipulator joint, it is considered most appropriate to place the motors directly on the joints they drive. However, this arrangement increases the overall dimensions and weight of the manipulator. This disadvantage is more pronounced the greater the distance of the joint from the base of the manipulator and the closer it is to the working element, because the greater the number of preceding joints and their drives that are loaded by this joint.

It follows from the above that as the distance of the link from the base increases, so does the advantage of moving the motor closer to the base of the manipulator. However, such a solution requires the introduction of a suitable mechanism for transmitting motion from the motor to the relevant link, which significantly complicates the design of the manipulator.

1.2 Gripping systems

Gripping systems are designed to grip, fix during movement and subsequently release the object after the required operation has been completed. The main types of handling equipment include mechanical, pneumatic and electromagnetic systems. Given the diversity of the objects being handled, a wide range of combinations of these basic principles are used in practice, as well as specially developed handling tools based on innovative mechanisms, such as adhesive, pinching or aerodynamic principles. Mechanical grippers are designed as handling units whose operation is based on a principle similar to that of the human hand. The simplest, two-finger variants are designed to mimic the function of pliers, supplemented by a drive mechanism. Depending on the nature of the objects being handled, grippers with three, four or, in specific cases, even more fingers are used in practice.

Information about the objects being handled is commonly obtained through touch, slip and force sensors built into the gripping systems. In addition to these, remote sensors, such as ultrasonic or optical sensors, are also used to detect objects near the gripper or between its fingers. Vacuum grippers are among the most widely used types of gripping systems. They use the principle of negative pressure to grasp and hold objects, which is created by sucking air between the surface of the gripper and the object. More complex shapes of objects are gripped by vacuum grippers equipped with multiple suction cups, which ensure even distribution of forces and stability of the grip. Magnetic grippers, like vacuum grippers, are widely used in the handling of ferromagnetic materials. In practice, electromagnetic grippers are used, especially in robotic systems, as well as grippers with permanent magnets. The release of the object is ensured by special mechanical elements or by changing the magnetic field. Grippers can be designed as universal systems or specialised tools for handling specific types of objects, such as fragile, elongated or textile materials. The gripper is often connected to the robot arm using flexible connecting elements that compensate for minor positional inaccuracies and at the same time reduce the mechanical load on the robot's motion units when handling objects that are mechanically restricted in their movement (e.g. during assembly, disassembly or precise placement in holders).

Gripping systems commonly use various types of sensors to ensure interaction with the objects being handled. The most commonly used are contact sensors (touch and tactile), slip sensors and force sensors, which measure the forces acting in one or more directions. In addition, non-contact sensors, such as ultrasonic or optical sensors, are also used to detect the presence of objects in the vicinity of the gripping mechanism or in the space between its fingers. The most common type of grippers using the vacuum principle are vacuum grippers with suction cups. The object is held in place by creating a vacuum by sucking air out of the space between the gripper and the surface of the object. More complex geometric shapes of objects are handled using vacuum grippers with multiple suction cups, which allow for a more even distribution of forces and a more stable grip. Similar to vacuum grippers, magnetic grippers have long been used to handle ferromagnetic materials. Modern robotic systems often use electromagnetic grippers that allow controlled activation and release of the magnetic field, but there are also variants with permanent magnets. In these systems, the release of the object is ensured by special mechanical elements or mechanisms.

Gripping systems can be universal in nature, designed for a wide range of handling tasks, or specialised, designed to work with specific types of objects, such as fragile, elongated or flexible materials (e.g. textiles). In most cases, the gripping mechanism is connected to the robot arm using flexible connecting elements. These components compensate for minor positional inaccuracies and at the same time reduce the mechanical stress on the robot's structural parts when handling objects whose movement is mechanically limited – for example, during assembly, disassembly, insertion of parts into clamping devices or when moving along guide tracks.

1.3 Robot sensors system

Robot sensor systems are precision measuring devices whose main task is to acquire and process information about the current state of the surrounding environment. Some robotic systems are equipped with additional sensors or measuring elements that are necessary for the proper functioning of individual subsystems, such as feedback sensors in drives or devices for monitoring energy sources. These elements monitor the robot's internal variables (such as position, speed or energy consumption), but since they do not provide information about the external environment, they are not considered part of the robot's sensor system in the broader sense. In terms of the type of data obtained, robot sensor systems are generally classified into three basic categories:

- Sensor systems for detecting the spatial properties of objects and the overall layout of the surrounding environment,
- Sensor systems for measuring physical quantities (e.g. pressure, temperature, force, acceleration),
- Sensor systems for detecting the chemical properties and composition of substances.

Common examples of sensor systems in the first category are coordinate measuring devices, such as scanning locators, laser or ultrasonic rangefinders, and optical position sensors, which enable robots to orient themselves in space and identify objects.

The second category of sensor systems, designed to measure the physical properties of objects, is the most diverse in terms of design and function. It includes, for example, pressure, temperature, touch, force, torque, acceleration and other sensors that enable precise control of the robot's interaction with the environment and monitoring of dynamic processes during manipulation. The most important types of sensors used in robotic systems are those that enable the measurement of force, density, temperature, colour and transparency of materials. Another category is sensors designed to analyse the chemical composition and physical-chemical properties of substances, which are mainly used in industrial quality control and biomedical applications.

The data obtained from the sensors is processed in the robot's control system, where it is used to identify objects in the vicinity and to precisely control the movement of the arms, end effector and mobile base. In terms of operating distance, sensor systems are classified into four basic groups:

- touch sensors,
- short-range sensors,
- long-range sensors,
- very long-range sensors.

Touch sensors are mainly used to monitor the active parts of robotic arms or the body of mobile robots (e.g. bumpers). These sensors register physical contact with objects, measure the forces acting at the point of contact and detect the displacement of an object when grasped. Despite their simple design and high reliability, they can limit the dynamics and speed of robot movements because they only provide information after contact with an object.

Short-range sensors provide data on objects located in close proximity to the end effector or robot body – i.e. at distances comparable to its own dimensions. This group includes, for example, position sensors, short-range optical and ultrasonic rangefinders, and devices for measuring density or distance without direct contact. Although these non-contact sensors are technologically more complex than touch sensors, they enable higher speed and smoothness of robot operation, as they provide information about the environment even before physical contact with the object occurs.

Long-range sensors allow robots to obtain comprehensive information about their surroundings, whether it is the working space of a manipulator or the wider environment in which a mobile robot moves. These systems provide data on the position, shape and distance of objects in the working area and play a key role in trajectory planning, navigation and obstacle avoidance.

Very long-range systems are designed to monitor objects located outside the robot's immediate working space. They are mainly used in mobile robotics for navigation, localisation and movement coordination, but they are also used in stationary robotic systems. In these cases, they enable early detection and prediction of the movement of objects entering the robot's working area, thereby increasing the safety and efficiency of work process control. In terms of their operating principle, contactless sensors are divided into active and passive systems.

Active sensors use their own transmitted signal – for example, an optical, ultrasonic, radio or laser pulse – and the receiver then detects the reflected or deformed signal from the surface of the object.

Passive sensors do not have their own radiation source; they receive natural emissions from the environment or objects, such as infrared radiation, thermal radiation or reflected light. These systems are simpler in design and less expensive, but they provide less information and have a limited range of applications. Sensor devices can be further classified according to the nature of the sensing:

- Fixed-direction sensors monitor a predefined area,
- Scanning sensors can change the angle of view or direction of sensing, allowing them to create spatial models of the environment.

In current robotics, the most commonly used sensor systems include:

- machine vision systems,
- localisation and navigation systems,
- force and torque sensors,
- touch and pressure sensors.

These technologies enable robots to acquire and process multi-level information about their environment, which is a prerequisite for autonomous decision-making, adaptive control and interaction with the surrounding environment.

Touch sensors are among the basic detection elements used in robotics. In addition to registering direct physical contact with an object, they are also used to measure the geometric and dimensional characteristics of objects through tactile feedback. From a design perspective, touch sensors can be implemented using various technical principles – most commonly limit switches, hermetically sealed magnetic contacts (reed switches), piezoelectric elements or conductive rubber (also known as artificial skin), which changes its electrical properties depending on the pressure applied. The key requirements for these devices are:

- high sensitivity, enabling the detection of forces in the order of grams,
- compact dimensions that do not restrict the robot's movement,
- mechanical resistance and reliability under long-term operational load.

The disadvantage of touch sensors is that they only provide information after contact with an object, which can slow down the robot's reaction time and reduce the smoothness of its movements. To increase the reliability and efficiency of work processes, modern robotic systems are increasingly using non-contact sensor arrays that allow objects to be detected before physical contact. These systems use, for example, optical (light) sensors, ultrasonic distance sensors or infrared detection elements, thereby significantly improving the accuracy, speed and safety of handling in automated processes.

The robot's control unit ensures automatic control of its actuators, thereby controlling handling operations and movement functions. Together with actuators and sensors, it forms an automatic robot control system that enables the execution of defined tasks without direct human intervention. Robot control units often also perform coordination functions within integrated technological units, where they ensure the synchronisation of the robot with other devices, such as technological instruments, transport systems or assembly lines. In terms of control methods, robot control systems are divided into three basic categories:

- Programmed systems – control is performed according to a predefined control programme that does not change during execution. This type of control is typical for repetitive technological operations with fixed parameters.
- Adaptive systems – the control process continuously adapts to the current environmental conditions and the state of the robot based on data obtained from sensor systems during operation.
- Intelligent systems – these represent an advanced form of adaptive control that includes elements of artificial intelligence enabling independent decision-making, planning and task optimisation.

Control units can be independent, i.e. integrated into each individual robot, or group-based, coordinating the activities of several robots in a shared work-space. Independent control units are usually constructed separately from the mechanical parts of the robot; less often, they are located in a shared structural enclosure.

2 Main Aspects of Modern Dental Production

Modern medicine is increasingly using implants to restore or replace bodily functions. These systems are commonly used to replace damaged hip, knee and elbow joints, as well as to manufacture prostheses for missing limbs. Implants are also widely used in jaw and maxillofacial surgery, for example in the reconstruction of parts of the skull. Various types of materials are used in their manufacture, with stainless steel and titanium alloys being particularly widespread due to their high strength and corrosion resistance. This chapter described the main aspects of modern dental production, e.g. classification of dental implants, history of materials´s development, also technologies descripton.

2.1 Dental implants

In dentistry, implants are classified by type as endosseous (intraosseous), transosseous and subperiosteal (Figure 2). Endosseous implants are the most commonly used type and are divided into root, plate and combined implants. They are usually made of titanium alloys and consist of three parts – the root, neck and head. Transosseous implants are used in cases of bone loss in the lower jaw and have a three-dimensional structure, most often made of titanium alloys. Subperiosteal implants are an alternative in cases where intraosseous implants cannot be used. They are shaped like a metal frame with supports protruding into the oral cavity and are usually made of titanium alloys.

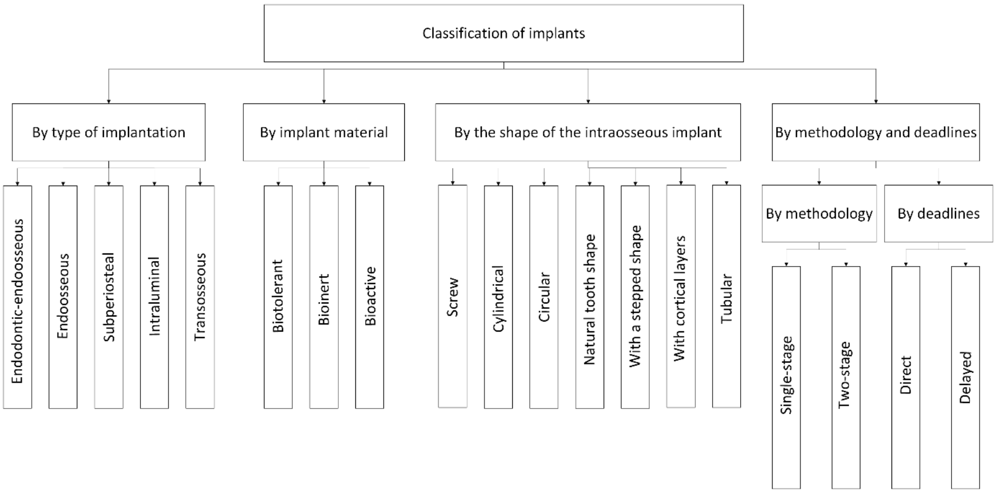

Fig. 2 Classification of dental implants

In terms of the material used, implants are divided into bioactive, biotolerant and bioinert. Bioactive implants are metal implants with a surface treatment of hydroxyapatite or tricalcium phosphate ceramics, which promote bonding between the implant and bone tissue. Biotolerant implants are made of stainless steel or chromium-cobalt alloys, which are well tolerated by tissues but do not form a direct bioactive bond. Bioinert implants are made of materials with high chemical stability, such as titanium, zirconium, gold, corundum ceramics or glass, and are considered to be of the highest quality in terms of workability and biocompatibility with tissues.

Dental implants are classified according to their shape and structural arrangement. The most commonly used are screw, tubular and cylindrical implants, which are manufactured by plastic forming or chip machining. Less common are plate implants in the form of frames or overlays, which are used to stabilise damaged areas of the upper or lower jaw. Bending and drawing technologies are used to manufacture these sheet metal semi-finished products. Most metals and their alloys used in dentistry are suitable for processing by plastic forming and machining.

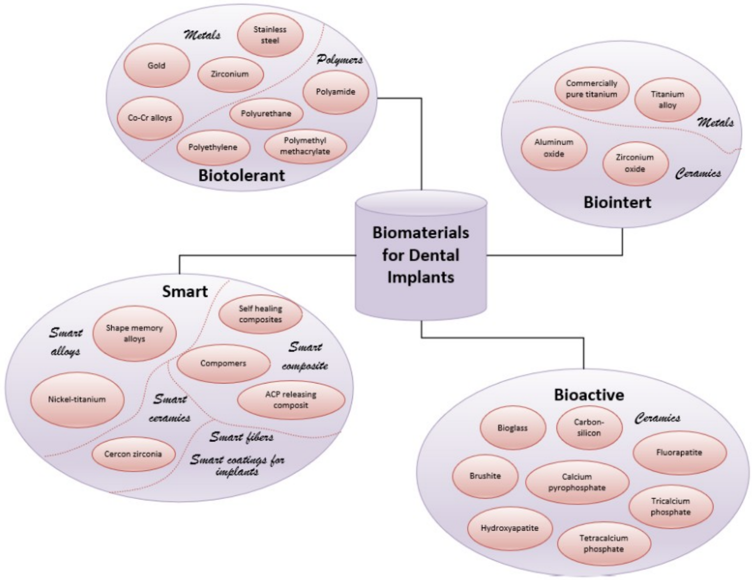

Fig. 3 Classification of biomaterials used in dentistry

Plastic deformation processes are not used as a final treatment in the manufacture of implants, but serve to improve the structure of the metal and thus increase its physical and mechanical properties. To achieve the desired shape, additional technological operations such as precision forming or machining are often applied after plastic deformation. The combination of plastic deformation and forming makes it possible to increase the resistance of implants while using softer, less rigid materials without reducing their functional properties.

Research in the field of plastic deformation of materials has shown that the presence of pores in the material structure of an implant can improve its biocompatibility and, in many cases, reduce the risk of implant rejection by the body. In recent years, scientific research has focused intensively on studying the biological compatibility of materials used in the manufacture of implants, with the aim of optimising their physical, chemical and biological properties for long-term clinical use.

Recent studies have shown that the commonly used titanium alloy Ti6Al4V, although characterised by high strength and corrosion resistance, may have potentially adverse effects on the human body due to the presence of alloying elements. This alloy is used in practice for the manufacture of dental pins for front teeth, as it provides the required strength while maintaining small dimensions, which many other dental materials do not allow. Currently, material research is intensively investigating ways to increase the strength of titanium alloys without the need for harmful additives, for example through the use of technically pure titanium Ti(2.5)Al(2.5)Fe. One of the approaches used in this research is intensive plastic deformation (IPD). IPD methods have been proven effective in the manufacture of certain types of implants, but their wider industrial use is currently limited by the complexity of the design of components manufactured using this technology and insufficient implementation in industrial production. A foldable screw implant with a root shape is shown in Figure 4.

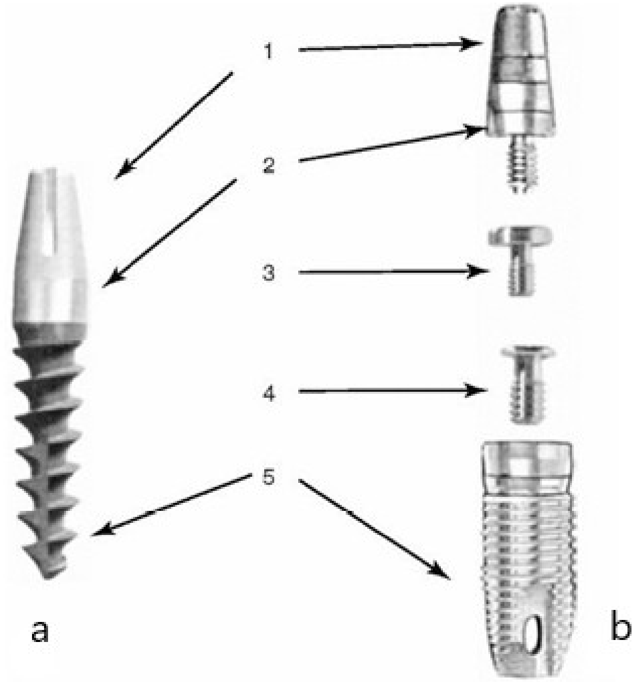

Fig. 4 Foldable root-shaped screw implant: a - complete implant in assembled state, b - individual structural parts. 1 - implant superstructure; 2 - abutment fixing screw; 3 - locking pin; 4 - connecting element; 5 - implant body

Due to the different design solutions and methods of implant placement, various procedures and terminological designations for implantation have been developed and are used in clinical practice. To im prove the integration of the implant with bone tissue, a porous layer with a pore size ranging from 0.05 to 0.25 mm is applied to its surface. This layer ensures a firmer anchorage of the implant in the patient's jawbone. In the case of some titanium alloys, it is not necessary to create an additional surface layer, as the material naturally contains micropores that support the osseointegration process.

Root-shaped implants are typically manufactured in cases where there is sufficient space in the bone tissue. Their design takes into account the minimum required implant height of 8 mm, a thickness of at least 5.25 mm in the direction from the buccal to the lingual side, and a width of at least 6.5 mm between adjacent implants. These implants are designed in two parts – a part intended for insertion into the bone (endosal part) and a part above the surface (extrasal part). The endosal part can be cylindrical or screw-shaped and, depending on the type of processing, can be designed as an assembled or non-detachable part.

From a manufacturing technology point of view, cylindrical implants have the smallest active contact area, as their surface is relatively smooth. For this reason, the surface of cylindrical implants is modified by creating a texture or applying a bioactive coating that enhances their functional properties. Currently, all cylindrical implants are manufactured as modular structures designed for multi-stage assembly.

Screw implants are among the most common types and are manufactured in many variants with different thread profiles. They can be designed as modular or non-modular, with a smooth, roughened or bioactive surface, depending on technological requirements and functional purpose.

The basic structural elements of these implants are anti-rotation mechanisms, which take the form of latches, recesses, platforms and longitudinal grooves located in the lower part of the implant. These elements ensure the stability of the implant during its operation and prevent its rotation in the bone bed.

The surface treatment requirements for lamellar (plate) implants are analogous to those for cylindrical implants. Lamellar implants can be designed as modular or non-detachable, and their surface is usually structured or has a rough, wavy shape resembling a snake, often with holes allowing bone tissue to penetrate and integrate. These implants are manufactured for cases where the thickness of the bone base is insufficient for the use of root implants. Their shape is flat and elongated, which allows them to be applied to narrow bone structures. The design takes into account the minimum required bone height of over 8 mm, thickness in the buccolingual direction of over 3 mm and mesiodistal width of over 10 mm (may be smaller when replacing a single tooth).

The group of combined implants includes lamellar, transmandibular (through the jaw), frame implants and implants with combined shape elements in the part intended for anchoring in the bone. Lamellar implants are used in cases where screw or cylindrical types are not suitable. Their manufacturing process requires specific technological processing. The main advantage of these solutions is the possibility of use in a wide range of bone bed construction conditions, regardless of the degree of resorption. Another advantage is the shorter production and processing time, which allows for quick preparation of the implant for subsequent clinical use.

Frame implants are structurally classified as implants intended for insertion into bone, although their shape differs. They are characterised by a branched plate structure and are intended for use in cases of significant bone loss in the lower jaw, where there is insufficient bone height for root implants. These implants serve as supporting elements for removable or fixed dental prostheses. Their design takes into account a minimum vertical bone height of 6 mm and a buccolingual thickness of more than 3 mm.

2.2 The history of the development of materials and technologies

The history of the development of materials and technologies clearly confirms that scientific discoveries and the improvement of production methods are closely linked. Over the millennia, there has been a transition from manual craftsmanship using natural raw materials to automated and digital production systems using synthetic and nanostructured materials.

In the early stages (the Stone and Copper Ages), manufacturing processes were based on the manual processing of natural materials such as stone, wood, bone and clay. The first technological operations included cutting, grinding and firing, which laid the foundation for deliberately influencing the properties of materials. With the development of metallurgy (in the Bronze Age), the smelting of copper, gold and tin was mastered, as well as casting – the first example of moulding, which enabled the larger-scale production of more complex products.

During the Iron Age, techniques for processing metals at high temperatures and forging were developed, enabling the transition from casting to methods of shaping materials through plastic deformation. The development of glassmaking and porcelain production marked the beginning of a chemical-technological approach to production, in which control of chemical composition and temperature became key factors.

During the Middle Ages, production gradually became more specialised. Craft workshops developed, in which water and wind energy began to be used to mechanise technological processes. The emergence of manufactories enabled the development of the first standards for material processing and, at the same time, increased precision in the production of individual components.

The Industrial Revolution in the 18th and 19th centuries represented a fundamental breakthrough, with the introduction of steam engines, mechanical presses and the vulcanisation process enabling the expansion of large-scale industrial production. During this period, metalworking processes – cutting, drilling and milling – were standardised and the foundations for the documentation of production processes were laid. Production systems were gradually mechanised, then powered by electricity and finally automated.

The 20th century was characterised by the integration of mechanical, chemical and physical processes into unified production units. New types of materials were developed, such as polymers, technical ceramics, composites and special alloys. During this period, automatic control systems were created and CAD/CAM technologies were implemented, enabling digital design and automated production of components.

The current stage (21st century) is characterised by the introduction of additive technologies (3D printing) and nanotechnologies, which enable the production of components with a precisely defined microstructure and high dimensional accuracy. The manufacturing process has been transformed into a flexible, modular and intelligently controlled system. The concept of Industry 4.0 is based on the integration of artificial intelligence, sensor systems, digital modelling and cyber-physical networks into a single interconnected manufacturing environment.

The development of technologies – from simple manual methods to modern intelligent manufacturing systems – documents the gradual evolution of knowledge about materials and the improvement of methods for their technological processing. The manufacturing process has transformed from an original tool for making products into a complex system that integrates science, engineering and digital automation into a unified technological ecosystem.

The graph (Figure 5) shows the historical development of technologies and raw materials used in manufacturing, from basic manual methods to modern digital and additive technologies within the Industry 4.0 concept. The data shown points to the fact that advances in materials development have run parallel to the development of manufacturing processes – from manual and craft-based methods to sophisticated, controlled automated systems.

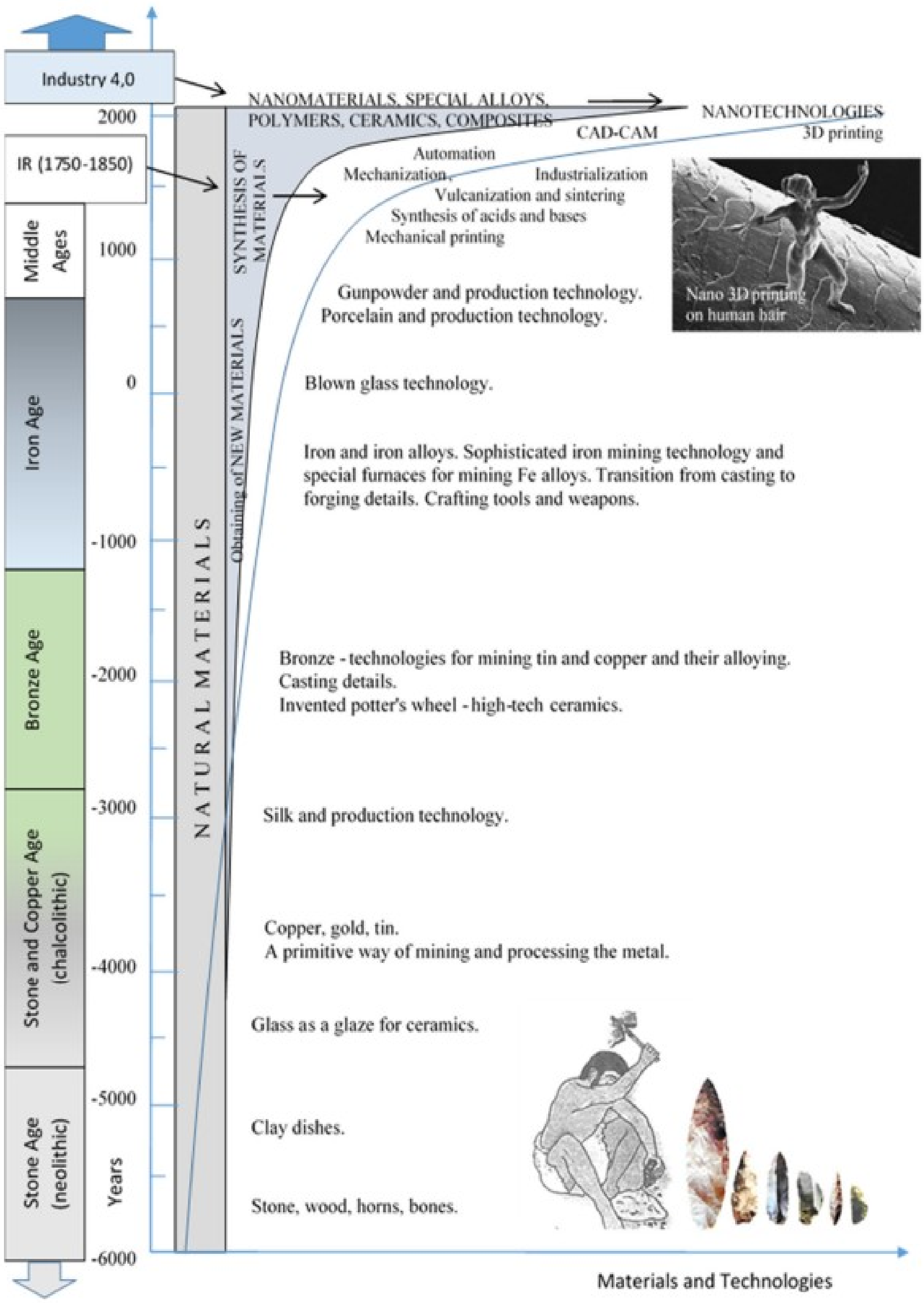

Fig. 5 Development of human resources, materials and technologies

The development of manufacturing technologies for dental prostheses has gone through four main stages from ancient times to the present day:

Ancient times – late 18th century

This longest period was characterised by the use of natural materials and exclusively manual production. Dental prostheses were mainly manufactured by dentists themselves, with low product quality and high prices. The availability of dental prostheses was limited to a narrow group of the population, and technological progress in production was very slow.

Early 19th century – first half of the 20th century

Mechanisation was gradually introduced into the manufacturing processes. New materials were discovered and procedures for their processing were developed. The introduction of machines made it possible to automate selected stages of production. During this period, specialisation began – clinical treatments were performed by dentists, while dental technicians ensured the production of replacements in laboratory conditions. The proportion of manual work decreased, but key operations affecting the accuracy of replacements continued to be performed by hand. The quality of dental replacements improved significantly, their production costs decreased, and their availability to the wider population increased, leading to an overall improvement in the level of dental care and accelerating technological progress.

1950s–1970s

This period was characterised by the introduction of automation into technological and manufacturing processes, which made production more efficient and increased the accuracy of dental prostheses.

Mid-1970s to present

The era of digitisation and the implementation of computer technology in manufacturing processes began. The introduction of computer systems (e.g. CAD/CAM technologies) fundamentally changed the way dental prostheses were designed and manufactured. Each of these periods had its own specific characteristics and contributed significantly to the gradual development of manufacturing technologies in dentistry.

The third stage of development, lasting approximately 20 to 30 years, was characterised by fundamental changes in the field of dentistry and dental technology.

During this period, the division of labour was clearly defined – dental treatment was performed by dentists, while the manufacture of dental prostheses was concentrated in dental laboratories run by qualified dental technicians. Gradually, specialised companies focused on the development and manufacture of dental materials, instruments and equipment emerged, and their product range was constantly being innovated. The most advanced companies took a comprehensive approach, including the development of materials, technological processes and equipment for the manufacture of dental prostheses.

To streamline production, semi-finished kits for individual stages of the technological process began to be manufactured. Dental laboratories were gradually equipped with automated devices, and dental technicians transformed from craftsmen into highly qualified specialists. The quality, functionality and aesthetics of dental prostheses improved significantly, with an emphasis on natural appearance. At the same time, dental care became more accessible to a wider section of the population. New materials and technological processes for dental prosthetics were constantly being developed.

The final, current stage of development is characterised by the digitisation of production processes and the use of computer communication in the manufacture of dental prostheses. The first CAD/CAM systems were implemented, enabling digital design and machining of components. This was followed by the successful introduction of additive technologies, which enabled the direct production of dental prostheses based on 3D models obtained by scanning the prosthetic field. The manual work of the dental technician was reduced to finishing operations, while the accuracy, quality and speed of prosthesis production increased significantly. At the same time, this has increased the demands on the professional qualifications of technicians – knowledge of computer technologies, control of automated equipment and continuous professional training are required. Globalisation and digital communication have enabled the flexible selection of dental laboratories with the optimal technological equipment for a specific type of prosthesis. At the same time, there has been exponential growth in the development of new materials, technologies and production equipment that define the modern stage of dental production development.

Historically, the first of these trends was simulation. The introduction of computers, which enabled the efficient performance of mathematical calculations, laid the foundation for the emergence of computer-aided engineering (CAE). This technology began to be used to simulate the operational behaviour and functionality of structures in order to optimise their design and mechanical properties.

As a result of the gradual digitisation of manufacturing processes, the first CAD/CAM systems were developed in the 1970s, enabling the integration of digital design and automated manufacturing. The implementation of these systems in the dental prosthesis manufacturing process eliminated many manual operations, increased the accuracy of the prostheses produced, and reduced the overall production time.

At the end of the 1980s, following the development of the first 3D printer, a fundamentally new approach to manufacturing was introduced – the creation of objects by additive means, i.e. by adding material layer by layer (Table 1). In this process, the object is assembled from a virtual 3D model through photopolymerisation, melting or sintering of the input material until the entire physical part is created. Additive technologies are an alternative to traditional subtractive machining methods. Various 3D printing processes enable the production of complex parts from virtually all major material groups – polymers, composites, ceramics, metals and alloys. The creation of an initial virtual model allows products to be designed with a full structure or with controlled porosity and surface roughness according to the requirements of the application. Devices operating on the principle of additive processes are designed and integrated as CAM modules in modern CAD/CAM systems, which allows for precise control of production parameters, high-quality surface finish and overall geometric accuracy of the final product.

Table 1
Classification of technologies for the production of dental structures

Type of processing technology	Process temperature	Technological process	Processed materials	Computer control
Plastic deformation	Room temperature	Bending	Metals and alloys	-
		Forging		
		Rolling		
		Drawing		
		Cold pressing		
Joining technologies	Room temperature	Screw connections	Metals, alloys, polymers, ceramics	-
		Threaded joints		
		Screw and nut joint		
	High temperature	Soldering	Metals and alloys	
		Welding		
Compact component manufacturing technologies	High temperature	Vulcanisation	Rubber	-
		Casting	Alloys, ceramics	
		Pressing	Polymers, ceramics	
		Sintering	Ceramics	+

Subtractive technologies	Room temperature	Carving	Wood, ivory	-
		Cutting	Metals, alloys, polymers, composites and ceramics	
		Milling		
		Grinding		
		Polishing		
		CAD/CAM milling	Ceramics and metal alloys	CAD-CAM systems
	High local temperature	Laser ablation	Ceramics	
Type of processing technology	Process temperature	Technological process	Processed materials	Computer control
Additive technologies	Room temperature	Stereolithography (SLA)	Light-curing polymers, ceramics mixed with light-curing polymers	CAD-CAM systems
	High local temperature	Fused deposition modelling (FDM)		
		Selective electron beam melting		
		Selective laser sintering		
		Selective laser sintering/melting		
	Room temperature	Inkjet printing		

2.3 Manufacturing technologies in dental production

Titanium and its alloys are among the most commonly used materials for the manufacture of medical implants, second only to stainless steel. Stainless steels are typically used for temporary replacements, while titanium is the preferred material due to its high strength, biocompatibility and low weight. In addition, titanium implants do not affect the results of imaging methods such as MRI and CT. The most widely used alloy is Ti6Al4V, which is used not only in the manufacture of dental implants, but also in hip and knee joints, bone screws and surgical instruments. Titanium and its alloys are classified as difficult-to-machine materials, as their physical and mechanical properties differ significantly from those of steels and nickel alloys. These materials are characterised by a high strength-to-weight ratio, good elasticity and toughness, as well as stability at elevated temperatures. They are chemically inert and highly resistant to corrosion. When machining them, it is necessary to take into account their high strength, low thermal conductivity, modulus of elasticity and high coefficient of friction. Thermal conductivity, which expresses the ability of a material to transfer heat, is relatively low in Ti6 Al4 V. While this parameter is not decisive when machining aluminium or steel, it has a significant impact on the quality of the process when machining titanium. During machining, mechanical energy is converted into heat, which is then distributed between the cutting tool, the workpiece and the surrounding environment. However, due to the low thermal conductivity of titanium, most of the heat accumulates in the tool, leading to faster wear. The Ti(6)Al(4) Valloy is also characterised by high elasticity and toughness, which makes it difficult to process with conventional cutting tools. During machining, it is necessary to prevent the formation of a built-up edge, which is created by welding material to the cutting edge. This phenomenon causes an increase in cutting forces, deterioration of surface quality and damage to the cutting edge, as the flaking built-up edge removes parts of the material from the tool. During machining, vibrations and uneven plastic deformation also occur, leading to the formation of segmented chips. For this reason, sharp and smooth tools with a positive rake angle must be used to prevent cracking, tearing or excessive compression of the material.

Turning titanium alloys is a technologically demanding process, mainly due to the high temperature generated in the cutting area. High-speed steel tools are not suitable for this process as they deform plastically at elevated temperatures. Sintered carbide tools can only be used at low cutting speeds, as higher speeds also cause thermal and plastic deformation of the cutting edge. During machining, the cutting tool is subjected to significant mechanical and thermal stress, and the cutting inserts are susceptible to plastic deformation. For this reason, it is essential that the cutting tool is characterised by high wear resistance, strength, toughness, thermal shock resistance and chemical stability at high temperatures. Increasing the cutting speed causes rapid chipping and degradation of the cutting edge, leading to intensive tool wear. Rapid wear is caused not only by high temperatures and plastic deformation of the material, but also by diffusion processes at the contact between the tool and the workpiece, which requires frequent replacement of cutting inserts. In the dental industry, titanium turning is mainly used for the production of dental implants from titanium rods. Due to the high chemical reactivity of titanium with the surrounding environment, it is necessary to ensure suitable process conditions and a protective environment during machining. The main technological problems in turning titanium alloys include:

- heat accumulation caused by low thermal conductivity and heat capacity,
- fluctuations in cutting force during the process due to the formation of segmented (serrated) chips, which are caused by local plastic deformation and heat concentration,

- intense friction of the chip against the cutting tool, leading to partial welding of the material and deterioration of surface quality,
- high vibrations – up to ten times more intense than when turning steel.

Milling is a universal method of chip machining that is suitable for processing flat, rotary and complex-shaped surfaces. The machining of titanium alloys by milling is currently a commonly used technological process, especially in the manufacture of dental implants and dentures, where this method is used to create the internal thread of the implant or to produce elements such as crowns, inlays and onlays. Unlike turning and drilling, milling is characterised by an interrupted cut. The main cutting movement is rotary and performed by the tool, while the sliding movement is provided by the workpiece. Titanium and its alloys can be machined by face or cylindrical milling, with the process being carried out in a conventional or non-conventional manner. Conventional milling is more advantageous from a technological point of view because the cutting force is directed into the material, which reduces clamping forces, improves process stability and allows for an increase in feed per tooth while maintaining tool life, thereby increasing overall machining performance. When machining titanium alloys, it is essential to correctly determine the cutting conditions, select the appropriate tool material and type of cutting fluid to minimise problems associated with the low machinability of the material. Sintered carbides with a higher cobalt content are most commonly used as tool material, as they ensure high toughness and heat resistance of the cutting edges. When milling prosthetic replacements, it is necessary to take into account the thickness of the chip being removed, because if its value is less than the radius of the cutting edge, a phenomenon known as gouging occurs, in which the material is pressed under the tool instead of being cut. This condition leads to increased pressure on the cutting edge and the machined surface, causing process instability, deterioration of surface quality and accelerated tool wear. When machining Ti(6)Al(4) Valloys, it is essential to limit the cutting speed, as increasing it significantly shortens the service life of the cutting tool. Due to the low thermal conductivity of titanium, heat accumulates in the cutting edge area during the process, which negatively affects the tungsten carbide from which the cutting inserts are usually made. Since the amount of heat generated depends directly on the cutting parameters, especially the cutting speed, it is technologically effective to reduce it. When rough machining titanium and its alloys using coolant, a cutting speed of approximately 60 m/min is recommended, which ensures a cutting tool life of 30 to 45 minutes. However, a lower cutting speed requires the use of a machine tool with sufficiently high power and torque to ensure process stability and smooth cutting.

Laser processing of biocompatible materials, including dental ceramics, is constantly being improved to increase the precision, efficiency and quality of surface treatment. This method is based on the use of concentrated laser beam energy to create controlled cracks, vaporise material or cut with local surface melting. Lasers with a pulsed mode (with a pulse length in the range of microseconds to milliseconds) or a continuous mode of operation are used for processing ceramic materials. Laser machining is based on the principle of removing material using a narrowly focused beam of monochromatic light concentrated on a small area of the workpiece. At the point of impact, light energy, most often infrared radiation, is converted into heat, causing rapid heating of a thin surface layer of the material. Depending on the laser power, exposure time and physical and chemical properties of the material, it is locally melted or vaporised. Compared to conventional methods such as grinding, laser machining allows for high precision details, complex geometric shapes and sharp edges without the need for tool-to-material contact. The disadvantages of this method include the higher purchase price of the equipment and the risk of microcracks due to local thermal stresses. Materials with high light energy absorption, low reflectivity, and low thermal conductivity are considered most suitable for laser machining, as they allow for more efficient use of beam energy and more precise process control.

In dentistry, grinding technology is most commonly used in the manufacture of dental prostheses, which is a key process in the finishing of dental materials. It is estimated that more than 15 million dental procedures are performed daily, in which grinding of dental materials is an essential part of the treatment. Grinding is a high-precision finishing method that allows for high dimensional accuracy and quality of the machined surface. The tool used does not have a defined cutting edge geometry, and the abrasive grains are randomly oriented in the tool. During the grinding process, intense, locally confined stress fields are created at the points where the abrasive grains penetrate the ceramic workpiece. The thin surface layer of the material is exposed to high mechanical and thermal stress, which can lead to permanent plastic deformation in the form of dislocations and microscopic cracks. Such structural changes can negatively affect the strength of the material or, in extreme cases, cause its destruction. Diamond grinding tools are most commonly used for grinding dental ceramics, as they allow for precise machining of hard and brittle materials. Dental grinding tools are small (with a diameter of a few millimetres) and operate at high peripheral speeds of up to 25 m/s. The most commonly machined material is mixed oxide ceramics, characterised by an unusual combination of high strength and toughness, which increases its resistance but also makes it more difficult to machine. Compared to other technological methods, grinding is more expensive per unit of volume of material removed, but at the same time it provides the highest precision and surface quality. In micro-grinding, it is necessary to select small sections of material removal so that the layer is removed by plastic deformation, thus preventing the formation of a new damaged layer and maintaining high surface quality. In general, as the toughness of the ceramic material increases, so does the wear on the grinding tool. For this reason, grinding materials with high toughness is less efficient and requires optimisation of grinding parameters, cooling and tool geometry.

During the grinding process, interaction occurs between the individual abrasive grains of the tool and the machined material, whereby this process is characterised by abrasive machining with significantly negative cutting geometry. Since the exact shape of the abrasive grains is not defined, their geometry is usually approximated by mathematical models. Due to the variety of shapes and irregular distribution of abrasive grains on the tool, uneven chip removal and local differences in cutting depth occur during grinding. In certain cases, loose abrasive grains are used for grinding, which are fed to the contact point by means of a suspension in the cutting fluid. However, dental grinding usually involves the use of tools with firmly bonded grains, with the cutting fluid ensuring the removal of heat and chips generated during the process. To compensate for tool vibrations and ensure the stability of the grinding process, it is necessary to anticipate the cutting forces involved, which is very difficult due to the multiple contact of the abrasive grains with the workpiece. When grinding dental ceramics, material is removed by repeated penetration, friction and scraping of the grinding grains across the surface of the workpiece at high peripheral speeds. Material removal can be of a brittle, ductile or combined mechanism, depending on the physical properties of the ceramic material and the selected technological parameters. When grinding at high feed rates, material removal is accompanied by higher mechanical stress, which can lead to radial cracks and damage to the surface layer of the workpiece, thereby reducing the quality and roughness of the surface. For this reason, the aim of the process is to achieve material removal mainly by a plastic deformation mechanism, even though this approach slows down the machining process and reduces the volume of material removed. Plastic chip removal is only possible if the cutting depth is less than the critical cutting depth, which is defined by empirical relationship (1). If this value is exceeded, there is a transition from a plastic to a brittle removal mechanism, which leads to the formation of microcracks and a reduction in surface integrity.

$$d_c \approx \left(\frac{E}{H}\right) \times \left(\frac{T}{H}\right)^2 \tag{1}$$

, where:

d_c [mm] – critical cutting depth

E [N*mm^{-2}] – modulus of elasticity of the material

T [N*mm^{-2}] – toughness of the material

H [N*mm^{-2}] – hardness of the material

3D printing is a widely used technology that reduces production time, increases production capabilities and allows for the use of a wide range of materials. During the process, these materials are transformed by physical or chemical processes that may cause a change in their state. It is a versatile method in which the material is gradually transformed into a solid form. The final effect depends on the dimensions of the printed object, which can range from microscopic to macroscopic sizes. If the shape of the 3D model needs to be adjusted, its design can be easily modified in the appropriate 3D software. Conversely, the production of a complex shape by casting requires additional time for the geometry to be reworked by an expert and also involves higher financial costs. Changing the physical form is therefore more economically demanding than digitally modifying a 3D design. 3D printing is based on the additive principle of production, in which material is applied in layers to create the desired shape of the object. Before the actual process, the digital model is divided into horizontal layers, which are then gradually stacked on top of each other during printing. Unlike conventional 2D printing, a 3D printer also has a Z-axis, which determines the spatial dimension and allows the object to grow vertically. The main principle of 3D printing is therefore the gradual application of digitally defined layers, which are created by cutting the 3D model into sequential slices and then physically reconstructing them. This process can be illustrated by analogy with slicing and stacking salami – the object is first virtually divided into thin layers, which are then gradually stacked to form a three-dimensional whole. Before printing begins, the resin is thoroughly mixed to ensure even distribution of all its components. For this purpose, a mixer is used to ensure the optimal consistency of the material before the printing process itself. Subsequently, a thin layer of liquid resin is poured into a smaller container, into which the printing pad is immersed. This container serves as a resin reservoir and its bottom is transparent, allowing the material to be cured from below using a light source. To prevent unwanted solidification of the entire resin layer, the plate is only immersed to a depth corresponding to the thickness of one printed layer. During the printing process, the printing pad is repeatedly immersed in resin and after each immersion it is exposed to a strong light beam, which causes polymerisation and hardening of the layer. After one layer has hardened, the pad is raised by the height of the next layer, gradually forming the object in three dimensions. During production, it is necessary to ensure the presence of support structures (supports) that stabilise the object and prevent its deformation during printing. These supports separate the object from the printing bed, minimising the risk of damage or printing failure when separating the finished model.

SLA printers, which use a UV laser and liquid photopolymer, are among the pioneering devices in the field of 3D printing. They were originally used mainly in the jewellery industry, where high precision and detailed processing were required. The printing process is carried out by gradually curing photoreactive resin using a laser beam generated by a lamp or diode. Unlike other 3D printing technologies that use plastic filament, SLA printing uses liquid resin that reacts exclusively to UV light. This type of printer is particularly suitable for creating smaller objects, as it is characterised by high processing accuracy and the ability to reproduce fine details and smooth surfaces. The material is cured by a laser beam with a very small cross-section, which systematically renders the individual surfaces of the model. For this reason, the printing speed is directly dependent on the speed of the laser, which is influenced by the quality of the optical system, electronics and control unit of the device. The main disadvantage of SLA printers is their higher purchase price compared to other additive manufacturing technologies, which limited their wider industrial application in the early stages of development.

DLP (Digital Light Processing) is a 3D printing technology that, like SLA (Stereolithography), uses photosensitive resin as the base material. The printing process is carried out by simultaneously irradiating the entire layer of the object with UV light projected through an optical lens. The light source is generated by a chip that precisely renders the shape of the desired layer through an optical system. The accuracy of the final print is directly determined by the resolution of this chip. As a result, the resin is cured across the entire surface, i.e. the entire layer at once, which allows for significantly higher production speeds. For example, the same areas are printed in approximately 5 seconds using DLP technology, while SLA technology would take approximately 30 seconds for this process. The use of DLP technology is determined by the requirements of the specific application. It is commonly used in jewellery making, where the ability to reproduce very fine details is essential. In dentistry, however, this method is only used marginally, as the production of dental models in this way would be time-inefficient. Materials used in DLP printing include various types of plastics, metals (such as chrome, aluminium, cobalt, copper, steel and titanium), concrete, special food mixtures for space travel, modelling compounds and ceramics (e.g. for the production of mugs or vases).

The essence of the SLM (Selective Laser Melting) method lies in the selective melting of metal powder with a laser beam, whereby individual layers of the product are gradually created. Each layer is formed by melting metal powder, which solidifies into a compact structure after cooling. After applying the next layer, the process is repeated, with the new layer bonding to the previous one as a result of local melting and subsequent cooling of the material. The similarity to SLA technology lies only in the scanning method, but unlike SLA, SLM technology does not use UV radiation, but a laser emitting white light. The layer of metal powder is melted by the laser and firmly bonded to the previous layer, after which another layer of material is applied and the process is repeated cyclically until the entire object is created. A significant advantage of this method is the possibility of recycling unused metal powder, which makes the process economically efficient and environmentally friendly. Unlike conventional metal cutting methods, which produce significant amounts of waste and require regular replacement of cutting tools due to wear and tear, SLM technology minimises material loss and reduces operating costs.

PolyJet (PJ) technology, developed by Stratasys, is based on the use of UV-sensitive resin and works on a principle similar to that of an inkjet printer. The print head, equipped with number of microscopic nozzles, is controlled to gradually apply small doses of resin material to the surface of each layer. Immediately after application, the material is cured by UV light generated by a lamp integrated directly into the print head. During the process, the lamp moves synchronously with the print head, ensuring uniform curing of each layer. After the layer has hardened, the print platform is automatically moved down by the thickness of one layer, and the process of applying resin droplets is repeated.

The number of print heads is usually around eight, which allows for the simultaneous application of different types of materials. The main advantage of PolyJet technology is the high precision and detail of the prints, with the surface of the created objects being very smooth and accurate. However, the process is more time-consuming compared to other additive methods. A key feature of the technology is the ability to use multiple materials independently, as each print head can apply a different material. This allows objects to be printed from multiple materials within a single layer, similar to printing colour images with an inkjet printer. A typical example of its use is the production of complex plastic elements, such as protective mask components. On the other hand, the use of PolyJet technology in the manufacture of prosthetic devices is currently limited, as biocompatible materials suitable for medical applications are not yet available.

Electron Beam Melting (EBM) technology uses powdered materials that are produced by a gas atomisation process. Most of these powders are based on metallic materials, which represents a significant contribution to the development of 3D printing. This process is primarily intended for the production of metal and ceramic frame structures, which are manufactured by layer-by-layer melting of the material using a precisely controlled electron beam. In the EBM process, the energy of the electron beam is precisely focused on the metal powder, minimising heat and energy losses. The beam speed reaches approximately 8000 m/s, enabling high productivity and production efficiency. The resulting products are characterised by high quality and material density, with a melt compaction degree of approximately 99%. Maintaining a constant temperature and stable vacuum in the working chamber also eliminates the risk of deformation during the melting process. The main limitations of EBM technology include the maximum size of the manufactured components, which is limited to a diameter of 350 mm and a height of 380 mm, as well as the requirement for electrical conductivity of the processed material, which is necessary for interaction with the electron beam. Additive manufacturing, also known as 3D printing, has become a common feature of CAM software and represents an alternative to subtractive machining such as milling.

The biggest advantage of 3D printing is design flexibility. Production no longer starts with a solid block of material. Products are created by gradual layering, which allows for complex geometric shapes to be achieved. We can manufacture products with different internal structures and the desired external form. It is not yet clear whether this possibility is being fully exploited in the design of dental prostheses. Although there are seven different 3D printing technologies, four are most commonly used in dentistry: stereolithography (SLA), digital light processing (DLP), material jetting (MJ) and material extrusion (MD), but others are also being explored. One of the first applications of 3D printing was the production of models used to manufacture orthodontic aligners. Today, 3D printing enables the production of a wide range of dental components, from simple models, wax casts, coloured temporary replacements and surgical templates to more complex long-term metal and ceramic prostheses and completely digitally manufactured dentures. Depending on the system used, a variety of materials are available, including glass ceramics, cobalt-chromium, composites, PMMA, resins/polymers, wax, titanium, zirconium, and new ones are constantly being added. The quality of products manufactured by 3D printing is at least comparable to products manufactured by traditional methods. Various studies have shown that temporary crowns printed using 3D printing fit better, drilling templates are accurate with a deviation of 0.25 degrees from the planned implants, and occlusal splints have a comparable polished surface and similar wear. The accuracy of the outer and inner surfaces, edges, and occlusal surfaces of 3D-printed zirconia crowns was comparable to that of milled crowns. Customised templates and cranio-maxillofacial prostheses achieve good aesthetics and a better fit than traditional methods. 3D printing plays an important role in diagnosis and treatment planning, improving communication with patients, skills training and maxillofacial surgery. Low-cost printers can be a suitable alternative for in-house production. They can create clinically acceptable temporary crowns and bridges, models of entire dental arches, and digital copies of plaster orthodontic models. They produce realistic models with sufficient dimensional accuracy for various applications. They are also successful in creating facial masks for face transplants, ensuring similarity to the donor without risk to the transplanted graft.

Computer-aided design (CAD) is based on the use of digital imaging methods such as CBCT (Cone Beam Computed Tomography), scanning imaging and digital photography, with the data obtained then being processed and edited in specialised software. In contrast, computer-aided manufacturing (CAM) involves technological processes carried out through 3D printing (additive manufacturing) and milling (subtractive manufacturing). CAD/CAM technologies are currently widely used in biomedical engineering, clinical medicine, the manufacture of customised medical implants, tissue engineering, dentistry, the manufacture of artificial joints and robotic surgery. Their use in various fields of medicine and dentistry is constantly growing as a result of advances in digitisation, automation and data processing accuracy. Basic devices and aids that can be digitally designed and manufactured using CAD/CAM systems include various types of dental fillings, fixed and removable prostheses, surgical templates, occlusal splints, dental models and orthodontic aligners.Like other areas of human activity, dentistry is constantly evolving and modernising through the use of advanced technologies. Cooperation between the dental technician, dentist and patient is maintained in a similar form as in traditional dental prosthesis manufacturing processes, but the exchange of information and data is faster, more accurate and more efficient. CAD/CAM technology is characterised by high processing accuracy, and its main advantage is the speed of production, which significantly reduces the time needed to make a prosthesis. As a result, the number of patient visits to the clinic is reduced, and the work of both the dental technician and the dentist is made more efficient. Traditional dental prosthesis manufacturing processes are digitised using CAD/CAM technologies and transferred to a computer environment. The physical model is converted into a digital system using optical or mechanical scanning, and the data obtained (scans) serves as the basis for the digital design of the prosthesis in a three-dimensional programme. Based on this design, the data is then transferred to production equipment that enables the creation of a physical prosthesis, such as an anatomical zirconium crown. When digitally designing dental replacements, both their functionality and aesthetic properties must be taken into account. The replacement must be functional in order to ensure maximum comfort for the patient and eliminate the risk of health complications. In dentistry, this method is most often used to produce metal and zirconium structures that form the basis or supporting framework for bridges and crowns.

A patient with a missing tooth who needs a functional and aesthetic solution is treated with a dental implant with a crown. The necessary patient data is obtained by the dentist using an intraoral scanner (IOS), facial scanner or computed tomography (CT). The data obtained is stored in cloud storage, which is also accessible to the dental technician. The dental technician downloads the data into their work software, where the patient's information (name, indication, scope and location of the replacement, selected material, colour and other parameters) is analysed. Based on this data, a three-dimensional digital design of the replacement is created, which is then sent to the doctor for approval. The doctor checks the design in specialised software, planning the optimal position of the implant with regard to the future replacement. In many cases, an implant template is also created to enable precise implant placement. Once approved, the final visualisation is sent via a cloud system to the manufacturing centre. If the patient is only missing part of the tooth and the root remains intact, the procedure is similar. Data from the oral cavity is obtained using IOS and transferred to cloud storage or sent to a technician. After checking the data, a digital design of the replacement is created and sent to the dentist for assessment in a three-dimensional view (on a computer, mobile phone or tablet). At this stage, it is possible to add comments, adjust the shape or other details of the design. Once approved by the dentist, the crown is sent to the production centre, where it is manufactured automatically. It is then finished in the dental technician's laboratory, where colour adjustment, glazing and final surface finishing are carried out. After these adjustments, the replacement is delivered to the dental office for final placement. This modern digital method offers advantages for patients, laboratories and dental offices. It saves time, reduces the number of patient visits, eliminates the need for physical impressions (which is particularly beneficial for patients with a gag reflex) and ensures immediate and backed-up data transfer. This optimises material consumption and minimises the risk of errors during production. When used correctly, CAD/CAM procedures reduce the incidence of human error and enable digital planning of implants with precise positioning. This technology is also beneficial for novice dentists, as it allows them to adhere to aesthetic principles and simplifies the treatment process. Despite the high level of automation, the human factor remains crucial. The skill, precision and attention to detail of the dental technician are key to producing natural-looking dental prostheses, especially in cases where crowns are placed next to natural teeth. Each clinical case is individual and requires a specific approach. The overall success of the treatment depends on the functional properties of the replacement, the aesthetic quality of the workmanship, the technical expertise of the technician, as well as good communication between the dentist and the technician and their knowledge of biology, anatomy, tooth morphology and gentle tissue handling.

The basic principles of computer-aided design and manufacturing (CAD/CAM) are applied in the processing and transformation of three-dimensional information in the field of dental prosthetics. This process is carried out through the processing of numerical data, computer analysis, the creation of specific data files and the subsequent automated control of the production of dental prostheses. As a result of continuous technological advances in information and digital systems, new generations of products and devices are being developed that meet the highest requirements for accuracy, quality and functionality. CAD/CAM technologies enable the implementation of accurate clinical reconstructions with a high level of biocompatibility, mechanical stability and aesthetic results. This approach is based on digital communication between the dentist and the dental technician, ensuring efficient data exchange and minimising errors during the manufacturing process. Digital CAD/CAM technologies are currently widely used in dental laboratories not only for the production of fixed and removable prosthetic replacements, but also for the creation of auxiliary working models, individual impression trays and implant templates. CAD/CAM systems were quickly implemented in dental laboratories as they enabled increased work efficiency, elimination of redundant production steps and thus reduced costs and the risk of errors during processing. These digital technologies can be used to produce a wide range of prosthetic replacements – from working models and temporary solutions to final constructions made of metal, ceramics, zirconium or polymers, including crowns, bridges, as well as partial and complete dentures. In current practice, two basic manufacturing strategies are most commonly used – subtractive and additive methods.

Subtractive methods are the dominant manufacturing approach, in which the prosthetic structure is created by machining (milling) from a homogeneous block of material. After creating a digital design in a CAD system, the model is exported to a CAM environment (usually in STL format) and then automatically machined by a milling machine in a dental clinic or laboratory. In this way, it is possible to precisely create the desired shape of the prosthetic replacement according to the defined digital design. Originally, this method was used mainly for the production of metal-ceramic crowns, but today subtractive technologies are used in the processing of a wide range of materials used in dentistry, such as ceramics, zirconium, polymers, resins, pre-sintered and sintered zirconium, cobalt-chromium and titanium alloys, and aluminium oxide.

3 Principles of Simulation in Production

Simulation, derived from the Latin "simulō" (to imitate), is the process of engineering modelling of a system (e.g. a production process or production structure) in order to solve engineering design problems. Also defined as a scientific method, simulation involves replacing the analysed system with a simulation model. Experiments are then carried out with this model to obtain data and knowledge about the original system. Reasons for using simulation include:

- The complexity of the system under study makes it impossible to apply a suitable mathematical method or adequately formulate the problems.
- The properties of the analysed system evolve too slowly or, conversely, too quickly.
- Experimenting with the analysed system can lead to catastrophic consequences with risks that are difficult to estimate.
- Controlling the analysed system is difficult (e.g. economic systems), making experimentation impossible or too costly.

The application of simulation techniques allows for extensive capture of dynamic (time-varying) and stochastic (random) phenomena in the system, as well as the performance of experiments that would otherwise be unavailable for various reasons (financial costs, risk, time consumption, lack of a real system) under controlled conditions. The development of computing technology in the 1990s was motivated by the need to process large volumes of 2D and 3D data, optimally in real time, not only in the construction of simulation models and the preparation of experiments, but also during their course and subsequent evaluation.

Simulation is a key methodological technique for solving real-world problems. It is used in the description and analysis of systems, in the investigation of hypothetical "what if" situations within real processes, and in the support of the design and optimisation of real systems.

Simulation models differ fundamentally from analytical models in the way results are obtained. In simulation models, solution values are obtained by observing the course of the model in simulated time, with data recorded based on changes in system states during the simulation. Simulated time is completely independent of real time.

In contrast, analytical models provide results in the form of explicit functional relationships in which variables represent model parameters. The solution to a specific problem is obtained by substituting specific values of these parameters into the relevant functional formulas.

Simulation approaches are among the standard tools used in the evaluation of production systems. In this context, simulation is understood as a discrete event-driven simulation that allows detailed monitoring of the progress and status of production processes within a production system. A model created according to these principles provides an accurate overview of the dynamics of the system, with the simulation software being time-synchronised with events occurring in the production process. Simulation understood in this way represents an important analytical and control tool in the field of production system management. For these reasons, event-driven simulation is used as the main methodological technique in this work.

Simulation is used primarily in the design phase of production systems, where it serves to determine the optimal number of production, handling and support equipment, to determine the appropriate location and capacity of machines and storage areas, and to select appropriate production management strategies. It also allows the impact of various combinations of these parameters on the performance and efficiency of the proposed system to be evaluated.

Advantages of simulation modelling:

- Deeper understanding of systems through modelling: The very process of constructing a simulation model often leads to a broader and more detailed understanding of the dynamics of the real system. This analysis can reveal weaknesses, inefficiencies or new opportunities for optimising processes and organisational structure. During the modelling phase, opportunities to improve the real system often emerge.
- Time manipulation: Simulation allows you to dramatically speed up the time frame, enabling you to analyse long-term impacts and trends in a fraction of real time. Alternatively, it is possible to slow down extremely fast processes for more detailed analysis, for example in chemical reactions, allowing for a better understanding of their course and identification of critical factors.
- Non-disruptive experimentation: Simulations provide the opportunity to experiment with different scenarios and strategies without any risk of disrupting or affecting the operation of the existing system. This is particularly valuable when analysing critical or costly operations.
- Flexibility and adaptability: Simulation models are much more adaptable and flexible than traditional mathematical models. They can effectively model complex systems with non-linear relationships and random variables where standard analytical methods fail.
- Training and education tool: Simulations serve as an effective means of education and training, allowing participants to gain practical experience in a controlled and safe environment. Examples include operational management simulations and project management simulations.
- Predictive analysis and scenario planning: Simulations allow different scenarios to be explored and their potential impacts analysed using a "what if" approach. This supports strategic decision-making and

minimises the risk of unexpected events.Limitations of simulation modelling:

- Investment and uncertainty: Simulation projects require significant investment in financial, technical and human resources. Nevertheless, there is no guarantee that the simulation model built will be suitable for the purpose.
- Validation and verification: Objectively evaluating the credibility and reliability of simulation models is a challenging task. Due to the inclusion of stochastic elements in the models, it is difficult to determine their accuracy and validity, especially for predictions of future events.
- Potential inaccuracy: Due to the inclusion of probabilistic aspects, simulations may produce less accurate results compared to analytical methods. If the problem being analysed can be adequately represented by a mathematical model, an analytical solution is preferred in terms of accuracy and efficiency.
- Time and financial demands: The construction of large and complex simulation models can take a disproportionate amount of time and require extensive financial resources. In such cases, it is necessary to weigh the costs against the expected benefits.
- Lack of standardisation: Despite progress in the field of simulation, there is no universally accepted standardised procedure for creating simulation models. The final form of the model is largely influenced by the subjective decisions of the creator, which can lead to different interpretations and models for the same system.
- Computing power requirements: Simulating large and complex systems can place extremely high demands on hardware resources such as computing power and memory. This can be a barrier to the application of simulation in situations with limited resources.

Currently, there is an increasing emphasis on the use of real-time simulation to support operational decision-making processes in planning, scheduling and direct production management. In this context, simulation makes it possible to analyse and optimise the way production tasks are assigned, determine the optimal size of production batches, set priorities for individual tasks and their passage through the system, minimise downtime, evaluate alternative management strategies and perform reliability analysis of the production process.

3.1 Classification of simulation models

Simulation models can be classified into diverse categories based on various criteria. Depending on our understanding of the structure and interactions in the simulated system, two different perspectives can be distinguished:

- Structure model: This approach represents the system through its components and existing interconnections. Emphasis is placed on the explicit representation of elements and links that define the configuration of a given system.
- Behaviour model: In this case, the system is abstracted as a "black box", with no emphasis on internal architecture. The description is limited to the transformation of input parameters into output data, ignoring the internal mechanisms that enable this transformation.

In terms of the time dimension, simulation models can be divided into:

- Static models: In these models, the parameters remain invariant throughout the simulation experiment. They are constant and do not reflect any changes over time.
- Dynamic models: These models characterise transformation processes that are not static but evolve during the simulation. Their main feature is temporal variability.

Based on the domain of definition of variable quantities, simulation models can be further categorised into discrete models and continuous models.

Discrete simulation, also known as discrete event simulation (DES), is a simulation approach in which system operations are modelled as discrete time points arranged chronologically. Each of these points represents a specific event that triggers a change in the state of the system. These events are considered instantaneous, which means that the system transitions between states without any time delay after the event occurs. Along with the change in system state, the simulation time is also updated. The intervals between state changes are considered insignificant or non-deterministic. The discrete simulation algorithm begins by initialising the initial state. It then checks whether the simulation termination condition is met. If the termination condition is not active, the algorithm moves on to waiting for the next event, which it obtains from the simulation timeline. After the event occurs, the algorithm updates the time in the simulation and changes the system state. It then collects relevant data for analysis, statistical evaluation, or determination of future system states. After this step, the algorithm returns to checking the termination condition and then waits for the next event until the termination condition is met. A significant advantage of DES is its ability to simulate both deterministic and stochastic systems. In the case of stochastic models, it is necessary to integrate known probability distributions for random variables that affect the state of the system. In this step, a set of potential next states is generated before transitioning to a new system state. In general, DES is suitable for modelling, simulation, optimisation and visualisation of manufacturing processes. It allows the user to perform analyses of system characteristics, identify bottlenecks in production, improve resource utilisation and prevent errors in processes. Thanks to this extensive flexibility, DES is one of the most widely used simulation techniques in the field of production systems.

Thanks to the above attributes, the DES concept closely corresponds to the concept of digital twins. A digital twin serves as a virtual model of a real system that collects and processes data coming from its real counterpart. This data is then used for various purposes, which were also described in the aforementioned chapter. For most of these operations, the capabilities of DES, which prove to be the most suitable, are primarily used. In this case, a digital model of a gearbox manufacturing factory was created using discrete simulation. This digital model was able to receive real data from the company, thus ensuring that the production status was up to date. In addition, based on this data, the model was able to calculate and continuously update the set KPIs and provide suggestions for potential optimisation of production processes.

Given the widespread use of discrete simulations, there is a number of software programmes designed for this purpose. Among the best-known commercial software programmes are Arena (Rockwell Automation) and Tecnomatix Plant Simulation (Siemens). Open-source alternatives include JaamSim (JaamSim Software) and Salabim in the Python programming language.

Continuous simulation is an alternative approach to modelling, different from discrete simulation. While discrete simulation tracks changes in the state of the system based on the occurrence of discrete events, continuous simulation updates the state of the system at regular, fixed time intervals. This approach is based on knowledge of the initial state of the system, from which the state at the next time moment is derived using differential equations or other mathematical models, using a small, incremental time step. Theoretically, if this time step approaches zero, it is possible to approximate the continuous development of the system over time, which justifies the name of this type of simulation. Continuous modelling is based on physical laws and allows for detailed capture of the dynamics of continuous processes. Numerical integration methods are used to simulate such models, for example, the Euler method, the Runge-

Kutta method, or implicit schemes for stiff systems. Since the calculation is performed in small time steps, continuous simulations tend to be more computationally demanding, but they provide a more accurate picture of the behaviour of the system over time.

The main advantages of continuous modelling include the ability to realistically capture physical and technical processes in which state variables change continuously, such as fluid flow, changes in substance concentration, and electrical or thermal processes. Continuous models also allow for analytical interpretation of results through differential equations, which provides scope for verifying stability, equilibrium states or the sensitivity of the system to parameter changes. In many cases, these models are used in system dynamics theory, which tracks the relationships between flows and states in a system through feedback loops. On the other hand, the disadvantage of continuous models is their high computational and mathematical complexity, as well as the need for precise knowledge of the physical laws that govern the system. Incorrectly chosen equations or parameters can lead to significant deviations from reality, and the validation of such models is often more difficult than for discrete models.

A comparison of the two approaches shows that the choice between a discrete and a continuous model depends on the nature of the system being modelled. If the system consists of entities that occur and change their state at precisely defined points in time, such as customers arriving at a bank or products on a production line, it is more appropriate to use a discrete model. However, if the system is characterised by smooth transitions and changes in variables, such as the water level in a tank, the temperature in a furnace, or the concentration of a substance in a reaction mixture, a continuous model is preferred. In practice, we often encounter complex systems that exhibit combined behaviour – for example, in the chemical industry, where fluid flow (a continuous phenomenon) takes place in a reactor, while the dosing of raw materials or sampling (discrete phenomena) occurs at specific moments. In such cases, hybrid simulation models are used, which integrate both discrete and continuous components and allow for a more realistic representation of the behaviour of the system as a whole.

From a methodological point of view, it is important to note that both approaches are dynamic simulation models, as time is their key variable. Both discrete and continuous models can be deterministic or stochastic, depending on whether random influences are applied in the model. The development of computing technology and simulation platforms such as Simulink, AnyLogic, Arena, ExtendSim and Simio now allows both types to be modelled in a common environment and supports the integration of multiple paradigmatic approaches. Modern software tools allow event-driven, process-driven, agent-based and continuous modelling to be combined within a single project, providing researchers and engineers with a high degree of flexibility in creating models of different types of systems.

3.2 Phases of simulation in production

System simulation is considered a special form of the cognitive process, which is successfully applied in the analysis and design of objects, as well as in the fields of education, professional training and in various situations in which knowledge is mediated and hypotheses are formulated. The focus of system simulation is on systems defined on the basis of objects of study and their dynamic behaviour, which is understood as any change over time.

Simulated systems can be created based on objects that already exist in reality, as well as on objects that are in the design stage. In addition, it allows for the study of systems that have no direct relationship to the real world. The basic principle of system simulation is to formulate conclusions about the system under study based on experiments carried out with its model, more precisely with a simulator of this model. The definition of the object of knowledge is understood as the delimitation of the examined object in relation to its surrounding environment, or the formulation of criteria for the designed object and the identification of suitable components necessary for its construction. In order to clearly define the subject of the investigation (i.e. the simulated system), it is necessary to first specify the perspective from which the object is analysed and to select an appropriate level of detail. This perspective is usually determined by the purpose of the investigation itself. However, during the analytical process, there may be dynamic changes in the level of detail – this usually increases as knowledge deepens, but in some cases it may be reduced if certain details are found to be irrelevant. The sequence of modelling and verification of the simulation model in production can be illustrated using a block diagram.

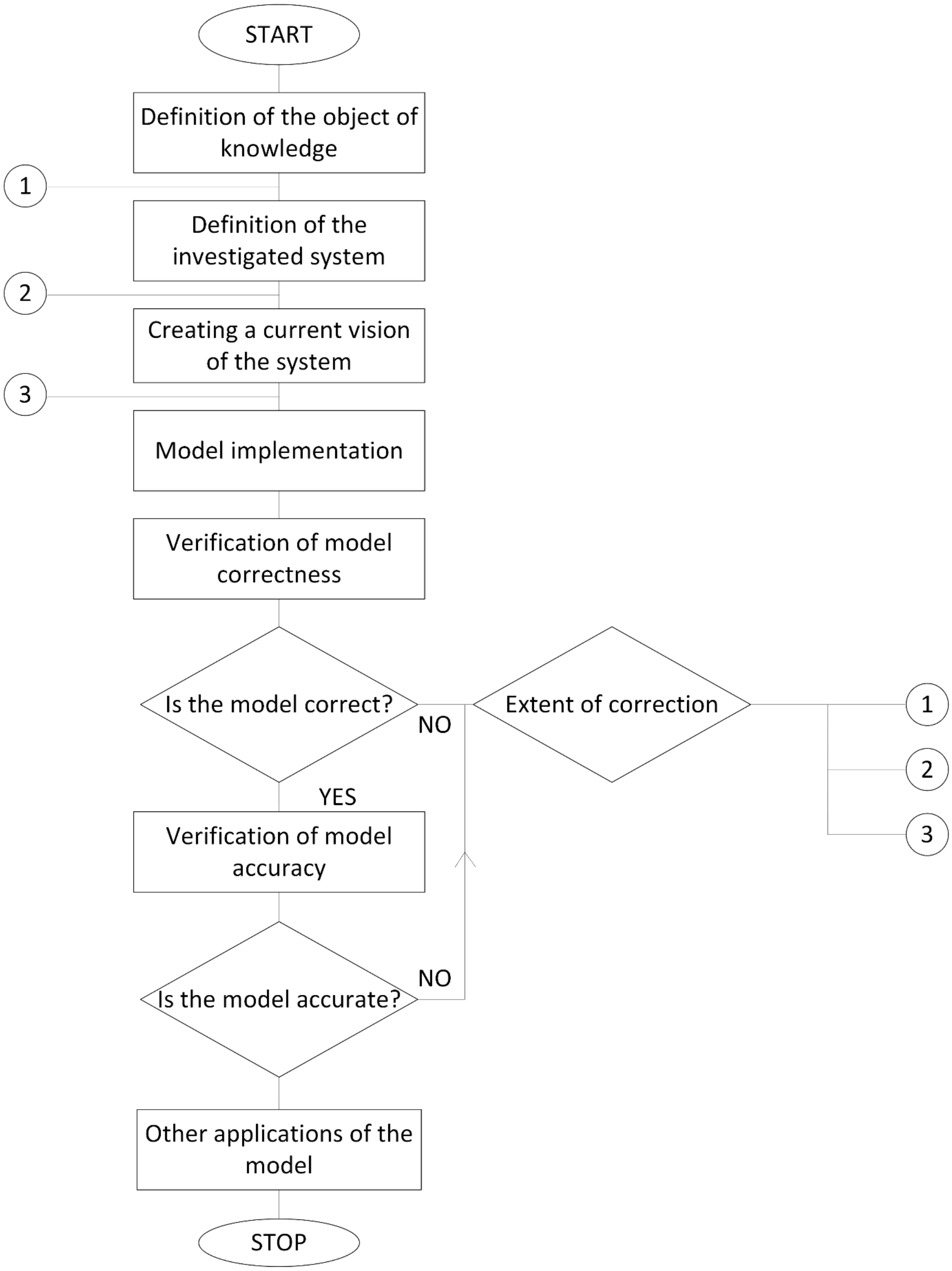

Fig. 6 The sequence of modelling and verification of the simulation model in production

The diagram shows the complex process of modelling, verification and validation of a simulation model of a system, which is a methodically organised and iterative process ranging from the formulation of the subject of study to the practical application of the model. The process begins with the definition of the object of knowledge, where the phenomenon or system under investigation is identified and precisely delimited in relation to its environment, and the objectives, purpose and criteria of the investigation are set. This is followed by the definition of the system under investigation, within which its structure, functional links, dynamics and input-output parameters that define its behaviour are determined. The third step is to create a current idea of the system, i.e. to formulate a conceptual model that expresses the current knowledge about the functioning of the system, integrating theoretical knowledge, empirical data and expert hypotheses. The creation of the concept is followed by the implementation of the model, where the concept is transformed into a formal or computational form that allows its implementation in a simulation environment.

The next phase is to verify the correctness of the model, assessing whether it has been constructed in accordance with the specified requirements and whether its structure, algorithms and logical links correspond to the original design. At this stage, the first decision point arises: "Is the model correct?" If the answer is yes, the process continues to model validation. If the answer is no, a correction scope analysis is performed to identify the degree and nature of the errors and determine which previous phase to return to. The correction branches are marked in the diagram with symbols (1, 2, 3), which represent feedback to previous steps: (1) definition of the object of knowledge – if a fundamental conceptual deficiency is found; (2) definition of the system under investigation – if its boundaries, links or parameters are incorrectly defined; and (3) creation of a current idea of the system – if it is necessary to adjust the theoretical or conceptual framework of the model. This decision node thus provides adaptive feedback that ensures the methodological correctness and consistency of the entire modelling process.

After eliminating any inconsistencies and successful verification, the model's accuracy is verified (validation) to determine whether the model accurately represents the behaviour of the real system. This is followed by a second decision point: "Is the model true?" If the model shows consistency with empirical or experimental data, the process proceeds to the final phase. In case of inconsistency, the model is revised and retested, ensuring iterative improvement of its accuracy and reliability.

After successfully meeting the validation criteria, the model moves on to the final stage – further use of the model, where it is applied as an analytical, optimisation or decision-making tool in research, design or system management. The entire process is concluded with a STOP step, which ends the modelling cycle.

In terms of decision tree logic, the diagram clearly represents the cyclical and iterative nature of the modelling process, in which decision points and feedback loops ensure ongoing control of the quality, accuracy and scientific validity of the model.

Given that simulation is not the only available solution methodology, it is possible that when comparing the investments and returns of a large-scale simulation project, the application of more elementary approaches may appear more appropriate. Conversely, if the complexity and difficulty of the problem being solved is insufficiently assessed, the implementation of a simple method can escalate into irreversible economic losses, wasted time and effort.

3.3 Simulation in production

The current understanding of a simulated system includes the current state of knowledge about the system under investigation, its complex structure, dynamic changes over time, and a detailed analysis of the system design, including the identification of its individual components. The modelling process involves the design of a simulation system and its implementation using a suitable simulation tool, most often a digital computer. The model concept may or may not be based on mathematical formalism expressing existing knowledge about the simulated system. Only a model that preserves the sequential arrangement of temporal changes and reproduces the course of its states over time when imitating the dynamics of a real system is considered a simulation model. The mathematical description of the model usually distinguishes between the following basic elements:

- state variables, representing quantifiable quantities describing the current state of the system;
- transfer functions, expressing the relationships between the elements of the system or the interactions between the system and its environment;
- excitation functions, which represent input variables or factors determining the behaviour of the system;
- parameters, i.e. constant quantities characterising the basic properties of the system.

The model is considered valid if it adequately reflects current knowledge about the simulated system. Model validation consists of verifying hypotheses about the system under investigation and assessing whether the proposed system meets the specified specifications and is feasible in practice. If the validation does not produce satisfactory results, the process returns to the previous stages of modelling, where the necessary adjustments are made. The method and scope of the correction depend on the nature and severity of the identified discrepancies between the model and reality.

The verified model can then be applied in various areas of scientific knowledge – for example, to identify system parameters, forecast its behaviour, make scientific predictions, optimise processes, as well as in the field of education and professional training, where it serves as an effective tool for developing knowledge and experimentally verifying theoretical concepts.

A computer simulation model is a tool that generates a user-defined set of performance metrics obtained as a result of simulating the analysed business process. These metrics, usually presented in numerical or graphical form, provide quantitative and qualitative information about the behaviour of the system during the simulation. Their specific content is always determined by the nature of the modelled system and the specific requirements of the user, thus ensuring the relevance of the outputs for the given application.

The most common indicators provided by computer simulation include:

- capacity and resource utilisation, which includes absolute and relative values of operational activity, failures or inactivity of production capacities, together with their graphical time progression;
- queue and waiting time analysis, tracking minimum, average and maximum waiting times and queue lengths for resources with limited capacity, including identification of system bottlenecks;
- inventory management, which includes monitoring material consumption, replenishment frequency and visualisation of inventory status over time;
- time analysis, focusing on the minimum, average and maximum duration of individual activities and the total duration of the process;

- system throughput, expressed as the number of requests, products or orders processed by the system during the simulation, as well as the average number of requests at a given moment;
- quality and reliability, expressed by the number of unfulfilled requests, errors and complaints, together with a statistical evaluation of failure rates and losses;
- cost analysis, which includes the calculation of direct, overhead and total costs for individual products, services or processes and their variability;
- validation and robustness, i.e. assessment of the reliability of the above indicators through statistical and sensitivity analysis.

In addition to these quantitative indicators of system performance, qualitative and supplementary outputs are also obtained as part of the simulation process. These mainly include obtaining new data that was necessary for compiling the model but was not previously systematically monitored in the company; structural analysis, which provides a detailed description of the organisational and process structure of the analysed system; process visualisation, which enables a deeper understanding of the dynamics of the modelled system through graphical representation; and the learning process, which, although difficult to quantify, represents a key benefit for the participants in the simulation project. During the creation of the model, knowledge is developed, relationships within the system are better understood, problems are identified, and realistic goals are formulated.

In some cases, this learning process can be so significant that it is referred to as "self-destructive" simulation models – situations where the knowledge gained during modelling leads to fundamental organisational changes even before the model itself is completed. However, the model created in this way does not lose its value – it can be used to train staff after the changes have been implemented, as well as to manage, monitor and optimise processes in the future.

Simulation as a methodological approach is a universal tool for examining complex systems, which determines its wide application in various fields of science and practice – from biology, medicine and chemistry through technical sciences and industry to military and business applications. The continuous growth in computing power and the increasing sophistication of simulation tools are significantly expanding its possibilities of use, making simulation an integral part of modern scientific research and strategic decision-making in the business environment.

In industrial practice, computer simulation can be implemented, for example, in the following processes:

- Optimisation of large-scale production systems of various types, such as those in the engineering, food and chemical industries. Simulation is focused on shortening production cycles, minimising operating costs, increasing labour productivity, allocating production resources more efficiently, as well as preparing projects for new production systems and designing the spatial layout of production facilities with the aim of optimising the flow of materials and information within production.
- Analysis of logistics processes within the company and within supply chains (Supply Chain Management) with a focus on reducing excess inventory, reducing the volume of work in progress and minimising the risk of unfulfilled requirements, thereby increasing the reliability of supply processes and the overall smoothness of material flow.
- Optimisation of storage rules, which includes streamlining handling systems for materials and finished products, increasing the throughput

of warehouse operations, and improving the organisation of receiving and shipping processes, including optimising the use of loading and unloading ramps.

- Supply chain management, where simulation takes into account the variability of demand types and frequencies and includes multi-level supply systems that enable the coordination of deliveries across multiple levels of the distribution chain.
- Production planning, where simulation covers multi-product and batch processes, as well as the implementation of online planning systems that ensure resource allocation, deadline monitoring and real-time operational management of production activities.
- Optimisation of various types of service systems with a focus on the effective provision of services and product support, the organisation of emergency medical services, the management of hospital bed utilisation and the allocation of costly medical technologies, thereby increasing the efficiency and availability of the services provided.
- Management and planning of large-scale projects, where simulation uses various approaches to model time and resource coordination of tasks, optimise schedules and predict possible collisions within the project cycle.
- Management of internal transport systems with the aim of optimising transport flows, reducing waiting times and increasing the throughput of transport hubs and routes.
- Management of communication systems and document circulation rules, which are analysed in terms of streamlining information flows, reducing data redundancy and speeding up decision-making processes within the organisation.

- Financial planning and risk management through simulation models, in which simulation enables the prediction of the economic impact of decisions, the analysis of the sensitivity of financial indicators, and the evaluation of investment strategies in conditions of uncertainty.
- Simulations of complex shutdowns of production facilities during planned maintenance, where it allows for the optimisation of maintenance work schedules, minimisation of the impact on production, and increased availability of equipment after restart.

In the case of one-off simulation projects, it is usually more cost-effective to entrust their implementation to an experienced consulting firm than to embark on them without prior experience, as simulation projects are methodologically and technically demanding. Larger companies have a significant advantage in this respect – regardless of whether they use internal or external expertise, they can achieve significant overall benefits even with relatively small unit savings. Thanks to the scale of production, these benefits often exceed the investment made many times over in the case of a successfully implemented project, confirming simulation modelling as an effective tool for strategic management and optimisation of business processes.

The benefits of simulation can be categorised into two groups: quantitative and qualitative. Quantifiable returns are easily measurable using conventional management calculation tools. This category includes, for example, cost minimisation (reduction of personnel costs, optimisation of material consumption in the production process, reduction of inventory levels, more efficient use of machine time). On the other hand, qualitative benefits are difficult to quantify, but illustrative examples include increased operational reliability of processes, increased employee satisfaction, and elimination of incorrect decisions. When deciding whether to use simulation to solve a specific problem, company management should take the following cost items into account:

- Software and hardware acquisition costs: Although the prices of computer technology are on a permanent downward trend, the financial resources required to purchase simulation software can be considerable. A representative example is the Witness simulation software, the basic version of which costs around €28,000. However, the purchase price is only the initial investment, with maintenance and operation of the simulation programme generating additional costs.
- Operating costs: This category includes, for example, licence fees, energy consumption and the resolution of any technical complications.
- Labour costs: The remuneration of employees who are part of the project team can account for up to 80% of the total costs of a simulation project. The most significant labour costs are related to the engagement of qualified experts in the field of simulation. Courses and training for other employees and staff, which are necessary for the effective implementation of the entire project, may generate additional labour costs.

The benefits and costs are always determined by the specifics of the particular simulation project. The extent of the benefits and investments also depends on whether it is an initial, so-called pilot project or a repeat project.

4 Methodology for Design of Robotic Work Environments

The development of automation technologies, digital simulation and intelligent control systems is fundamentally changing the way modern robotic workplaces are designed and implemented. In the context of Industry 4.0, the design process is shifting from a traditional empirical approach to a system-oriented and data-driven methodology that allows robotic processes to be created and verified in a virtual environment before their physical implementation. This methodology is based on the digital transformation of design activities, the core of which is the creation of a digital twin of the robotic workplace.

4.1 Framework for design of robotic workplaces

The aim of this section is to define a comprehensive methodological framework for the design of robotic work environments, covering all key stages – from problem analysis and goal definition, through the design of layout and technological solutions, to the implementation of off-line programming and validation through simulation experiments. This framework enables an integrated approach to design, in which two interconnected methodologies are developed in parallel:

- Robotic workplace design methodology, focused on design, layout solutions, selection of technological components and modelling of process links.
- Off-line programming methodology, focused on the creation, simulation and optimisation of control algorithms for robotic manipulators in a virtual environment.

The mutual integration of these methodologies creates a cyclical process of iterative optimisation, in which the results of simulation experiments retroactively influence design decisions. This process allows for the gradual refinement of the workplace model until it reaches the stage of full digital verification. The basic principle of the proposed methodology is modularity and hierarchical structure, which allows the level of modelling detail to be adapted to specific technological requirements and the degree of automation.

The proposed methodology aims to support the creation of robotic systems that are efficient, flexible, safe and energy-optimised, while reducing the need for physical experiments and shortening the time to bring the workplace into operation. Off-line programming in this process is a digital validation tool that allows testing, debugging and optimisation of robotic paths, algorithms and interactions between devices without interrupting actual production.

The following subchapters therefore detail a comprehensive methodology for designing a robotic workplace as a superordinate system framework, as well as an offline programming methodology, which represents its integral experimental verification component. Together, these approaches form a comprehensive methodological model for the digital design of robotic work environments, enabling the transition from conceptual design to implementation and optimisation of the real system.

The basic objective of the methodology is to create a systematic, modular and verifiable procedure for the design of a robotic workplace, which will ensure:

- optimal spatial and functional arrangement of workplace elements,
- safe and collision-free movements of robotic manipulators,
- ergonomic and technological suitability of the solution,
- readiness of the model for off-line programming and simulation,

- the possibility of quantitative evaluation of the effectiveness of the proposed solution.

The methodology is formulated to be universally applicable – from single-purpose work cells to multi-robot lines or integrated production systems.

The process of designing a robotic workplace consists of several consecutive stages that are interconnected by information and feedback links. Each stage has precisely defined inputs, outputs and tools that are used to process them.

Task analysis and definition of robotisation objectives stage is the initial analytical step in which the technological process to be robotised is examined, including:

- analysis of input conditions (product type, cycle time, quality, number of variants, required performance),
- identification of robotisable activities,
- setting criteria for evaluating success (cycle time, accuracy, repeatability, capacity, availability).

The output is a technological specification of the task, which defines the scope and objective of robotisation. At this stage, a basic matrix of input-output operations is also prepared, which is later used to create control logic and an off-line programme. Based on the task specification, a conceptual design of the solution is created, which determines:

- the number and type of robots,
- the type and function of peripheral devices (containers, conveyors, fixtures, sorting systems),
- the method of cooperation between robots and other devices,
- the basic parameters of the workspace.

The aim is to define the general architecture of the system, which enables subsequent modelling. At this stage, several solution variants are compared – using multi-criteria decision-making methods, parameters such as price, complexity, space requirements and serviceability are evaluated.

One of the main phases is the creation of the layout, as it determines the spatial relationships and arrangement of the individual elements of the system. At this stage, it is necessary to implement:

- modelling of the spatial coordinates of work positions,
- design of the optimal position of robots in relation to technological objects,
- definition of working ranges, handling zones and safety envelopes,
- optimisation of the orientation of tools and semi-finished products.

For this purpose, CAD systems and virtual simulation environments (e.g. Process Simulate, RoboDK, ABB RobotStudio) are used, which enable three-dimensional verification of geometric and kinematic relationships. The output of this stage is a 3D layout model, which serves as the basis for kinematic analysis and off-line programming.

The fourth stage involves the parameterisation of the model – the precise technical and dynamic characteristics of the individual components are determined. At the same time, the activities of the robotic manipulators are defined, which include:

- assigning tasks to individual robots,
- creating logical sequences of activities,
- setting motion parameters (speed, acceleration, stopping),
- creating interaction links between robots and peripherals.

This step forms the conceptual basis of off-line programming, whose framework is characterised in the next section of the monograph. Based on these definitions, virtual paths and trajectories are then generated, which can be tested in a simulation environment. In the next step, it is necessary to perform the simulations of partial tasks themselves, i.e. to verify the feasibility of individual operations in the simulation.

For each task (e.g. gripping, storing, assembly, welding, inspection), a separate simulation scenario is created in which the following are evaluated:

- the time course of the task,
- collisions between moving objects,
- the actual achievability of positions and angles,
- the accuracy of the work movement.

The results of the simulations are analysed and used to adjust the model parameters or activity logic. This process can be repeated several times until the optimal behaviour of the system is achieved. This stage represents a point of connection with the off-line programming methodology, as it already works with the same data structures and kinematic models that are used in programming environments.

After successful verification of partial tasks, all components are integrated into a complex digital model.

The aim is to verify the functionality of the entire system as a whole – the synchronisation of robot activities, interaction with conveyors, material transfers and responses to external signals. At this stage, a digital twin of the robotic workplace is created, which is a complete virtual copy of the real system. The following are then carried out in the digital twin environment:

- work cycle simulations,

- time analyses,
- control logic testing,
- preliminary validation of off-line programmes.

The outputs from these experiments are used to optimise the design, thus completing the iterative cycle of the methodology.

The proposed methodology is cyclical in nature, meaning that its individual stages are not strictly linear, but allow for a return to previous steps if optimisation is necessary. For example, the results of partial task simulations may lead to a modification of the layout or a change in the type of robotic manipulator. This feedback creates a closed methodological cycle that connects the design, simulation and programming levels of the process. Off-line programming is thus not only the final stage, but an active tool for ongoing verification and refinement of the design.

The described methodology for designing a robotic workplace creates a comprehensive framework for a systematic, digitally supported and iterative process of creating automated work systems. Its application benefit lies in linking conceptual design, layout, simulation and verification into a single integrated model that forms the basis for a digital twin of the real workplace. The result of this procedure is an optimised, collision-free and functionally verified solution, ready for implementation in practice. Although the design methodology provides a robust framework for the creation and validation of robotic workplace architecture, its full effectiveness is only achieved through the follow-up methodology of off-line programming. This methodology is a natural continuation of the design process and focuses on the generation, simulation and optimisation of control algorithms for robotic manipulators in a digital environment. The following chapter therefore develops the previous findings in the context of virtual programming, trajectory verification, time optimisation and digital validation of robotic processes, which are essential prerequisites for the transition from design to actual implementation of a robotic workplace.

4.2 Off-line programming framework

The starting point for the off-line programming methodology is a precise definition of the problem to be solved through automation or robotisation. The objectives of this phase are:

- identify the needs of the production process,
- define optimisation criteria (time, accuracy, productivity, costs),
- and define system limitations (technical, spatial, safety).

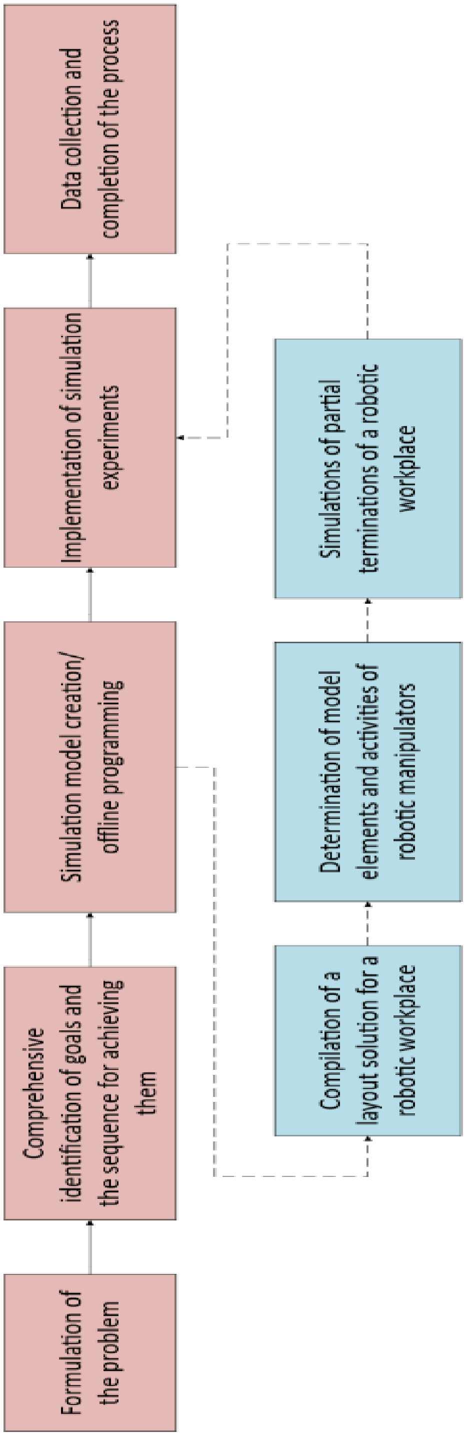

Fig. 7 Framework of design the robotic workplaces

Based on the defined problem, a comprehensive identification of objectives follows, specifying measurable performance indicators (e.g., cycle time, handling accuracy, energy consumption). This stage includes the decomposition of processes into elementary activities and their subsequent logical arrangement. In this way, a process map is created and priority areas are identified on which the simulation and off-line programming will focus. This stage also defines the methodology for measuring and evaluating the performance of the simulated system, which enables quantitative evaluation of the results achieved in the following phases.

The simulation model creation phase is at the core of the methodology. Based on previous analyses, a digital model of the robotic workplace is created, consisting of representations of:

- the spatial layout of the workplace,
- technological components (manipulators, conveyors, storage bins),
- dynamic links between objects.

Offline programming is then carried out in a simulation tool environment (e.g. ABB RobotStudio, Process Simulate, RoboDK), which enables the generation and optimisation of robot paths, collision testing and verification of time sequences. At this stage, individual technological operations such as handling, assembly, welding and palletising are also implemented, with an emphasis on minimising downtime and maximising the utilisation of robot working time.

After creating and verifying the basic model, simulation experiments are carried out to validate the correctness of the designed trajectories, work cycles, and interactions between robotic elements. The experiments include:

- testing of sequences and cycles of robotic tasks,
- analysis of time and space coordination between manipulators,

- optimisation of movement trajectories and speed profiles.

The results of the simulations allow for iterative adjustments to the model, thereby gradually refining the digital twin of the workplace and its readiness for implementation in a real environment.

The final stage of the methodology involves the collection and evaluation of data obtained from experimental simulations. This data is both quantitative and qualitative in nature – it includes time parameters, number of collisions, robot capacity utilisation, and process efficiency indicators. Based on their analysis , the final optimisation of the model and the generation of the resulting off-line programmes are carried out, which are then implemented into the control system of the real robotic workplace.

This achieves full digital validation of the robotic solution prior to its physical implementation, significantly reducing the risk of errors, commissioning time and testing costs in a real environment.

5 Practical Approach to Simulation of Material Handling in Dental Production

For the effective virtual commissioning of robotic production systems, it is necessary to use specialised simulation software tools that enable the creation of complex three-dimensional models of the proposed systems. These models include complete kinematic structures and logical control elements, which then serve as the basis for simulating and testing individual operations. With the growing importance of virtual commissioning, the portfolio of available software solutions designed for accurate modelling, analysis and optimisation of robotic manufacturing processes is expanding.

5.1 Simulation software for modelling of material handling in dental production

RobotStudio software developed by ABB is a sophisticated tool for offline programming of ABB industrial robots. It contains an extensive library of ABB products that enables quick and accurate configuration of simulation models, while also supporting the import of external 3D models in commonly used CAD formats (OBJ, STL, SAT, and others). A key feature of the system is the "VirtualRobot™" technology, which implements an identical replica of the real control system. As a result, simulated cycle times correspond exactly to actual values. The software also offers intelligent "Smart" components that enable realistic modelling of robotic workcell behaviour and optimisation of their functionality even before physical implementation.

RoboGuide (FANUC)

RoboGuide software from FANUC is a powerful off-line simulation system designed to model robot movements and application commands. It is based on

FANUC virtual control units, which guarantees high accuracy of simulated movement and cycle times compared to real operation. Like RobotStudio, RoboGuide has an extensive library of FANUC products and supports the import of user CAD models. In addition, the latest versions implement support for the OPC communication standard, which enables connection to external devices and PLC systems from different manufacturers, increasing versatility and integration within digital manufacturing solutions.

Tecnomatix RobotExpert

RobotExpert is a sophisticated software tool designed for the design, simulation and optimisation of robotic work cells. It enables offline programming, which significantly reduces workplace preparation time, increases system adaptability and ensures the smooth running of automated processes. The use of an intuitive three-dimensional (3D) user interface enables effective optimisation of robot movements and minimisation of work cycle times.

The software implements an approach to robot workstation modelling based on 3D libraries of robots and automation elements and supports the design and modification of additional kinematics for any objects available in the library, enabling flexible adaptation of the work cell to specific production requirements. Precise simulation of robot and mechanical system movements significantly reduces the time required for testing and optimisation. RobotExpert generates realistic robot trajectories, based on which it is possible to accurately calculate work cycle times. The simulation also enables the detection of collisions between individual objects through proximity or surface contact analysis, minimising the risk of damage to equipment and increasing personnel safety.

The software provides advanced capabilities for 3D modelling of robot and automation equipment kinematics, extensive support for a wide range of industrial robots, real-time collision detection during simulation, visualisation of simulation progress and duration using Gantt charts, a user-friendly environment enabling intuitive interaction, and compatibility with real programmes used in industrial operations.

Robot Programmer

Robot Programmer, a sophisticated module of the 3DEXPERIENCE platform, is a comprehensive solution for programming industrial robots. It allows designers and engineers to design, simulate and optimise robotic operations in a fully digital environment. Through features such as automatic trajectory generation, collision detection and offline programming, it provides systematic support for the efficient creation and management of robotic operations.

Robot Programmer significantly speeds up and streamlines the process of programming industrial robots, enabling the generation and simulation of robotic sequences. The software includes an extensive library of robot models, tools for trajectory optimisation and advanced interference detection, minimising programming time and increasing the accuracy of task execution. It is primarily designed for engineers, technicians and operators who require fast and reliable creation of robotic work cycles. Robot Programmer supports productivity, ensures smooth collaboration between users and contributes to achieving high-quality results in robotic programming across various industries.

The software integrates a module for modelling the kinematics of user-defined tools, fixtures and other peripherals. It allows you to specify starting positions, speeds and acceleration parameters, as well as define the mounting interface and Tool Centre Point (TCP) position. A demonstration of program creation and simulation for Pick & Place operations illustrates its simple and intuitive use. Integrated tools allow you to configure trajectories, speeds and motion parameters to ensure safe handling of components. Realistic simulation enables programme validation, collision elimination and performance optimisation, ensuring effective deployment in a real production environment.

Analysis of the capabilities of the 3DEXPERIENCE platform using the Robot Programmer application demonstrates the simple preparation and simulation of programmes for robotic welding. Intuitive setting of trajectories, welding parameters and speeds gives users full control over the welding joint creation process and allows them to optimise the quality and efficiency of welding operations.

Tecnomatix Process Simulate

Tecnomatix Process Simulate software is a key component of SIEMENS' integrated digital factory portfolio, alongside tools such as Process Designer and Plant Simulation. This system enables comprehensive planning, analysis and simulation of manufacturing processes, reducing the time required to commission production lines, identifying potential errors at the design stage and minimising the financial costs associated with implementing new technologies.

Tecnomatix Process Simulate supports detailed simulation of manufacturing and technological operations, focusing primarily on the configuration of robotic kinematics and the creation of operations such as welding, painting and parts handling. The software enables collision detection during the manufacturing process, adjustment of the kinematics of other production line elements, and verification of assembly procedures before physical production begins. This increases the efficiency of work activity design and optimises workplace ergonomics.

In addition, the programme provides functions for simulating logistics and material flows through discrete event simulation, which enables the analysis of production capacity and performance. This approach ensures the identification of critical points in production, the tracking of material movement and the evaluation of resource utilisation over time for multiple production process variants. Another important area is the simulation of human work and ergonomic factors, which enables the creation of safer and more physiologically appropriate work procedures, contributing to increased productivity and reduced risk of occupational accidents. In the Tecnomatix environment, the simulation of production processes can be defined as a time-ordered sequence of operations using a Gantt chart, or alternatively as a sequence of event-driven processes activated on the basis of input signals from the control unit. This approach allows for accurate modelling of system dynamics and responses in real time, significantly increasing the reliability of virtual commissioning.

5.2 Practical implementation of created methodology – design of robotic workplace for dental implant production using simulation

The practical implementation of the methodological framework was carried out on a model of a robotic workstation representing a fully automated production line designed for the manufacturing of dental implants. The model consists of five main technological nodes: a material and semi-finished product warehouse, a 3D printer, a machining center, a surface finishing station, and a final inspection station. The individual nodes are interconnected by a conveyor system and operated by two industrial robots responsible for handling workpieces between the respective production stages. The entire system was designed, simulated, and validated in the Tecnomatix Process Simulate environment, which enables the creation and verification of a digital twin of manufacturing processes.

The first step in the design process was the analysis of the task and the definition of the objectives of robotization. The goal was to automate the flow of materials and implants between individual workstations, with an emphasis on precision, continuity, and repeatability of handling operations. The manufacturing process involves the processing of biocompatible metallic materials, primarily titanium and its alloys, which are used in the production of dental implants. The input parameters included the type of product, a required production cycle of 60 seconds per implant, the number of production variants, and the required surface quality.

The main objectives of robotization were to eliminate manual handling between workstations, minimize downtime, and ensure collision-free, safe, and smooth movements of robotic manipulators. The outcome of this phase was a technological task specification defining individual operations between nodes in the sequence: warehouse – 3D printing – machining – surface finishing – final inspection.

Based on this specification, a conceptual design of the robotic system was developed, establishing the general architecture of the production line. The material warehouse serves as the system's entry point, where semi-finished products are automatically fed onto the conveyor. In the 3D printing node, additive manufacturing of implants is performed using laser melting of metallic powder. Upon completion of the printing process, the robot collects the printed parts and transfers them to the CNC machining center, where threads, grooves, and precision mating surfaces are processed.

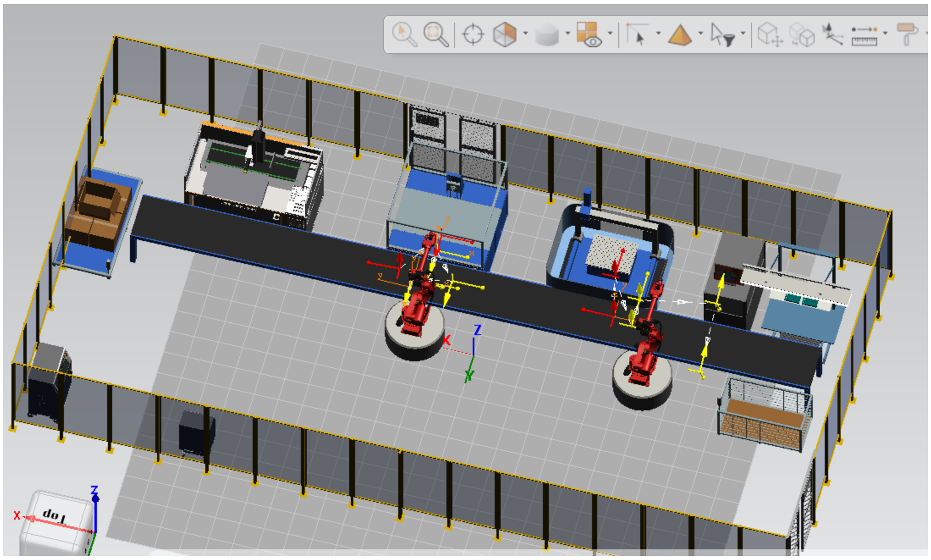

Fig. 8 Created model of robotic workplace for dental implant production

Following machining, surface finishing operations take place, simulating grinding, polishing, and cleaning of the implant surface. The robot ensures part handling between the individual stations within this section. The final node is the inspection station, where automated measurement and dimensional comparison of the implant against its digital model are carried out.

Based on this analysis, two robots were defined: the first dedicated to handling between the warehouse, 3D printing, and machining nodes, and the second responsible for operating the section involving surface finishing and quality inspection.

In the next phase of the methodology, the layout design and spatial optimization were carried out. Within the Tecnomatix Process Simulate environment, a detailed three-dimensional model of the workstation was created, including all technological equipment, conveyors, robotic arms, and safety fences. The positions of individual devices were optimized to achieve minimal handling distances while ensuring sufficient workspace for robot motion. A separate coordinate system was defined for each node, allowing precise identification of work positions and trajectories. Based on the analysis of robot reachability, the optimal positions of manipulators relative to technological equipment were determined. This phase also included collision detection and the design of safety zones in accordance with the international standard ISO 10218-2. The result was a validated 3D layout ready for parameterization and subsequent kinematic simulation.

Parameterization of the model and definition of activities involved precise configuration of the robots' kinematic parameters, such as speed, acceleration, working ranges, and tool center point (TCP) definitions. Logical sequences of operations were created for each robot, specifying the order of tasks and their time dependencies. A control algorithm was developed, consisting of individual commands such as "Pick," "Place," "Wait," and "Move," defining the handling of parts between work positions. In parallel, interaction between the robots and the conveyor was established through virtual signals simulating PLC system states, such as "part_ready" or "machine_busy." This step created the foundation for subsequent offline robot programming.

The next stage involved the simulation of partial operations, during which individual work tasks were tested. The simulations included material handling from the warehouse to the 3D printer, transfer of printed parts to the CNC center, transportation of machined implants to the surface treatment station, and their subsequent delivery to the inspection station. Each simulation focused on verifying timing, collision-free movement, trajectory reachability, and motion accuracy. The results demonstrated collision-free operation of all manipulations and an average production cycle of 58 seconds per implant, meeting the requirements of a synchronized production process.

After successful verification of individual tasks, an integrated simulation of the entire system was developed, representing a digital twin of the production line. The digital model enabled simultaneous real-time simulation of both robots, the conveyor, and all technological equipment.

Four key simulation scenarios were implemented and validated in Process Simulate:

- material loading and 3D printing sequence,
- validation of transfer paths and robot–printer coordination.

CNC Machining Handling

- verification of fixture accessibility and collision-free toolpath loading/unloading.

Surface Treatment Operation

- simulation of robotic polishing movements, evaluating motion smoothness and cycle time.

Automated Quality Inspection

- validation of positioning accuracy in relation to scanner field of view.

Obtained results:

- All trajectories successfully validated (no collisions or reach limit violations).
- Achieved process cycle: 58.2 seconds per implant.
- Robot utilisation: R1 = 86%, R2 = 83%.

Table 2

Expected values and obtained results from simulation

Parameter	Expected value	Obtained value
Total cycle time	≤ 60 s	58.2 s
Robot collisions	0	0
Robot utilisation	≥ 80%	R1: 86%, R2: 83%
Conveyor idle time	≤ 3 s	< 2 s

Next figure shows a graph of the movement of robot no. 1 (Arcmate_120) during a simulation cycle in the Tecnomatix Process Simulate environment. The graph is used to analyse the robot's kinematic parameters, such as the angular positions of individual joints, tool centre point (TCP) speed, and the speeds and accelerations of individual robot axes over time.

The upper graph shows the angular positions of all six robot joints (J1–J6) as a function of time. Each colour represents one axis (see legend on the right). The graph shows that the individual axes perform a smooth movement in the range from approximately –100° to +150°, with position changes occurring without sudden fluctuations, which indicates stable and smooth movement of the robot during component handling.

The middle section shows the TCP (Tool Centre Point) speed, i.e. the speed of the robot's end effector in space. The values range from approximately 0 to 850 mm/s, with several phases of movement and stopping identifiable. These changes correspond to the handling of the part – gripping, moving, inserting into the machine and releasing.

The bottom graph shows the speed and acceleration of the individual joints of the robot. Solid lines represent speed and dashed lines represent acceleration over time. The graph clearly shows that the greatest changes in speed and acceleration occur in the initial and final phases of movement, i.e. during the start-up and stopping of the robot. The maximum acceleration values reach approximately 200°/s², which corresponds to the dynamics of the robot during precise manipulation.

Overall, it can be concluded from the measured curves that the trajectory of robot No. 1 is smooth, without sudden changes in direction or instability, and that the robot performs its activities in accordance with the programmed simulation parameters. This curve confirms the optimal setting of speeds, angular trajectories and synchronisation of the movements of all robot axes during the component handling production process.

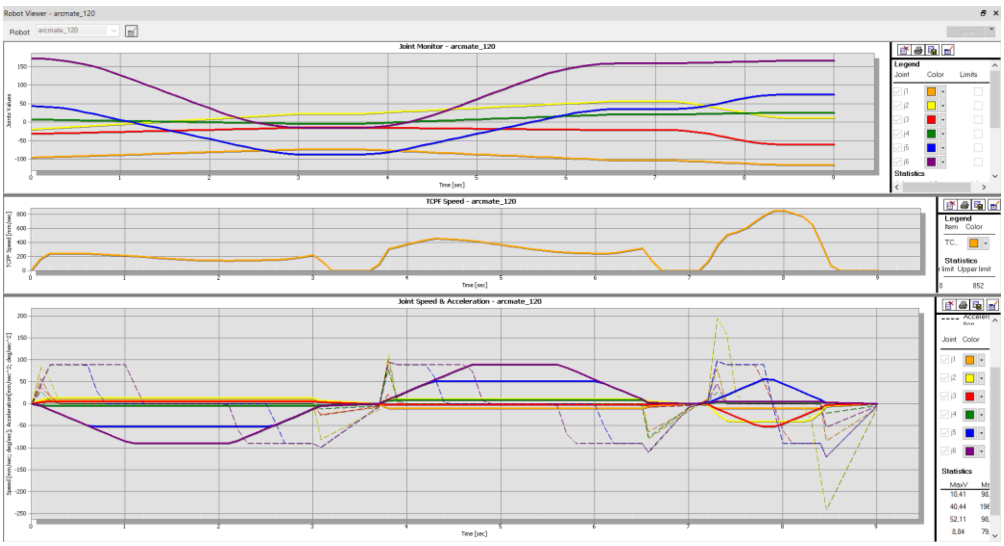

Fig. 9 Movement of Robot 1 – simulation cycle

Figure 10 presents a graph of the movement of robot No. 1 (Arcmate_120) during handling operations in the Tecnomatix Process Simulate simulated environment. This graph is used to analyse the robot's kinematics, specifically the changes in the angles of individual joints (J1 – J6) over time, and to assess their operational limitations.

The upper part of the diagram shows the time course of the angular positions of individual joints. Each curve represents one of the robot's joints, with the colours (yellow, red, green, blue, purple, orange) corresponding to axes J1 to J6. The graph shows that the robot performs smooth and coordinated movements without sudden changes, indicating stable motion control during component handling. The maximum values of the individual axes range from approximately -100° to +270°, with none of the axes exceeding the defined limits.

The lower part of the graph ("Joint Status") shows the percentage utilisation of each joint in relation to its maximum permissible range of motion. All axes are shown in green, confirming that they are operating within safe working limits. Small indicators on the paths of the individual axes mark the points of maximum deflection during the cycle. Based on the data displayed, it can be concluded that robot No. 1 is operating under optimal conditions without exceeding the permissible movement limits. The movement trajectory is smooth, symmetrical and without significant dynamic changes, which confirms the correct setting of the movement parameters and the reliability of the robot's working cycle within the production process.

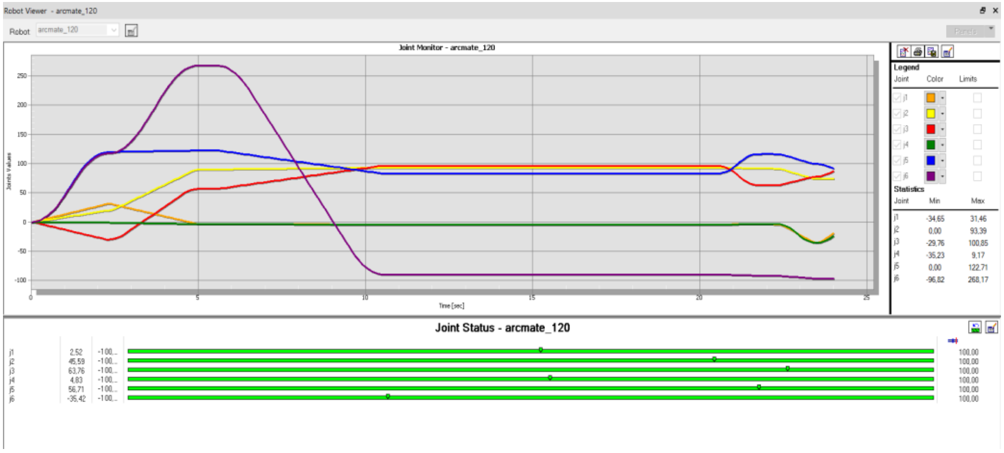

Fig. 10 Movement of Robot 1 – handling operation

Figure 11 shows a graph of the gripper's activity (Gripper 1 – RG2_v2_1), which is part of the robotic workstation simulated in the Tecnomatix Process Simulate environment. This graph documents the time course of the gripper jaws' movement during component handling, specifically during the gripping and releasing of the part.

The upper graph shows the angular positions of the two moving parts of the gripper (J1 and J2) as a function of time. It is clear from the graph that both jaws perform a symmetrical movement – closing and opening at specified time intervals, with maximum deflections reaching values of approximately ±5 mm. This movement corresponds to the cycle of gripping the part, transferring it and then releasing it.

The middle graph, showing the TCP (Tool Centre Point) speed, is practically zero in this case, as the gripper does not perform any spatial movement – its function consists solely of linear opening and closing of the jaws without changing position in space.

The bottom graph shows the speed and acceleration of the individual jaws. The solid lines represent the speed of movement, while the dashed lines represent acceleration. The graph shows that the greatest changes occur at around 4–6 seconds and 20–22 seconds, which corresponds to the moments of closing and opening the gripper. The maximum acceleration values reach approximately 90°/s², which is typical for a fast but precisely controlled gripping movement.

The graph shows that the gripper operates smoothly and symmetrically, without sudden changes or delays. The graph thus confirms that the gripper works in accordance with the simulation programme, ensuring reliable gripping and release of the implant during the production cycle.

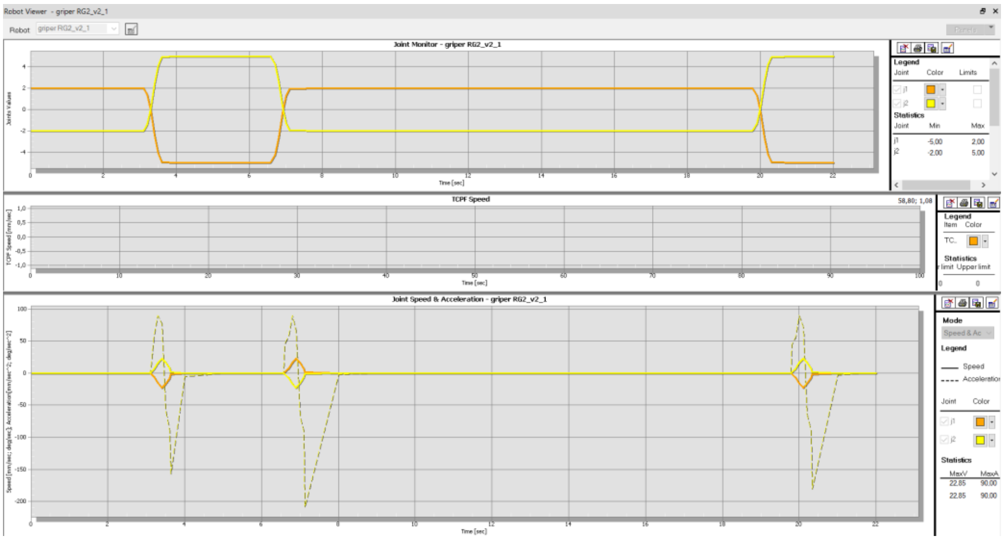

Fig. 11 Graph of the Gripper 1 activity

Figure 12 shows a graph of the movement of the second robot (Arcmate_120_1) during component handling in the Tecnomatix Process Simulate simulation environment. The graph is used to evaluate the kinematic characteristics of the robot, including the angular positions, speeds and accelerations of individual joints, as well as the speed of the end tool (TCP) during the work cycle.

The upper part of the graph shows the angular positions of all six robot axes (J1–J6) as a function of time. The coloured curves show the change in position of individual joints during component handling. It is clear that the robot performs smooth and coordinated movements in a range of approximately –150° to +150°, without sudden changes or stops, indicating a stable and precisely controlled operation.

The middle part of the graph shows the TCP (Tool Centre Point) speed, i.e. the speed of movement of the end effector in space. The graph shows that the maximum speed reaches approximately 1300 mm/s. The acceleration and deceleration phases are clearly distinguishable and correspond to individual operations – gripping, moving and placing the component within the production cycle.

The lower part of the graph shows the speeds and accelerations of the individual joints. The solid lines represent instantaneous speeds, while the dashed lines represent the corresponding accelerations. The highest acceleration values are recorded during changes in the direction of movement, i.e. during the start-up and stop of the robot. These maxima are characteristic of the dynamic phases of precise positioning.

Based on the recorded curves, it can be concluded that robot No. 2 performs movements smoothly, synchronously and without collisions, with all axes operating within defined limits. The simulation results confirm the correct setting of the trajectory, speeds and accelerations, which ensures efficient and precise handling of dental implants during the manufacturing process.

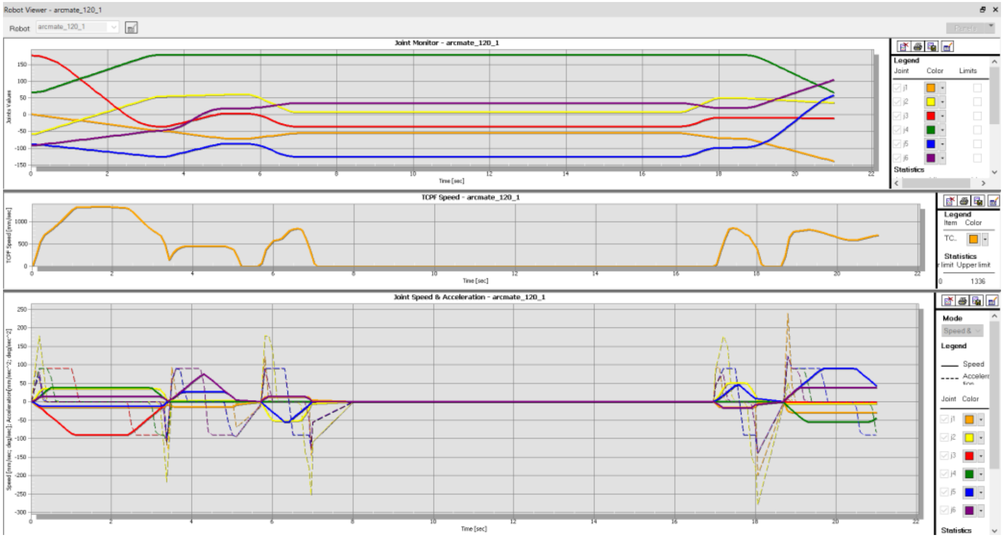

Fig. 12 Movement of Robot 2 – simulation cycle

Figure 13 shows a graphical representation of the movement of robot No. 2 (Arcmate_120_2) during handling operations in a simulated environment. This graph is used to analyse the kinematic behaviour of the robot, specifically the changes in the angular positions of the individual joints (J1 – J6) over time and their use in relation to operational limitations.

The upper part of the diagram shows the angular positions of all six axes of the robot as a function of time. Each coloured curve represents the movement of one axis (yellow, red, green, blue, purple and orange). The curves show that the robot performs smooth and coordinated movements throughout the entire work cycle, without sudden changes or exceeding the set limits. The highest angle values of the individual joints range from -95° to +200°, which corresponds to the design capabilities of the device.

The lower part of the graph ("Joint Status") shows the percentage utilisation of individual joints in relation to their maximum permissible range of motion. All axes are shown in green, confirming that the robot operates within a safe range throughout the entire work cycle. Small markings on the individual bars indicate the points of maximum deflection of the individual axes.

Based on the results displayed, it can be concluded that robot No. 2 is operating stably and efficiently, without collisions or undesirable dynamic phenomena. The movement of all joints is synchronised and smooth, confirming the correct setting of the robot's trajectory, timing and movement parameters within the automated production process.

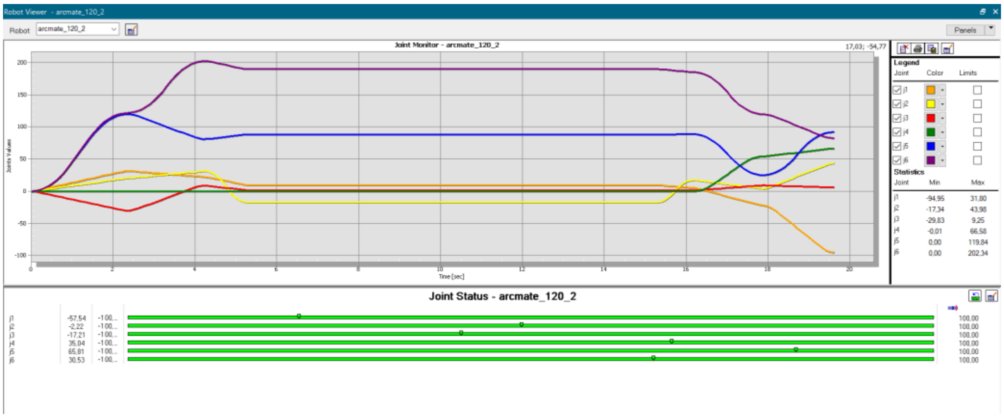

Fig. 13 Movement of Robot 2 – component handling

Figure 13 presents a diagram of the operation of the second gripper (Gripper 2 – RG2_v2_1_1), which is part of an automated workstation designed for handling components in the Tecnomatix Process Simulate environment. The diagram shows the time and position, speed and acceleration of the gripper jaws during the individual phases of the work cycle – gripping, moving and releasing the component.

The upper part of the diagram shows the angular positions of both jaws (J1 and J2) as a function of time. The curves show a symmetrical pattern, indicating that the jaws open and close evenly. The maximum deviation is approximately ±5 mm, which corresponds to the gripper being fully opened and closed. The first change in position occurs at approximately 5 seconds, when the part is gripped, and the second at approximately 20 seconds, which corresponds to its release after handling. The middle part of the diagram shows the TCP (Tool Centre Point) speed, which in this case is zero, as the gripper does not perform any spatial movement – only the jaws move without changing their position in space. The lower part of the diagram shows the velocity and acceleration of both axes of motion. The solid lines represent the velocity of the jaws, while the dashed lines represent the acceleration. The highest acceleration values occur at the moments of opening and closing the gripper, which is typical for short, precisely controlled gripping cycles. The maximum acceleration reaches approximately 90°/s², while the maximum speed of movement is around 22 mm/s.

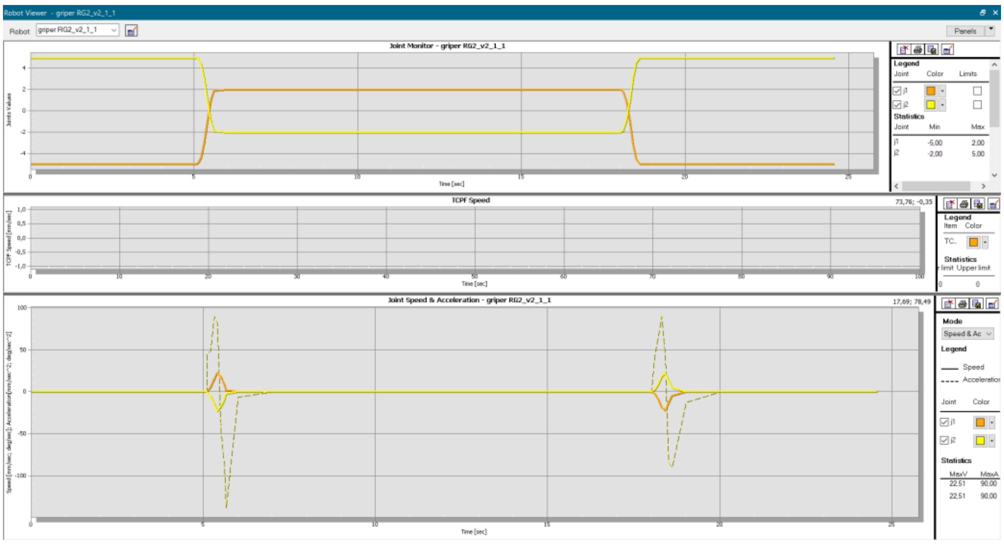

Fig. 14 Graph of the Gripper 2 activity

The diagrams clearly show that the gripper operates smoothly, symmetrically and without dynamic deviations, with individual cycles running precisely according to the defined programme. This confirms the correct functioning of the gripper during the handling of dental implants in a robotic manufacturing process.

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